AN OPTIMIZATION MODEL TO SAVE FUEL ENERGY IN ELECTRICITY GENERATION*

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<CONTENTS>

ABSTRACT

Of late, there has been a sharp increase in the peak electric power load which is attributal to weather-dependent power load. It is this peak load that forces the power generation company to build gas turbine plants that have a low capital cost per KW but high marginal cost per KWH resulting in inefficient use of input fuel energy.

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One of the main objectives of this research is to examine the nature of optimality in the use of input fuel energy for electricity generation by shifting the peak power load to off-peak hours via a certain energy storage system such as solar heating in winter, thermal energy (coolness) storage for summer, or the hydroelectric pumped-storage system which is given a serious consideration in Korea today.

(1) A linear regression model was adapted to quantify the relationship between weather conditions and system peak load.

(2) The weather-dependent load is segregated or estimated from the total load on the system using the adapted model.

(3) The fuel energy consumption to meet the total load including the full weather-dependent portion is calculated using the marginal cost curve of the area in concern.

(4) The same quantity as in (3) is calculated assuming that a certain percentage of the weather-dependent portion is shifted to off-peak hours via a load-flattening energy storage technique.

(5) The quantity obtained in (3) minus the quantity obtained in (4) is defined as the net fuel energy saving.

(6) The quantity defined in (5) is calculated for various values of shift-over percentages.

(7) From the result obtained in (6), the optimum value of shift-over percentage that gives rise to the maximum fuel energy saving for the system is found.

Finally, the possible control of SO_2 pollution problem by virtue of the energy storage system is discussed.

CONTRIBUTIONS FROM THE WORK

Major contributions done by the work are as follows:

(1) The study has shown that there does exist an optimum value among possible shift-over percentages of weather-sensitive electric power load when a certain energy storage system is adopted to shift the weather-sensitive peak portion of the system load to off-peak hours.

(2) The study has also proposed methodological steps by which one can find the optimum value mentioned above.

(3) The optimum value thus found could be used to determine the optimum size of an energy storage system such as hydroelectric pumped-storage system which is currently given a serious consideration in Korea.

I. INTRODUCTION

During the ten year period from 1964 through 1974, the demand for electricity in Korea increased at a rate of approximately 22.3 percent per year. [1] In light of the 22.3 percent increase in electric power consumption per year, it is necessary for the power-generating company to double their power system capacity about every 3.48 years.[2]

In addition, there has been a sharp increase in the peak demand which is attributal to the weather-dependent load. It is the peak load due to weather-dependent demand that forces the generation company to build gas turbine plants which have a low capital cost per KW but high marginal cost per KWH with a result of inefficient use of fuel energy such as coal or oil.

Lately, public acceptance of, and demand for, summer air conditioning has introduced a new and volatile factor in load variability in Korea. As of July 1975, Korea Electric Company has announced, weather-dependent summer load has resulted in a change from winter to summer annual system peak load in Korea.[3]

1. Calculated from page 81, Statistics of Electric Power in Korea, Korea Electric Co., 1973
2. Calculated using $A(1.223)^n=2A$.
3. The Seoul Kyungje, July 26, 1975

In view of this sharp increase in weather-dependent peak demand for electric power and its entailing impact on the power generation system resulting in a considerable loss of efficiency in use of fuel energy, we will examine the conditions of optimality, if there exists one, in shifting the peak power load to off-peak hours via a certain energy storage system such as solar residential heating in winter thermal coolness storage in summer, or the hydroelectric pumped-storage system which is given a serious consideration in Korea.

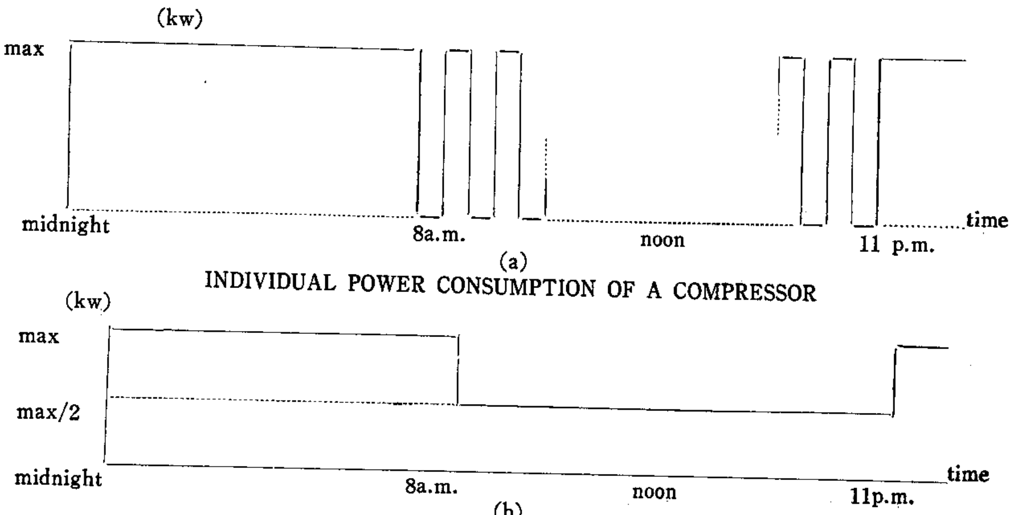
A hydroelectric pumped-storage system is a load flattening technique by means of energy storage. The main function of pumped storage is to store in the form of hydraulic potential energy that surplus energy which is available in power systems during off-peak hours. The stored energy is then used during peak periods when either the demand for power exceeds the combined generating capacity of the power systems, or when it is uneconomical for some reason to supply this demand through other means.[4]

A thermal energy storage system is analogous to a pumped storage hydro system which, in this case, stores the off-peak energy in the form of coolness in a thermal energy storage material for later use during the peak period. In other words, the basic control philosophy utilized for a thermal energy storage air conditioning system is to fill up the thermal energy storage (TES hereafter) unit during the off-peak period (11 p.m.-8 a.m.) and to use the stored coolness in the TES unit during the peak period to supply or to supplement the compressor in satisfying the cooling requirements.[5] Depending upon the compressor size, varying amounts of compressor usage time during the peak period are required to meet the cool-load demand. If all the TES air conditioning compressors in a certain region were in use simultaneously, a peak in power consumption would be experienced. Hence,

4. Baldwin and Houser
5. National Center for Energy Management and Power

it is proposed that a staggering approach of compressor usage is a better alternative. The approach divides users of a region into different groups with each utilizing their compressors at different times; thereby evenly distributing compressor utilization and power consumption.

The implementation of the staggering approach is obtained by the following control scheme. Two thermostats will be used to control coolness generated by the compressor; one will control the coolness supplied to the home and the other the coolness delivered to the TES unit. The space temperature control thermostat turns the air circulation fan on and delivers coolness when the temperature is above its set point. The TES internal thermostat turns the compressor off when the TES temperature is below its storage value. Therefore, if needed, the compressor will be permitted to run continuously during the off-peak period.[6] During peak-period hours the compressor will be constrained to run only a fraction of the hour. The power consumption of a TES air conditioning system appears as shown in Figure 1.



EFFECTIVE INDIVIDUAL COMPRESSOR POWER CONSUMPTION

FIGURE 1

THE IMPACT OF STAGGERING CONTROL POLICY

6. Yoon, S.C.

The same line of reasoning as with the thermal coolness storage system could be utilized to explain the possibility of transferring peak power load in winter to off-peak periods via the use of solar energy and associated heat storage for residential heating purposes.

When implemented, the proposed model could be used to find ways to make better use of our power generation system and to lessen the future demands for costly plant expansion, while it is directed at the goal of fuel energy saving by curtailing the utilization of low-efficiency marginal generators installed and standing by to meet the peak demand only.

II. RELATIONSHIP BETWEEN SUMMER WEATHER AND SUMMER LOAD

It has been observed that the following weather variables affect summer daily peak loads: dry bulb temperature and relative humidity at the time of system peak, temperatures during the hours and days antecedent to the peak, rain, wind velocity, and sky cover.[7]

In this work, a linear regression technique was adapted to quantify the relationship between weather conditions and system peak load. The following general mathematical model was selected for the analysis (this model is the same as that adapted in Heinemann et al.):

Daily Peak Load = Base Load + Weather-Dependent Load

or $$DPL = B + (CDF)(WV) \qquad (1)$$

where the base load (B), cooling demand factor (CDF) and weather variable (WV) will now be discussed.

<u>Base Load</u> : The base load B is defined as the portion of load which is independent of the changes in the weather conditions. In this study B was assumed constant throughout each month and step changes in their values

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7. Heinemann, Nordman & Plant

was assumed to occur from month to month.

Cooling Demand Factor (CDF) : The coefficient of the weather variable WV, called the cooling demand factor, is constant and proportional to the amount of cooling equipment installed. This is a measure of, predominantly, connected air conditioning load. It is expressed in megawatts per unit of weather variable. Since it is known that the sale of air conditioners has increased at a relatively smooth rate, the coefficient CDF exhibits a relatively smooth monotonic increasing trend.

Weather Variable (WV): The weather-dependent load was assumed to be linearly related with the weather variable WV, or

$$\text{WDL(Weather-Dependent Load)} = k_1 \, WV \qquad (2)$$

where $k_1 = CDF$.

The weather variable WV was found to be a linear combination of two separate components. One expresses instantaneous weather conditions (WV_{inst}) and the other expresses preceding weather conditions (WV_{prec}).

Specifically,

$$WV = k_2 \, WV_{inst} + k_3 \, WV_{prec} \qquad (3)$$

where WV_{inst} is a second-degree equation utilizing air heat content (HC), or

$$WV_{inst} = k_4 \, HC^2 + k_5 \, HC \qquad (4)$$

WV_{prec} is a second-degree equation utilizing a variable that will be called dry-bulb buildup(DBB), or

$$WV_{prec} = k_5 \, DBB^2 + k_7 \, DBB. \qquad (5)$$

HC is air heat content, measured in British thermal units per cubic foot at the hour of daily peak load. It can be read from a psychrometric chart given any two of the three variables: dry bulb temperature, wet-bulb temperature, and relative humidity.

DBB expresses heat buildup during days preceding the peak load in the following manner:

$$DBB = k_8 \ (SV_1 e^{-24/T} + SV_2 e^{-48/T} + SV_3 e^{-72/T}) \qquad (6)$$

where T=exponential time constant of heat buildup and,

$$SV_1 = k_9 \ DBH_1 + k_{10} \ DBC_0 \qquad (7)$$

$$SV_2 = k_9 \ DBH_2 + k_{10} \ DBC_1 \qquad (8)$$

$$SV_3 = k_9 \ DBH_3 + k_{10} \ DBC_2 \qquad (9)$$

where DBH_1, DBH_2, and DBH_3 are the dry bulb temperatures at the hottest hours of three days preceding the peak day, and DBC_0, DBC_1, and DBC_2 are the dry bulb temperatures at the coolest hours of the peak day and the two days preceding the peak day. It can be seen that this exponential relationship applies the most weight to recent (that is, yesterday's) weather. Each day's severity is represented by drybulb temperatures at the hottest hours of the day in combination with dry bulb temperatures at the coolest hours of the next morning.

WV in equation (2) has now been completely described by equations (3) through (9). These equations, when combined, produce a single variable representing the severity of the weather conditions which can be substituted for WV in equation (1).

Total system peak load on any given summer day may be thought of as the summation of three components:

(1) normal basic load,

(2) weather-sensitive load, and

(3) random load.

The random load may be either positive or negative and is precisely equal to the difference between actual peak load for that historical day and the peak load calculated by Equation (1) for that day. If an attempt were made to explain this random load component, the following partial list of causes might be set forth:

(1) normal variation in large motor loads in industrial processes,

(2) variations in general business levels,

(3) television viewers' interest in a specific event, such as big sports games.

In this anaysis, the random load variation each year is measured in terms of standard deviation (s.d.) which is defined as:

$$\text{s.d.} = \sqrt{\sum_i (\text{Actual load}_i - \text{Calculated load}_i)\,2/N}$$

where N is the number of observations (days) used in the regression analysis for the summer season under consideration.

The model can be applied to the daily peak load and weather experiences of the area in concern for summer periods of several consecutive years. This application provides us with the trend of coefficient CDF and basic load B for the applied area during the period.

Once one has calculated the model constants and coefficients that provide the best fit to actual historical daily observations in a recent summer season, we can predict (or calculate) the power demand situation for a typical hottest day and for an average summer day on the basis of the model. We designate the percentage of weather-sensitive load on the hottest day as P_{hot} while that on an average day as P_{ave}.

On the basis of the above data, that is P_{hot} and P_{ave}, and using other data on the characteristic load pattern in metropolitan area, shown in Figure 2, we can calculate the percentage of weather-sensitive load from total load at non-peak hours.

In calculating the percentages of weather-sensitive load from total load at non-peak hours, we assume the following:

(1) During the peak hours, 2 p.m. through 5 p.m., weather-sensitive load remains at its full level.

(2) From 11 p.m. through 7 a.m., when temperature drops to about 70's degree F, the percentage of weather-sensitive load to total load is 9.7% as obtained from the model discussed previously.

(3) Between 7 a.m. through 2 p.m., and from 5 p.m. through 11 p.m., we assume linear increase or linear decrease, respectively, in the percentage of weather-sensitive load.

These assumptions can be represented graphically as in Figure 3.

Figure 2.

Characteristic Metropolitan Load Pattern[8]

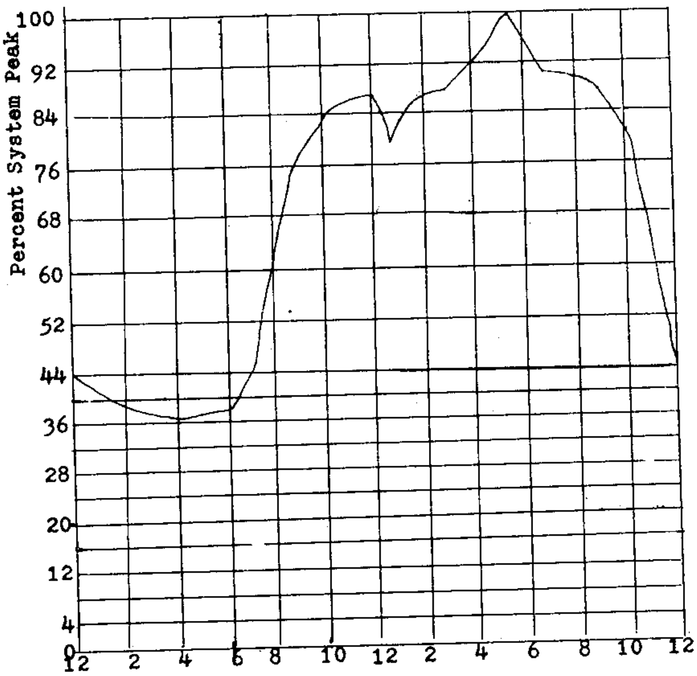
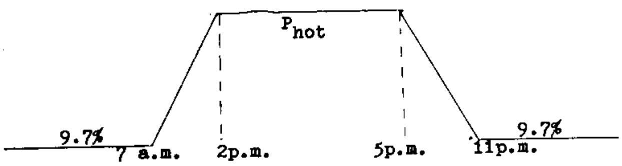


Figure 3.

Assumed Weather Sensitive Load Percentage



8. Standard Handbook for Electrical Engineers, p. 16.

III. FUEL ENERGY SAVINGS DUE TO WSL-SHIFT

The general objective of the unit commitment problem is to minimize system total operating costs while simultaneously providing sufficient spinning reserve capacity to satisfy a given security level. Various approaches to solution of the optimal unit commitment problem have been advanced. The general approach of the method is that of dynamic programming coupled with newly developed means of quantitatively assessing system security in near-term future. Dynamic programming has been shown to be applicable to the problem of selecting the optimum combination of generators to run to supply a given load from the point of view of minimum running costs.[9]

Stated in power system parlance, the essence of dynamic programming is; for the total running cost of carrying x MW of load on N generating units to be a minimum, the load y MW carried by unit N must be such that the remaining (N−1) units also at minimum fuel cost. In mathematical form:

$$f_N(x) = \text{Min}\ g_N(y) + f_{N-1}(x-y)$$

where

$f_N(x)$ is the minimum running cost of carrying x MW load on N generation units,

$g_N(y)$ is the cost carrying the y MW load on unit N, and

$f_{N-1}(x-y)$ is the minimum cost of carrying the remaining $(x-y)$ MW load on the remaining (N−1) units.

Thus, knowing g_N and f_{N-1}, we are able to calculate the minimum cost f_N for the N unit combination.

Dynamic programming is used in two ways: first, it is used to determine the combinations of units yielding minimum running costs for loads ranging

9. Ayoub and Patton

in convenient steps from the minimum permissable load of the smallest unit to the sum of the capacities of all available units; second, dynamic programming is used to compute the minimum running cost for a given combination of units and a given load.

Hence, a dynamic programming can be performed to investigate the marginal generation units and corresponding marginal generation costs associated with the weather-sensitive electric load in summer for our model area.

The reduced electric power load (REPL hereinafter) during the i^{th} peak hour, resulted when certain percentage of the weather-sensitive load of the model area on a summer day is shifted to off-peak hours by the thermal energy storage air conditioning system, can be calculated using the following relationship;

$$REPL(i) = \text{Total load } (i) - WSL(i) \times \text{Takeover } \%. \qquad (10)$$

The amount of fuel saving represented by the marginal generation cost saved during each hour of peak load period is calculated by the following relationship;

$$MGCS(i) = Cost_{tot}(i) - Cost_{REPL}(i) \qquad (11)$$

where MGCS(i) is the marginal generation cost saved during the i^{th} hour of peak period,

$Cost_{tot}(i)$ is the total generation (fuel) cost which will accrue to the system when no TES system is adopted, and

$Cost_{REPL}(i)$ is the total generation (fuel) cost which is to accrue to the system when TES system is in operation.

On the other hand, the increased electric power load (IEPL hereinafter) during the j^{th} hour of off-peak period, resulting when certain percentage of the weather-sensitive load of the model area on a summer day is shifted to off-peak hours by the TES system, can be calculated as follows;

$$\text{IEPL (j)} = \text{Total load (j)} + \frac{\text{TPR}}{\text{OPH}} \quad (12)$$

where TPR stands for total power requirements to store enough energy for peak hour usage, and

OPH stands for the time-length of off-peak hours during which the storage operation is performed to store energy for later use.

It should be noted here that TPR is a function of shift-over percentage since if one plans to shift over the bigger percentage of weather sentitive load during peak hours to off-peak period, the power requirements to store the needed energy gets bigger. With TPR being a function of shift-over percentage, IEPL (j) is also a function of shift-over percentage.

The increased amount of fuel usage represented by the marginal generation cost increase during each hour of off peak period is calculated as follows:

$$\text{MGCI(j)} = \text{Cost}_{\text{tot}}\text{(j)} + \text{Cost}_{\text{IEPL}}\text{(j)} \quad (13)$$

where MGCI(j) is the marginal generation (fuel) cost increase during the j th hour of off-peak period,

Cost tot(j) is the total generation (fuel) cost which might have accrued to the generation system if no energy storage system were adopted, and

Cost $_{\text{IEPL}}$(j) is the total generation (fuel) cost which accrues to the system when an energy storage system is in operation.

Since IEPL is a function of shift-over percentage, so is MGCI (j) as discussed previously.

IV. INCREMENTAL GENERATION COST CURVE

A generating station usually contains several sets or units, i.e., oil or coal fired stations are equipped usually with combinations of boiler, turbine and auxiliary plant. Nowadays, these sets are usually designated so as to function independently of one another.[10]

The marginal cost per KWH sent out by any set in such a station is: (i) the marginal cost of heat delivered per BTU divided by (ii) marginal KWH sent out per BTU.

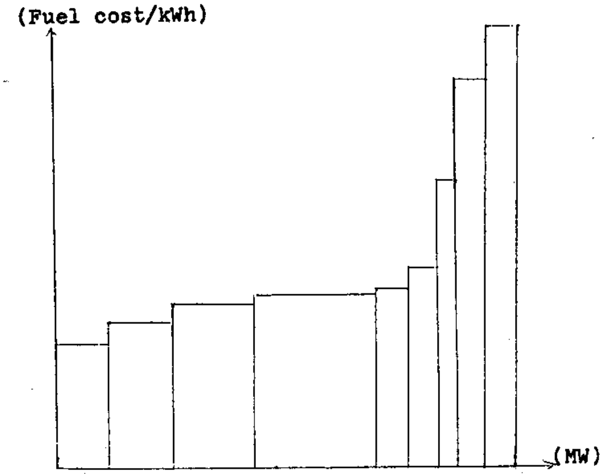


Figure 4 A Rising Marginal Cost Curve

For any given hour, the merit order can be represented as a rising marginal cost curve. A typical case is represented as in Figure 4.

In a large system, the possibility that it is stepped loses importance, so one can treat it as continuous, if needed. At any rate, when the system load is not too high, that is, during off-peak period, the generating operation is performed using higher efficiency units corresponding to the lower and flat portion of the marinal cost curve in Figure 4. When the system load is very high, however, that is, during peak period, low-efficiency units corresponding to the steep and right-handside portion of the marginal cost curve in Figure 4, begin to take part in the operation to generate electricity.

This logical practices lead us to the following conclusion:

$$\Sigma_i MGCS(i) > \Sigma_j MGCI(j) \quad (14)$$

10. Turvey, R.

where MGCS(i) came from Equation (11) and

MGCI(j) came from Equation (13).

From Inequality (14), we define net fuel saving (NFS) as

$$NFS=\Sigma_i MGCS(i)-\Sigma_j MGCI(j) \tag{15}$$

the amount of which is always a positive quantity meaning that with the introduction of an energy storage system a positive net fuel energy saving can be resulted.

V. EXISTENCE OF AN OPTIMUM

When we discussed about Equation (12) and (13), we noted that MGCI(j) is a function of shift-over percenage. When we consider Equation (10) and (11), we immepiately notice that MGCS (i) is a function of shift-over (or takeover) percentage, too.

With our knowledge of MGCS(i) and MGCI(j) being functions of shift-over percentage, Equation (15) immediately reveals us that the net fuel saving (NFS) on account of the peak load shifted to off-peak period via a TES system is a function of shift-over percentage.

On the other hand, when we note Figure 4, we can see that at the beginning of the weather-sensitive load shift, the amount of fuel cost savings increases rapidly due to the sharp rise of the marginal cost curve on right-hand side in Figure 4. However, beyond a certain point (corresponding to the optimum) this rate of increase in fuel cost savings during peak period gets slower than the rate of increase in fuel cost during off-peak period.

This phenomenon is due to the typical characteristics of marginal cost curves which are usually of S shape as shown in Figure 4. This point of optimum can be found by a computer simulation once the shape of the marginal cost curve of the area in concern is given.

VI. SAVING OTHER THAN FUEL ENERGY

In addition to the possible benefit coming from fuel savings, our interest is also focussed on the possible savings in capital cost due to the marginal units which could become dispensible as a result of alleviated peak load by the introduction of an energy storage system.

In other words, some marginal generation units which are operated only for those peak hours can be dispensible.

Those marginal units which could be dispensible if certain percentage of weather-sensitive load could be shifted to off-peak hours can be identified easily from the dynamic programming output table discussed previously.

The capital cost required for those marginal units including transmission is currently estimated at more than $100 per KW of installed capacity. Using this figure the calculation of total capital cost savings in terms of the shift-over percentage of the weather-sensitive load for a model area can be done.

VII. ENVIRONMENTAL CONSIDERATIONS

There are growing concern with the environmental impact of power utilities. This include air polution, thermal pollution of rivers and streams, aesthetic pollution, as well as concern about radiation hazards from nuclear power plants. Coal and oil combustion now contributes about 77% of the SO_2 emmission in the United States of America, with about 55% of the total coming from power generation plants.[11] Pertinent data about Korea are not available as of the date of this writing.

In view of the rapidly growing demand for electric power two thirds of the total SO_2 emissions in 1980s are expected to originate from power plants.[12] As shown in this stndy, an thermal energy storage system can

11. Hottel and Howard.
12. Ibid.

make it possible for power utilities to have low-efficiency generation units be idle or totally dispensible.

When utilities can afford to have some generation plants be idle by virtue of the thermal energy storage system, they can possibly control the SO_2 pollution problem to considerable extent by reordering their generation unit commitment in consideration of

(i) localities and emission rate of SO_2 of generation plants, and

(ii) on-off schedule in running the most polluting units with time intervals that minimizes the concentration of SO_2

VIII. INTEGRATION OF HEATING/COOLING SYSTEMS

From an architectural and planning point of view, it appears that the concept of a total system combining components of solar heating, auxiliary heating, cooling, and thermal energy storage is the most reasonable approach to the overall problem. Such a system should allow enough flexibility to be able to respond to the various conditions of the market place and the environment.

The various parts of the system could become primary or secondary components depending on the location, orientation, climate, etc. The thermal energy storage system remains the core of any system and is therefore central to the development of the concept of energy conservation.

In order to make thermal energy storage and solar heating systems economically competitive with other methods of residential space heating and cooling, the system must be integrated into buildings. For it is easy to show that the initial cost of the components of a solar heating system (when added to the cost of a complete house) are so high as to preclude recovery through reduced operating costs over any reasonable life span. A considerable amount of effort must therefore be spent on uncovering techniques for integrating components of the thermal energy storage and/or solar heating system into other components of buildings.

IX. CONCLUSIONS

A model to save fuel energy in electricity generation has been proposed in this paper. The model draws its line of reasoning from the fact that it is the peak load that forces the power generation company to build gas turbine plants which have a high marginal cost per KWH resulting in inefficient use of input fuel energy. It is known that the peak power load is mainly due to weather-dependent power demand.

Hence, a thermal energy storage system to alleviate the peak hour power demand was considered in the model. It has been shown in the model that when portions of the weather-sensitive electric load in the summer is shifted to off-peak hours by the thermal energy storage system, significant amount of savings in fuel as well as in capital costs can be accrued.

The model has also shown that the fuel saving reaches a maximum when a certain percentage of the weather-sensitive load is shifted to off-peak hours. A simulation procedure was presented to find the value of the percentage that gives rise to the maximum in fuel saving.

The possible control of SO_2 pollution problem by virtue of the thermal energy storage system was also discussed.

X. RECOMMENDATIONS FOR FURTHER STUDY

Due to lack of pertinent data the model was unable to be applied to realities. It is recommended that the model be applied to real world data and the optimum value of the shift-over percentage of the weather-sensitive load be found for, say, Seoul area so that it could be used to determine the optimum size of an energy storage system such as hydroelectric pumped storage system which is currently given a serious consideration in Korea.

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