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TOTAL ENERGY PLANT - SIMULATION MODEL

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ABSTRACT: A case of Total Energy Plant (TEP) has been modeled and the operational characteristics simulated. Applying the simulated data to the model will assist the TEP dispatcher in deciding on the operational schedule for the plant energy generating components, to attain an optimal cost of generating consumer demands for various types of energies.

1. INTRODUCTION

In recent years simulation models of energy systems have received special attention. This paper addresses the development of a model for a centralized energy system for a large self-contained operating complex. The system is characterized by multiple energy sources, multiple energy demands and varied energy conversion equipment. This type of system has been termed a Total Energy Plant (TEP), and has become increasingly popular in recent years for large recreational complexes, hotels, educational facilities, etc., where the combination of energy modes make a flexible self-contained energy plant economically attractive.

In most cases, operating decisions for a TEP are made by a chief dispatcher on the basis of his experience and empirical knowledge of the plant equipment operating efficiencies and the impact of their interactions. This basis is generally developed via trial and error. The decisions are generally good if simple, however, as the variables and the interface among the various operating equipment escalate to a point beyond an individual's ability to comprehend their total effect on the overall plant efficiency, it becomes impossible for the dispatcher to make good decisions. Even for simple operations, it is difficult to determine how the system will respond to changes in various operating parameters. It is also noted that although an acceptable operating configuration can be selected, it probably will not be the optimum selection. For optimum configuration a TEP must at all times satisfy all the consumer demands for various types of energy within the complex while meeting constraints peculiar to the system, and at the same time utilize available equipment at its peak operating efficiency. This will minimize the total cost of energy by minimizing fuel and operation/maintenance costs.

A simulation model can be used to relate the operation parameters and constraints for a given TEP which will indicate the equipment assignment profile for optimal operation. Through the use of predictions from simulated model plant operational procedures can be formulated for a given operational requirement to assist the dispatcher. It should be emphasized that these procedures must be viewed as guides only since the actual field situation may vary, and only the dispatcher can assess the total conditions at the time of decision. Nevertheless, the simulation model is a valuable tool to assess "What if" situations before they happen.

To orient the research toward practical application, the model was developed around the operational characteristics of the Reedy Creek Utilities Central Energy Plant at Walt Disney World. Operations in this plant involve generation of electrical power, high temperature hot waters, and chilled water from electric, oil and gas fuel inputs. It is believed that the model might be adopted to similar energy plants or simpler ones by modifying the relationships governing the operational parameters.

2. SYSTEM DESCRIPTION

The system used in the study is typical of a total energy plant. The system is represented schematically in Figure 1, with each major piece of equipment represented by a block, and energy paths through the network represented by directional lines.

The system is designed to use three sources of energy; electricity, natural gas, and fuel oil, from which it produces and distributes three forms of energy: electricity, chilled water and high temperature hot water as required to service the facility.

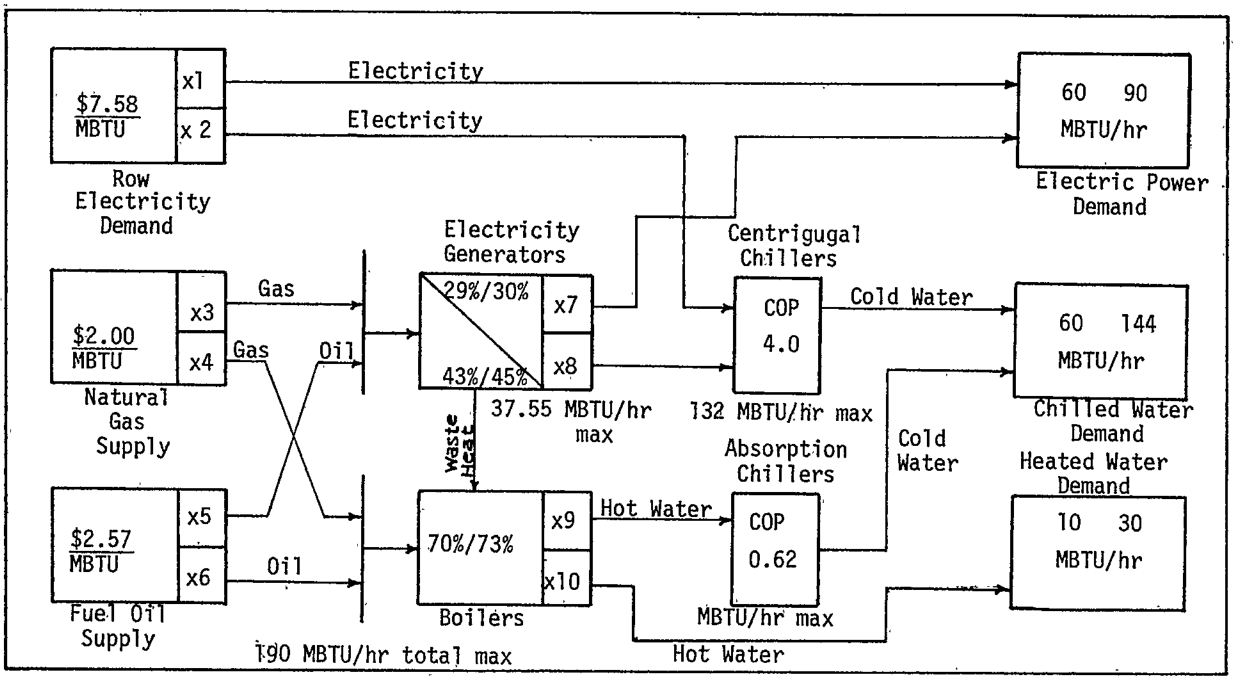

Fig. 1. Case Study Central Energy Plant Block Diagram

Electrical power can either be purchased from an electric utility or generated within the plant by two Orenda modified Hawker-Sidley engine turbine-units. This equipment can provide a maximum of approximately 11 million watts (MW) of electricity power using natural gas or fuel oil. Each of the turbine generators is rated at 5.5 MW or 18.78 BTU capacity. On the average, test data has shown that 29% of the energy used to operate the turbines is converted into electricity, 43% becomes waste heat, and 28% of the input energy is lost. When fired on natural gas, in lieu of fuel oil, the unit efficiency will increase approximately 1%.

High temperature hot water is a by-product of electricity generated via the hot gases from the turbine drive. Waste heat from these generators passes through waste heat boilers which produce 350°C hot water pressurized to 350 psi at a maximum rate of 80 MBTU/hr. The boilers can also be overfired with natural gas or fuel oil at a maximum of 100 MBTU/hr., to produce the total high temperature hot water capacity of 180 MBTU/hr. Tests have shown that energy recovery for the waste heat system is approximately 70% efficient. Using natural gas in place of fuel oil will increase the efficiency to approximately 73%.

Chilled water for air conditioning is also generated in the plant. Six Trawe absorption chillers using high temperature hot water as an energy source can produce 8000 tons/hr. or 96 MBTU/hr. of refrigeration. Electrical driven centrifugal chillers can generate an additional 11,000 tons/hr. or 132 MBTU/hr. for a total of 19,000 tons/hr. installed capacity. The chiller plant is one of the largest in Florida. The coefficient of performance (COP) for the absorption chillers is 0.62, and for the centrifugal chillers is 4.0 in energy utilization.

Studies (1) indicate that the thermal efficiency of a turbine engine is between 0% and 20% at 60% load or less and varies from 20% to 30% if load is in the range of 60-100%. Thus, the minimum operating load of a turbine is 60%, which is considered a fixed or set up cost of a turbine. The coefficient of performance of centrifugal chillers, absorption chillers and the efficiency of boilers were assumed to be relatively constant within their normal load range.

The problem facing the dispatcher can be summarized as: given that three types of energy demands, how should he operate the plant so that the total energy cost is minimized? More specifically, two types of questions need to be addressed:

1. Which units (turbines, boilers, chillers) should be on and off and when?
2. What amount of energy flows from unit to unit for each operating combination?

For example, since running a turbine incurs a set-up cost, it might be cheaper to purchase electricity from outside rather than generate in the plant to meet a small increase in electric power demand (which happens to be feasible in this case).

3. THE SIMULATION MODEL

Development of the simulation model consisted of 3 basic efforts:

1. Defining system variables, and establishing the relationships among the components.
2. Determining a cost function that relates the operating variables to the total cost of operation.
3. Simulate demand data based on the pattern of demand for the three types of energy (electric power, chilled water, and heated water).

The system operational variables were found to be as follows:

X_1 = hourly electricity purcahsed from outside utility company
X_2 = hourly electricity generated in the plant
X_3 = hourly fuel oil input to the first turbine
X_4 = hourly fuel input to the second turbine
X_5 = hourly fuel consumption to operate boilers
X_6 = hourly electricity generated to meet demand
X_7 = hourly electricity generated to run centrifugal chillers
X_8 = hourly hot water produced to operate absorption chillers
X_9 = hourly hot water produced to meet demand
Y_1 = 1 first turbine run by fuel oil
0 first turbine off
Y_2 = 1 second turbine run by fuel oil
0 second turbine off
EPD = Electric Power Demand
CWD = Chilled Water Demand
HWD = Hot Water Demand

Relationships between variables to reflect the operating condition, as well as between variables and the demand values are:

$$X_3 - 100.0Y_2 \leq 0 \quad (1)$$

$$X_4 - 100.0Y_2 \leq 0 \quad (2)$$

$$0.29X_3 \leq 18.78 \quad (3)$$

$$0.29X_4 \leq 18.78 \quad (4)$$

$$0.70X_5 \leq 100 \quad (5)$$

$$0.43X_3 + 0.43X_4 \leq 80 \quad (6)$$

$$4.0X_2 + 4.0X_7 \leq 132 \quad (7)$$

$$0.62X_8 \leq 96 \quad (8)$$

$$X_1 + X_6 \geq EPD \quad (9)$$

$$4.0X_2 + 4.0X_7 + 0.62X_8 \leq CWD \quad (10)$$

$$X_9 \leq HWD \quad (11)$$

$$0.29X_3 + 0.29X_4 + X_7 - X_8 = 0 \quad (12)$$

$$0.43X_3 + 0.43X_4 + 0.70S_5 - X_8 - X_9 = 0 \quad (13)$$

The cost function as related to the previously defined variables can be established as follows:

$$\text{Cost} = 7.68X_1 + 7.68X_2 + 28.91Y_1 + 2.57X_6 + 28.91Y_1 + 2.57X_4 + 2.57$$

The coefficient of the variables in the cost function are unit costs for the various energies flowing in the system. A linear programming model can be formulated and applied to optimize the cost function subject to the relationships (1) to (13) as constraints. Applying the optimization technique enables the determination of the optimal values of the variables, which can be translated into a time schedule for the generating equipment. This type of model is termed "charge problem." The first two constraints are to ensure that a fixed charge or set-up cost is incurred if a turbine is operated. The reason being that if X_3 is greater than 0, then Y_1 must be 1, however, if $X_3 = 0$, then Y_1 can be either 1 or 0. But, due to the cost in the objective function, Y_1 is forced to be 0. Constraints 3-8 are to make sure that the unit capacity limits are satisfied. Constraints 9-11 are to meet electricity, chilled water and hot water demands. The last two constraints are the conservation of energy.

Patterns of demand were determined based on historical data for previous years. These data were used to determine mean, variance, and a distribution to describe the pattern of demand by hour for each day within the month; and for each month within the year. Time dependent values for the energy mode demands were generated from the simulator model which were then used by the L.P. model to find optimal operative configuration within the constraint. This information was then translated into time loading schedules for each energy generating equipment.

Certain assumptions and operating conditions had to be included in the model and which might vary from one application to another. Specifically, the set-up costs for the equipment (in our case it is the turbine). Assuming 60% is the minimal operating load, the set-up cost for each turbine is the product of the load fraction, the full load and cost of fuel as 0.6 x 18.78 x 2.57 (or $28.91) for fuel oil. To run a turbine by fuel oil for 1 hour, for example, the hourly cost is $28.91 = 2.57 \times X_3$ if $X_3 > 0$; and 0, otherwise. Note that this cost is not the real out-of-pocket cost, but, if a turbine is needed, such a cost term can ensure the turbine running at 60% higher.

MODEL RESULTS

Figure 2 shows energy demands on the Central Energy Plant for a typical summer and winter day. In the case study, simulated demands shown in Table 1 were used, where each day was divided into three 8-hour periods: midnight - 8:00 a.m., 8:00 a.m. - 4:00 p.m., and 4:00 p.m. - midnight.

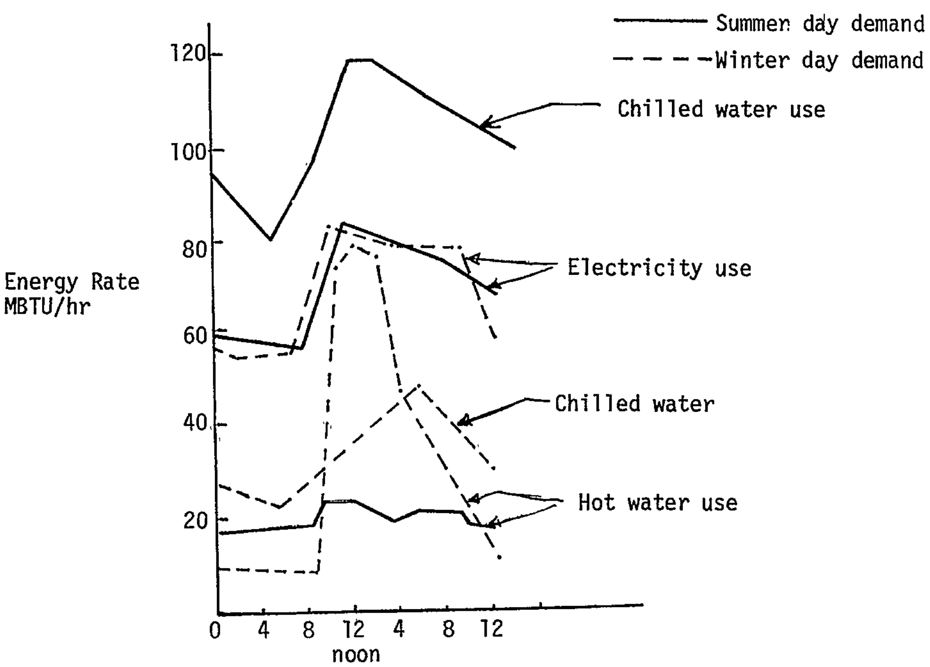

Fig. 2. Sample Energy Demand

Table 1. Approximate Demands

Demand	Midnight to 8 a.m.	Summer day 8 a.m. to 4 p.m.	4 p.m. to midnight	Midnight to 8 a.m.	Winter day 8 a.m. to 4 p.m.	4 p.m. to midnight
Electricity	60	85	80	60	85	80
Chilled Water	90	140	130	27	45	50
Hot Water	20	24	22	10	80	50

(All units in MBTU/hr.)

Results of the typical summer and winter day cases are shown in Table 2. The results may provide the plant operator with an insight as to which units should be on or off and what amounts of power should be purchased from the outside utility company to meet the total electric power requirement. Take, for example, the midnight - 8:00 a.m. period of the summer day. This requires 22.4 MBTU/hr. of electricity be purchased and 37.6 MBTU/hr generated in the plant to meet the electric demand of 60 MBTU/hr. Both sets of turbine generators should operate at full capacity, each consuming 64.8 MBTU/hr of fuel oil. Without overfiring the boilers, the wast heat produces 55 MBTU/hr. as hot water, 35 MBTU/hr. of which was used to run the absorption chillers and 20 MBTUL/hr. to meet the hot water demand. Of the 90 MBTU/hr. chilled water needed, 68.0 MBTU/hr. is provided by the centrifugal-chillers and the remaining 22.0 MBTU/hr. by the absorption chillers.

Table 2. Case Study Results

		Summer day			Winter day		
		Midnight to 8 a.m.	8 a.m. to 4 p.m.	4 p.m. to midnight	Midnight to 8 a.m.	8 a.m. to 4 p.m.	4 p.m. to midnight
Electricity Purchased							
for electric use	X_1	22.4	47.4	42.4	45.4	47.4	42.4
for chillers	X_2	17.0	30.1	27.3	--	57.3	11.8
Fuel oil consumed							
by turbine 1	X_3	64.8	64.8	64.8	64.8	64.8	64.8
by turbine 2	X_4	64.8	64.8	64.8	--	64.8	64.8
by overfiring	X_5	--	--	--	--	34.7	--
Electricity generated in plant							
for electric use	X_6	37.6	37.6	37.6	14.8	37.6	37.6
for chillers	X_7	--	--	--	4.0	--	--
Hot water generated							
for chillers	X_8	35.7	31.7	33.7	17.8	--	5.5
for hot water use	X_9	20.0	24.0	22.0	10.0	80.0	50.0
Chilled water generated by							
centrifugal chillers		68.0	120.3	109.2	16.0	45.0	47.2
absorption chillers		22.0	19.7	24.8	11.0	--	3.3

(All units in MTBU/hr.)

Based on the initial results of this study, the following recommendations were provided as a guide to operate the plant. On a summer day: (1) load up the turbine generators; (2) use part of hot water to run the absorption chillers to meet hot water demand; (3) use the remaining hot water to run the absorption chillers to meet part of the chilled water demand; (4) generate the remainder of the chilled water demand by the centrifugal chillers; and (5) meet the electricity demand by purchased electricity augmented by that generated in the plant.

On a winter day, the system operation would be similar except that typically the hot water demands are higher, less hot water would be available to operate the absorption chillers; however, less chilled water would typically be required.

OBSERVATIONS/CONCLUSIIONS

The model presented in this paper describes a complex Total Energy System and presents a method for investigating/determining the optimum (lowest cost) equipment operating configurations. The system of equations developed in the model can be expanded or reduced to accommodate a variety of system combinations.

It must be recognized, however, that the model as presented has some inherent weaknesses and more work will be required to make it acceptable to an experienced plant operator. Clearly, the closer the model can follow or anticipate the energy demand curves, the better it can predict plant equipment requirements for cost effective performance. This can be achieved by updating demand volume from which simulation is generated from year to year.

The model should be modified to reflect the maintenance/operational requirements of the equipment. For example, the absorption chillers generally cost less to maintain than their centrifugal counterparts, but they require more time to bring on line. On the other hand, the centrifugal units may be limited in the number of starts per day due to the size of the drive motors. The experienced operator knows these tradeoffs and will be reluctant to accept output from a model which does not recognize them.

A further consideration which should be introduced in the model is the variation in peak power demand cost which would be experienced in the real world as the electrical energy requirements are shifted between plant-generated and purchased power. As more power is purchased, an additional surcharge should be included on the unit cost of electricity. This is a very real operational cost problem and one which would directly impact the decision to generate or purchase additional power.

It is submitted, however, that costs, such as equipment maintenance and peak demand, could be added by introducing another cost term in the objective function. In the same manner, additional constraints, energy flows, equipment demand, etc., can be handled with no change in the basic model structure. It is believed that this work represents a start toward development of a generalized model of a total energy or cogeneration plant which can be used for analysis and optimum operation.

REFERENCE

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