THE CITY COLLEGE OF NEW YORK

Solar Hot Water Heating for the Sotomayor Houses

Abstract: The New York City Housing Authority is set to replace the central boiler plant of the Sotomayor Housing development in the Bronx, New York. This project evaluates the feasibility of replacing the steam boilers with a solar collector system for domestic hot water heating. Two system designs are compared thermally, environmentally, and economically: flat-plate and evacuated tube collectors. The results indicate that while installing an evacuated tube system provides the most environmentally friendly solution, a flat-plate collector system is the most economically sensible with only marginally greater environmental impact. Replacing the steam boiler with a solar array will save 6,000 metric tons of carbon dioxide emissions over the system's 20 year lifespan, and save over $8,000,000 in fossil fuel costs. Overall, 92% of annual hot water production can be met with a solar system.

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I. Introduction

Improvements in the science and economics of utilizing solar energy for domestic hot water heating have made solar an appealing option for a wide variety of property owners. The sun provides enough heat to satisfy hot water production needs in many locations. The primary obstacles to wide-spread adoption of solar thermal systems are economic and logistical. Property owners must weigh the benefits of installing such a system to its costs and the feasibility of installing solar arrays on the premises. The technology is mature enough that reliability concerns should no longer drive the decision to implement such a system. Solar thermal is a tried and true technology, relied upon by millions of residents around the world.

This project will seek to analyze the viability of installing a solar hot water system for the Sotomayor Houses, a large residential complex located in the Bronx, New York. The Sotomayor Houses is a low-income housing project owned and managed by the New York City Housing Authority (NYCHA). The complex consists of 28 seven story buildings, with each building containing 49 units. Currently the Sotomayor Houses have a single boiler room with five natural-gas-fired steam boilers that provide space heating and hot water to all 28 buildings. All five boilers were installed in 1980 and have surpassed their expected useful lifetime. Due to the fact that the steam boilers provide the campus with hot water, the boilers must be run in the summer time when no space heating is required. The result is an inefficient, leaking domestic hot water system with much room for improvement. All five boilers are due for a replacement at the start of 2019.

In order to evaluate the feasibility of converting the Sotomayor Houses to solar hot water, we must first decide what type of solar system to use. The two most common options are photovoltaic (PV) electric hot water and solar thermal. PV systems place solar panels on the property that convert sunlight to electricity. This electricity is then used to heat hot water through electric resistance. Solar thermal collectors on the other hand harness the sun's energy to directly heat hot water. This is accomplished by running hot water (or another fluid medium) through a series of tubes in the solar collector.

By consulting existing literature we can weigh the advantages and disadvantages of each method. In two papers written by Kalogirou et al and Parida et al, solar thermal collectors and photovoltaics are separately analyzed. Solar thermal requires less roof-top space and has a higher overall efficiency for heating hot water. Photovoltaic based water heating is less expensive to install and does not require a separate storage tank in the basement to separate it from the backup heater (as solar thermal does). B.J. Huang et al also study the concept of a hybrid photovoltaic-solar thermal setup for both hot water heating and electricity generation. The result of their study found that the hybrid methodology produces good thermal efficiency. However the integrated photovoltaic-solar thermal system costs more than either standalone technology, and photovoltaic systems alone require a large amount of rooftop space.

The Sotomayor Houses have limited rooftop space, which restricts the possibility of using a photovoltaic based hot water heater. Because of their space efficiency, a solar thermal system is the most viable option. There is still a decision to make though, as solar thermal systems come in flat-plate and evacuated-tube varieties. As analyzed by Chris Williams in the publication *Heat Spring*, flat-plate collectors are simpler and cannot overheat. Evacuated tubes, while less cumbersome, are more fragile and more difficult to manufacture. The performance is comparable in similar operating conditions, with evacuated tubes gaining a slight efficiency advantage in climates with high temperature variances.

As part of the thermal analysis, flat plate collectors and evacuated tube designs will be directly compared. Kang, Shin, and Cho contrasted the two systems in a 2017 paper and found that the evacuated tube collector operated more efficiently when water was used as the fluid medium. However they also noted that the flat plate collector design was more economical to implement. In this study we will look at both the thermal efficiency as well as the economic implications of each system to determine which is best for Sotomayor.

Finally, environmental and economic analyses will be performed to determine if a solar thermal hot water solution sufficiently offsets the significant green-house-gas emissions of the current steam boiler setup, and can be implemented in a financially practicable manner.

II. Methods

For the purposes of this analysis, we will assume full rooftop area utilization for placing solar collectors. This will maximize the amount of hot water production, which is vital due to the high-density population of the housing campus. From this assumption we can calculate the total gross area that is available for collector plate placement. The gross area number will determine how many collector plates can be installed. Finally, the number of plates will govern the volume of hot water produced. Most solar collector applications cannot provide sufficient hot water loads to meet peak demand in winter months when there is less sunlight. Therefore this project will assume a complete replacement of steam boiler hot water heaters, but rather relegate that system to a role as the auxiliary system to be used only when the demand for hot water exceeds the production capabilities of the solar collectors.

Once the number of solar collectors is known, we estimate incident solar radiation received by the system in order to perform the thermal analysis. Using the Isotropic Model and Matlab, along with Class I TMY3 data from New York City, the incident solar radiation on the plates is calculated. This value is an important variable in the overall heat gain of the collector. The code used to find the incident solar radiation used below can be found in Appendix A.

We will use analytical equations to solve for the thermal performance of two collectors. This comparison will help decide what type of collector is best for this application. The governing equation generally used for determining total heat gain of a flat plate collector is the Hottel-Whillier-Bliss equation:

$$Q_u = F_R A\big(S - U_T(T_i - T_a)\big)$$

Where Q_u is the useful heat gain of the collector transmitted to the fluid, F_R is the heat removal factor, A is the area of the collector, S is the incident solar radiation, U_T is the overall loss coefficient of the plate, T_i is the fluid inlet temperature, and T_a is the ambient air temperature. For the purposes of this analysis, all variables are assumed constant over a short period of time (<1 hour). The useful heat gain can then be used to find the mean water temperature (T_f) as well as the overall efficiency (η) using the following equations:

$$T_f = T_i + \frac{Q_u}{AF_R U_T}(1 - F_R)$$

$$\eta = \frac{Q_u}{IA}$$

An environmental analysis will be conducted to calculate how much greenhouse gases would be eliminated from the atmosphere by curbing the natural gas usage that would have resulted if the solar thermal system was not installed. The amount of natural gas abatement as a result of the solar conversion will be calculated from the total solar hot water production load. Additionally a life-cycle-emissions study will be done to calculate the overall environmental impact of the solar system. This study will be performed for both flat plate collectors and evacuated tube collectors.

Finally, an economic analysis will be performed to understand the implementation and ongoing costs associated with such a conversion. These numbers will be contrasted with NYCHA's operating and capital improvement budgets. A Life-Cycle-Analysis, as well as Present Worth, will be calculated to gauge the quality of a solar investment and how long it will take NYCHA to recoup its expenses. The economic analysis plays a large part in determining which solar collector design is most feasible.

III. Results and Analysis

a. Thermal Analysis

i. Incident Solar Radiation

The radiation calculation is done in December to size the collectors properly when there is a minimum of solar radiation available to heat water. Figure 3 is the result of the Matlab code used to estimate solar radiation in New York City on December 17th, 1997 (the representative day of December in a representative year). For this project we will assume that the collectors are stationary and tilted at an angle equal to the latitude of their location (a standard assumption for efficient absorption of maximum solar energy). The azimuth angle is set to 0^{o}, due south. The result of the Matlab code is a vector containing the average hourly radiation for every hour during December 17th using Class 1 TMY3 data taken in Central Park, close enough in proximity to the Bronx to be valid. Integrating over the length of the day will allow us to calculate the total daily solar radiation energy. Performing the integration in Matlab yields a result of $\mathbf{2.9}\ \boldsymbol{kWh/m^2/day}$. This equates to an average of about $\mathbf{240}\ \boldsymbol{Wh/m^2/hr}$ during daylight hours.

We can compare this figure to empirical results. The website PVWatts is a program run by the National Renewable Energy Laboratory. The goal of the site is to estimate solar panel electricity production for locations selected by the user. One of the pieces of information given by the site is average daily solar radiation. PVWatts compiles this data through the use of TMY3 data. Thus we can use the site as a reference for the value calculated with Matlab. Figure 4 shows the results of the PVWatts estimation for a solar collector identical to the one in Figure 3.

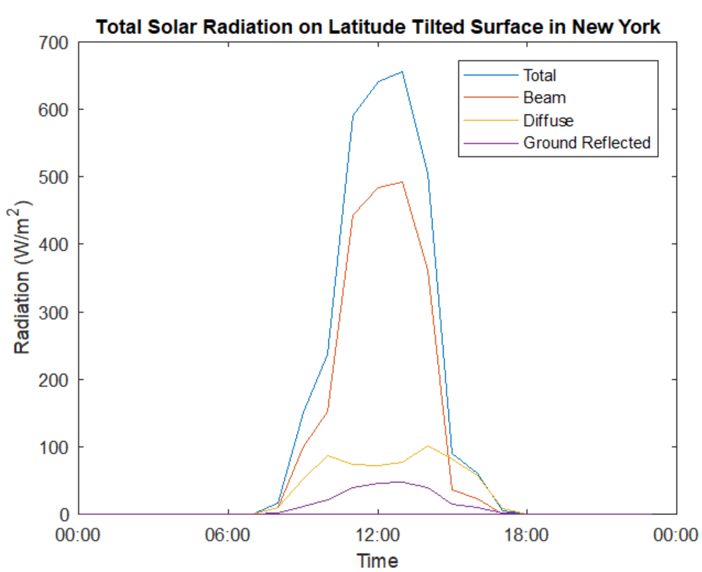

Figure 3

Month	Solar Radiation (kWh / m^2 / day)
January	3.67
February	4.61
March	4.92
April	5.26
May	5.18
June	5.53
July	5.82
August	5.54
September	5.32
October	4.64
November	3.66
December	3.02
Annual	4.76

Figure 4

We can see that for the month of December, the average daily solar radiation is 3.02 $\boldsymbol{kWh/m^2/day}$. This represents a difference of around 4% from the Matlab calculated value. The agreement between the two values is enough to conclude that they are valid. For simplicity we can take the value of $\mathbf{3}\ \boldsymbol{kWh/m^2/day}$ for the remainder of our calculations. This value represents S in the Hottel-Whillier-Bliss equation above.

The next step is to find the total area of solar collectors that the Sotomayor Houses can reasonably install. If we multiply this area with our value of $\mathbf{3}\ \boldsymbol{kWh/m^2/day}$ we will know the total output power of the solar collectors which can be translated to the volume of hot water that can be produced.

ii. *Solar Collector Design*

Due to the dense urban environment of the Sotomayor Houses, we are limited in where we can place the solar collectors. For this project we will only consider roof area as the location for the collectors. The roofs of the Sotomayor houses are unused and restricted access, which makes them the ideal location for installation. The online tool Pictometry allows a user to precisely measure rooftop area using high definition satellite imagery. This tool is used to calculate total installable area for the Sotomayor Houses, using a single representative building and extrapolating across the entire campus. We can see from Figure 5 that the area of a single building is 6,467 ft^2. The area of the elevator and mechanical room must be subtracted from this value to get the usable area. The area of the room is 530 ft^2, making a total of 5,937 ft^2. Since all 28 buildings have identical architecture, we can say that the total campus area available for solar collector installation is 166,236 ft^2. However we will also round this number down, accounting for the parapet walls, a slight spacing between each panel, and the small bezel of the collector housing. The final total area for the Sotomayor Houses is $\mathbf{150,000\ ft^2}$ or $\mathbf{13,935.5\ m^2}$. We can now multiply this number by our solar radiation value from above to estimate the total heat available to be absorbed by the array:

$$3\ kWh/m^2/day \times\ 150{,}000\ ft^2 \times 0.0929\frac{m^2}{ft^2} = \mathbf{41,806\frac{kWh}{day}}\ or\ \mathbf{150,502\frac{MJ}{day}}$$

Figure 1

If we assume standard solar collector dimensions of 2 m × 1.3 m, each collector will have an area of 2.6 m^2. This equates to a total of **5,359 solar collectors** across the Sotomayor Houses. We can use these values to find the total amount of hot water produced by multiplying 150,502$\frac{MJ}{day}$ by the efficiency of each panel. This final heat value will govern how much hot water can be heated each day.

iii. *Solar Heat Transfer for Flat Plate Collectors*

We now have the information we need to perform an analytical calculation to estimate how much hot water the collector array can generate. The calculation will be done for a single solar collector and then scaled to find the production of the entire array.

To solve for useful heat gain, we first calculate the constant heat removal factor F_R. This variable can be broken into two constituent parts:

$$F_R = F'F''$$

Where F' is the collector efficiency factor and F'' is the flow rate factor. Some assumptions must be made to find F', including the flow rate of the liquid, plate thickness, tube spacing and diameter, overall loss coefficient, and heat transfer coefficient of the plate material. These assumptions are based on empirical data from solar collector manufacturers and specification sheets[1]. These assumptions are listed in Table 1:

Tube Spacing	*150mm*
Tube Diameter	*10mm*
Plate Thickness	*0.4mm*
Thermal Conductivity	$385\ W/m^2\ {}^0C$
Heat Transfer Coefficient Inside Tubes	$300\ W/m^2\ {}^0C$
Overall Loss Coefficient	$8\ W/m^2\ {}^0C$
Water Flow Rate	*0.03 kg/s*
Water Inlet Temperature	$35\ {}^0C$

Table 1

The equation describing collector efficiency is:

$$\mathrm{F'} = \frac{1}{U_T} \times \frac{1}{\mathrm{W}\left[\frac{1}{U_T\,[\mathrm{D} + (\mathrm{W} - \mathrm{D})\,\mathrm{F}]} + \frac{1}{\pi \mathrm{Dh}}\right]}$$

Plugging in values from Table 1, we get a value of $F' = 0.82$. Using this value we can now solve for the flow factor F'' using the following equation:

$$F'' = \frac{\dot{m}C_P}{AU_TF'}\left(1 - \exp\left(-\frac{AU_TF'}{\dot{m}C_P}\right)\right)$$

Using the values from Table 1 we get a result for $F'' = 0.93$. Finally we now know $F_R = 0.93 \times 0.82 = 0.76$. Keeping the assumed water inlet temperature as above and an ambient temperature of -12^0C, we solve for the useful heat gain of the collector during the peak hour of 12:00-1:00PM:

$$Q_u = 0.76 \times 2.6\big(2.25 - 8(35 - (-12))\big)x3600 = 0.900\frac{MJ}{hr}$$

This is the solar gain of each collector during peak production hour in December. To determine how this energy effectively heats water, we plug Q_u into equation 2 to get mean fluid temperature in the tube:

$$T_f = 35 + \frac{0.900 \times 1000}{2.6 \times 0.76 \times 8}(1 - 0.76) = 46^0C$$

We can also solve for the efficiency of the collector during this hour:

$$\eta = \frac{0.900}{1.2 \times 2.6} = \sim 30\%$$

Thus the peak efficiency of each collector plate during the representative day in December is **30%**. With the total heat incident on each collector known, as well as the collector efficiency, we can now calculate how much hot water the array can produce:

$$150{,}502 \times 30\% = 43{,}645\frac{MJ}{day}$$

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[1] http://www.htproducts.com/literature/lp-364.pdf

This value can be directly converted into the number of gallons of hot water produced knowing inlet (35^0C) and required hot water supply temperatures (48^0C), as well as weight of water per gallon:

$$43{,}645\frac{MJ}{day} = 41{,}367{,}478\frac{BTU}{day}$$

The definition of a BTU is the amount of heat it takes to raise the temperature of 1 pound of water by 1-degree Fahrenheit. Therefore the total amount of gallons that $41{,}367{,}478\frac{BTU}{day}$ can heat is **198,405 gallons** from 35^0C to 48^0C per day. Assuming a total resident count of 3,500 occupants, each needing around 40 gallons of hot water per day, the total Sotomayor hot water need is **140,000 gallons**. Therefore even during the winter months, based on these numbers, the proposed flat plate collector installation should be able to produce sufficient hot water for the campus.

However this calculation assumes that there is clear sky radiation every day of the year, which is certainly not the case. In order to get a more accurate estimate, we need to account for the number of cloudy days. Using meteorological data from NOAA we can estimate the percentage of days with clear sky in New York City. With the remaining days of the year with cloud cover, we can de-rate the solar system efficiency to account for the loss in collector efficiency during cloud cover[2]. These effects are included in Table 2 below.

iv. Comparison to Evacuated Tube Collectors

An analysis can be done to compare how the above proposed flat plate collector installation would compare to an evacuated tube installation of similar design. An equivalent to the Hottel-Whillier-Bliss equation for evacuated tube collectors is not available, however empirical data can be used to compare the efficiency of such systems. Figure 6 shows how the efficiency of both flat plate collectors and evacuated tubes compare as a function of the difference in temperature between the ambient air and the tube inlet (a standard performance benchmark).

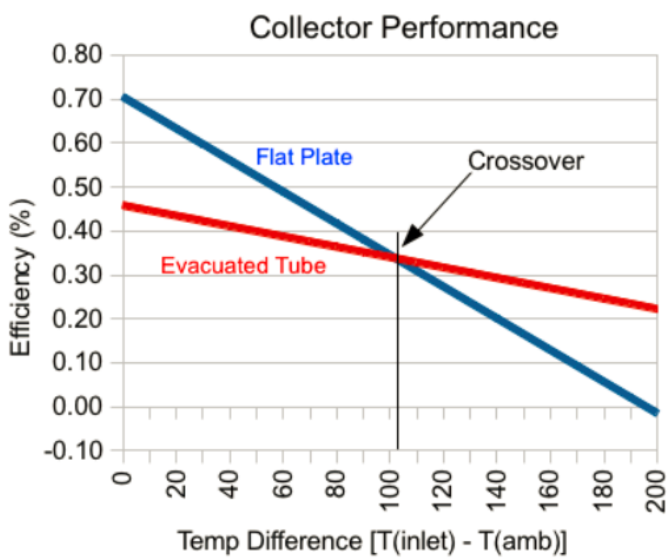

Figure 2[3]

These efficiency curves show that for the warmer seasons in New York City a flat plate collector will be more operationally efficient than an equivalent evacuated tube system. However in the winter months when the ambient temperature drops, evacuated tube systems retain their ability to produce hot water much more efficiently. Additionally, evacuated tube collectors are able to produce more hot water during cloudy days. Thus the decision about whether to use a flat plate or evacuated tube system may very well depend on the severity of the winter and

[2] https://www.ncdc.noaa.gov/oa/wdc/index.php?name=climateoftheworld
[3] http://www.solarhotwater-systems.com/evacuated-tube-versus-flat-plate-solar-hot-water-panels/

cloud cover throughout the year. An efficiency analysis of the two systems for different times of year is presented in Table 2. Another consideration is that evacuated tube systems are up to twice as expensive per kWh as flat plate collectors. This will be an important factor in the economic analysis to determine which system should be installed for Sotomayor.

System	Peak July Efficiency	Peak December Efficiency	July Water Production (gallons)	December Water Production (gallons)	July Cloud Cover Efficiency[4]	December Cloud Cover Efficiency	Cloud Adjusted July Production	Cloud Adjusted December Production
Flat Plate Collector	65%	30%	755,203	198,405	48%	18%	657,608	123,242
Evacuated Tube Collector	45%	35%	522,833	231,473	37%	27%	475,654	197,955

Table 2

The results from Table 2 suggest that the flat plate collector will not provide enough hot water in the winter months to fully meet the hot water demand of the Sotomayor Houses. The overproduction in the summer months is not helpful either, since hot water cannot be economically stored for a long period of time to cover the need in the winter. This will necessitate an auxiliary system to provide hot water during these time periods, in this case the space heating boiler plant. The evacuated tube system on the other hand will meet the hot water demand year-round. This fact is taken into account in the economic analysis below.

v. Hot Water Storage

Each of the 28 buildings has an existing 5,0000 gallon insulated homogenous hot water tank installed in the basement. The tanks are clad in 4 inches of fiberglass insulation, which greatly improves thermal retention. We can calculate the heat losses of the tank, and thus the efficiency, through a simple heat conduction equation:

$$Q = UA\Delta T$$

Where U is the thermal resistance value, A is the surface area of the tank, and ΔT is the difference in temperature between the hot water and the ambient air of the mechanical room. We can look up the U-value for four inches of fiberglass insulation and easily calculate the area:

$$U - value\ for\ 4''\ fiberglass: 0.07\frac{W}{m^2K}$$

$$Surface\ Area\ of\ Tank: 15\ m^2$$

$$Q = 0.7 \times 15 \times (48 - 32) = 168\ W$$

Multiplying this value by 28 total storage tanks we get **4,704 W** of heat loss from the tanks. With a total heat production of 43,645 MJ/day, this represents a tank efficiency of 97%. Additional system losses due to piping and distribution are estimated and subtracted from tank efficiency to give a final efficiency of 95%. When compounded with the plate efficiencies listed in Table 2, we can get final values for December hot water production for a solar system at Sotomayor:

[4] The July and December cloud-adjusted values are derived from the number of clear sky hours per month taken from NOAA weather data in footnote 2. The de-rated efficiency is used for the remaining daylight hours of the month. The cloudy month efficiencies are derived from the empirical study: http://www.its-solar.com/wp-content/uploads/flat-plate-vs-evacuated-tube1.pdf

System	System Production[5]	Tank and distribution Efficiency	Total Usable Hot Water in December
Flat Plat Collector	123,242	95%	117,079
Evacuated Tube Collector	197,955	95%	188,057

Table 3 – All Values in Gallons

b. Environmental Analysis

The environmental analysis is done through a Life Cycle Emissions (LCE) study as well as a direct comparison to carbon emissions of the alternative to the proposal solar installation. The LCE is governed by the following equation:

$$LCE = \frac{\sum GWP \times (E_f + E_c + E_o + E_d)}{Q}$$

Where GWP is the global warming potential factor, E_f is the amount of direct emissions from the solar collector array, E_c is the amount of emissions released during the construction of the array, E_o is the emissions during operation and maintenance of the array, and E_d is the emissions during the decommissioning of the array at the end of its life-cycle. The majority of the carbon emissions of the solar array will come during its installation since it is a mostly passive system once it is in place. The following table shows the total LCE for the solar hot water system based on values gathered in the literature survey.

	Flat Plate Collector		Evacuated Tube Collector	
	$g - CO_2/kWh$	Share	$g - CO_2/kWh$	Share
Construction	40	71%	41	74%
Circulator Pumps	9	15%	9	15%
Control Units	3	5%	3	6%
Make-Up Power	3	5%	1	2%
Total Operation	14	25%	12	22%
Decommissioning	2	4%	2	3%
Total	57	100%	55	100%

Table 4

In relative terms, both the flat plate collector and evacuated tube design have similar emissions. Yet the flat plate collector will lead to more carbon emissions over its lifetime. Comparing both totals of 57 and 55 $g - CO_2/kWh$, we see that it is far less than comparable LCEs for other energy production methods such as coal (975), fuel oil (742), and liquid natural gas (607). Therefore we can conclude that it is significantly better for the environment than keeping the status quo of the natural gas fired steam boilers. We can estimate how much natural gas use is avoided by using the solar hot water system:

[5] System Production is the total yearly production from the collectors assuming a linear distribution of cloudy days in the months between July and December

For a flat plate collector, assuming 140,000 gallons of hot water is heated from 35^0C to 48^0C using steam from the natural gas boilers, this equates to 15,178,800 BTU of heat every day. This is the equivalent of 152 therms of natural gas saved, which is equal to 1,769 pounds of carbon dioxide per day[6]. Over the course of a year, the total carbon abatement of the solar system compared to existing natural gas boilers is **645,995 pounds of carbon dioxide saved**. Over the 20 year anticipated lifespan, this is the equivalent of almost **6,000 metric tons** of carbon dioxide that is not emitted into the atmosphere. An evacuated tube collector is even more environmentally friendly, releasing **6,250 fewer metric tons** than a natural gas boiler.

c. Economic Analysis

There are several factors that come into play when calculating the economics of installing a solar hot water system. Installation costs for solar versus the alternative traditional system, tax incentives, loan financials, and inflation all play roles in the financial analysis. A Life-Cycle-Analysis is the most effective way to quantify the cost of installing a solar system. For both the flat plate and evacuated tube systems we assume an initial capital expenditure of $2,000,000, with the remaining up-front costs financed at 5% interest. The following values are derived in part from the System Advisor Model software package, screen shots of which are attached in Appendix B.

	Flat Plate Collector	*Evacuated Tube Collector*
Installation Cost	*$600/m^2*	*$1,100/m^2*
Operations & Maintenance Cost	*$50/kW/yr*	*$50/kW/yr*
Parasitic Energy Cost	*$21,560/yr*	*$21,560/yr*
Auxiliary Hot Water Production Cost[7]	*$8,500/yr*	*$0/yr*
Mortgage Cost	*$216,000/yr*	*$340,000/yr*
Tax Incentives[8]	*$2,508,300*	*$4,598,550*
Total Installation Cost	*$5,900,000*	*$10,700,000*
Total Annual Recurring Cost	*$270,000*	*$386,410*
Total Debt	*$3,900,000*	*$8,700,000*
Total 20 Year Cost	*$11,300,000*	*$18,428,200*

Table 5

We can see from Table 5 that there is a significant cost difference between installing an evacuated tube system and a flat plate collector system. Due to the large discrepancy in pricing, and the minimal operational benefit of evacuated tubes, the sensible decision is to opt for **flat-plate collectors**.

In order to compare these numbers to the cost of a conventional hot water system, we can perform a lifecycle savings analysis. This analysis includes calculating the present worth of future solar savings to quantify in today's

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[6] https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[7] The Auxiliary Hot Water Production cost is the amount spent to heat hot water by conventional gas boiler methods due to a lack of solar capacity in winter months and cloudy conditions.

[8] Tax incentives include a 30% federal tax credit on installation cost with no limit, and a maximum of $5,000 state credit.

dollars how much money is saved by avoiding conventional fuel sources. The equation for present worth for a series of payments is given by:

$$PW = \frac{A(1+i)^{N-1}}{(1+d)^N}$$

Where PW is the present worth, A is the principle sum, i is inflation rate, d is the discount rate, and N is the time period. For the given 20 year period of the flat plate collector, we can compare the costs to the natural gas boiler system. These results are tabulated in Table 6[9].

Year	Fossil Fuel Savings[10]	Solar Annual Cost	Tax Deductions	Present Worth of Solar Savings
1	$125,000	$270,000	$5,000	-$145,000
2	$137,500	$270,000	$0	-$132,500
3	$151,250	$270,000	$0	-$118,750
…	…	…	…	…
20	$840,937	$270,000	$0	$570,937
Total	$8,000,312	$5,670,000	$0	$2,330,312

Table 6

The present worth factor represents how much money would have to be invested now at market rates to equal the total value in the future, accounting for inflation. The total present worth of the amount saved by switching to solar is **$2,330,312**. On top of that value, because new space-heating boilers must be installed anyway, there is an added economic incentive to install a solar flat plate collector system.

Another interesting data value we can derive is the solar fraction, which is the percentage of the hot water load that can be heated only with solar energy. Using the System Advisor Modeling software, this value was computed to be 92% for this flat plate collector system. This means that during the winter months when the gas boilers are required to supplement the solar collectors, the percent of total hot water they heat is 8% of the total annual load. This is a high percentage and indicates that the collector array as proposed is well sized. Finally, the Simple Payback is a calculation used to specify how many years are required to recoup the initial investment in the energy saving measure. In this case, based on the analysis outlines in Table 5, the Simple Payback for installing a flat plate solar hot water system is **11 years**. In a separate calculation not included in the table above, the Simple Payback for the evacuated tube system is close to 20 years, which we estimate to be the expected useful life of the array.

[9] Standard values of 2.5% inflation and 3% discount rate are assumed. The evaluation time period is 20 years

[10] An estimate of 10% annual increase in cost for fossil fuels year over year is used

IV. Discussion

The objective of this study was to investigate the operational and economic viability of replacing Sotomayor's current steam driven domestic hot water system with a solar collector system. Through the analysis conducted above, we can conclude that a flat plate solar collector array would be able to provide almost all of Sotomayor's domestic hot water needs. Even though such an installation would require a large capital expenditure, the amount of money saved in operation costs provides adequate return on investment. Additionally, the current opportunity to install solar comes at an economically advantageous moment, as Sotomayor's boiler plant replacement project necessitates a large capital expenditure regardless of an upgrade to solar. If the Sotomayor development chooses to implement solar, they will be able to downsize their current boiler plants. This will reduce the amount spent on carbon emitting systems and lead to lower natural gas usage over the lifetime of the boilers.

One of the goals of this project was the comparison of flat plat collector and evacuated tube systems. The thermal analysis showed that the evacuated tube design would deliver more reliable hot water throughout the winter due to the higher efficiency of the design in cloudy weather. However because of the sophistication and complexity required to properly manufacture evacuated tubes, they prove to be economically unrealistic. This point is emphasized by the fact that NYCHA, the owner and operator of the Sotomayor Houses, is a publically funded non-profit entity with strict monetary concerns and a perpetual budget deficit. Though the flat plate maintains a solar fraction of 92%, the cost of natural gas required to make up the remaining 8% is economically reasonable. The flat plate system will also provide a significant carbon emission reduction over its lifetime.

One assumption made in this analysis is that the insulated hot water tanks will hold sufficient heat to keep the hot water at proper delivery temperatures throughout the nighttime when solar power is not available. Given the high R-value of the tank insulation, such an assumption would likely not impact the thermal analysis profoundly. However a possible subject of further research is how accurate this assumption is, and if any supplemental heating systems are required.

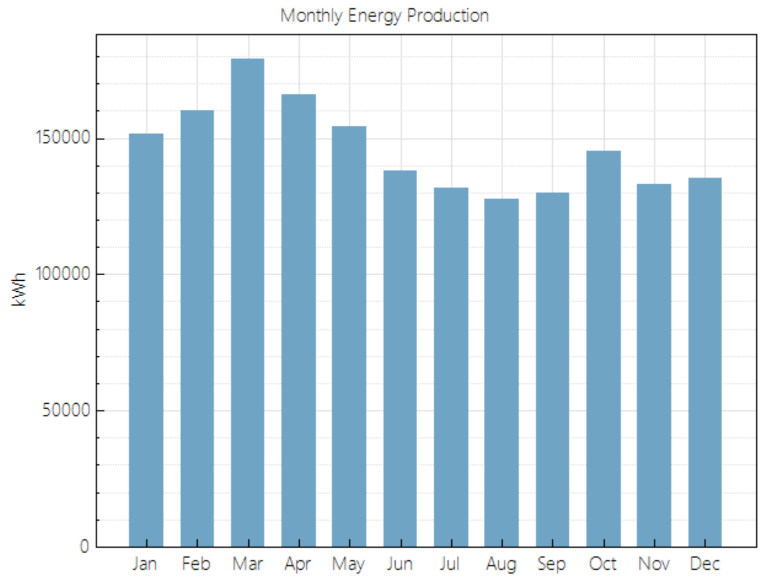
The goal of this study was successfully met, and a final conclusion from this effort is that installing a flat-plate collector solar hot water system is both environmentally and fiscally prudent. Despite the financial gravity of NYCHA's situation, the solar hot water system as proposed will save money in the long run. Additionally, installation will signal New York City's willingness to be at the forefront of environmental action and to serve as a model to be emulated by other local governments.

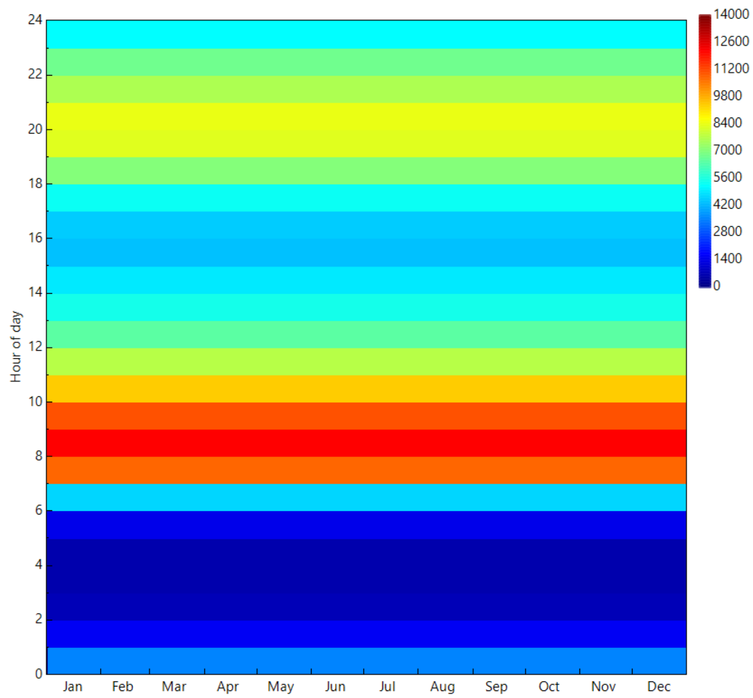
Appendix A: Matlab Code

```
Estimate total hourly radiation on a tilted surface using beam and
% diffuse radiation as input using the isotropic model

clear all

%fid = fopen('data1.csv');
data = csvread('new york.csv');
I = data(385:408,1);
Ib = data(385:408,2);
Id = data(385:408,3);

fid = fopen('datehour.csv');
traw = textscan(fid,'%q');
traw2 = vertcat(traw{:});
time = datetime(traw2,'inputformat','yyyy-MM-dd-HH-mm'); % properly formatted date and hour vector

% Calculations are based on December 17th, 1987 in New York City

n = 351 % Julian day
phi = 43 % Local latitude
beta = 43 % Slope angle of surface
omega = -165:15:180 % Hourly angle 15*hour from solar noon.
delta = 23.45*sind((360/365)*(284+n)); %declination
rho = 0.8 %reflectivity of the ground

Rb = ((cosd(phi - beta).*cosd(delta).*cosd(omega)) + (sind(phi - beta).*sind(delta)))./...
    ((cosd(phi).*cosd(delta).*cosd(omega))+(sind(phi).*sind(delta)));
% This equation for Rb is for the northern hemisphere only


It = (Ib.*transpose(Rb)) + Id*((1+cosd(beta))/2) + I*rho*((1-cosd(beta))/2);
Ig = I.*rho.*((1-cosd(beta))./2);
Ib2 = Ib.*transpose(Rb);
Id2 = Id*((1+cosd(beta))/2);

figure(1);
plot(time(4729:4752),It,time(4729:4752),Ib2,time(4729:4752),Id2,...
    time(4729:4752),Ig)
legend('Total','Beam','Diffuse','Ground Reflected')
title('Total Solar Radiation on Latitude Tilted Surface in New York');
xlabel('Date')
ylabel('Radiation (W/m^2)')
```

Appendix B: SAM Screenshots

Metric	Value
Annual energy saved (year 1)	1,752,620 kWh
Solar fraction (year 1)	0.92
Aux with solar (year 1)	157,712.4 kWh
Aux without solar (year 1)	1,910,416.6 kWh
Capacity factor (year 1)	2.5%
Levelized COE (nominal)	67.70 ¢/kWh
Levelized COE (real)	62.34 ¢/kWh
Electricity bill without system (year 1)	$1,664
Electricity bill with system (year 1)	$-34,676
Net savings with system (year 1)	$36,341
Net present value	$-11,666,946
Payback period	NaN
Discounted payback period	NaN
Net capital cost	$9,074,917
Equity	$2,722,475
Debt	$6,352,442





Hot Water Demand (Gallons)

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