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- Munters Corporation
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- National Energy Consultants
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...for Energy Industry Professionals
From the Editor

What’s an Energy Manager to Do?

So, the new U.S. administration is (mostly) in place and many major cabinet and sub-cabinet positions have been filled. Let’s assess the current conditions. The person appointed to head the U.S. Department of Energy (DOE) previously campaigned to eliminate the DOE. Granted, he (now) admits that he did not understand the mission of the federal agency. Nonetheless, he is now the U.S. Secretary of Energy. In his welcoming address to the agency (which you can find online), he describes himself as a great manager, even though he still does not fully understand what the DOE scientists and engineers are seeking to accomplish.

Similarly, the person appointed to head the U.S. Environmental Protection Agency (EPA), who disbelieves in climate change, made a career out of taking the EPA to court in repeated attempts to void environmental regulations.

Furthermore, Executive Order 13783, Promoting Energy Independence and Economic Growth, was signed, eliminating several energy and environmental directives and regulations. To top this off, the 2018 federal budget, submitted by the administration, proposes to reduce the EPA budget by 31% and reduce the DOE budget by 6%, including the elimination of Energy Star, the Advanced Research Projects Agency-Energy (ARPA-E), and other energy efficiency programs.

Since their inception, both the U.S. Department of Energy and the Environmental Protection Agency have been major advocates for energy efficiency and energy management. I personally believe the DOE Office of Energy Efficiency and Renewable Energy budget should be enhanced rather than depleted. Many of the DOE and EPA energy-efficiency-related programs provide a net-cost benefit to the country’s economy, even creating higher-quality jobs. With this new leadership in mind, it is reasonable for an energy manager to be concerned about making continued progress. So, what is an energy manager to do? I empathize with your concern, but your efforts are needed now more than ever.

As I noted in “And Now for Something Completely Different” (Vol. 114, No. 2), I believe energy management is good/sound business practice. My advice, for those concerned, is to consider taking a different
approach when seeking approval for new energy projects. One energy executive advisor I admire recommends presenting energy projects in terms of what the management most wants to accomplish, using the language they value. Personally, I like return-on-investment. If I can borrow money at 5%, and if the company’s current capital return is (let’s say) 8%, then if a proposed new sales project is expected to return 10% and a proposed new energy project is expected to return 25%—then the energy project is more likely to be funded. However, some executives might not speak that language.

Business executives generally have some key goals and use specific metrics to ensure decisions are aimed at achieving those goals (e.g., increase sales, increase margins, improve customer retention, avoid regulatory conflicts, and a host of other key performance indicators). Present the benefits of your energy project using terms your finance department and executive officers value, and articulate how the project is aligned with the company’s goals and objectives. Remember, it is our job to speak in terms of their language and values. (You will never see a new advertising campaign or modernized production-line proposal presented in terms of payback. So, why should you?)

I don’t want to ignore the issues presented earlier, so I will give you some good news from a recent report by the U.S. Energy Information Agency (August 2016).

In contrast to Executive Order 13783, I interpret these cost data as good energy and environmental news. Clean energy sources are now less expensive than other alternatives (and these cost data exclude tax credits). The average life of a coal-fired power plant is 40 years and 74% of existing coal-fired plants exceed 30 years old (National Association of Regulatory Utility Commissioners, March 12, 2013). Utilities are businesses, and they make decisions driven by costs. The table’s data indicate that coal is just not cost effective today. In the U.S., solar and wind accounted for almost 2/3 of the new generating capacity brought online in 2016 (US EIA, March 1, 2016). In Europe, renewable energy sources accounted for almost 90% of new power in 2016 (The Guardian, February 9, 2017).

I’ll close this note with a final thought. Energy-efficiency is the cleanest energy source and can be the resource with the lowest levelized cost. As advocates of energy efficiency, we bring tremendous value to our companies and clients.

Steven Parker, PE, CEM
Editor-in-Chief, Energy Engineering
steven.99.parker@gmail.com
U.S. Average Levelized Cost of Energy (LCOE) for New Generating Plants ($/MWh, 2015 dollars)

<table>
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<th>Plant Type</th>
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<td>Hydroelectric</td>
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<td>Natural Gas-fired Conventional Combined Cycle</td>
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<td>Geothermal</td>
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**Excel in Excel®!**

_Ganesh Ayer, PE, CEM, LEED-AP®_

**ABSTRACT**

Regression analysis is a statistical technique that can be used to identify and analyze the relationship between one or more independent variables and a dependent variable. In plain language, regression basically answers the following two questions:

- Can we get an equation that relates the variables?
- Can we assess the strength of the relationship?

In short, the goal in regression analysis is to identify a function of the independent variables that adequately accounts for the behavior of the dependent variable. In this article, we will learn about the tools and methods available in Excel for performing regression analysis. We will confine our discussion to linear regression as this is what you will frequently see in energy engineering calculations.

**LINEAR AND NON-LINEAR REGRESSION**

Regression analysis can be classified into 2 broad categories:

- Linear regression, where the coefficients of the model are linear. What this means is that when the independent variable is varied in one direction, the dependent variable varies in only one direction, which may be increasing or decreasing. Linear regression can be a straight line or curved. For example, the form \( y = mx + c \) yields a straight line and a second order or quadratic equation such as \( y = ax^2 + bx + c \) yields a curve. For example, if you plot the kW/ton of a twenty-year old centrifugal chiller at various loads, you would expect to see a curve because in most cases the chiller efficiency is best between 70 and 90% of the rated capacity depending on the manufacturer. We can fit many straight lines or a curve for a given set of data, but we are interested in finding the most suitable line or curve. The best fitting straight line or curve is the one that has
minimum sum of the squares of the deviations from the line. This is called as the method of least squares.

- Non-linear regression is when the coefficients of the model are non-linear. For example, \( y = Ae^{-x} + C \) is a function where for the lower values of \( x \), \( y \) almost varies linearly but then the rate of decay flattens out at higher values of \( x \) variable.

**MANUAL METHOD**

The manual methods for regression analysis are pretty math intensive and further, if one data point gets changed, added or deleted, we may have to perform the analysis again from the beginning. With Excel, all the complex math is done behind the scenes and regression analysis is effortless.

While the manual method is cumbersome, it is worth looking at the calculations to understand the steps involved in the analysis. Let us look at the relationship between the chiller load in tons and input power consumed in kW, as shown in Figure 1. We know the kW consumed by the chiller at different load capacity. This may come from manufacturer or from field measurements. We may want to derive an equation relating the power consumption as a function of chiller load so that we can use this equation in energy savings calculation models such as the ones that use the temperature bin data.

Figure 1 shows the steps to get an equation of the form \( y = mx + c \). The independent variable ‘\( x \)’ is the chiller capacity in tons and dependent variable ‘\( y \)’ is the power consumed in kW corresponding to the chiller capacity. To get the linear equation, you need to calculate \( x^2 \) and \( xy \) product for each data point, calculate the sum of \( x, y, x^2 \) and \( xy \) values and compute the quantities \( \Delta, D_1 \) and \( D_2 \). It can be seen that multiple steps are involved in arriving at the regression equation.

**REGRESSION USING EXCEL**

Excel provides a number of functions that allows users to perform regression analysis. Detailed below are four ways to use Excel for regression analysis, from simple to advanced methods.
The simplest tool that Excel has for regression is *trendline*. We will use the same data set (chiller load vs. kW) shown in Figure 1. The first step is to select the x and y data and draw the scatter chart with just the markers. If you recall from the Excel charting article (Energy Engineering, 113-4, pp 26-40), scatter charts have numerical values along both x and y axis. Scatter charts are frequently called as ‘xy’ charts. Scatter charts help us see visually if there is a relationship between two variables. In our example, chiller load in tons is the x variable and kW input is the y variable. “x” is the independent variable or the predictor variable, meaning we are trying to find the kW consumed at a given tonnage. “y” is the dependent or predicted variable. It is also called a response variable, meaning for the given tonnage, the model will predict the kW input required by the chiller.

After you draw the scatter chart, right click on one of the data points on the chart and select “Add Trendline” and choose the trend/regression type. In this case, the points appear to be linear and therefore we can choose the linear option. Check the boxes for display equation on chart and display R-squared value on chart, as shown in Figure 2. As you can see, Excel automatically draws the trend line and shows the equation of the straight line and $R^2$ value. Note that this method provides only the equation and $R^2$ value as text on the chart. If you want to use the equation and conduct advanced analysis such as significance tests, you need to use one of the other methods.

A few important points:

1) What is $R^2$?
$R^2$ is called the coefficient of determination. In simple terms, it tells you about the goodness of fit for our line. $R^2$ has a value between 0 and 1. If all the points are on the line, then $R^2$ will be equal to 1. As the value goes towards 0, the model is not a strong predictor, meaning erroneous results are likely. A value anything close to 1 means our model predicts well. $R^2$ can be used for linear as well as nonlinear relationships.

2) Which type of trend line to choose?
There are six types of trend lines to select from in Microsoft Excel. When your data points appear to be in a straight line, you must first try the linear type. If your plotted data points increases or decreases sharply at first and then starts to become nearly constant,
### Table 1: Linear Regression Data

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<thead>
<tr>
<th>Tons</th>
<th>kW</th>
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<tbody>
<tr>
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</table>

<table>
<thead>
<tr>
<th>n</th>
<th>x (Tons)</th>
<th>y (kW)</th>
<th>$x^2$</th>
<th>xy</th>
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<td>1</td>
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<td>22,500</td>
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<td>160,000</td>
<td>68,400</td>
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<td>Σ</td>
<td>5,550</td>
<td>2,438</td>
<td>3,862,500</td>
<td>1,699,400</td>
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\[
\begin{align*}
\Delta &= \left| \begin{array}{cc}
\Sigma x^2 & \Sigma x \\
\Sigma x & n \end{array} \right| \\
D_1 &= \left| \begin{array}{cc}
\Sigma xy & \Sigma x \\
\Sigma y & n \end{array} \right| \\
D_2 &= \left| \begin{array}{cc}
\Sigma x^2 & \Sigma xy \\
\Sigma x & \Sigma y \end{array} \right|
\end{align*}
\]

\[m = \frac{D_2}{\Delta} \quad b = \frac{D_1}{\Delta}\]

\[
\Delta = \begin{vmatrix}
\sum x^2 & \sum x \\
\sum x & n
\end{vmatrix}
\]

\[
D_1 = \begin{vmatrix}
\sum xy & \sum x \\
\sum y & n
\end{vmatrix}
\]

\[
D_2 = \begin{vmatrix}
\sum x^2 & \sum xy \\
\sum x & \sum y
\end{vmatrix}
\]

\[
\Delta = \begin{vmatrix}
\sum x^2 & \sum x \\
\sum x & n
\end{vmatrix} = \begin{vmatrix}
3862500 & 5550 \\
5550 & 10
\end{vmatrix} = 7822500
\]

\[
m = \frac{D_2}{\Delta} = \frac{1699400}{7822500} = 0.44271
\]

\[
b = \frac{D_1}{\Delta} = \frac{2438}{7822500} = -1.9041
\]

\[
y = 0.4427 \times 1.9041
\]

Figure 1. Steps Involved in Linear Regression
Figure 2. Using Scatter Chart and Trendine

<table>
<thead>
<tr>
<th>Tons</th>
<th>kW</th>
</tr>
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<tr>
<td>150</td>
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<td>900</td>
<td>402</td>
</tr>
<tr>
<td>1000</td>
<td>436</td>
</tr>
</tbody>
</table>

\[ y = 0.4427x - 1.9041 \]
\[ R^2 = 0.9986 \]

\[ X = \text{Tons} \Rightarrow \text{independent variable} \]
\[ Y = \text{kW} \Rightarrow \text{dependent variable} \]

**TRENDLINE OPTIONS**

- **Exponential**
- **Linear**
- **Logarithmic**
- **Polynomial** Order 2
- **Power**
- **Moving Average** Period 2

**Trendline Name**

- **Automatic** Linear (kW)
- **Custom**

**Forecast**

- **Forward** 0.0 periods
- **Backward** 0.0 periods

- Set Intercept 0.0
- Display Equation on chart
- Display $R$-squared value on chart
you should use a logarithmic trendline. A logarithmic trendline can have both positive and negative data points. For example, if you expect the electricity escalation factor to rise sharply year after year for the first few years and then flattens out, you should use a logarithmic trendline.

If the plotted data appears in a shape of curve (either upward or downward), choose power trendline. Basically a power trendline illustrates a data series that either increases or decreases sharply but at a constant rate. However, for plotting a power trendline you must have non-zero positive data values. If the data changes sharply at constant increasing rates, you should use exponential trendline. Exponential trendlines are very similar to power trendline but are curvier at one end than the other. If you find that the data are fluctuating (i.e. changing direction more than once in a definite fashion), you should try a polynomial trendline. If the fluctuation is more, go for higher order. If you have data with a lot of variation on a day-to-day basis, using moving average trendline will let you see the trend more clearly if you plot it weekly or monthly. A moving average takes the average of defined number of points (set by period) and plots it as the next point. When in doubt, try plotting all the suspect candidates and look at the R² values and choose the one with the highest R². In our example here, the R² value is 0.99, which is very good.

The second method is to use the SLOPE, INTERCEPT and RSQ functions. In the equation of the form \( y = mx + c \), \( m \) is the slope and \( c \) is the intercept. With SLOPE and INTERCEPT values, we can construct the equation of the line. Excel offers separate functions to calculate the slope and intercept in a user specified cell so that they can be used for further analysis. The SLOPE function calculates the slope “m” for known y’s and known x’s. The INTERCEPT function calculates the intercept or “c” for known y’s and known x’s. The RSQ function computes the value of R². Figure 3 shows the calculations for slope, intercept and R² values using the same data set used in the previous example. With the values calculated using the Excel’s functions, we can now construct the same equation we saw using the trendline. We can now calculate the kW input (variable y) for known chiller loading in tons (variable x) as shown in Figure 3.
The third method is to use the LINEST function. LINEST stands for ‘Linear Estimator’ and provides the slope and the intercept in adjacent cells. LINEST is an array function and with this, instead of using two different functions, you select two ranges, use the LINEST function, select the data required and enter the function with the ctrl + shift + enter combination (Figure 4). In addition to the regression coefficients, LINEST can return things like degrees of freedom, regression sum of squares, residual sum of squares, etc.

The fourth method is to use the Analysis Toolpak. Microsoft’s Analysis Toolpak add-in includes a number of advanced data analysis tools, including regression. The regression procedure provides regression statistics, ANOVA (analysis of variance), regression coefficients and their standard errors, t stats, p values and upper and lower confidence values.

To obtain regression output, you first select the y variables including the label and then select the x variables including the label. We then have to define the output range where we want the table. You may also want to select the residuals if you want a test of the regression assumptions. It is always a good idea to format the output table so that it is easier to read. Figure 5 shows the regression output and in terms of equation, we have

\[ y = mx + c \]

\( m \) is the slope and \( c \) is the intercept

**SLOPE, INTERCEPT and RSQ FUNCTIONS**

<table>
<thead>
<tr>
<th>Slope</th>
<th>Intercept</th>
<th>RSQ</th>
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<tbody>
<tr>
<td>0.4427</td>
<td>-1.9041</td>
<td>0.9986</td>
</tr>
</tbody>
</table>

\[ =\text{SLOPE(C3:C12,B3:B12)} \]
\[ =\text{INTERCEPT(C3:C12,B3:B12)} \]
\[ =\text{RSQ(C3:C12,B3:B12)} \]
\[ =E7*E14+F7 \]

**Figure 3. Using SLOPE, INTERCEPT, and RSQ Functions**
$kW = \text{Tons times the coefficient 0.442 plus the intercept, which is negative 1.904}$

This is the same equation we got using the trend function on the scatter chart. The predicted values shown here are what we will get by plugging the corresponding values in this equation. The residuals are the deviations from the actual value. If the residual is negative, then the estimated value is higher than the actual value.

Looking at the regression statistics (Figure 5), we know that $R^2$ is the correlation and it measures how the two variables move in relation to each other. $R^2$ is the proportion of the variability in the dependent variable $y$ that is explained by the $x$ variable. Adjusted $R^2$ is a more reliable statistic. The value of $R^2$ statistic can be inflated artificially by including independent variables in a regression function that have little or no logical connection with the dependent variable. The adjusted $R^2$ statistic accounts for the number of independent variables included in the regression model and is considered a better indicator. Typically, the adjusted $R^2$ value is used as a rule of thumb to decide if addition of

Figure 4. Using LINEST Function

<table>
<thead>
<tr>
<th>A</th>
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<th>E</th>
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SLOPE AND INTERCEPT 
USING LINEST FUNCTION

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<td>-1.9041</td>
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{=LINEST(C3:C12,B3:B12)}
an independent variable enhances the predictive ability of the model. However, this is not a foolproof way. The table also shows the standard error, which measures the variability of actual y values from predicted variables.

SUMMARY

Regression analysis is used by energy professionals for a wide variety of analysis related to energy conservation and management. As discussed in this article, Excel offers many functions and features to perform regression analysis that can be used for estimating energy savings, analyzing energy consumption data and in measurement and verification.

ABOUT THE AUTHOR

Ganesh Ayer, PE, CEM, LEED–AP, has nearly 30 years of solution design experience in energy conservation and demand management. Over the course of his career, he has investigated, analyzed and quantified various energy efficiency and load reduction measures in a variety of commercial and industrial facilities. He has also trained and mentored energy engineers at Fortune 100 companies. Mr. Ayer received his Master of Technology in Energy Conservation and Management from School of Energy, India, Master of Science in Industrial Engineering from Oklahoma State University, and Master of Business Administration from the Kellogg School of Management at Northwestern University. He currently serves as the advisor and course instructor at Energy Efficiency & Demand Management, Inc. He may be contacted at ganesh@eedmnc.com.
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<tr>
<td>1000</td>
<td>436</td>
<td>440.81</td>
<td>(4.81)</td>
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**SUMMARY OUTPUT**

**Regression Statistics**

- Multiple R: 0.999307
- R Square: 0.998615
- Adjusted R Square: 0.998442
- Standard Error: 5.155756
- Observations: 10

**ANOVA**

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**Coefficients**

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</table>

*Figure 5. Using REGRESSION from Analysis Toolpak*
Heating Degree-Days for Estimating Energy Consumption in Poultry Houses and Incubators in Nigeria

J.A. Olorunmaiye and O.O. Awolola

ABSTRACT

Energy is consumed for heating in poultry hatchery operations such as incubation of eggs and brooding of chicks even in a tropical country like Nigeria. Hourly dry bulb temperature data for 18 places spread over the six geopolitical zones in Nigeria were obtained from Nigerian Meteorological Agency, Oshodi, Lagos, Nigeria, for a 15-year period (either 1994-2008 or 1995-2009). Using Microsoft Excel spreadsheet 2007 version, heating degree-days for the 12 months of the year for the 18 locations were computed for the base temperatures: 30, 32, 34, 36, 37, 38 and 40°C. Values of heating degree-days can be substituted in equations relating energy consumption to heating degree-days to predict energy requirements for poultry houses or incubators. From the results of the annual heating degree-days for the eighteen locations, the three places having the lowest heating degree-days and hence cost of heating are Yola, Bauchi and Owerri whereas the places where heating degree-days are the highest are Jos, Kaduna and Ondo. The months having the lowest heating degree-days, which is the best time to raise day-old chicks, were identified for each location.

INTRODUCTION

Cooling and heating degree-days are used to quantify the severity and duration of hotness and coldness of a climate, respectively. Degree-day is the accumulation of one sided differences between a base temperature value and the set of temperature values measured. In tropical countries like Nigeria, most of the time the weather is warm or hot and ventilation only or cooling with ventilation is what needs to be done for human and livestock comfort. However, energy is consumed for heating
in poultry hatchery operations such as incubation of eggs and brooding of chicks even in tropical environments.

Thomason et al. stated that poultry houses need to be maintained at certain controlled temperatures for chicks to survive for the first 2 weeks after they are hatched because they don’t have the ability to adapt to large temperature variations at that stage of their lives [1].

In Nigeria, many small poultry farmers have 100-W incandescent bulbs installed in their poultry houses to provide radiant heating, but because electricity supply from the national grid is unreliable, they use charcoal stoves during the day and kerosene stoves at night to provide the necessary heating. The charcoal stoves used are shielded to protect the birds in the brooding house from getting hurt. Heat loss from the brooding house is minimized with the use of locally-sourced lagging materials on the wall and thatch roof in some commercial poultry farms. Ventilation holes in the walls are blocked to maintain the highest desired room temperature during the first week with the newly hatched chicks in the brooding house.

The farm supervisor of a commercial farm in Kaduna (Nigeria) (where they reared the red neck, black neck, and blue neck varieties of ostrich) reported that artificially incubated ostrich eggs took an average of 42 days to hatch and they were brooded for about 5 weeks to ensure the young ostriches were not subjected to cold weather, which could kill them, especially during the rainy season [2].

Incubation is the provision of conditions that make the eggs to develop from embryo to healthy birds with high efficiency. There is casual heat gain in the incubator due to the embryo generating increasing levels of metabolic heat release after a few days of incubation and the amount of fresh air intake is optimized based on carbon dioxide and relative humidity levels inside the incubator [3]. Each type of poultry has its own incubation period, as shown in Table 1[4].

Incubators may be still-air type or forced-air type. Forced-air incubators have fans to circulate air, whereas a still-air incubator has no circulating fan but it has holes in the sides to provide air circulation.

Using materials available locally at Giza (Egypt), Harb et al. [5] fabricated an economical 60-egg capacity table top incubator having an electric heater and a thermostat to maintain the temperature at 37°C. Forty-five eggs were hatched at the end of the experiment and the energy consumed during the incubation period was 320.5 Wh.

Using meteorological data provided by the Institute of Agriculture
Ecology, Biscarini et al. [6] calculated heating degree-days and duration of the heating period for the 20-year period (1970-1990 for Perugia in Italy) for optimized planning of the microclimate in livestock buildings. They recommended that the base temperature for calculating heating degree-days for livestock buildings should be lower than the room temperature, taking into consideration the free thermal contributions due to the sensible heat released by the animals, species breed and size and thermal insulation of the building.

Atilgan and Akyuz [7] determined the heating degree-days and cooling degree-days for a poultry house equipped with radiant heating systems, in a location that was not stated, during Dec. 1997 and Nov. 1998. Using long-term temperature records of 16 stations obtained from General Directorate of State Meteorology works, Atilgan et al. calculated heating degree-days and cooling degree-days for a boiler house in Isparta and its districts in Turkey for the following base temperatures 31.0, 29.0, 25.0, 23.5, 22.5 and 20.5°C [8].

Shah et al. [9] evaluated the effects of rates of application of sodium bisulphate to reduce ammonia build up on the propane and electricity consumption in commercial broiler houses in eastern North Carolina. They found that electricity and propane use increased linearly with both cooling and heating degree-days which they computed from the average of the 24 hourly values of dry-bulb temperature obtained from Elizabethtown using desirable room temperature based on the age of the chicks as the base temperatures.

In a case study of a walk-in incubator in a farm at Ilorin, Nigeria, Olorunmaiye and Awolola [10] found that the relation between energy consumed by incubator \( E_H \) and heating degree-days \( D_H \) was \( E_H = 4.448D_H \). This work was extended by Olorunmaiye and Awolola [11] by using this equation on a unit floor area basis of the incubator to get \( E'_H \).

<table>
<thead>
<tr>
<th>Poultry type</th>
<th>Incubation Period (days)</th>
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<tr>
<td>Chicken</td>
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</tr>
<tr>
<td>Turkey</td>
<td>26–28</td>
</tr>
<tr>
<td>Duck</td>
<td>26–28</td>
</tr>
<tr>
<td>Goose</td>
<td>33–35</td>
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<td>Pigeon</td>
<td>17–19</td>
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<td>Guinea fowl</td>
<td>26–28</td>
</tr>
<tr>
<td>Ostrich</td>
<td>40–42</td>
</tr>
</tbody>
</table>

Table 1. Poultry Type and Incubation Period [4]
= 0.327D_{H\prime}, where E'_{H} is energy consumption per unit floor area (kWh/m²). This equation was then applied to compute E_{H} values for the 12 months of the year for 18 locations in Nigeria from the values of heating degree-days computed for a base temperature of 37°C.

The heating degree-days method is a useful instrument in preliminary energy audits to estimate the effectiveness of energy conservation measures (ECM) that depend on seasonal and outdoor temperature for which simple methods are more appropriate than complex and time-consuming methods [12].

The objective of this work is to extend the earlier work reported above by computing values of heating degree-days for the 12 months of the year for 18 locations in Nigeria for the following base temperatures: 30, 32, 34, 36, 37, 38 and 40°C. The appropriate values of base temperature estimated for any locations if it differs from the seven base temperatures can be used to interpolate to get the appropriate heating degree-days to be substituted on the right-hand side of the equation relating energy consumption to heating degree-days. The ratio of energy consumed per year in GJ to floor area in m², which is the intensity of energy consumption [13] can be estimated. This is good for the purpose of energy planning because it helps to predict energy requirements for poultry houses.

METHODOLOGY

Meteorological data of hourly dry-bulb temperature were obtained from the Nigerian Meteorological Agency, (NiMet), Oshodi for the following cities for a 15-year period of either 1994-2008 or 1995-2009 for the locations depicted on Table 2. These cover all the six geopolitical zones in Nigeria. Figure 1 illustrates the relative locations on a map of Nigeria.

Hourly dry-bulb temperature data were analyzed using Microsoft Office Excel spreadsheets 2007 version having keyed each hourly data into the computer system. The calculation for heating degree-days from hourly weather data is given as:

\[
D_{H} = \frac{1}{24} \sum_{i} f(T_{i})
\]  
(Equation 1)

\[
f(T_{i}) = T_{b} - T_{i} \quad \text{if } T_{b} > T_{i}
\]  
(Equation 2a)

= 0 \quad \text{if } T_{b} \leq T_{i}
\]  
(Equation 2b)
Table 2. The 18 Locations Chosen for This Study, Their Latitudes, Longitudes, Geopolitical Zone and Altitude

<table>
<thead>
<tr>
<th>S/No</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Geopolitical Zone</th>
<th>Altitude (m)</th>
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<td>Bauchi</td>
<td>10.17° N</td>
<td>9.49° E</td>
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<td>591</td>
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<tr>
<td>3</td>
<td>Benin City</td>
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<td>5.36° E</td>
<td>South-south</td>
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<td>5</td>
<td>Enugu</td>
<td>6.28° N</td>
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<td>137</td>
</tr>
<tr>
<td>6</td>
<td>Ibadan</td>
<td>7.22° N</td>
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<tr>
<td>7</td>
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<tr>
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<td>Ilorin</td>
<td>8.26° N</td>
<td>4.30° E</td>
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<tr>
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<td>10</td>
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<td>12.26° E</td>
<td>North-east</td>
<td>191</td>
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</table>

Figure 1. Map of Nigeria Showing the 18 Locations
Where:
\[ D_H = \text{Heating-degree day} \]
\[ T_i = \text{Hourly ambient dry-bulb temperature}. \]
\[ T_b = \text{Temperature in the incubator, which is the base temperature}. \]
\[ n = \text{Number of hours over which temperature values were measured}. \]

RESULTS

The results obtained from this work for the monthly heating degree-days at 7 base temperatures are presented in Figures 2 to 4 for the 18 locations. The annual heating degree-days at the seven base temperatures are presented in Table 3.

DISCUSSIONS OF RESULTS

Looking at the graphs for monthly heating degree-days for the 18 locations shown in Figures 2 to 4, it can be seen that the four locations with the highest range of monthly degree-days were Maiduguri, Kano, Yola and Minna in descending order of magnitude. The range for the other locations was appreciable with magnitudes being about half that of Maiduguri for Sokoto, Abuja, Bauchi, Ibadan, Ilorin and Kaduna. The other locations had lower magnitudes of ranges with that of Port Harcourt being the least. The importance of magnitude of ranges is that the cost of incubation or raising chicks will vary much if the range of monthly heating degree-days is high depending on the months in the year when one chooses to carry out those activities. Whereas if the range is low, like that of Port Harcourt, the amount expended on energy for incubation on raising chicks will not vary much from one period to another during the year.

The month having the highest monthly heating degree-days was August for Abuja, Benin, Calabar, Enugu, Ibadan, Ikeja, Ilorin, Minna, Ondo, Owerri, and Port Harcourt. Yola had its own highest monthly heating degree-days in July. In these locations, the months of July and August fall in the raining season, and the weather is cloudy most of the time and solar radiation is minimal.

For Bauchi, Jos, Kaduan, Kano, Maiduguri and Sokoto, January
was the month having the highest heating degree-days. These places are in the northern part of Nigeria and the effect of Harmattan is felt much in these locations from November to January. Each of these six locations also had a secondary maximum in August lower than that of January. August also falls in the rainy season and solar radiation is minimal because of cloud cover.
March was the month for minimum monthly heating degree-days for Abuja, Enugu, Ilorin, Minna and Sokoto. April was the month for minimum heating degree-days for Bauchi, Jos, Kaduna, Kano and Yola. For Benin, Calabar, Ibadan, Ikeja, Ondo, Owerri and Port Harcourt. February had the minimal heating degree-days. Maiduguri had its minimum monthly heating degree-days occurring in May. The dry-bulb tem-
Figure 4. Monthly Heating Degree-Days for Minna, Ondo, Owerri, Port Harcourt, Sokoto and Yola At Base Temperatures of 30, 32, 34, 36, 37, 38 And 40°C
Temperature is highest in the months before the rainy season starts. These are the months when heating degree-days are minimal. The variations of the months of minimum heating degree-days as listed above for various locations is caused by variations in duration and commencement of the rainy season for the eighteen locations.

Poultry farmers in Nigeria usually prefer to raise a lot of broiler chickens to be ready for sale during the annual Christian and Muslim religions festivals, such as Easter, Christmas, Eid ul-Adha and Eid ul-Fitr, when demands are higher that other periods in the years. They sell the broiler chickens live from 6th to 12th week and after the 12th week, the ones not sold are killed, dressed and frozen.* For locations that have a second minimum for heating degree-days around October or November such as Abuja, Bauchi, Enugu, Ilorin, Kano and Maiduguri, it is advantageous to raise broiler chickens for Christmas because energy consumed to

* Adeyemi, J.B., Personal Communication, January 2, 2016
keep the freshly hatched chickens warm will be low. The best time to raise day old chicks is in the months having minimum heating degree-days for each of the locations because that is when energy consumed to keep the brooder houses warm is at a minimum. From energy consumption point of view, it is advisable to avoid or minimize raising day-old chicks in the months having maximum heating degree-days for the various locations unless the farmer is targeting meeting the demands during a religious festival, which will come up about 6 to 8 weeks after that time.

Table 3 shows the annual heating degree-days for the 18 locations. The three places where the costs of heating poultry houses or incubators are least are Yola, Bauchi and Owerri. The three places where the cost of heating are highest are Jos, Kaduna and Ondo. When one has a choice on the location for citing a poultry farm, the results in Table 3 are useful to guide the investors in choosing the place where energy consumption is least among the possible alternatives.

To make use of the results in Figures 1 to 3 and Table 3, it is necessary to determine an appropriate base temperature based on the thermal capacitance, type of walls and roof of the chicken house or the incubators, and the metabolic heat release rate of the species or eggs occupying the space.

It may be necessary to interpolate if the heating degree-day values for the exact base temperature calculated are not tabulated or plotted on the graphs.

For species having incubation or brooding periods covering only some days in a month or if the brooding or incubation is not started at the beginning of the month, (the heating degree-day contribution for that month) = (number of days of brooding or incubation in the month) / (number of days in the month) x (heating degree-day for that month read from Figures 1 to 3).

CONCLUSIONS

The monthly heating degree-days and annual heating degree-days for 18 locations in Nigeria have been presented. They are useful for estimating energy consumption for heating poultry houses or incubators because heating degree-days is proportional to energy consumed and hence cost of heating. The results are useful for poultry farmers and agricultural engineers in planning for poultry production in Nigeria and other places in the world having climate similar to the locations considered in this work.
Revised and edited, this new third edition reference covers the full scope of energy management techniques and applications for new and existing buildings, with emphasis on the “systems” approach to developing an effective overall energy management strategy. Foremost in the enhancements to the new edition is content that reflects the emphasis on conservation for green energy awareness. Building structural considerations are examined, such as heat loss and gain, windows, and insulation. A thorough discussion of heating and cooling systems basics is provided, along with energy management guidelines. Also covered are conservation measures which may be applied for lighting systems, water systems and electrical systems. Specific energy management technologies and their application are discussed in detail, including solar energy systems, energy management systems, and alternative energy technologies.

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<th>Book Title</th>
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<th>Price</th>
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<td>0727</td>
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ACKNOWLEDGEMENTS

The authors acknowledge with appreciation the provision of the weather data used in this work by the Director and members of staff of Nigerian Meteorological Agency (NiMet), Oshodi, Lagos, Nigeria.

References

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**John A. Olorunmaiye** graduated from University of Ibadan, Ibadan, Nigeria, in 1979 with B.Sc. in mechanical engineering. He completed a PhD programme at The University of Calgary, Calgary, Alberta, Canada, in 1985. He is a professor of mechanical engineering at University of Ilorin, Ilorin, Nigeria, where he has served as head of department for over 6 years and dean of faculty of engineering and technology for over 4 years. He is registered as a Mechanical Engineer by the Council for the Regulation of Engineering in Nigeria and he is a Fellow of Nigerian Society of Engineers.

**Olalekan O. Awolola** holds a Bachelor of Engineering (B.Eng) degree in mechanical engineering from University of Ilorin, Ilorin, Nigeria, and Master of Science in mechanical engineering from University of Lagos. He also has Master of Engineering degree from University of Ilorin. He is a member of the Nigerian Society of Engineers, and registered as a Mechanical Engineer by the Council for the Regulation of Engineering in Nigeria. He is currently doing his PhD research in meteorological data statistics for refrigeration and air-conditioning systems in Nigeria. He is a lecturer at the Federal Polytechnic, Ilaro, Ogun State, Nigeria.
Development of a MATLAB based Educational Software (UISOLAR) For Solar Application

A.S.O. Ogunjuyigbe, T.R. Ayodele, E.E. Ekoh

ABSTRACT

This article presents a MATLAB based educational software “UISOLAR,” which could aid in teaching and learning of photovoltaic technology at the undergraduate level. The application, whose core is the single-diode, five-parameter mathematical model, can evaluate the characteristics of solar photovoltaic (SPV) modules under changing meteorological conditions. It is also effective in determining the extracted power of a PV module from a local solar regime with or without maximum power point tracking. The accuracy of the developed software was ascertained by using the software to extract the parameters of some commercially available solar panels and to determine the maximum power with and without power point tracking. The software, UISOLAR, shows good agreement with available experimental data. Experimental testing of the software reveals that students who are taught using UISOLAR easily understood the concept of a photovoltaic system and the role of maximum power point tracking in improving the power output from solar photovoltaic modules.

Keywords: Teaching and Learning, Engineering Education Research, Application Software, Photovoltaic Technology, Undergraduate Student,

INTRODUCTION

The fundamental goal of teaching is to foster learning, and learning takes place in many different circumstances and contexts. It is generally believed that effective teaching and learning is a vital pre-condition to effectively mastering new concepts and skills. However, understanding
new concepts depends on good teaching aids, state of the art laborato-
ries, equipment, and exposure to modern pedagogical methodologies. These are presently a huge challenge to many higher institutions of
learning, especially in sub-Saharan Africa.

One of the top priorities of governments in sub-Saharan Africa is to
foster sustainable development through the provision of affordable and
clean energy. To achieve this, efforts are geared toward grid integration
of renewable energy. Of the various available renewable energy resour-
ces in the sub-region, solar photovoltaic (SPV) has earned its place as a
candidate choice in the gradual transition from polluting non-renewable
fossil fuels to clean renewable energy sources. This assertion can be at-
tributed to the growth rate of solar installations, which surpasses other
energy sources in the region [1], abundant solar energy resources avail-
able in almost every part of the region, maturity in SPV technology and
rapid fall in the cost of SPV material in recent years. Solar photovoltaic
is therefore seen as a regional potential solution to electricity poverty
[2], and a lot of capital investments are currently going towards this by
various governments within the region. For example, a $5 Billion public-
private-partnership with Sky Power FAS to deploy a 3-GW utility solar
power plant has just been initiated by the Nigeria Government [3]. Table
1 depicts the investment on solar power technology in selected countries
in the sub-region. The table revealed that there is presently increasing
investment in solar projects in the sub-region.

To sustain an asset requiring this high level of capital investment,
there is a need for indigenous competent personnel, who have been

Table 1. Selected Solar Project in Sub-Saharan Africa and Their Investments

<table>
<thead>
<tr>
<th>No.</th>
<th>Solar Project</th>
<th>Size</th>
<th>Location</th>
<th>Developer</th>
<th>Investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Tenergie Senegal PV Projects [5, 6]</td>
<td>50 MW</td>
<td>Taif, Darou Mousty and Merina Dakhar, Senegal</td>
<td>Tenergie Senegal</td>
<td>Not reported</td>
</tr>
<tr>
<td>4</td>
<td>Segou Solar PV project [9, 10]</td>
<td>33 MW</td>
<td>South Mali</td>
<td>Scatec Solar</td>
<td>US $57 million</td>
</tr>
<tr>
<td>5</td>
<td>Zagouli Plant [11, 12]</td>
<td>30 MW</td>
<td>Ouagadougou, Burkina Faso</td>
<td>T.B.D.</td>
<td>US $90.7 million</td>
</tr>
</tbody>
</table>
trained to design, install and maintain these installations. To keep up with this, a new curriculum in many institutions of higher learning is now being developed to include the study of renewable energy technology, especially the solar PV. However, training of indigenous engineers, technicians and other allied technical personnel on renewable energy involves huge capital investments to build new research labs and acquire equipment. The possibility of affording this by many institutions of higher learning is quite low considering the poor state of funding of institutions in the region. The percentage annual budget on education of some selected countries within the region is depicted in Table 2.

Table 2. Selected Countries in Sub-Saharan Africa and Their Percentage Annual Budget on Education [14]

<table>
<thead>
<tr>
<th>S/N</th>
<th>Countries</th>
<th>Annual Budget (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nigeria</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>Senegal</td>
<td>20.7</td>
</tr>
<tr>
<td>3</td>
<td>Guinea</td>
<td>9.5</td>
</tr>
<tr>
<td>4</td>
<td>Liberia</td>
<td>8.1</td>
</tr>
<tr>
<td>5</td>
<td>Chad</td>
<td>10.1</td>
</tr>
<tr>
<td>6</td>
<td>Cameroun</td>
<td>14.9</td>
</tr>
<tr>
<td>7</td>
<td>Burkina Faso</td>
<td>15.9</td>
</tr>
<tr>
<td>8</td>
<td>Mali</td>
<td>18.3</td>
</tr>
<tr>
<td>9</td>
<td>Niger</td>
<td>19.2</td>
</tr>
<tr>
<td>10</td>
<td>Togo</td>
<td>17.2</td>
</tr>
</tbody>
</table>

The table reveals that many countries within the region have budgets on education that are far less than the prescribed 26% recommended by the United Nations 15. The low level of funding for education has led to a wide gap between the teaching and the learning of renewable energy technology in higher institutions of learning. To surmount this challenge, there is a need to develop a software package that is user friendly, less complex and adaptable to the sub-region. Various software have been developed in the past on renewable energy technology [16, 17], as depicted in Table 3. However, most of the software are developed for industries and for research purpose, and only a few serve as a teaching and learning aid. Hence, they are either developed to suit some specific geographic locations or are too complex to understand or too expensive to buy.
Table 3. Some of the Available Software around the world with their limitations

<table>
<thead>
<tr>
<th>Software</th>
<th>Manufacturer</th>
<th>Purpose</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid 2</td>
<td>RERL, University of Massachusetts</td>
<td>Research</td>
<td>Relatively complex to understand</td>
</tr>
<tr>
<td>HOMER</td>
<td>NREL, USA</td>
<td>Research</td>
<td>Relatively complex to understand</td>
</tr>
<tr>
<td>RETscreen [18]</td>
<td>Natural Resources Canada</td>
<td>Research</td>
<td>Difficult to obtain the required data</td>
</tr>
<tr>
<td>SAM</td>
<td>NREL</td>
<td>Research</td>
<td>Limited to North America and Europe</td>
</tr>
<tr>
<td>IMBY</td>
<td>NREL</td>
<td>Quick check</td>
<td>Limited to North America</td>
</tr>
<tr>
<td>TRNSYS [19]</td>
<td>University of Wisconsin, Madison, USA</td>
<td>Education</td>
<td>Expensive to buy</td>
</tr>
<tr>
<td>INSEL [20]</td>
<td>University of Oldenburg</td>
<td>Research</td>
<td>Expensive to buy</td>
</tr>
<tr>
<td>RAPSIM [21]</td>
<td>University of Murdoch Australia</td>
<td>Research</td>
<td>Expensive to buy</td>
</tr>
<tr>
<td>WebOpt [22]</td>
<td>Lawrence Berkeley Laboratory</td>
<td>Research</td>
<td>Expensive to buy</td>
</tr>
<tr>
<td>HOGA</td>
<td>University of Zaragoza</td>
<td>Research</td>
<td>Expensive to buy</td>
</tr>
<tr>
<td>RAPSYS</td>
<td>University of South Wales</td>
<td>Research</td>
<td>Relatively complex to understand</td>
</tr>
<tr>
<td>SOLSIM</td>
<td>Fachhochschule Konstanz Germany</td>
<td>Research</td>
<td>Relatively complex to understand</td>
</tr>
<tr>
<td>SolarPro</td>
<td>University of Wisconsin</td>
<td>Professional/</td>
<td>Limited to North America</td>
</tr>
<tr>
<td>PV*SOL</td>
<td>Valentin Software, Germany</td>
<td>Educational</td>
<td>Limited to North America</td>
</tr>
<tr>
<td>PV F Chart</td>
<td>S.A. Klein and W.A. Beckman</td>
<td>Professional/</td>
<td>Limited to North America</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Educational</td>
<td></td>
</tr>
</tbody>
</table>
The few software that are educational software such as SolarPro, PV*SOL, PV F-Chart, TRNSYS etc. have limited suitability for sub-Saharan Africa owing to several reasons, such as: the cost, usage complexity and location specificity. This article contributes by developing a user-friendly MATLAB based-GUI (graphic user interface) teaching aid purposely for teaching SPV technology to undergraduates in higher institutions of learning in sub-Saharan Africa (UISOLAR). The proposed software provides for SPV module characteristics modelling, analysis of the effect of maximum power point tracking (MPPT) on SPV module output, as well as the design and analysis of DC-DC converters for standalone SPV.

ARCHITECTURE OF UISOLAR

The basic architecture of UISOLAR is depicted in Figure 1. The software is comprised of three teaching modules: module 1 is designed to aid student understanding of the extraction of five parameters of any solar PV panels; module 2 explains the characteristics of PV panels in response to environmental conditions, i.e., solar irradiation and temperature; while module 3 is designed to assist student to understand the effect of MPPT as well as DC-DC converters in a standalone PV application. These modules can be accessed by the user from the main interface “HOME” of the software. In this interface, the user is required to supply the PV panel data that he wants to study. The data are usually made
available by the manufacturer at the point of purchase of the panel and they are: the maximum power point current and voltage \((I_{mpp} \text{ and } V_{mpp})\), respectively, the maximum power \((P_{mp})\), the short circuit current \((I_{sc})\), the open circuit voltage \((V_{oc})\), temperature coefficient for short-circuit current \((\alpha)\), temperature coefficient for open-circuit voltage \((\alpha)\) and the technology class of the SPV module.

## MODULE DESCRIPTION

In this section, the description of each of the modules in UISOLAR and how they are mathematically modelled is discussed. This is to aid in the understanding and repeatability of the article.

### Module 1: 5-Parameter Extractor

This module aids teaching and learning for the extraction of 5-unknown parameters of a single diode model. Any solar PV panel can simply be described using a 5-parameter single-diode model [23], as depicted in Figure 2. The model consists of a current source \((I_{ph})\) antiparallel with a diode to account for the reverse saturation current \((I_o)\) resulting from recombination effect at the band gap, lumped series \((R_s)\) and parallel \((R_{sh})\) resistors connected at the terminal of the diode for metallic contact and leakage losses. The parameters in the model are termed “unknown” because they are not part of the data that are made available by the manufacturer. However, the parameters are needed to understand the characteristic and response of any PV panel to the meteorological conditions. Hence, the parameter has to be determined

![Figure 2. Equivalent Circuit of the Single-Diode, 5-Parameter Model](image-url)
by the intending user/researcher from the other common data that are made available by the manufacturer.

Applying Kirchhoff’s law and the Shockley’s diode equation to the circuit in Figure 2 results in the single-diode mathematical equation shown in Equation 1 [23].

\[
I = I_{ph} - I_o \left( e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}}
\]

Equation 1

Where \( n \) is the diode constant, usually having numerical value between 1 and 2 depending on the technology class of the PV panel; it shows how closely the diode is to an ideal diode, \( k \) is the Boltzmann’s constant and \( q \) is the electron charge.

The parameters \( R_s, R_{sh}, I_o, I_{ph} \) and \( n \) in Equation (1) are the 5-unknown parameters, which are left to be determined. It is difficult to obtain these parameters numerically; hence, iterative algorithm as utilized in [24, 25] are used to extract the unknown parameters.

**Module 2: Characteristics Module**

Having determined the 5-unknown parameters in module 1, the parameters are then used in module 2 to predict the voltage-current and power-voltage characteristics of the solar PV panel at the user-specified meteorological conditions - solar irradiance (G) and temperature (T). UISOLAR applies the five modifying Equations (2) through (6) and the Newton-Raphson algorithm to obtain the current and power of the module at different voltages [24].

\[
E_{g_{oc}} = E_g \left( 1 + \Delta E_g \left( T_{oc} - T \right) \right)
\]

Equation 2

\[
R_{s_{oc}} = R_s
\]

Equation 3

\[
I_{ph_{oc}} = \frac{G_{oc}}{G} \left( I_{ph} + \alpha \left( T_{oc} - T \right) \right)
\]

Equation 4

\[
R_{sh_{oc}} = R_{sh} * \left( \frac{G_{oc}}{G} \right)
\]

Equation 5
\[ I_{oc} = I_o \left( \frac{T_{oc}}{T} \right)^3 \exp \left( \frac{q}{nK} \left( \frac{E_g}{T} - \frac{E_{g,oc}}{T_{oc}} \right) \right) \]  
\text{Equation 6}

\[ n = n_{oc} \left( \frac{T}{T_{oc}} \right) \]  
\text{Equation 7}

\[ E_{g,oc}, R_{sh,oc}, R_{s,oc}, I_{ph,oc}, I_{O,oc}, G_{oc}, T_{oc}, \text{ and } N_{oc} \text{ represents the parameter values at the given operating condition; while } E_g, R_{sh}, R_s, I_{ph}, I_O, G, T \text{ and } n \text{ are the values for the module at Standard Condition (STC), i.e., } T = 25°C, G = 1000 \text{ W/m}^2. E_g \text{ gives the energy bandgap of the PV cell and it is dependent on the type of PV technology, also the parameter } \Delta E_g \text{ (usually less than zero and dependent on the technology) is a constant that shows the dependence of the bandgap energy on temperature. The five modifying equations are used to model the changes in the parameter values as meteorological conditions changes [26], while the Newton-Raphson algorithm is used to obtain the current of the solar PV module for voltage range of zero to a little above } V_{oc} (1.1 \ V_{oc}), \text{ which is used for plotting the state output SPV characteristics.} \]

\textbf{Module 3: Standalone Module}

Module 3 is used to evaluate the effect of MPPT on solar PV panel’s output power and the output characteristics of different DC-DC converter configuration. UISOLAR performs the computations required by both processes using hourly time series of global solar irradiance and temperature data. On entry to the standalone mode in the HOME page of the software, the user is prompted to select the data file, which must be in .xls format. To enhance the suitability of the software to sub-Saharan Africa, the global solar radiation and temperature data of major cities within the region are provided in the data base of the software. The data base is perpetually updated from the National Aeronautics and Space Administration (NASA) website once connected to the internet and prompted by the user. There are two modes within module 3: mode 1, which can be used to perform study on the influence of MPPT on Solar PV panels; and mode 2, which was designed to aid the understanding of the effect of different converter technology on the power output of a PV panel.
Mode 1: Effect of MPPT on Solar PV Panels

Under this mode, the hourly power produced from the SPV module with or without MPPT is determined and displayed on the graphical interface. This computation is hinged on equation (8), which is derived from the multiplication of the current produced by the module (1) and the module operating voltage. Without MPPT, the operating voltage is simply that specified by the user. On the other hand, with MPPT the operating voltage is the optimum voltage, which is gotten using a specialized search algorithm. To obtain the optimum voltage, the search algorithms compute equation (8) for all voltage values between 0 and 1.1 V_{oc} at a step increment of 0.1. It then outputs the optimum voltage, which is the voltage that gives the highest power value.

\[
P = \left( I_{ph} - I_o \right) \left[ \exp \left( q \left( \frac{V + IR_s}{nkTN_s} \right) \right) - 1 \right] - \left( \frac{V + IR_s}{R_{sh}} \right) \right] V
\]

Equation 8

Mode 2: Converter Characteristics

In this mode, the standalone module (module 3) outputs the current and power characteristics of a DC-DC converter. Three different types of DC-DC converter models (i.e., bulk, boost and buck-boost converters), which are usually employed in solar PV systems [27] for transferring maximum power from the PV panels to the load are modelled, implemented and made available in UISOLAR. The models of the converters as implemented in this software are depicted in Figures 3 through 5. In the figures, the solar PV panels producing current I_{pv} are supplying a load Z with current I_z across a potential V_z through the converters.

Figure 3. Circuit Diagram of a Buck Converter
The generalized current and voltage characteristics for different intervals of operations of the circuit were determined using Kirchhoff’s law as follows:

\[
\frac{dI_L}{dt} = \frac{aV_{pv} - bV_c}{L} \quad \text{Equation 9}
\]

\[
\frac{dI_L}{dt} = \frac{1}{C} \left( cI_L - \frac{V_z}{Z} \right) \quad \text{Equation 10}
\]

The values a, b and c have different interval of operations for different converter model and are provided in Tables 4 and 5.

Controlling the duty cycle of the switching device is performed using Perturb and Observe algorithm, as implemented by Mohammed, et al. [28] and Kumaresh, et al. [29].
A number of learning scenarios were performed to assess the effectiveness of UISOLAR as a tool for teaching. These cases are step-wisely illustrated in the subsequent sub-sections.

### Modelling Solar PV Panel Characteristics

Solar PV has a non-linear output characteristic with a unique point (i.e., the maximum power point) under a set of operating global solar irradiance and temperature conditions. Hence, this point can be tracked to extract the maximum power derivable from any PV panel. It is a common theoretical knowledge that solar power varies as the meteorological condition changes [30]. However, knowing how or to what extent the power changes will require a practical setup or suitable simulator. UISOLAR shows (in easy steps) this characteristic visually and how it changes as the weather conditions changes.

**Step 1: Defining the PV module**

After the launch of UISOLAR, the parameters (provided by the manufacturer) of the solar PV panel to be used for the analysis are entered at the home page of the software, as depicted in Figure 6. Editable labelled text boxes are used to fill in the panel parameters from the manufacturer datasheet. In this article, the parameter of Kyocera Solar KD210GX-LPU panel will be used for demonstration. The parameters, as obtained from the manufacturer data sheet, are shown in Table 6.

<table>
<thead>
<tr>
<th>Converter</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Boost</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Buck-Boost</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**CASE STUDIES**

| Table 4. Interval when the switching device Q is ON and diode D is OFF |
|---------------------------|----------------|----------------|
| Converter | a  | b | c |
| Buck      |    |   |   |
| Boost     |    |   |   |
| Buck-Boost|    |   |   |

| Table 5. Interval when the switching device Q is OFF and diode D is ON |
|---------------------------|----------------|----------------|
| Converter | a  | b | c |
| Buck      |    |   |   |
| Boost     |    |   |   |
| Buck-Boost|    |   |   |
Table 6. Manufacturers’ data of Kyocera Solar KD210GX-LPU

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{sc}$</td>
<td>8.58 A</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>33.2 V</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>7.90 A</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>26.6 V</td>
</tr>
<tr>
<td>$\beta$</td>
<td>-0.12</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.0005</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>210 W</td>
</tr>
<tr>
<td>$N_s$</td>
<td>56</td>
</tr>
</tbody>
</table>

Figure 6. Home Page of UISOLAR

Step 2: Defining the PV module

The ‘Extract Five Parameters’ toggle button on the bottom right of the home page is clicked to extract the five unknown parameters from the manufacturers’ data sheet. A pop-up window titled ‘Extracted’ showing the five-unknowns will then be displayed over the Home page.
of the computation. The Extracted window showing the obtained five-unknowns parameters of the solar PV panels under study is shown in Figure 7.

![Figure 7. The Extract Window Showing the Five-Unknowns of the Solar PV Panel](image)

**Step 3: PV Characteristics**

The solar PV panel characteristics can be accessed from the Characteristic module window. It is opened when the Characteristics toggle button is clicked on the home page. On the Characteristics window, the user specifies the meteorological conditions for which the SPV characteristics are being analyzed. Three modes exist on UISOLAR to specify the meteorological conditions. They are: the single point, varying irradiance and varying temperature.

Single point is used when analysis of the SPV is based on one solar irradiance and temperature point. UISOLAR takes in single values for temperature (°C) and irradiance (W/m²). It then displays the current-
voltage and voltage-power characteristics when the Plot button is clicked. A plot of the solar PV panel (Kyocera KD210GX-LPU) at STC is shown in Figure 8. The points on the plots show the MPP.

![UI SOLAR](image)

Figure 8. The Characteristics at STC of the SPV Test Module Using UISOLAR

Varying the irradiance toggle is used to analyze the changes in the solar PV panel characteristics as the global solar irradiance changes under a constant temperature. Here, UISOLAR accepts an array of solar irradiance values but only one temperature value. Results of varying irradiance value are shown in the Figure 9. The converse applies for the varying temperature mode, which is shown in Figure 10.

**Effect of Maximum Power Point (MPP) on PV Panel**

Analyzing the effect of MPPT on the output characteristics of the solar PV panel is done simply by accessing the Standalone module in the home page of the software. UISOLAR is able to display the current
and the power produced per hour for a given panel once the hourly time series of meteorological data is made available. The required meteorological inputs are defined in an Excel file (.xls). The user is prompted to select the file via a pop-up window, as depicted in Figure 11. An image of UISOLAR’s output after computing the effect of MPPT on the PV panel under study for a 24-hour period is shown in Figure 12.

**Simulating Characteristics of DC-DC Converters with UISOLAR**

The DC-DC converters, which are the physical components employing the MPPT algorithm to transfer the maximum power to the load, can be analysed with the software. Simulating their output characteristics enables students to see graphically the operation characteristic of the converters. It can also give good inputs to aid component selection for design projects on solar PV converters. In UISOLAR, performing this analysis involves defining the solar PV panel, selecting the required
Figure 10. Output Characteristics SPV Module at Irradiance of 800 W/m² and Temperatures of 20, 25 and 30°C

meteorological data file and defining the converter components. The analysis for a converter with the components data (R-L-C) shown in the pop-up window was performed for Buck converter configurations and the result is shown in Figure 13. The performance characteristic of PV panels with the other two converters can be similarly obtained through the same procedure.

EXPERIMENTAL ASSESSMENT OF UI SOLAR

The effectiveness of the software in teaching and learning was tested using two groups of electrical engineering undergraduate students consisting of 15 students each. The two groups are new to the concept
Figure 11. Pop-up Window Indicating the Selection of .xls File.
Figure 12. UISOLAR Showing the Effect of MPPT on the Output of Kyocera KD210GX-LPU Solar Panel Over a 24-hour Period

Figure 13. Standalone Windows Displaying the Output Characteristics of a Buck Converter Connect to the Solar PV Panel
of solar PV technology. The first group of students were taught using the UISOLAR, while the other group were also taught the same concept without the software. At the end of the exercise, a questionnaire was distributed to test the understanding of the student in each of the groups. The questionnaire was collated and analyzed; the result is presented in Table 7. The questionnaire assessed the understanding of each of the group at the subject of presentation.

Table 7. Assessment of UISOLAR

<table>
<thead>
<tr>
<th>S/N</th>
<th>Assessment Criteria</th>
<th>S/N</th>
<th>Students Assessment</th>
<th>Group A (With UISOLAR)</th>
<th>Group B Without UISOLAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>4</td>
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<td>b</td>
<td>Partially understand and need the lecture to be repeated for full grasp</td>
<td>4</td>
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<td>3</td>
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CONCLUSION

This article has presented the development and application of UISOLAR as a tool for teaching and learning solar PV technology. The software is easy to use and runs on MATLAB. The software is adaptable to sub-Saharan Africa and is designed with a robust help feature that allows easy navigation. An assessment of the software using two sets of students reveals that it can effectively support teaching and learning solar PV technology at the undergraduate level. UISOLAR is currently in use at the University of Ibadan at the undergraduate level. It is also in use to execute various undergraduate research projects. Presently, it has
three modules; however, effort is ongoing to incorporate other modules that will allow for further complex analysis and study.

Declaration of Conflicting Interests
The authors declare that there are no conflicts of interest.

References


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Experimental Analysis of an Improved Solar Still System with Cooling Fan and Preheating Oil

Ehab Bani-Hani, Hussain Qassem, Mohammad Al Kandari, Salem Al Azmi, Musaed Khalid, Hadi Bu-Mijdad, Khalil Khanafer, and Ahmad Sedaghat

ABSTRACT

The performance of a traditional solar still system can be improved by modifying the desalination processes involved. In this work, a simple experimental model of a one-sided solar stiller is build and tested. The solar still system is modified with a solar cooling fan and a preheating solar collector. The fan is used to increase the cooling rate of external surfaces of the glass cover to increase the condensation rate of vapors and thus increase the amount of distilled water. The fan is powered by a small PVC (photovoltaic cell). In addition, the preheating solar collector uses the hydraulic oil as the working fluid for indirect heating of the feed sea water within the still device. A series of measurements consist of basin and ambient temperatures and rate of production of distillate are carried out in the winter in the State of Kuwait during November 2015 and then the results are analyzed and compared with some previously published data. It is observed that the improved solar still system produces 3%, 10%, and 50% more distillate than the basic solar still system by applying a cooling fan, oil preheating, and both cooling fan and oil preheating systems, respectively.

Keywords: Fan cooling; Kuwait; Preheating oil; Solar still system.

INTRODUCTION

Passive solar water distillation is considered as an appropriate technology because it operates based on the same principles of rainfall; it starts with purifying water through a process of evaporation, condensation, and then collection. The solar distillation process can be...
performed on brackish, salty water or from sources such as rain, municipal, well, or spring. This is done by utilizing the plentiful energy of the sun to evaporate water. Dissolved salts and minerals are separated from contaminated water. The basic principles of solar water distillation are effective, as distillation replicates the way nature makes rain. The sun’s energy heats water to the point of evaporation. As the water evaporates, water vapor rises condensing on the glass surface for collection. This process removes impurities such as salts and heavy metal ions, as well as eliminates microbiological organisms.

A conventional solar distiller is a box with a glass roof, referred to as a glaze, set at an angle from the horizontal plain to ensure optimal sun exposure. This angle is roughly equal to the latitude of a topological location. The distiller faces south if it is in the northern hemisphere, but it faces north if it is in the southern hemisphere. Untreated water is routed into a holding basin inside the distiller. Radiation from sunlight penetrates the glass and heats the inside content of the distiller, causing the water in the basin to evaporate. The absorption of higher frequency radiation heats the water and solar still internals. The glaze traps infrared re-radiation causing a greenhouse effect resulting in higher temperatures. The evaporation process separates contaminants from the water and results in a thin condensate on the underside of the glass cover. The condensed, distilled water then runs off the glass into a water storage container for domestic use. Contaminants and particulates remain in the basin and must be washed away periodically.

BACKGROUND STUDIES

Many papers have addressed solar stills of various configurations such as hemispherical solar still, pyramid solar still, double-basin solar still, triple basin solar still, and tubular solar stills [1-10]. Flat-plate solar collectors are extensively used to harness solar energy. They absorb radiation through a black absorbing surface and transfer energy to the working fluid flowing through it. The performance of these collectors depends on several aspects, such as climatological and microclimatic factors, geographical factors, geometry, and orientation of the collector [11]. Due to the shortcomings of the flat-plate black-surface absorbers (such as relatively high heat losses, corrosion effects, and limitations on incident flux density [11], different concepts were proposed in
the literature to allow the working fluid to directly absorb the incident radiation. Use of black liquids [12] and particles mixed with a gaseous working fluid [13-15] are some notable examples. Typical working fluids used in the solar thermal collectors exhibited relatively low absorptive properties over the solar spectrum [16]. Abu Hiljeh and Rababah [17] performed experimental performance tests of solar still with different size energy absorbing materials like black coal, and black steel cubes. They found that there is a great improvement in distillate output of solar still from 18% to 273% compared with conventional solar still. Some other investigators used different dyes [18-20] in a solar still. They proved that the black dye increases the distillate output of solar still compared to other dyes. Inlet temperature of water can also increase the distillate output of solar still, hence some researchers [21, 22] recommended various external sources like flat-plate collector, storage tank, etc. They showed that, there was a great improvement in solar distillate production ranging from 25% to 200%.

Medugu and Ndatuwong [23] conducted a theoretical analysis of water distillation using a solar still. Energy balances were made for each element of the still; solar time, direction of beam of radiation, clear sky radiation, and optical properties of the cover, convection outside the still, convection and evaporation inside were also accounted. Theoretical analysis of the heat and mass transfer mechanisms inside the solar still was developed. The measured performance was compared with results obtained by theoretical analysis. Their results showed that the instantaneous efficiency increased with the increase of solar radiation and with the increase of feedwater temperature.

From the above literature, it is confirmed that a solar still is a very efficient device to convert brackish water into drinkable water. The main goal of the present study is to evaluate the effect of preheating the feedwater and cooling the glass cover on distillate output. In the present work, the basic design of a single effect solar distiller was studied and investigated experimentally. It was manufactured as a simple model of a one-sided solar stiller unit. The model was tested and operated in Kuwait during November 2015. Methods of improving the efficiency of the solar stills include oil preheating the feedwater and cooling the glass cover using a fan. A solar panel was used to power the oil pump and the fan. The parameters measured included ambient wind speed, glass cover and water temperatures, amount of fresh water produced, and the inlet water salinity.
SPECIFICATIONS OF THE SOLAR STILL SYSTEM

The solar still was manufactured from chrome sheet and galvanized iron. The bottom and sides of the chrome box were well insulated by polystyrene insulation material. The thickness of polystyrene insulation is 5 cm in east and west sides, and 10 cm in other sides of the still and these are covered by galvanized sheets. The thickness of the glass is 4 mm, which covers the top of the solar still. A chrome channel is fitted under the lower side of the glass cover to collect the condensed water. The channel ends with a small plastic pipe to drain the fresh water into an external vessel. The glass was mounted at an angle of 38° to the solar still to ensure that the condensate flows down the glass into the condensate-collecting channel. Two aluminum collecting channels were stuck to the glass cover to collect condensate fresh water flowing down.

The absorbing chrome plate has the effective area equivalent to 0.689 m². The plates were welded in order to be connected to other parts of the solar still. Three holes were drilled into the solar still, one for sea water inlet, second for condensed water outlet and the third for discharging of remaining seawater. After construction of the solar still, it was painted by cellulose-based black paint. The insulation material was fixed between the chrome sheets and the galvanized sheets. The aluminum collecting channels were stuck to the glass cover and then the glass cover is fitted to the structure of solar still. The full apparatus system is shown in Figure 1. The long side of the solar still is aligned in north-south direction. Sea water is drawn with a galvanized pipe into the still. During the testing, the solar still is fed by sea water; the water depth is fixed to 2.5 cm in the solar still. The distilled water produced is measured on an hourly basis. The fan is used to cool down the glass cover and to improve performance of the solar still. The fan was operated using solar cells. Basin area, length, and width are 0.8 m², 1 m, and 0.8 m, respectively.

Generally, the solar thermal collectors capture and retain heat from the sun and transfer this heat to a liquid. As shown in Figure 2, the flat-plate collector was used in the preheating system for feeding water to solar still. It is an extension of the basic idea to place a collector in an ‘oven’-like box. Here, a pipe is connected to the water tank and the water is circulated through this pipe and back into the tank. The water tank is outside the collector. Because the surface-to-volume ratio increases sharply as the diameter of a pipe decreases, most flat-plate collectors have pipes less than 1 cm in diameter. The efficiency of the heating pro-
cess is therefore sharply increased.

The design of a flat-plate collector, therefore, typically takes the shape of a flat box with a robust glass top oriented towards the sun, enclosing a network of piping.
In many flat-plate collectors, the metal surface of the pipe is increased with flat metal fins or even a large, flat metal plate to which the pipes are connected. Formed collectors are a degenerate modification of a flat-plate collector in that the piping of the collector is not enclosed in a box-like ‘oven’. Consequently, these types of collectors are much less efficient for liquid heating. Solar collector specifications are listed in Table 1. The solar preheating unit, which is designed in this research, included the following parts: absorber, solar collector box, storage tank, flexible hoses, check valves, insulation, and circulating pump.

Table 1. Specifications of solar collector

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Flat-plate collector</td>
</tr>
<tr>
<td>Size</td>
<td>80 cm x 80 cm</td>
</tr>
<tr>
<td>Absorber</td>
<td>sheet metal, 83 cm x 83 cm</td>
</tr>
<tr>
<td>Thickness of absorber plate</td>
<td>0.2 mm with black coating</td>
</tr>
<tr>
<td>Glass width</td>
<td>85 cm</td>
</tr>
<tr>
<td>Glass type</td>
<td>clear</td>
</tr>
<tr>
<td>Glass thickness</td>
<td>4 mm</td>
</tr>
<tr>
<td>Glass angle</td>
<td>38°</td>
</tr>
<tr>
<td>Glass length</td>
<td>104 cm</td>
</tr>
<tr>
<td>Solar total area</td>
<td>0.884 m²</td>
</tr>
<tr>
<td>Effective area</td>
<td>0.689 m²</td>
</tr>
<tr>
<td>No. of tubes</td>
<td>12, copper, with diameter of 5/16 inch</td>
</tr>
<tr>
<td>Tube pitch</td>
<td>6 cm</td>
</tr>
<tr>
<td>Header</td>
<td>copper, 1/2 inch</td>
</tr>
<tr>
<td>Pump</td>
<td>centrifugal with 5-10 L/min, DC, 12v</td>
</tr>
<tr>
<td>Working fluid</td>
<td>W10 hydraulic oil</td>
</tr>
<tr>
<td>Collector box</td>
<td>90 cm x 90 cm x 10 cm</td>
</tr>
</tbody>
</table>

The solar-powered system specifications are listed in Table 2. Special oil can be used (such as W10 hydraulic oil) as a working heat transfer fluid in preheating solar heating system. This oil is used on the heat transfer devices such as solar heat exchanger, electrical heaters, etc. W10 hydraulic oil can work in high temperature conditions reaching to 350°C. This oil is proper in most low or medium operating temperatures (lower than 300°C). For temperatures higher than
300°C, heat transfer oil such as silicone oil can be used. The solar powered system includes the following components: DC fan, DC pump, solar panel, voltage protection controller, and charger (DC battery).

Different heat exchanger (HE) configurations are generally used, such as collector heater pipes, condensing heat exchangers, and evaporating heat exchangers. In the present work, the collector HE consists of 12 copper tubes with inner diameter of 5/16 inch. There was a 60-L storage tank in addition to a 10-L feed tank. The following components were used as auxiliary parts: one-way valves, float, manuals valves, and voltage regulation device.

METHODS OF IMPROVEMENT

The productivity of stills is defined as the amount of fresh water output (L/day). The productivity can be increased by the following methods:

1. Applying cooling for glass cover
2. Preheating the feedwater
3. Using efficient insulation for different components
4. Using reflectors as solar concentrator

In this research, the forced fan cooling and the oil preheating the feedwater are considered and explained next.

**Forced fan cooling for the glass cover**

The forced fan cooling will increase the condensation rate due to the increase in the temperature difference between temperature of water vapor in the basin and glass cover surface temperature. Increasing the temperature difference by 10 to 20 degrees will increase the efficiency of the solar still.

<table>
<thead>
<tr>
<th>Table 2. The solar powered system specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fan specifications</strong></td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Flow rate</td>
</tr>
<tr>
<td><strong>Pump specifications</strong></td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Flow rate</td>
</tr>
<tr>
<td><strong>Solar cell specifications</strong></td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Capacity</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>Battery</td>
</tr>
</tbody>
</table>
Preheating feedwater

The preheating unit is used to heat sea water before entering into the solar still as shown in Figure 2. It is expected that efficiency of the solar still will be increased by preheating feedwater. The preheating unit consists of the flat plate collector. It used W10 hydraulic oil as a heat transfer fluid and was fabricated from copper tubes. The collector consisted of twelve 5/16-inch copper tubes and ½-inch header for diameter.

The box was manufactured from compressed wood and insulated using glass wool material with thickness of 5 cm. Then, different connection tubes were used to connect the tank with the flat plate collector.

The device consists of a flat plate collector and a desalination tower. A copper piping system connects these two components. As solar radiation reaches the collector, the working fluid (oil) is heated up and flows, by natural convection or by aid of a small pump, to the highest point of the system, where the heat exchanger is located. The oil flow releases its sensible heat to the salty water on the other side of the equipment. The heat exchanger works as the first stage of the desalination unit.

SYSTEM TESTING AND OPERATION

The system was tested in four modes: traditional system (the basic solar still), the solar still with cooling fan, the solar still with (W10 hydraulic oil) preheater, and the solar still with both cooling fan and hydraulic oil preheater. In all modes, the operation of the model is tested from 9:00 am to 3:00 pm. The water depth was fixed at 25 mm, and the water output was measured on an hourly basis. In the first mode, the saline water was fed into the system tanks, the main storage tank, and the small feedwater tank. Then the manual valve was used to enter the water into the basin. The back wall was attached to the device by hinges and sealed shut by latches. To fill the basin, the back wall was opened and the basin is half-filled with sea water. The 30 (approximately) liter input storage tank was then filled with sea water and the manual valve was used to control water level in the basin to a depth of 25 mm.

RESULTS AND DISCUSSION

A series of experiments in different days during November 2015 were carried out in the State of Kuwait. The following parameters were
measured: ambient temperature, basin water temperature, glass temperature, oil temperature at inlet and outlet, fresh water output, and water vapor temperature.

The measurements were performed every 1 hour during the operating intervals from 9:00 am to 3:00 pm. The measurements were taken for the solar stills in different operating modes and at different ambient temperatures.

It can be seen from Figure 3 and Tables 3 through 6 that as the ambient temperature is increased, the basin temperature is also increased linearly; however, the basin temperature is higher when oil preheating (by solar radiation) is used. A linear correlation is found between the basin temperature and the ambient temperature during November 2015 in the State of Kuwait as shown in Equation 1.

\[
\text{Basin water temperature} = [1.2141 \times (\text{ambient temperature})] + 33.104 \quad \text{(Equation 1)}
\]

The experiment was performed in November 2015, when the ambient temperature is relatively low compared to normal ambient tempera-

![Figure 3. Basin water temperature versus ambient temperature during November 2015 in Kuwait](image)
Table 3. Distilled water production rate without cooling fan and oil preheating system (traditional system) during November 2015 in the State of Kuwait

<table>
<thead>
<tr>
<th>Time</th>
<th>$T_{\text{amb}}$ ($^\circ$C)</th>
<th>$T_{\text{basin}}$ ($^\circ$C)</th>
<th>Productivity (liter/hr)</th>
</tr>
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<tr>
<td>9 am</td>
<td>15.5</td>
<td>50</td>
<td>0.24</td>
</tr>
<tr>
<td>10 am</td>
<td>16</td>
<td>55.2</td>
<td>0.5</td>
</tr>
<tr>
<td>11 am</td>
<td>18</td>
<td>59</td>
<td>0.65</td>
</tr>
<tr>
<td>12 pm</td>
<td>21</td>
<td>61</td>
<td>0.85</td>
</tr>
<tr>
<td>1 pm</td>
<td>23</td>
<td>64</td>
<td>1.05</td>
</tr>
<tr>
<td>2 pm</td>
<td>25</td>
<td>71</td>
<td>1.15</td>
</tr>
<tr>
<td>3 pm</td>
<td>24</td>
<td>63</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 4. Distilled water production rate for system with cooling fan during November 2015 in the State of Kuwait

<table>
<thead>
<tr>
<th>Time</th>
<th>$T_{\text{amb}}$ ($^\circ$C)</th>
<th>$T_{\text{basin}}$ ($^\circ$C)</th>
<th>Productivity (liter/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 am</td>
<td>18</td>
<td>53</td>
<td>0.44</td>
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<tr>
<td>10 am</td>
<td>19.5</td>
<td>56</td>
<td>0.76</td>
</tr>
<tr>
<td>11 am</td>
<td>22</td>
<td>58.9</td>
<td>0.81</td>
</tr>
<tr>
<td>12 pm</td>
<td>23</td>
<td>62</td>
<td>1.21</td>
</tr>
<tr>
<td>1 pm</td>
<td>27.0</td>
<td>66</td>
<td>1.22</td>
</tr>
<tr>
<td>2 pm</td>
<td>27.8</td>
<td>70</td>
<td>1.65</td>
</tr>
<tr>
<td>3 pm</td>
<td>27.2</td>
<td>64</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 5. Distilled water production rate for system with oil preheating during November 2015 in the State of Kuwait

<table>
<thead>
<tr>
<th>Time</th>
<th>$T_{\text{amb}}$ ($^\circ$C)</th>
<th>$T_{\text{basin}}$ ($^\circ$C)</th>
<th>Productivity (liter/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 am</td>
<td>21</td>
<td>53</td>
<td>0.45</td>
</tr>
<tr>
<td>10 am</td>
<td>26</td>
<td>58</td>
<td>0.77</td>
</tr>
<tr>
<td>11 am</td>
<td>29</td>
<td>64</td>
<td>0.92</td>
</tr>
<tr>
<td>12 pm</td>
<td>31</td>
<td>72</td>
<td>1.3</td>
</tr>
<tr>
<td>1 pm</td>
<td>33</td>
<td>74</td>
<td>1.45</td>
</tr>
<tr>
<td>2 pm</td>
<td>32.5</td>
<td>75.8</td>
<td>1.92</td>
</tr>
<tr>
<td>3 pm</td>
<td>31</td>
<td>71</td>
<td>1.80</td>
</tr>
</tbody>
</table>
ture in Kuwait during hot season when the temperature reaches 50°C. Therefore, high temperature differences between ambient and basin water is observed, as shown in Figure 4, which has a positive impact on water production rate.

As the basin temperature is increased, as seen in Figure 3, the flow rate of distilled water increased. The maximum temperature of basin water was when the oil preheating system was used (around 78°C) yielded a maximum water flow rate of 2.60 L/hr. Generally speaking,
the increase of ambient temperature causes the basin water temperature and distilled water production rate to increase.

The amount of distilled water produced for the four different system arrangements vary from 0.2 to 2.6 L/hr. The best system, in terms of distilled water production rate, was the system where oil was preheated and fans were used.

Figure 5 shows a comparison of the four system arrangements with results of Badran and Fayed [24]. As expected and shown, the best arrangement was the solar still with oil preheating and fan cooling. The maximum still water produced was between 2:00 pm and 3:00 pm for all system arrangements. The increase in still water production relative to the traditional solar still system was 3%, 10%, and 50% for the solar still system with cooling fan, with oil preheating, and with both cooling fan and oil preheating systems, respectively.

Interesting, our basic still system exhibited a 130% increase in water production flux compared with Badran and Fayed [24].

In Figure 6, the solar radiation intensity (I) for the State of Kuwait during November 2015 per Ghoneim et al. [25] is compared with the data from Badran and Fayed [24]. From Figure 6, it is observed that the solar radiation intensity was lower during November than the Badran and
This book is designed to serve as a resource for exploring and understanding basic electrical engineering concepts and principles, as well as related analytical and mathematical strategies. Topics include critical electrical engineering components of energy projects, electrical-related energy cost factors, tips on improvement of electrical energy intensity in industrial and commercial settings, an update on generation of electricity from renewal sources, principles of illumination and efficient lighting, and an explanation of important energy engineering terms and concepts. This new edition adds an in-depth chapter on the battery. Batteries play a crucial role in our phones, computers, watches, light sources, kitchen appliances, health care equipment, automobiles, aircraft and more; and they play a vital role in making renewable energy sources more practical, viable and versatile. The basic facets of the battery and its sustainable and safe operation are explored. Also included is a discussion of the skills and preparation necessary for succeeding in the electrical engineering positions of various certification and licensure exams. Examples and case studies are included.

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Fayed [24] data; although much higher water production was observed in our study (see Figure 5). This can be contributed to two important factors: 1) the larger difference between the cold and hot side of our system, and 2) implementation of the fan cooling and the oil preheating system. But from Figure 4, no significant differences between cold side and hot side temperature profiles are observed. This may suggest that the main contribution of fan cooling and oil preheating is improving heat transfer coefficients rather than the temperatures of the system, which requires further research.

CONCLUSIONS

An improved solar still system is manufactured and experimentally tested in the State of Kuwait during November 2015. The effects of using a solar cooling fan and a solar oil preheating collector on performance of the one-sided solar still system are investigated. Stilled water production is measured from 9:00 am to 3:00 pm in hourly intervals in four different operational modes of the still water system. The modes of operation are the basic solar still mode, the solar still assisted with a fan, the solar still assisted with an oil preheating system, and the solar
still system assisted with fan and oil preheating modes. Experimental measurements are performed for obtaining the basin and the ambient water temperatures and the water production rates. Results indicate that the fan has improved the heat transfer rate of the glass while the preheating oil has increased the basin temperature. Utilizing the cooling fan improves the water production rate by merely 3%, while using the oil preheating system indicates an increase of 10%. However, the combined effects of using both the cooling fan and the preheating oil have significantly increased still water production by 50%. The results of the present distillate production rate were compared with some available data for similar basic still system, which shows a significant increase of 130%. This may be attributed to careful selection of materials and design of the present solar distilled water system.

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ing Conference, Boston, MA, August 5-10, 1979.

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Targeting Customers by Industry—Steam System Optimization

Joseph R. Bickham and Joseph F. Wadel

ABSTRACT

The focus is to reach natural gas customers who have specific high energy use and identify prospective energy saving projects. Steam systems are identified as heavy consumers of natural gas. By targeting this specific industry, trends and analysis are established, resulting in categorization based on facility type and steam use. There are well established best practices used to implement projects and processes that lead to energy savings. Through optimization of a steam system, the customer can see energy reduction savings ranging on average of between 5 and 15%. The savings vary, but by targeting large customers, the potential from project implementation has shown average annual fuel savings of over $100,000 per facility. The steps taken to target steam customers and identify savings opportunities can be obtained by the following:

- Identify Targeted Customers
- Identify Steam Use
- System Assessment/Audit Savings
- Trends/Analysis of Steam Systems.

The examples in this article have been identified from the Consumers Energy Business Energy Efficiency Steam System Optimization Pilot Program with a goal to increase gas saving project implementation within Consumers Energy territory [1]. The Steam System Optimization Pilot is designed to take a holistic/non-biased approach, identifying projects that lead to energy reduction action. The target natural gas customer must have an annual base usage consumption of 20,000 MCF or 20,560 million Btu. The program is in direct correlation with the Consumers Energy Comprehensive Business Energy Efficiency Program, established to reward implementation of energy efficient upgrades or modifications. The resulting lessons learned can be scaled across organizations.
INDENTIFY TARGETED CUSTOMERS

The first step for optimization is to identify natural gas customers who utilize steam, followed by reaching as many customers as possible who are most likely to implement the identified energy savings projects. With the push for energy reduction from end users rather than building power plants, utilities are establishing incentive programs to gain energy savings. Utility corporate account managers can identify the largest customers and encourage participation in energy optimization. A list of customers who participated previously in incentive programs also may be available and sorted based on steam related measures. A few of those measures include: steam trap replacement, boiler tune-ups, and linkageless controls.

Another method used for identifying customers is to reach out to the licensing and regulatory affairs department (LARA) and find issued permits, installers, repairers, and inspectors of existing boiler and boiler accident investigations. Also, as part of government regulation for pressure vessels, each steam boiler is registered with the information made available from the Freedom of Information Act (FOIA). Boilers are checked annually for ASME CSD-1 inspections and compliance lists may also be available.

Trade allies or contractors who actively participate in energy efficiency programs can identify customers looking to upgrade systems and install new equipment. These trade allies can include boiler tune-up companies, steam trap survey/replacement companies or equipment sales representatives.

The customer industries most commonly identified to have significant steam systems are shown in Figure 1 and include: manufacturing; health services; food services; schools, universities and colleges; packaging/paper; chemicals/biological; and other.

IDENTIFY STEAM USE

Steam is commonly used in large buildings or campuses with multiple buildings. It is important to identifying the customer’s utilization of steam because each customer could have different uses based on a unique process or application. However, some commonalities among customers can be identified and lead to a better understanding of op-
timization strategies. The uses identified for steam are; space heat, domestic hot water, sterilization, distillation, still heating, unit heaters, drum heaters, pasteurization, preheat, absorption chillers, electric generation turbines, direct injection, and humidification. Steam used for electric generation can be utilized in the summer for absorption chillers, but optimization and evaluation should be done to confirm steam generation vs. electricity utilization is continuously monitored. Steam elimination could also be a recommendation for facilities only using steam for space heat or facilities that could utilize the more efficient hot water boilers.

SYSTEM ASSESSMENT/ AUDIT ANALYSIS

Contractors and equipment sales representatives present ideas/projects to customers, but lack an understanding or support of a customer’s entire system. By presenting a customer with non-biased assessment recommendations, a customer can receive multiple quotes and use their preferred contractor to prioritize implementation based on savings, payback, or safety. These opportunities can be broken down into three main steam categories: generation, distribution, and recovery.

According to the U.S. Department of Energy (DOE), the many advantages that are available from steam are reflected in the significant amount of energy that industry uses to generate it. For example, in 2006, U.S. manufacturers used about 4,762 trillion Btu of steam energy, which
represents about 40% of the total energy used in industrial process applications for product output [2]. Steam system optimization can be summarized as using water efficiently to create steam, while recovering excess heat to limit the amount of generation and energy used. Table 1 shows common performance improvements for steam systems. These recommendations are well known and defined in detail by the DOE.

A complete system assessment/audit identifies all aspects of the steam system. The following example shows a recommendation for facilities in the food service industry, which use heated city water for cleanup and sanitation, but does not utilize the heat from waste water.

**Install Waste Water Heat Exchanger**

Heating fresh water to 100°F is a significant portion of the steam load given the volume of warm water used. That load can be reduced by heating the city water with warm waste water.

A storage and pump system for the waste water is already in place to provide a steady flow to the waste water treatment plant. The ability to access the warm waste water at a single point and a steady flow are beneficial when performing waste water heat recovery.

**Measure Summary**

Install a waste water heat exchanger to remove heat from the waste water to warm the hose water.

- **Annual Energy Savings** = 21,471 million Btu/yr
- **Estimated Annual Cost Savings** = $83,380/yr
- **Estimated Implementation Cost** = $60,000
- **Simple Payback Period** = 0.72 years

**Energy Savings Calculations**

Assumptions:
1. 200,000 gal/day of hose water use (total fresh water use was stated to be 225,000 gal/day). Thus, average flow is 139 gpm.
2. 30°F temperature rise for the hose water in the heat exchanger. This is based on the assumption the waste water is 100°F and the fresh water will rise from 55°F to 85°F.
3. 85% boiler efficiency.

The amount of energy recovery is given by the following:
Heat Recovery = (Temperature Rise) * (Specific Heat) * (Water Volume) * (8.34 lbm/gallon)  (Equation 1)
Heat Recovery = (30°F) * (1 Btu/lbm-°F) * (200,000 gal/day) * (8.34 lbm/gallon)
Heat Recovery = 50.0 million Btu/day
Considering the boiler efficiency and running this all year obtains the fuel savings:
Fuel Savings = (Daily Heat Recovery) * (365 days/year)/(Efficiency)  (Equation 2)
Fuel Savings = (50.0 million Btu/day) * (365 days/yr)/(85%)
Fuel Savings = 21,471 million Btu/yr or 20,845 MCF/yr
With a fuel cost of $4.00/MCF, this provides an annual savings of $83,380.

**Implementation Cost and Payback**

Waste water has few contaminants that would clog a conventional plate-and-frame heat exchanger, providing the most economical approach. However, waste water heat exchangers are seldom conventional plate-and-frame because contaminants tend to clog the tortuous path through the heat exchanger. To combat this problem and still obtain the superior performance of plate-and-frame heat exchangers, suppliers have developed non-clogging (or free flow) plate-and-frame heat exchangers. These units typically have a slightly larger gap between the plates and smoother surfaces that will not catch material. They may have more plates to compensate for the reduced surface area of each individual plate. A free-flow plate-and-frame heat exchanger is recommended for this application.

A suitable heat exchanger was quoted at less than $10,000. The heat exchanger cost is likely to be a minor component of the project cost because it would need to be installed, and the city water would have to be piped through it. The total project cost is assumed to be $60,000.

This would result in a simple payback less than 1 year.

Payback = (Cost/Savings) = ($60,000 cost)/($83,380/year savings) = 0.72 years

**Audit Analysis**

When conducting audits, the most important consideration is to identify opportunities for savings that make the most sense. While it is
Table 1. Common Performance Improvement Opportunities for the Generation, Distribution, and Recovery Parts of Industrial Steam Systems

<table>
<thead>
<tr>
<th>Opportunity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generation</strong></td>
<td></td>
</tr>
<tr>
<td>Minimize excess air</td>
<td>Reduces the amount of heat lost up the stack, slowing more of the fuel energy to be transferred to the steam</td>
</tr>
<tr>
<td>Clean boiler heat transfer</td>
<td>Promotes effective heat transfer from the combustion gases to the steam</td>
</tr>
<tr>
<td>Install heat recovery equipment (feedwater economizers and/or combustion air preheaters)</td>
<td>Recovers available heat from exhaust gases and transfers it back into the system by preheating feed water or combustion air</td>
</tr>
<tr>
<td>Improve water treatment to minimize boiler blowdown</td>
<td>Reduces the amount of total dissolved solids in the boiler water, which allows less blowdown and therefore less energy loss</td>
</tr>
<tr>
<td>Recover energy from boiler blowdown</td>
<td>Transfers the available energy in a blowdown stream back into the system, thereby reducing energy loss</td>
</tr>
<tr>
<td>Add/restore boiler refractory</td>
<td>Reduces heat loss from the boiler and restores boiler efficiency</td>
</tr>
<tr>
<td>Optimize Deaerator vent rate</td>
<td>Minimizes avoidable loss of steam</td>
</tr>
<tr>
<td><strong>Distribution</strong></td>
<td></td>
</tr>
<tr>
<td>Repair steam leaks</td>
<td>Minimizes avoidable loss of steam</td>
</tr>
<tr>
<td>Minimize vented steam</td>
<td>Minimizes avoidable loss of steam</td>
</tr>
<tr>
<td>Ensure that steam system piping, valves, fittings, and vessels are well insulated</td>
<td>Reduces energy loss from piping and equipment surfaces</td>
</tr>
<tr>
<td>Implement ad effective steam-trap maintenance program</td>
<td>Reduces passage of live steam into condensate system and promotes efficient operation of end-use heat transfer equipment</td>
</tr>
<tr>
<td>Isolate steam from unused lines</td>
<td>Minimizes avoidable loss of steam and reduces energy loss from piping and equipment surfaces</td>
</tr>
<tr>
<td>Utilize backpressure turbines instead of pressure reducing valves (PRVs)</td>
<td>Provides a more efficient method of reducing steam pressure to low-pressure services</td>
</tr>
<tr>
<td><strong>Recovery</strong></td>
<td></td>
</tr>
<tr>
<td>Optimize condensate recovery</td>
<td>Recovers the thermal energy in the condensate and reduces the amount of makeup water added to the system, saving energy and chemicals treatment</td>
</tr>
<tr>
<td>Use high-pressure condensate to make low-pressure steam</td>
<td>Exploits the available energy in the returning condensate</td>
</tr>
</tbody>
</table>

Source: DOE 2012 [3]
easy to recommend improvements to controls or replacing equipment, it may not be feasible for them to make a large capital expenditure for limited return. Through analysis of the complete steam system, it is more apparent where the customer should focus their attention.

Low cost/no cost changes to a system tend to be no-brainers for customers. Examples may be: reduce pressure, optimize boiler sequencing, use the more efficient boiler more frequently, increase tune-up frequency, replace failed steam traps, repair leaks, shutdown idling boiler, and add/repair insulation.

Large capital expenditures may also be very beneficial for a customer to consider, but budgeting could be an issue. Showing payback period for the system upgrade or new equipment can help prioritize projects to meet their reduction goals. Utility incentives should also be considered and can greatly help reduce the upfront cost of these projects.

Savings potential for optimization measures varies by site but common saving percentages can be applied for estimation, as shown in Table 2.

### Table 2. Some Quantified Energy Savings Opportunities for Boilers

<table>
<thead>
<tr>
<th>Technique / Method</th>
<th>Energy Savings Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved operation and maintenance of boilers</td>
<td>Up to 5%</td>
</tr>
<tr>
<td>Improved water treatment and boiler water conditioning</td>
<td>Up to 2%</td>
</tr>
<tr>
<td>Total dissolved solids (TDS) control and boiler blowdown</td>
<td>Up to 2%</td>
</tr>
<tr>
<td>Blowdown heat recovery</td>
<td>Up to 3.75%</td>
</tr>
<tr>
<td>Boiler and burner management systems, digital combustion controls and oxygen trim</td>
<td>Up to 5%</td>
</tr>
<tr>
<td>Flue gas shut-off dampers</td>
<td>Up to 1%</td>
</tr>
<tr>
<td>Economizers</td>
<td>Up to 5%</td>
</tr>
<tr>
<td>Combustion air preheating</td>
<td>Up to 2%</td>
</tr>
</tbody>
</table>

Source: Sustainability Victoria 2015 [4]

Note: Individual energy savings measures are not usually cumulative, and implementing one will reduce the potential savings of another

### TRENDS/ANALYSIS OF STEAM SYSTEM

From information gathered, trends can be developed based on types of facilities and uses for steam. The types of facilities generally have similar trend and operational procedures within the organization. In general customers with less staff support lack in areas of common best practices such as steam trap replacement, insulation, tune-up frequency,
and steam pressure reduction. Manufacturing facilities that are proactive in energy savings tend to have more opportunities in heat recovery and optimizing boiler sequencing.

The uses of steam also tend to have trends at these facilities. When steam is being used solely for space heat, domestic hot water, and/or humidification, most facilities can benefit from proper sizing based on seasonal requirements, insulation, and heat recovery options that can be used for pre-heating domestic hot water. When steam is used for processes such as sterilization, distillation, still heating, or pasteurization, pay extra attention to waste water heat recovery, excess steam use, and stack economizers. Large campuses that use steam for absorption chillers and electric generation turbines need focus on having the correct approach to optimizing the balance of the cost to generate steam cost versus electric, especially in summer months.

Although these trends can change drastically solely on the level of understanding at a particular facility, it is still beneficial for a customer to receive an audit.

Findings from an audit show the customer the prioritization of the implementation recommendations and focuses on energy savings through payback analysis. It also reinforces any good practices that are already in use.

CONCLUSION

The optimization of a steam system is a beneficial way for a customer to find significant savings in their natural gas usage. Even modest efficiency gains can lead to significant annual cost savings. By focusing on steam system customers, it has become apparent there is a need for awareness of savings potential. Steam system technology hasn’t grown significantly in the last 30 years, but implementing good operating practices and optimization strategies have been proven to be very successful. The Consumers Energy Business Energy Efficiency Program has seen significant uptake in participation by targeting this market segment. This last year, the program has identified potential energy savings projects totaling 226,265 MCF or over $1,000,000 in customer annual fuel savings [1].

Through the awareness an assessment brings, the customer benefits, the trade ally benefits, and the utility benefits. The operating prac-
tices recommended as well as capital projects proposed will lead to a game plan for energy savings for many years to come.

References


media/resources/documents/services%20and%20advice/business/srsb%20em/

ABOUT THE AUTHORS

Joe Bickham is with Franklin Energy and serves as the Steam System Optimization Program Manager contracted by Consumers Energy. He holds a Bachelor’s Degree in Mechanical Engineering from Michigan State. His prior work experience includes 4 years with ThermalNetics, a Commercial HVAC Representative, developing and designing innovative HVAC systems. In addition he held a 2-year internship with Michigan State Universities Commissioning Department optimizing the campus predictive maintenance program plus 2 years Coop with DTE Energy in vibration analysis of steam turbines. Mr. Bickham may be contacted at jbickham@franklinenergy.com.

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