PLANT OPTIMIZATION PROGRAM (POP) AND ITS APPLICATION IN RATE MODEL FOR A LARGE DISTRICT ENERGY AND COMBINED HEAT AND POWER SYSTEM

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ABSTRACT

District energy systems provide commercial and residential space heating, air conditioning, domestic hot water, steam, and industrial process energy, as well as sometimes co-generating electricity in systems. Though the district energy system is usually more economical and energy-efficient than individual heating and cooling systems, it is also much more complicated system. The dynamics of the energy markets, changes of building and whole campus load profiles, and increasing discretion of the end users under increasingly higher utility cost make it more challenging for the facility to better plan its operation, such as develop budget for new fiscal year and generate bills for its customers. Therefore, a thorough understanding of the whole system operation, interactions among buildings' load fluctuations and plant operation, impact of the energy price on rates of utilities it produced, and balance between energy efficiency and operation cost, is critical. A reliable thermo-economical simulation model for the existing district energy combined heat and power plants can be a very powerful analysis tool in assisting decision-making of the facility management.

This paper discusses the results of efforts to develop the Plant Optimization Program (POP), a program specifically designed to conduct thermal and economical analysis and optimzation for a large district energy and combined heat and power system. Following the description of the conceptual model and procedures developed for the thermo-economic simulation, this paper presents the modeling techniques, cost allocation principles, and optimization principles adoped by the POP. Then this paper presents the Rate Model, an application of the POP to a large university campus in central Texas for energy budget and cost allocation for billing purposes.

KEYWORDS

Combined Heat and Power, District Energy System, Rate Model, Load Profile, Power Plant Simulation

INTRODUCTION

Unlike most other commodities, electricity (ELEC), steam, heating hot water (HHW), domestic hot water (DHW), and chilled water (ChW) are very difficult to store in a practical manner on a large scale. Therefore, a reliable supply of these commodities was always and still is a major priority. In the past few years, a new priority has been set by a global trend to deregulate the energy market. Deregulation and competition have brought about a need for flexibility, reliability, increased automation, and cost minimization in generating plants. To stay competitive, power plants will need to run optimally all the time, requiring advanced control and optimization strategies (Oluwande 2001).

There are many literatures about operation optimization, assessment of costs, and economic effects of combined heat and power generation (e.g., Marecki 1988; Kehlhofer et al. 1999; Sarabchi 2001; Donne et al. 2001). However, the determination of the profitability and feasibility of proposed combined heat and power plants is generally the focus of those literatures. Many computer simulating programs had also been developed, such as DEUS, COGEN3, CELCAP program, and so forth. These simulation tools were mainly developed to complete feasibility and finanical analysis of cogeneration systems (Zhou 2001; Baxter 1997). Much of the thermal economic literature is also directed toward design evaluation and optimization rather than the practical cost analysis for existing systems (Femming 1997). However, the operation of plant equipment is often radically different from the design assumptions and frequently changes. The dynamics of the energy markets, such as the changes and fluctuations of fuel price and electric cost and changes of load profiles, add more complexity to the determination of the operational cost of existing utility plants. There are real needs of tools to conduct the operational thermo-economic analysis for utility plants. Under the circumstance of high cost and high volatility in the deregulated energy market, a thermo-economic analysis tool for operation optimization of existing plant can be critical. Many tools had been deveoped for this purposes, such as Fennel (1993) and Baxter (1997) each developped spreadsheet-based thermodynamic and economic evaluation programs.

However, there are very few documented cases of applications in real world projects. This paper intends to demonstrate a case of successful application in this field.

CONCEPTUAL MODEL

The conceptual model of a thermo-economic model of a District Energy System (DES) should consist of at least two layers of models, i.e. physical model and cost allocation model. The physical model, which is similar to the conceptual model proposed by Beasley (1999, 2002), also consists of three parts: (1) primary energy to the DES, (2) plant process used to consume primary energy, such as natural gas (NG), ELEC, and fuel oil, and to produce various thermal and electrical commodities, such as ChW, HHW, DHW, steam, and ELEC, and (3) the thermal and electrical commodities supplied by the DES to the buildings it serves (see Figure 1). Some facilities may purchase ELEC from the grid, but some of them my sell ELEC to the grid.

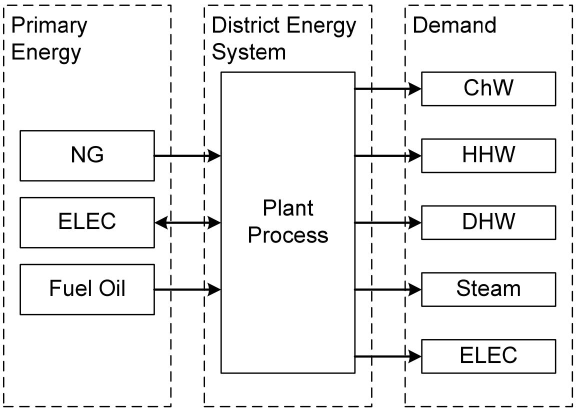

Figure 1 Conceptual physical model for a district energy system

The conceptual cost allocation model also consists of three parts: (1) primary energy cost to the DES, (2) cost allocation process of the primary energy cost to the production of various thermal and electrical commodities, and (3) the costs of the various commodities produced by the DES, as shown in Figure 2. Many literatures include other costs, such as overhead, tax, and so forth, into their cost allocation models, which tends to make the system model too complex to be practical. This paper limits the cost allocation model to primary energy only. For more advanced economic evaluation model, the third layer of model can be developed. An example would be the Rate Model, which is developed to allocate not only the cost of primary energy, but also the cost of labor, O&M expenditure, cost contribution due to debt service, infrastructure repair, depreciation, and so forth for each of the utility production. More details of the Rate Model will be given in later portion of this paper.

The objective of the modeling process at the physical model level is to project the system response including the primary energy use required to meet the facility energy demand, which is achieved by a model representing the energy flow of the facility and the equipment utilized to meet the energy requirements, which proceed from right to left in Figure 1. The objective of the modeling process at the cost allocation level is to calculate the costs of (1) the primary energy consumption, (2) thermal medium in the plant process, such as steam at various pressures, and (3) the thermal and electrical commodities produced by the DES, which proceed from left to right in Figure 2.

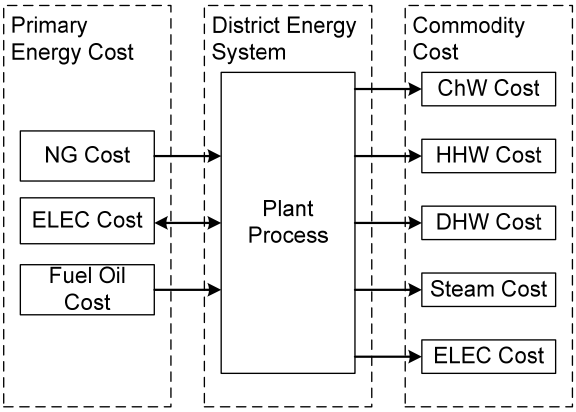

Figure 2 Conceptual cost allocation model for a district energy system

SIMULATION PROCEDURES

The conceptual model can be used to conduct thermo-economic evaluation for a given scenario under a given moment. In reality, all plants are operated dynamically, which means the performance of a plant at any moment isn’t adequate to represent the performance of it over time. In order to evaluate the performance of the utiltiy plant, the impact of thermal and electrical demands fluctuation, primary energy rate schedule, changing equipment operation schedules, and many other situations need to be taken into consideration. Therefore, it is necessary to conduct thermo-economic analysis for extended period of time, such as a month or a year. Procedures to conduct simulation are presented as following:

1. The first step is to develop campus load and weather profiles, which describe the demands of thermal/electrical commodities and amient weather conditions over extended period of time. In order to capture the campus load fluctuation and to calculate NG and especially ELEC rates more accurately, hourly and even 15-minute load profiles are preferred.

2. The second step is to obtain NG, ELEC, and fuel oil rates or rate schedules.

3. The third step is to generate scenario simulaion input. The simulation of a DES is rather complicated. In order to simulate the operation of the entire DES,

key information or so called scenario such as load distribution, equipment operation schedules, etc is required. For example, a chiller plant has two 1,000-ton chillers. Assuming the campus cooling load is 1,000 tons for a given moment, scenario 1 of chiller plant operation could be only one chiller is in operation at full capacity. Scenario 2 could be both chillers are in operation at 50% capacity each. Scenario 3 could be both chillers are in operation with 40% and 60% capacity respectively. In order to simulate the chiller plant energy flow profile, the simulation program needs to have adequate inputs to identify a single scenario. The ChW cost will be different under different scenario. If the simulation is conducted over extended period of time, the scenaio for each time step needs to be determined. By evaluating the cost of different scenarios, cost effective operation can be identified.

4. The fourth step is to generated input database.

5. The fifth step is to execute the plant operation simulator. It pulls data from the input database for a given time and performs thermo-economic analysis for that moment. The converged results of the simulation are the predicted system profile, which include not only the predicted primary energy consumption and cost, but also the energy flow and cost allocation at equipment level and plant level. By changing, replacing, or adding new equipment models in the simulator, retrofit or plant expansion options could be explored.

6. The sixth step is to save the results of the previous step into output database. The output database could be populated by repeating Step 5 and 6 for extended period of time, which could be on daily, weekly, monthly, and annual bases, or any given period of time.

7. The seventh step is a summing module, which summarizes the output database to calculate the predicted amount and costs of the primary energy consumed and the thermal/electrical commodities produced, and other information saved in the output database.

In the previous two sections, the basic concepts of the methodology and simulation procedures were explained. Because the simulator simulates the thermal dynamic and economic behavior of a system under given operating scenario and load over specified period of time, it can provide comprehensive information regarding the performance of not only the individual equipment but also the entire system. The plant operation simulation is a very useful tool to conduct various engineering evaluation, such as to develop monthly thermal and electrical rates, to estimate savings due to equipment operation changes or retrofit, to project primary energy use and cost, and so forth. However, the key to the usefulness of the simulation results relies on the accuracy of the plant operational simulator.

Following the description of the case study facility, a plant operational simulator developed specifically for this facility and one of its applications will be presented.

CASE STUDY DISTRICT ENERGY SYSTEM DESCRIPTION

The case study facility is a large district energy and combined heat and power system, which consists of a Central Utility Plant (CUP) and four Satellite Utility Plants (SUP1/2/3/4). This facility provides the campus with virtually all needed utilities – ChW, HHW, DHW, steam, and a portion of the electricity. Its primary energy supply are natural gas and electricity, which are purchased from deregulated energy market.

The CUP is a combined heat and power plant. It has a 16.5 MW gas turbine generator; two extraction-condensing steam turbine generators rated at 5 MW and 12.5 MW, respectively, and a 4 MW backpressure steam turbine generator. The total installed steam generation capacity of its three gas-fired boilers and heat recovery steam generator is 850,000 lb/hr (385,554 kg/hr). CUP has 10 chillers with 21,000 tons (73,861 kW) cooling capacity and six steam-to-water heat exchangers with 330 mmbtu/hr (96,717 kW) heating capacity. The total installed cooling capacity of the SUP1 is 10,000 tons (35,172 kW). The SUP1 also has three natural gas fired 400-BHP (3,924 kW) boilers to provide HHW for the West Campus heating purpose. The SUP2 contains three identical electrically driven certrifugal chillers with 1334-ton (4,692 kW) capacity each and two natural gas fired 500-BHP (4,905 kW) rental boilers for HHW purposes. The SUP3 has three 1,100-ton (3,869 kW) and one 1400-ton (4,924 kW) electrically driven centrifugal chillers and two 8.4 mmbtu/hr (2,462 kW) natural gas fired DHW generators. The SUP4 use three 20 mmbtu/hr (5,862 kW) steam-to-water heat exchanger to produce HHW for the West Campus. Because this facility has two seperate campuses, which have their own ChW and HHW distribution systems, its has separate ChW and HHW demand profiles. This facility also obtain its natural gas from multiple sources, each has different natural gas rate. The energy use and production of most of the major equipment are metered and saved in industrial grade database. A schematic of the utility plant equipment and the relationships of each other are shown in Figure 3.

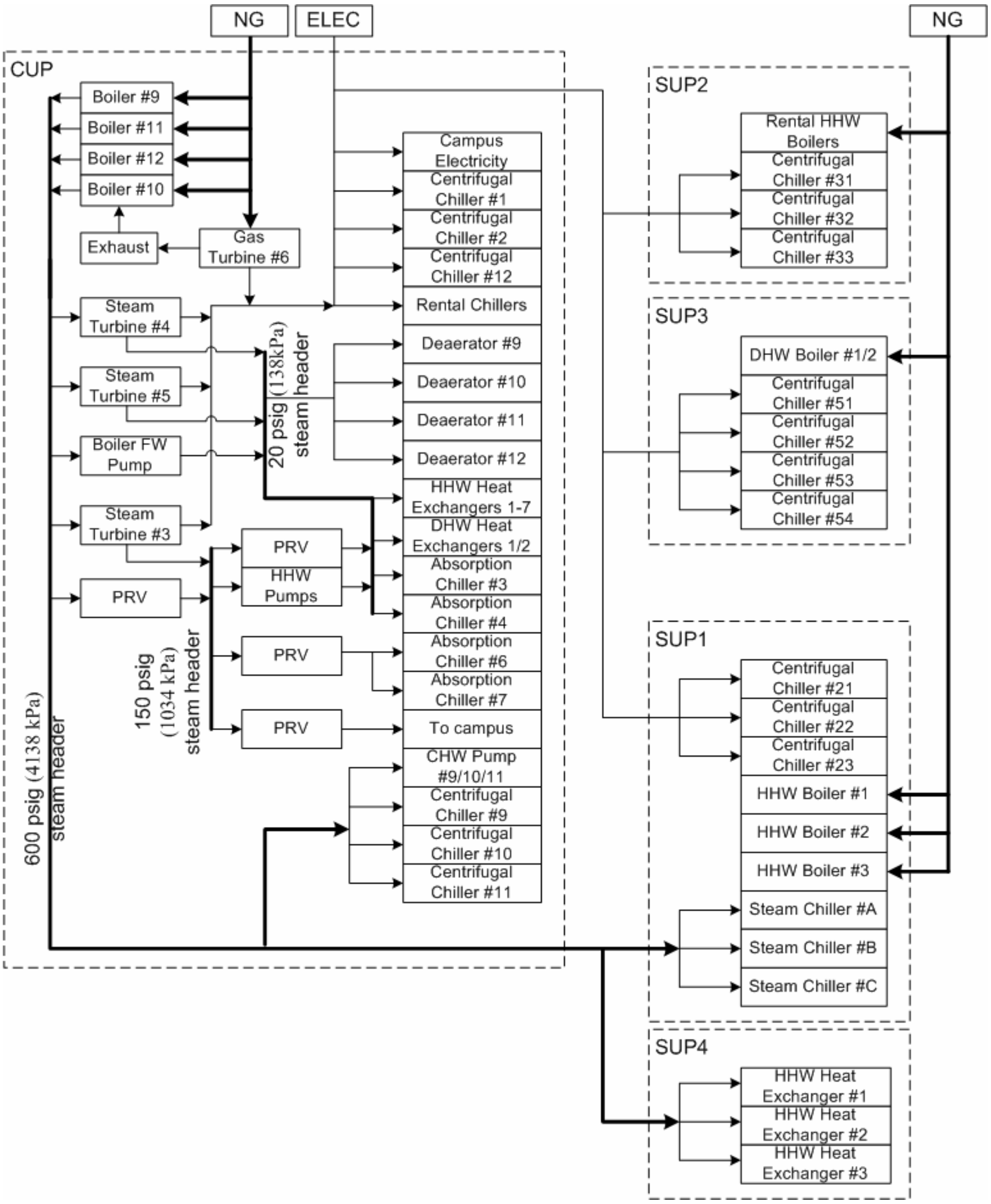

Figure 3 Simplified one-line diagram of the case study district energy and heat and power system

PLANT OPTIMIZATION PROGRAM

The Optimization Program (POP) is a plant operational simulator specifically developed for a large district energy and combined heat and power system. The POP has been used to conduct primary energy purchasing projection, utilities energy budget, and various engineering analysis for the past four years to assist the case study facility in decision making. The following section presents methodology and principles adopted to develop the POP from its conceptual model. The specific techniques and some background are also provided to give overall picture on how they are integrated together to create the POP.

Objectives of the POP

The POP is developed: (1) To simulate the interconnected combined cycle cogeneration and district energy plants of a large university, (2) to perform thermo-economic cost allocation to calculate the production cost of various thermal commodities and electricity generation, and (3) to identify optimal operational scenario with minimum energy cost.

Modeling strategy

The key to the usefulness of the program relies on the accuracy of the equipment models. Three types of modeling strategies are widely adopted, i.e. the fundamental models, the first-principle models, and the empirical models (Zhou 2001). The complex and dynamic nature of most primary equipment has discouraged the use of fundamental and first-principle models for energy calculations (ASHRAE 1997). Instead, empirical models, i.e. regression models, have traditionally been widely utilized for plant equipment modeling. Because there is no consistent hourly data avaialbe, Beasley (1993) developed equipment performance models by using manually recorded daily data. Consequently, performance of almost all equipment were represented by linear or change point linear relationships between energy input and outputs throughout the entire load range.

The equipment models in the POP program are mostly regression models based on metered hourly data. Chen (2004) demonstrated multiple-regression method for constructing simulation models by using stastistics and optimization algorithms to improve model accuracy. Figure 4 is a comparison between model predicted hourly throttle steam flow rate and metered data of a steam turbine generator. For fiscal year 2003 data, the statistical indicators of R^2, and the coefficienct of variation of the root mean squared error [CV(RMSE)] are 0.997 and 2.3% respectively. Additonal models for other pieces of equipment and modeling methodology are explained further in Chen (2004).

All models were constructed seperately and then linked together to replicate the operation of the entire system. A set of the input data is called an operating scenario, which provides a description of a specific operational condition for the entire plant. The scenario could be either actual or proposed operation of the plant. The POP then calculate the energy balance of the entire system to establish the inputs and outputs at equipment and system level.

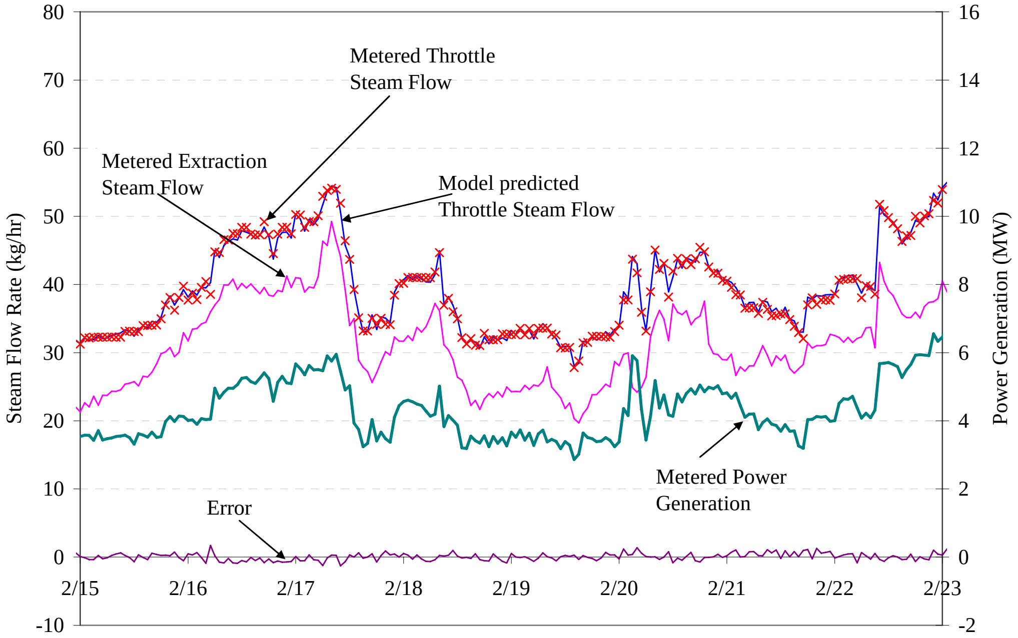

Figure 4 Steam turbine generator simulation model performance

Cost allocation principles

The thermodynamic and economic behavior of large district energy and combined heat and power system is difficult to characterize because of the complex interactions among components. Similar to the equipment physical modeling, each equipment has a cost allocation model. The objectives of the equipment cost allocation model are: (1) to determine the cost of each of the commodities the equipment consumes and (2) to determine the costs of commodities each equipment produces. Cost allocation in systems with single output is simple. The real issue is how to allocate cost in systems with multiple outputs. Specially, the method used to divide the cost between the heat and electricity outputs of the gas turbine, heat recovery steam boiler, and the steam turbine generator. Marecki (1988) summerized seven methods to allocate cost in systems with multiple outputs: (1) the physical methods, (2) the thermodynamic method, (3) the intermediate method, (4) the exergetic method, (5) the enthalpy method, (6) the extraction method, and (7) the equality method. Each method also has many variations.

The basic thermoeconomic principles adopted in the POP cost allocation models are: (a) the conservation of cost principle, (b) zero cost principle for commodities, which are lost, destroyed, or rejected, (c) first law of thermodynamics principle for steam turbine generators, and (d) avoid cost principle for gas turbine and heat recovery steam boiler combined set. Each of the seven methods summerized by Marecki (1998) has its advantages and disadvantages and could be selected for principle (3) and (4) above. The current principles are results of cost allocation principles taking into account various factors, including client acceptance.

Often electric purchase contracts have certain rate structure. That is, the price changes with volume, time, and demand, and so forth. A couple of different natural gas purchase contracts are in place as well. Therefore, the primary energy cost of a plant not only depend on its equipment performance, but also strongly depend on the type of energy purchase contracts in place as well. The optimization software includes the features to model these contract features and can predict the plant primary energy expenses as operation changes.

Operation optimization algorithm

The capability to perform optimization is a unique feature of the POP. The economic load dispatching in a power generation system was described as a precedure for the distribution of total thermal generation requirements among alternative sources to achieve the lowest cost. As early as 1919, power system engineers began to take active interest in the economic allocation of generation among available units(El-Hawary and Christensen 1979), which is also call Economic Load Dispatching (ELD). The three major ELD techniques used fall into three major categories: equal percent allocation, equal efficiency allocation, and equal incremental cost allocation (Steinberg and Smith 1943 as cited in Zhou 2001). The operation optimization algorithm adopted in the POP falls into the category of equal incremental cost allocation. Mathematically, the incremental cost is defined as the first derivative of the unit's operation cost curve and it represents the cost of adding one unit of load to a given unit at a given load. Zhou (2001) expanded the incremental cost allocation method to the combination of several groups of parallel processing units that are extentively interralated with each other. Currently, the POP is able to identify cost economic dispacthing scenario for a given moment. It is still under development, so that the POP could identify optimized opeating strategy for extended period of time.

Table 1 Comparison between simulation results and actual purchasing data

Time	Actual Purchasing		Simulation Results		Error (%)	
	ELEC – million kWh	NG - mmbtu (GJ)	ELEC – million kWh	NG - mmbtu (GJ)	ELEC	NG
Jan-06	14.16	273,872 (288,935)	11.74	271,847 (286,799)	-17.1%	-0.7%
Feb-06	17.38	229,108 (241,709)	16.27	214,250 (226,034)	-6.4%	-6.5%
Mar-06	21.83	227,155 (239,649)	22.24	216,627 (228,542)	1.9%	-4.6%
Apr-06	22.36	228,463 (241,028)	23.37	219,084 (231,134)	4.5%	-4.1%
May-06	22.08	265,129 (279,711)	22.98	256,752 (270,873)	4.1%	-3.2%
Jun-06	22.88	270,421 (285,294)	24.08	266,340 (280,989)	5.2%	-1.5%
Jul-06	24.45	288,562 (304,433)	24.72	281,638 (297,128)	1.1%	-2.4%
Aug-06	27.43	283,902 (299,517)	27.92	266,991 (281,675)	1.8%	-6.0%
Sep-06	22.73	290,908 (306,908)	22.68	295,914 (312,189)	-0.2%	1.7%
Oct-06	19.29	310,510 (327,588)	19.58	316,712 (334,131)	1.5%	2.0%
Nov-06	19.68	257,654 (271,825)	19.37	256,770 (270,892)	-1.6%	-0.3%
Dec-06	18.98	240,774 (254,017)	18.71	237,656 (250,727)	-1.4%	-1.3%
Annual Total	253.25	3,166,458 (3,340,613)	253.66	3,100,582 (3,271,114)	0.2%	-2.1%

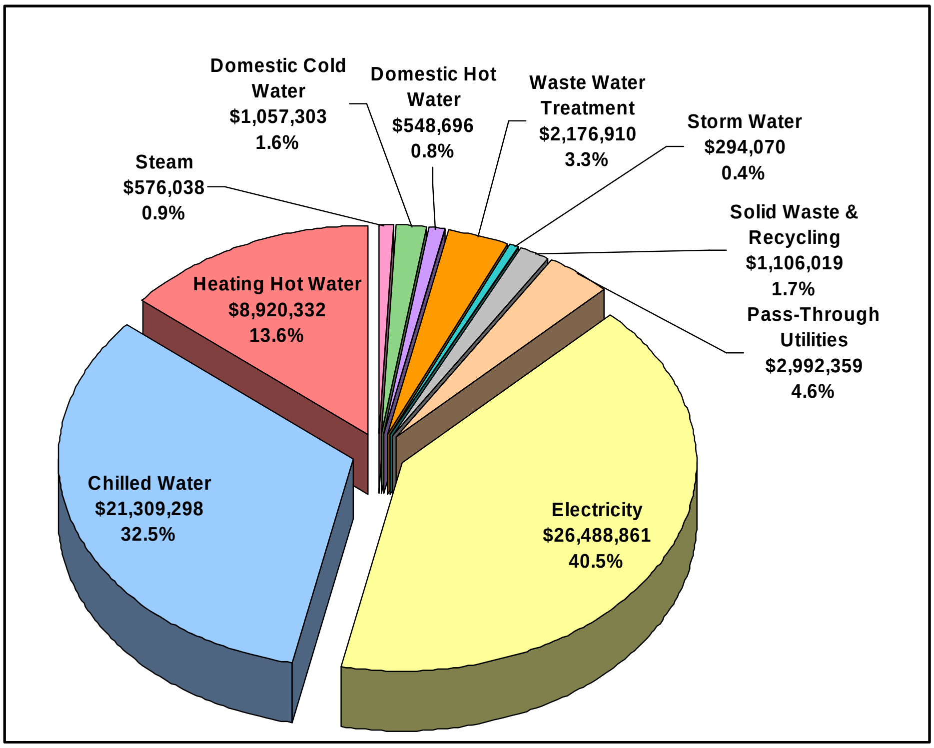

Figure 5 Rate Model Cost Allocation

System integration

All the input and output data are stored in a databases. The POP automatically pulls the data, initializes the input, runs energy balancing and solves the converged solution, and then stores the results back to the database. The program can solve solution for every hour for extended period of time, e.g. year 2006. Then the plant hourly simulation results will be combined to evaluate monthly and annual energy and cost performance.

Model Verification

The POP had been subjected to third party engineering consulting firm review and is undergoing constant update and upgrade. Actual metered campus load profiles, actual weather data, plant operation schedules, primary energy rates were utilized to verify the POP model.

Table 1 compares the results of the simulation results and the actual primary energy consumption at the plant. For calendar year 2006, the error between the annual primary energy purchasing and simulation results are 0.2% for electricity and -2.1% for natural gas. Since the upgrade of the metering system of the campus and plant electricity consumption in July 2006, the accuracy of the model predicted purchased electricity had been improved significantly. During the development of the POP model, it is realized that the good quality metering coverage and calibration program at equipment and plant level are very important. Not only because it help provide reliable performance evaluation for the equipment and plant to develop accurate model, but also because it has profound impact over the life cycle cost of the equipment evan there is small improvement in equipment efficiency, which requires a good metering data.

POP APPLICATION – RATE MODEL

An application of the POP is the Rate Model, which is a comprehensive model developed for the case study facility for its budget and customer billing purposes in 2004. The Rate Model is utiltized to develop utitlity bills based on actual building energy consumption. It can also be used to generate utility budget for the utility plant and various orgainzations on campus.

The Rate Model model calculates the rates for various utilities, such as ChW, HHW, DHW, steam, electricity, domestic cold water, waste water treatment, storm drainage, and solid waste & recycling, and so forth. The POP is the main engine of this model. It is utitlized to provide cost allocation for the natural gas and electricity purchasing.

On top of the the cost allocation of the purchased utilities generated by the POP, this model also allocate the cost of labor, O&M expenditure, cost contribution due to debt service, infrastructure repair, prior year rate reconciliation, encumbrance, depreciation, civil utility, and self-generated utility for each of the utility production. The debt service include debt payment for various capital projects for utilities and large O&M projects. Figure 5 is an illustratration of overall annual utility cost allocation generated by the Rate Model. This model not only provide cost allocation for the overall university utitlity production, it provides such analysis results for each utility as well.

DISCUSSION AND CONCLUSION

This paper demonstarted a thermo-economic analysis software developed for a large district energy and combined heat and power system and illustrated how the plant thermo-economic modeling combined with optimization on plant operational cost offers many practical applications for plant operation, billing, budgeting, and cost reduction purposes.

This paper also demonstrated how a thermo-econmic analysis software can be developed to provide essential engineering and economic analysis to assist the utility plant adminitration in various business activities and decisions.

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