Top-down Energy Modeling

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ABSTRACT

There are two fundamental approaches to modeling a facility's energy consumption: top-down and bottom-up. The bottom-up model requires metering installation and an exhaustive inventory of all facility equipment, as well as the energy consumption pattern of each facility device. To determine a facility's total energy consumption over any period of time, it's only necessary to sum the energy consumption of all the facility's equipment.

The top-down model uses the high-level information that a facility routinely collects regarding its activities and performance, and associates that data with the corresponding energy consumption.

The purpose of this article is to discuss the advantages and disadvantages of each modeling technique, with the result that the top-down model is preferred on the basis of cost, time to construct, model operation, model maintenance effort, accuracy, etc.

INTRODUCTION

Bottom-up Modeling Discussion

This model requires a substantial up-front commitment of both time and money to establish confidently an exhaustive and accurate inventory of all energy consuming equipment in the facility. Ideally all equipment should be metered, but metering can be financially justified only for major energy consumers. For smaller energy consumers, hours of operation and equipment loading must be estimated. For most commercial facilities such as office buildings, hospitals, or retail stores, most electric loads must be estimated, promoting model inaccuracy.

Large industrial facilities possess numerous electrical loads of sufficient size so as to deserve individual metering. Bottom-up energy modeling demands a significant commitment by management for funding the meters, installing and recording them, and analyzing the results. Typically, corporate-level management requires that already burdened plant operators and staff devote the man-hours to read and maintain meters, operate the model, etc. Enthusiasm for the bottom-up model quickly wanes at the corporate level due to its high initial cost, and wanes at the facility level due to continuing requirements for labor. However, a great deal of satisfaction is derived by management at all levels from the knowledge that they possess a thorough inventory of all facility equipment and each one's contribution to facility utility costs.

The bottom-up approach is also essential to quick and accurate identification of inefficient or malfunctioning equipment.

Top-down Model Discussion

The top-down model has as its hallmark ease of construction and use, translating to a lower cost. All facilities collect and maintain data considered essential to monitoring the operation, efficiency, and profitability of the enterprise. The top-down model utilizes data routinely collected by the facility and associates it with energy costs. It saves on both the material and labor efforts required by the bottom-down approach, but requires some statistical sophistication. Modeling energy consumption using limited and often seemingly inappropriate operational data takes courage, but is almost always surprisingly accurate. In fact, one of the most difficult assignments is explaining to management-level decision-makers how it can be proved so consistently accurate.

Unquestionably, there is no substitute for directly measuring energy consumption. However, in a facility with complex energy usage much consumption must be estimated. In addition, over time, meters, whether gas, electric, or water, require maintenance, otherwise becoming inaccurate. Also, over time, the equipment inventory changes as new equipment is added and old removed. Keeping an accurate equipment inventory, as well as changing equipment consumption profiles, requires time and dedication.

The key to a successful top-down model involves something as simple as multiple linear regression. PC spreadsheets all typically offer a linear regression function, which can associate not only direct energy inputs, but also their surrogates. Facility energy consumption tends to be surprisingly linear. Exponential regression or neural network approaches can be successful for consumption patterns that are nonlinear.

Spreadsheet multiple linear regression functions always include in their execution a display of statistical indicators, which advise on the efficacy of each input category. In other words the model can often be improved as much by what is excluded as by what variables are included. The idea of a surrogate is a simple and effective one. For example, all energy models for office buildings require an input for the number of people present in the building. If the number of people was never available, but for some reason, the number of pots of coffee brewed each day was always counted exactly, then some function using the number of pots could fairly accurately be used as a surrogate for the number of people present.

MAIN BODY

Top-down Model Advantages

1. The chief advantage of a top-down model is its low cost and quick implementation due to the small commitment of time for model construction, including a user- friendly input sheet.
2. It uses facility data currently available and routinely collected.
3. It typically requires a data history of only one year. A six-month history is acceptable if it includes some winter and summer months.
4. With careful modeling and judicious selection of inputs, plus or minus 5 percent accuracy can be achieved compared with actuals.
5. Since monthly facility data is routinely collected, model maintenance, data collection, etc., is minimal.
6. Predicting facility costs and performance is convenient because the input variables are typically the same as the variables that management routinely monitors.
7. The model can quickly identify and quantify effects originating from equipment changes.

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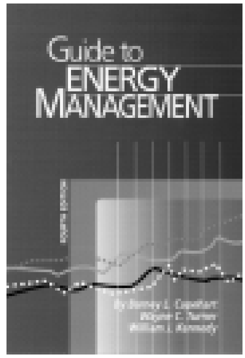

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8. The model can quickly identify changes in consumption due to unknown factors, such as a change in operational procedures not reported to management.
9. The technique is flexible enough to be used for all utilities (electric, natural gas, water) as well as non-utility items such as labor, raw materials, and other important production inputs.
10. The technique can accommodate both linear and nonlinear consumption results.
11. Its use and support by management is long-term because the cost to collect data, maintain the model, and perform monthly model runs is minimal.
12. Personnel receiving minimal training can run the model.

Top-down Disadvantages

1. It ideally requires a data history of 12 months.
2. If the data routinely collected by the facility is inappropriate, accuracy can be poor.
3. Someone familiar with statistics must construct the model.
4. If results suddenly vary significantly from model predictions, the facility process or equipment causing the aberration can not to be specifically identified.
5. Describing to management the statistical validity of the model is difficult.

Bottom-up Advantages

1. The chief advantage of this model is that it can quickly identify energy consumption performance down to the level of an individual facility process, and often to specific machines.
2. Theoretical accuracy is extremely good.
3. The model can accommodate the effects of each process or machine using a linear or nonlinear submodel.
4. No facility history is required. With proper metering and good

small equipment estimates, the model can begin operation with no prior facility experience.

5. This concept is easy to explain and defend to management. It simply involves summing the energy results from all facility equipment.

6. The model will quickly detect changes in consumption trends and quantify them.

Bottom-up Disadvantages

1. The chief disadvantage of this model is its initial cost, especially in terms of purchasing and installing meters. A complete, exhaustive, and time-consuming inventory of all facility equipment and processes must also be performed.

2. All of the often numerous meters must be maintained, and read routinely, requiring significant time and cost. In any facility metering assumes a secondary importance compared to equipment repair, maintenance, and operation.

3. Any significant meter malfunction or error adversely affects the model accuracy. Estimates for small loads not justifying metering further degrades accuracy.

4. Large quantities of data must be entered into the model, increasing the possibility of data entry errors.

5. Predicting consumption and costs becomes difficult because forecasting estimates must be made down to a machine and process level basis.

6. Model changes necessitated by the addition or retirement of any machine or process must be performed by a professional promptly or model accuracy degrades. This includes even the numerous unreported small equipment added over time such as PCs, lighting, copy machines, etc.

7. The model is only useful for the commodity or utility that is being metered. No inferences can be drawn about the facility's consumption of other commodities.

Table 1. Summary

TOP-DOWN	*BOTTOM-UP*
Advantages	
1. Low cost—no meters, no study	1. Identifies specific process usage
2. Uses available data	2. Excellent theoretical accuracy
3. Requires data history of 6-12 months	3. Usage can be linear/nonlinear
4. Typically good accuracy	4. No facility history required
5. Model maintenance and training is minimal	5. Concept validity easy to explain
6. Easy usage forecasting and prediction	6. Quickly detects usage changes
7. Quickly detects usage changes	
8. Flexible—useful for other production inputs	
9. Accommodates linear and non-linear usage	
10. Facilitates long-term support by facility	
Disadvantages	
1. Requires 6- to 12-month data history	1. Initial cost of installing meters
2. Appropriate data may not be available	2. Initial cost of facility study
3. Model construction requires statistical expertise	3. High cost of using/maintaining
4. Aberration causes can not be identified	4. Meter malfunction problems
5. Validity of concept is difficult to explain	5. High data entry requirements
	6. Forecasting usage is difficult
	7. Eqmt. changes require updates
	8. Metered commodity use only
	9. More labor intensive

8. The high initial capital, maintenance, and operational costs associated with this model quickly tax the endurance of both operational people and management.

Advantages and Disadvantages are summarized in Table 1.

Model Format

Table 2 is a diagram of the suggested model format using a commercially available spreadsheet such as Microsoft Excel®. The spreadsheet program should be arranged along the top left side of the spreadsheet so that the program description is the first thing the user sees. Each category—program description, input, and results—should have a background color distinctly different from the others, so as to aid the user, and prevent errors or confusion. The spreadsheet calculations block should be located visually distant from the other categories so as to prevent accidental user tampering. The completed model with raw data can be viewed in Appendix A.

Table 2. Spreadsheet Model Format

Program Description

This section should always appear first and at the top left side of the spreadsheet when first opened. The section should also be about "one screen" in width to avoid sideways scrolling for user convenience. At a minimum it should state:

1. The purpose of the program
2. How and in what form to enter the data
3. Where the entry data can be found
4. Who wrote the program
5. Who and how to call for help
6. Important assumptions used in the calculations

Input Section

Fill this section with a color different from the section above for user convenience, and maintain "one screen" width. The user should be prodded to enter data into bold framed cells located to the right of thoughtfully worded questions. Each question should clearly state the units of the data to be entered. Table 3 is an example of an input section.

Results Section

Fill this section with a color different from the section above, and maintain "one screen" width. This section contains all results necessary for preparing the routine usage report. In fact, it may even be in a formal report format. All units should be clearly stated.

Calculations Section

This section performs all calculations necessary to produce the results section or other necessary reports. It can be any color or width, but should be located well beyond the normal view of the user while he is engaged in using the above sections, and protected from inadvertent user changes.

Table 3. Input Section—Electric Consumption Model

This model estimates electric consumption at the XYZ plant in kWh based on the eight inputs below. Accuracy is generally plus/minus 5 percent. Simply answer the questions below.

1.	Is this month December, January, or February? (Answer Y for yes, N for no)	y
2.	Is this month May, June, July, August, or September? (Y or N)	n
3.	Enter the number of production days.	21
4.	Enter the number of faucets to be produced.	111,909
5.	Enter the number of total hours worked.	19,965
6.	Enter the number of Earned Standard Hours.	9,701
7.	Enter the number of days in this month.	31
8.	Enter the number of days expected on the electric bill.	33

(May be higher of lower than days in the month depending on when the meter is read.)

Top-down Model Construction

The first rule is that the model maker must use data that are readily available. The accounting department is usually the collector and keeper of this data. If the data are somewhat scarce, all of it can be assembled into a matrix line by line, with each line representing one month. Twelve continuous months is usually sufficient. Microsoft Excel® allows no more than 16 variable inputs and one output per line (row) to perform a linear regression. Run the regression and let the spreadsheet's automatic statistical analysis advise on which variables are important. By judgment or by experiment eliminate unimportant or redundant input variables. This is an important step because the model's accuracy can be improved as much by which inputs are discarded as by the ones that are included. Carefully review the description of the Microsoft Excel® function, LINEST. When this function generates a linear regression function, it also provides statistical information such as F and R2, which are vital in determining the quality of the suggested regression equation. LINEST also conveniently provides information to aid in determining T statistics to assess the quality of individual regression slope coefficients. If there are more inputs than a spreadsheet regression can handle, use judgment and trial and error to determine the most effective inputs. Often, in the course of testing the regression equation, a resultant actual consumption point or two will seem to be grossly aberrant. First check with the operational people to determine what special event or conditions may have caused it. If the points are rare, say one in ten, and no special causes can be identified, it's acceptable to discard the data points and their associated inputs. If the cause of the aberrant points is identified as the same in all those rare cases, enhance model results by including an upset indicator in the variable input data. The writer's experience has been that most facilities' energy consumption patterns are linear. However, Microsoft Excel's® LOGEST function can suggest the best exponential curb that fits your data. The user must decide which of the two results best fits the data. A neural network spreadsheet macro called "Brain Cell," written and distributed by Palisades Corp., is also effective in modeling nonlinear facility or equipment consumption.

Other Consumption Variables

In most cases consumption will be seasonal to some degree. In an energy intensive manufacturing facility, the seasonal relationship may be relatively minor. But in a commercial facility such as a restaurant, retail store, convention center, or grocery store, seasonality will play an important role because of the energy consumption of HVAC systems and the fuels they use. Therefore, it's important to test the importance of this input.

It's obviously important to associate consumption with the actual electric bill, and to understand that the electric bill presented in August was for July's consumption. In addition model adjustments must be made to account for the variability of the billing. For example, although the electric meter is read approximately once per month, some billing periods can be as long as 35 days, and some as short as 25 days. In other words, the model constructed and tested by comparison with the electric utility meter must take into account the number of days in each monthly billing. An accurate model should provide management with energy consumption data for any specific period of time, and can show the consumption and cost effects of any level of facility production.

CONCLUSIONS

The virtue of the top-down approach is that it is less costly than the bottom-up approach on all levels, specifically:

1. Initial cost of installing meters on major energy consuming equipment or systems
2. Initial cost of a thorough facility equipment audit
3. Meter maintenance and repair
4. Meter reading
5. Data collection
6. Data entry
7. Model updating due to equipment changes

The accuracy of either model is about the same (plus or minus 5 percent). Errors using the bottom-up model appear from:

1. The estimates required by numerous small loads not justifying metering
2. Meter malfunctions
3. Meter reading
4. Data collection and entry
5. Unknown unlisted equipment additions and deletions.

The top-down model can typically be implemented quickly, facilitates energy consumption forecasting, and the general approach is flexible enough to be applicable to electric power, fuels, water consumption, raw materials and labor requirements, and a host of other production inputs.

ABOUT THE AUTHOR

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APPENDIX A—COMPLETE MODEL

This model estimates electric consumption at the XYZ plant in kWh based on the eight inputs below. Accuracy is generally plus/minus 5%. Simply answer the questions below.

1.	Is this month December, January, or February? (Answer Y for yes, N for no)	y
2.	Is this month May, June, July, August, or September? (Y or N)	
3.	Enter the number of production days.	21
4.	Enter the number of faucets to be produced.	111,909
5.	Enter the number of total hours worked.	19,965
6.	Enter the number of Earned Standard Hours.	9,701

7. Enter the number of days in this month. 31
8. Enter the number of days expected on the electric bill. 33
   (May be higher of lower than days in the month depending on when the meter is read.)

Estimate of kWh used in billing period: 469,756
Estimate of kWh used in the month: 441,285

Calculations:

	X1 SUM	X2 WINTER	X3 PROD DAYS	X4 FAUCETS	X5 TOT HRS	X6 ESH	
	0	1	21	111909	19965	9701	
Factors	27469	34572	-13536	0.011	-1.213	5.826	657438
	0	34572	-284256	1230.999	-24217.5	56518.03	657438
sum	441285.5						
result	469755.5						

APPENDIX A—RAW DATA ANALYSIS USING MICROSOFT EXCEL LINEST

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.520296495
R Square	0.270708442
Adjusted R Square	-0.215485929
Standard Error	44305.19489
Observations	16

ANOVA

	df	SS	MS	F	Significance F
Regression	6	6557713306	1092952218	0.556790572	0.754943609
Residual	9	17666552649	1962950294		
Total	15	24224265955			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	657437.6722	271051.0135	2.42551269	0.038263127	44277.21319	1270598.131	44277.21319	1270598.131
X Variable 1	27468.92644	30696.08243	0.8948675	0.394160206	-41970.48922	96908.3421	-41970.48922	96908.3421
X Variable 2	34572.34004	31139.89579	1.11022658	0.295682086	-35871.05196	105015.7321	-35871.05196	105015.7321
X Variable 3	-13536.02823	13662.08612	-0.9907732	0.34768422	-44441.83775	17369.7813	-44441.83775	17369.7813
X Variable 4	0.011005327	1.2629736	0.00871382	0.993237561	-2.846041626	2.86805228	-2.846041626	2.86805228
X Variable 5	-1.213212588	11-90818576	-0.1018806	0.921085239	-28.15142083	25.72499565	-28.15142083	25.72499565
X Variable 6	5.826254766	20.02568062	0.29093916	0.777691175	-39.47501661	51.12752614	-39.47501661	51.12752614

(*Continued*)

RESIDUAL OUTPUT

Observation	Predicted Y	Residuals		
1	441283.7229	-47865.54105	-64498.88674	2
2	452759.4279	-10701.88949	-47865.54105	4
3	398495.0999	-6147.733227	-23082.01407	
4	414692.8893	-12318.37312	-21233.50918	
5	458230.6935	51217.9922	-15165.17125	
6	457745.8288	71848.32508	-12318.37312	
7	423054.1871	30923.24626	-10701.88949	
8	395848.4595	23941.54052	-6147.733227	
9	431285.0579	714.9420863	-2705.547514	
10	443344.5141	-23082.01407	714.9420863	
11	420784.1413	-2705.547514	7032.363982	
12	426871.536	7032.363982	18040.25552	
13	429388.3159	18040.25552	23941.54052	
14	403828.1713	-15165.17125	30923.24626	
15	444195.3274	-21233.50918	51217.9922	3
16	457687.8867	-64498.88674	71848.32508	1