DETERMINING THE FEASIBILITY OF COGENERATION USING DOE-2.1E FOR THE JOHN G. SHEDD AQUARIUM AND OCEANARIUM

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ABSTRACT

The Energy Resources Center at the University of Illinois at Chicago conducted an energy assessment of the John G. Shedd Aquarium and Oceanarium to increase the energy efficiency of the facility, while decreasing the operating costs. Part of this effort included determining the feasibility of implementing a cogeneration system as part of the detailed energy assessment for the facility. The DOE-2.1E program was selected as tool to determine the annual electrical, cooling and heating loads for so complex a facility, and then evaluate the economic benefits of investing in a cogeneration system.

INTRODUCTION

Cogeneration, or combined heat and power (CHP), is the use of a single fuel, such as natural gas, to simultaneously produce useful heat and electricity, and also for cooling. Cogeneration is a viable option for facilities that operate their plant 24 hours a day, seven days a week, use fuel to provide steam or heat, and require substantial air conditioning in their operation. The John G. Shedd Aquarium and Oceanarium (Shedd) meets all of these requirements, but further analysis was needed to determine if the facility did in fact have a proper load profile, in terms of coincidental needs for electrical and thermal. This in turn could facilitate a decision by the institution for investment into a CHP system.

The Energy Resources Center, a non-teaching department of the College of Engineering at the University of Illinois at Chicago, conducted an in-depth energy assessment of the Shedd, including inventory of all major energy using systems, with funding fromthe Illinois Department of Commerce and Community Affairs. This audit became the input for a baseline model of the Shedd using the DOE-2.1E computer simulation program. With a single primary mechanical plant currently used throughout the Shedd to provide the wide range of climatic conditions needed for the animals, and the planned addition of systems to support new exhibits, it was determined that a baseline model of the Shedd would facilitate evaluation of how the building and its system's operational characteristics could change with additional equipment or CHP.

With the completion of the model, the heating and cooling loads, as well as the associated utility costs for the Shedd were verified. The model was used to determine if combined heat and power was a viable alternative to purchased power, evaluate different CHP configurations and to determine if the existing systems loads were adequate for supporting such CHP systems.

BACKGROUND

As cogeneration or combined heat and power become more accepted for large, complex commercial and institutional facilities, it is important to carefully evaluate each project and consider the current usage trends for the facility being analyzed. Among parameters to be considered include heat to power ratio of the facility, demand patterns for electrical, heating and cooling, and required reliability of the electrical system. In order to properly evaluate the Shedd Aquarium, it was determined that an accurate thermal model was needed to best address the above mentioned parameters.

Figure 1: John G. Shedd Aquarium

The Shedd, depicted in Figure 1, is one of the oldest public aquariums in the world, located at the Museum Campus along Lake Michigan in Chicago, Illinois. Opened in 1929, the Shedd was created with a mandate to study, protect and exhibit all aquatic life and help visitors to learn about the natural world. Housed in a classical Greek-inspired Beaux Arts structure, the Shedd quickly became a sensation, attracting more than 4.6 million visitors in 1931 alone.

In the last decade, the venerable institution has undergone extensive restoration. Today, more than 6,000 fishes, reptiles, amphibians, mammals and invertebrates of approximately 750 different species are on display at Shedd. Much of this work was spurred by the overwhelming success of the latest addition to Shedd Aquarium, the Oceanarium, completed in 1991, bringing the total square footage of the facility to 395,000 (36,700 m^2). The layout of the Shedd facility, the original octagon and the curvilinear Oceanarium, is shown in Figure 2.

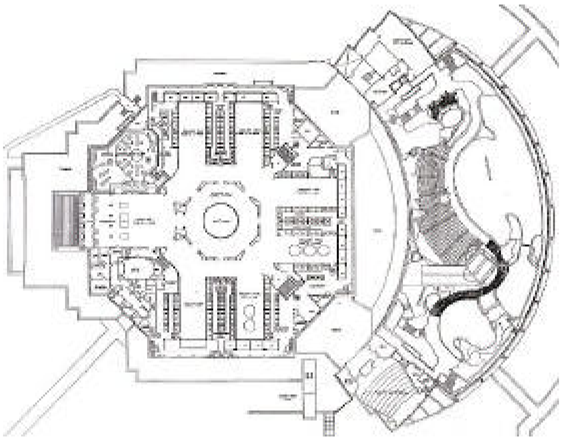

Figure 2: Shedd First Floor

Data for the DOE-2.1E simulation model was collected during a multiple day assessment of the Shedd facility. Included in the assessment were a detailed lighting survey as well as inventory and mapping of the facility's mechanical systems. Since there are many climate types that have to be simulated for the variety of habitats that the species require, an accurate account of space conditions was important.

The Aquarium complex contains 395,000 square feet of floor area (36,700m^2). The complex consists of the original Aquarium building (225,000 ft^2, or 20,900 m^2) and the Oceanarium (170,000 ft^2, or 15,800 m^2) with additions, such as the New Philippines Shark and Coral building that will open in the fall of 2003. In Table 1, the total area dedicated to animals and support of animals is 34% of the building area. This includes office spaces, labs, veterinary services and other animal support spaces.

Table 1: Shedd Area Breakdown

Space	Area (ft^2)	Area (m^2)	% of total area
Animals	54,000	5,000	14%
Support	80,000	7,400	20%
Mechanical	82,000	7,600	21%
Public	179,000	16,600	45%
Total	395,000	36,700	100%

SIMULATION

In order to evaluate the facility for cogeneration, information regarding the electrical, heating and cooling requirements for the Shedd was needed. It was determined that the most accurate way to predict this was to create a thermal model of the building using DOE-2.1E.

Using the data collected during the assessment, as well as additional input from the facility managers, the model was created. It was necessary to provide as accurate a representation of how the facility operates as possible. Details such as using the layers command to obtain a more accurate portrayal of the building envelope system, and dividing the occupancy schedule for visitors into four groups, due to the variance of occupancy throughout the year. The facility was broken down into 40 zones based on temperature control, orientation, schedules, and type of HVAC equipment. The Shedd, with its current facility equipment and operations, was modeled as the baseline case. The cogeneration case was created, by changing the plant for the Shedd, and then modified by adjusting the natural gas costs.

Schedules

Scheduling was an important factor in modeling the Shedd. Obtaining an accurate portrayal of the visitors schedule was important, in the tight climate controls required by the animals, and the added thermal loads varying depending on the number of people in a given space.

The Shedd has records of the number of visitors on a month-to-month basis. Based on that information and facility manager input; an accurate representation of the visitor schedule was created. The Shedd sees the highest percentage of visitors in July and August, and the least in January through March. The occupancy schedule for the public was then divided into four groups, to represent this detail.

Space Types

Since the Shedd has many large volume spaces, with multiple story heights, it was important to define these upper areas as volumes of air, rather than a well-mixed space, as would be the case if it were modeled as one large volume. Next -to commands were used in order to make the model more accurate, particularly for the relatively open floor plan that exists at the Shedd.

Though there are many different space types, for the DOE-2.1E simulation model, they were simplified. There are three main space types defined for the model. These include the public space, animal areas, and work/support space. The space types were created based on occupancy schedule and density, lighting schedule and density, and plug load schedule and density. The public space has specific operating hours and temperatures of 21ºC (70ºF). The animal space has year round operating schedules for climate control with temperatures usually around 10ºC (50ºF), but varying depending on requirements of each species. The work/support spaces for staff have longer daily operating schedules than the general public spaces, but maintain temperatures of 21ºC (70ºF). Sample operating temperatures for a few of the animal and public spaces is provided in Table 2.

Table 2: Sample Shedd Operating Temperatures

	Set Point Temperatures	
	Air ºC (ºF)	Water ºC (ºF)
Dry Holding	24 (75)	---
Dolphins	21 (70)	12.8 (55)
Penguins	40 (4.5)	50 (10)
Amazon	24 (75)	Varies
People	20-25 (68-77)	---

Envelope

Typical walls enveloping the Aquarium building consist of gypsum board, hollow clay tile, preformed mineral board insulation, heavyweight concrete block and marble facing. The Oceanarium walls consist of heavyweight concrete block; expanded polystyrene board insulation, and marble facing. The windows throughout 90% of the complex have been retrofitted. The retrofitted windows are metal framed, with green tinted double-insulated glazing. The non-retrofitted windows are metal framed with single glazing. Windows that have not been retrofitted are located in storage or mechanical equipment rooms. The flat roof on the Aquarium building is composed of multiple layers of built-up roofing: lightweight concrete and preformed roof insulation supported by a metal skeletal structural system. The flat roof over the Oceanarium consists of built-up roofing, wood decking, and preformed roof insulation supported by a massive steel truss system.

HVAC Systems and Zoning

The spaces in the DOE-2.1E model were characterized by not only space type, but by the type of system that served the area. Often several HVAC units are required to condition some of the large volume spaces to their required temperatures. These were combined, and modeled as one large system for that particular space.

The Shedd facility is conditioned primarily during occupied and visiting hours, as shown in Table 3, though animal areas are conditioned to the required climate twenty four hours a day, seven days a week. Both the general public building operating schedule, as well as the heating, ventilation and air conditioning (HVAC) equipment schedule for the facility are provided. This table does not reflect the equipment specifically for the animal areas.

Table 3: Shedd Operating Schedules

	General Building Public Schedule		General HVAC Operating Schedule	
	Wkday	Wkend	Wkday	Wkend
Opens	9:00 am	9:00 am	6:30 am	6:30 am
Closes	6:00 pm	6:00 pm	6:00 pm	6:00 pm
Total hours	9 hours	9 hours	11.5 hours	11.5 hours

Conditioning the work space, exhibit space, and animal space in the building cannot necessarily be separated, so the entire building is conditioned during working hours from 6:30 AM to 6:00 P.M. However, cooling water for the penguins and other local life support systems run 24 hours a day, 7 days a week as needed. During the heating season, the building follows the same schedule; with the building heating system being turned on at 6:30 A.M. and shut off at 6 P.M. In general, the animal space is always conditioned 24 hours a day, 7 days a week; the animals get the conditions they require at all times.

A typical primary hot water/cold water loop provides the heating and cooling for the facility. The three chillers defined in the plant all serve the chilled water loop. The chilled water system serves 24 air-handling units as well as heat exchangers used to cool exhibit pond water. Hot water is generated at 90.5 -98.9ºC (195-210ºF) by the installed boilers for use in the primary hot water loop. For the secondary hot water loop, hot water is circulated through heat exchangers, and then pumped throughout the building to be used in the air-handling units, unit heaters, and a few fin-tube radiant heaters.

Plant-Baseline Case

The DOE-2.1E model included the current plant, which is made up of three main chillers, two of which are run at a time and four natural gas-fired, hot water boilers.

Plant-Cogeneration Case

The cogeneration plant created in DOE-2.1E for the Shedd was a simple configuration, which operates during energy peak purposes, described following Economics section. During that peak period, the cogeneration plant operates at its maximum output, tracking both electrical and thermal requirements. An absorption chiller recovers the heat rejected by the generators, while a centrifugal chiller serves to help balance the thermal with electrical loads. Recovered heat from the generators is used for space heating, with a hot water generator as a supplemental source.

Economics

The Shedd provided two years worth of natural gas and electric utility data, which was used to create the rate structure for both natural gas and electricity. An accurate rate input was important, particularly for evaluating the cogeneration model, as the natural gas rates are broken down into block charges, while electricity has peak and off peak charges. Energy (kWh) peak hours are from 9:00am to 10:00 pm on Weekdays, while the off-peak rates apply to hours outside of peak hours, as well as weekends and holidays. Demand peak hours are from 9am to 6pm on weekdays. The same rate structure applies as for energy. Both the electric and natural gas rates are presented below in Table 4 and Table 5.

Table 4: Natural Gas Charges

	First 100 therms	Next 4,900 therms	Over 5,000 therms
Natural Gas	$0.58979	$0.45826	$0.3505

Table 5: Electric Charges

	Peak ($/kWh)	Off-Peak ($/kWh)	Demand ($/kW)
Summer	$0.05172	$0.02273	$16.41
Winter	$0.05172	$0.02273	$12.85

ANALYSIS

After creating the model, the following results were obtained from the Shedd DOE-2.1E model. The findings are presented in several sections starting with an overall energy usage breakdown by end-use. Then more detailed analysis of the heating, cooling, and electrical loads, and utility costs is presented.

Energy Use

The Shedd has an interesting load profile, which is unique to this particular facility type. Due to the requirements of the animals that inhabit the facility, there is a substantial base load, particularly cooling and electrical. The heating load is primarily due to space heating, with some amount required to generate hot water for the facility. In the natural gas usage breakdown, shown in Figure 3, the hot water usage makes up 44% of the total natural gas load. This is due to the bathrooms, showers and a small number of tanks that do require hot water.

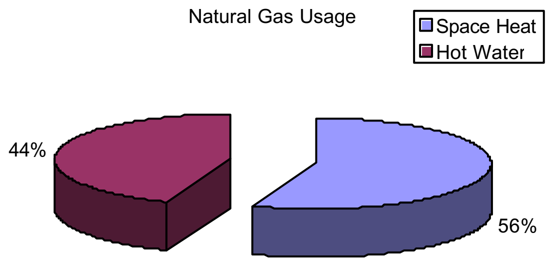

Figure 3: Shedd Natural Gas Usage Profile

The electrical usage by the Shedd is separated into the major end-uses in Figure 4. The Misc. Equipment is made up of various equipment loads as defined for the space condition, as well as the life support process loads. These loads are for all plug load equipment required to sustain animal life. For work areas within the Shedd, these loads are quite high, while in the visitor areas, they are usually much lower. This helps to explain its large percentage of the entire electrical energy usage.

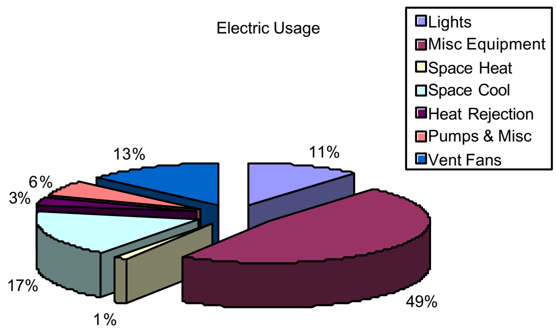

Figure 4: Shedd Electric Usage Profile

Supplemental cooling is only required during the summer months due to the outdoor temperatures and air-conditioning for offices and public spaces.

The animal environments maintain the same conditions year round. The heating load goes to zero during the summer months, as no space heating is required within the facility.

With this model, it was found that cooling and heating demands occurred at the same time for part of the year. Heating energy in this case does not include heat for domestic hot water supply. Figure 5 shows the cooling energy, heating energy and electrical energy on a monthly basis for a typical year at the Shedd. This clearly shows the flat usage trend for the electrical consumption, the bell curve for the cooling energy, and the inverse curve for heating energy. Electrical consumption was converted to millions of British Thermal Units (MMBtu) for this comparison.

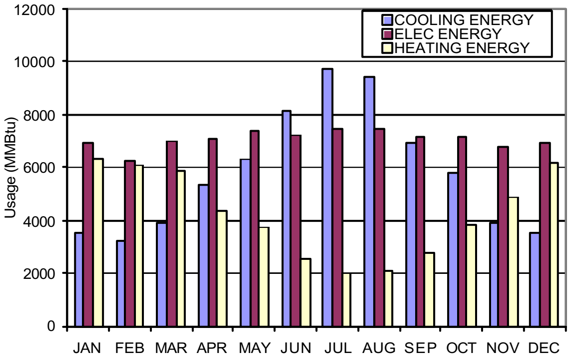

Figure 5: Shedd Monthly Energy Usage

This data was broken down in to the electrical, heating and cooling loads in kilowatts for the year to show the significant loads occurring during the peak hours as defined by the electricity provider. The monthly fluctuations in load for electric load, cooling load, and heating load for a typical day in each month is presented in Figures 6, 7, and 8. These charts are also useful in visualizing the base electrical, cooling and heating load for the facility.

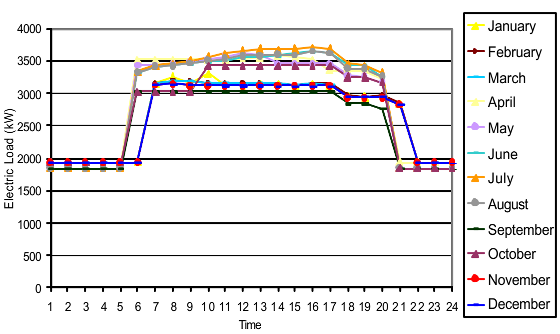

Figure 6: Shedd Monthly Electrical Loads

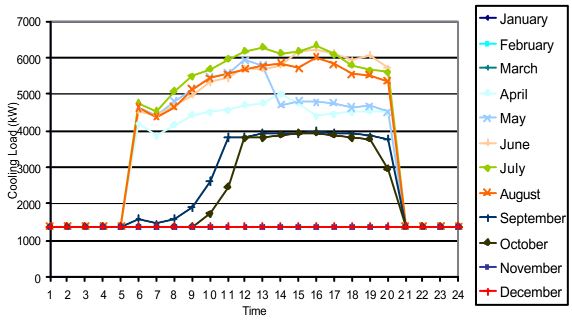

Figure 7: Shedd Monthly Cooling Loads

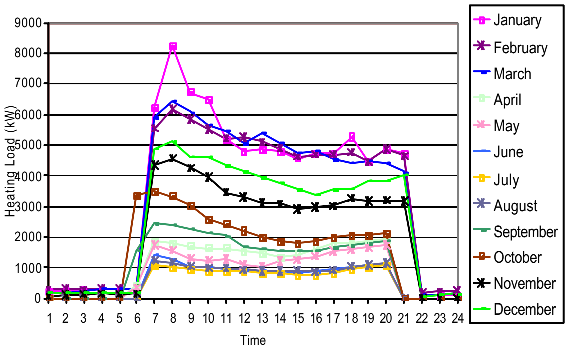

Figure 8: Shedd Monthly Heating Loads

Next the load factors for heating energy, cooling energy, and electrical energy were calculated. Load factors relate peak demands to the average demand for the facility so that the magnitudes of the energy requirements can be obtained.

The load factor can be calculated using the following equation:

$$\text{Load Factor} = \frac{\text{Total Annual Usage}/8{,}760}{\text{Annual Peak Demand}}$$

This load factor is important in that if a similar facility to the Shedd were being evaluated, that the numbers for electric load factors should be similar, no matter the geographic location. Location should adjust the amount of supplemental heating and cooling that the facility would require. Since these load factors are similar despite geographic location, the load factors show that it is in fact the cost of electricity and natural gas that will be the driving force in determining whether cogeneration is feasible for a particular facility. The Shedd model was used at different locations throughout the United States in order to prove this theory, and the results for the heating, cooling, and electrical loads are provided in Table 6.

Table 6: Load Factors for U.S. Cities

	Heating Energy	Cooling Energy	Electric Energy
Chicago	0.19	0.30	0.63
Boston	0.23	0.27	0.62
Albuquerque	0.22	0.30	0.63
Fort-Worth	0.20	0.34	0.62
Houston	0.22	0.36	0.62
Seattle	0.33	0.27	0.64
Tampa	0.25	0.39	0.63

Since the Shedd does operate on a time of use rate, with higher rates for on-peak usage and lower rates for off-peak energy usage, the operation of the cogeneration plant was inputted to reflect this. The cogeneration plant operates from 9 am to 10 pm at maximum output of the generators during this time. The cogeneration model for the Shedd was able to meet 94.3% of the electrical loads for the facility during peak hours, while providing waste heat for space heating and cooling.

Since it was determined that it is the utility costs that significantly impact the decision to invest in a cogeneration plant, the cogeneration DOE-2.1E model was re-run using higher natural gas prices in order to determine the breakeven point, or the point at which it would no longer be economically beneficial to operate a cogeneration facility. This was done by keeping the electric rates the same, and raising the natural gas costs by $0.50/therm. The baseline case, which represents the current operation of the Shedd, is compared with the simple cogeneration case, using several different natural gas costs in the cogeneration cases. The costs of electricity and natural gas, as well as the total utility cost per year are presented in Table 7.

Figure 9: Annual Operating Cost Comparison

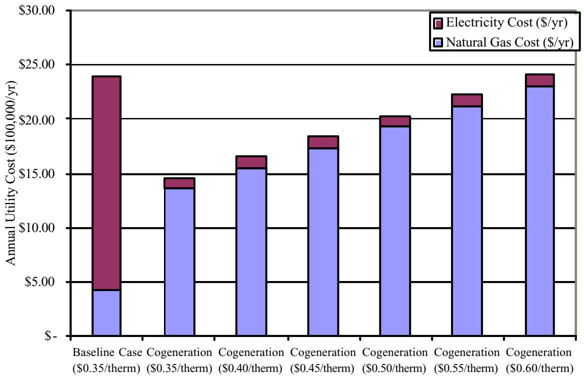

Table 7: Cogeneration Evaluation Based on Natural Gas Cost

	Natural Gas Cost ($/yr)	Electricity Cost ($/yr)	Total Utility Costs ($/yr)
Baseline Case ($0.35/therm)	$ 423,298	$1,969,213	$2,392,511
Cogeneration ($0.35/therm)	$ 1,358,507	$103,755	$1,462,262
Cogeneration ($0.40/therm)	$ 1,547,924	$103,755	$1,651,679
Cogeneration ($0.45/therm)	$ 1,737,342	$103,755	$1,841,097
Cogeneration ($0.50/therm)	$ 1,926,760	$103,755	$2,030,515
Cogeneration ($0.55/therm)	$ 2,116,177	$103,755	$2,219,932
Cogeneration ($0.60/therm)	$ 2,305,595	$103,755	$2,409,350

From both Table 7 and Figure 9, we can see that the cost of natural gas would have to increase by almost 60% from the current rate that the Shedd has in order to make cogeneration not economically feasible.

CONCLUSIONS

The analysis with the load factors for a variety of cities across the United States using the same DOE-2.1E input model, with the same operation of the baseline plant, showed that location would not have a significant impact on the feasibility of a cogeneration plant. It was determined that the deciding factor for implementing a cogeneration plant would be the utility structure at the location.

The utility rate structure must be examined as part of the feasibility analysis for a cogeneration facility. A first step is to simply compare electric rates to natural gas rates for the particular location. If it is determined that the utility rate comparison still favors cogeneration, then the electric rate itself must be examined. As with the Commonwealth Edison rate in Chicago, there is a peak and off-peak rate for this facility. This determined the operating schedule for the cogeneration plant. If there was a flat rate, which did not depend on the energy usage at time of day, cogeneration would not look as economically attractive for the facility, and would significantly impact the rate of return.

With the creation of the DOE-2.1E model of the Shedd, a cursory analysis was done in order to determine if cogeneration would be an economically feasible option for the facility. Preliminary analysis demonstrated that the Shedd did have the required electrical, cooling, and

heating profile that is desired for cogeneration. However, further analysis was needed to determine if it would be economically feasible for the facility to operate a cogeneration plant, and during what periods of the day.
If operated year round, the annual natural gas bill went up, but operating the generators at their maximum output during peak hours reduces the overall utility costs significantly under the current rate structure. Even if natural gas prices rose up to 60% above the current rate, cogeneration would still be an economically viable option for the Shedd.

The analysis presented here for the Shedd is a conservative analysis, as more economic natural gas contracts with a provider can be expected when bulk natural gas is purchased year round. The model can now also be used to evaluate different cogeneration plant equipment, configurations, operating schemes, and life cycle costs if the Shedd decides to invest in a cogeneration plant. Additionally the Shedd now has a useful tool to further predict building performance and operational costs changes in future renovations and expansions planned for the facility.

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