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HEAT AND POWER SYSTEM AS AN INDEPENDENT SOURCE OF ELECTRIC POWER. CASE STUDY

Wes GREBSKI
Pennsylvania State University

Robert ULEWICZ
Czestochowa University of Technology

Abstract:
The article describes a student capstone design project completed by a team of five students and implemented by a resort and casino in Northeastern Pennsylvania (NEPA). This project was completed within the framework of project-based learning (PBL). Students had the opportunity to apply the knowledge that they learned in the classroom in a real-world application. Students also had the opportunity to work as a team which was supervised by the faculty. The outcome of the project provided valuable experience in creating of grid, a reliable source of energy. The heat generated as a by-product was used for the purpose of heating hot water and a swimming pool as well as space heating for the hotel and casino during the winter. In the summertime the excessive amount of heat was used to dehumidify the air in the hotel and casino. Dehumidifying the air increased the level of comfort in the hotel and casino as well as in the enclosed swimming pools area. The article is focusing on the cost effectiveness of the off-grid heat-and-power solution. The net present value and internal rate of return as well as the payback time were calculated.

Key words: *PBL, energy, Combined Heat and Power (CHP), student project, learning experience*

INTRODUCTION

The student project described in this article was completed as a part of the *project-driven approach* to teach engineering courses at The Pennsylvania State University [1, 2, 3, 4]. The project was done for a commercial enterprise including resort, hotel, casino and racetrack. The facilitate is located in a secluded area in Northeastern Pennsylvania (NEPA). The electric power to the facility was provided by the local power company. The demand for electric power is 860 kW. In addition to the electric power there was also a need for natural gas for space heating as well as heating the indoor swimming pool and domestic water (Fig. 1).

The power company providing electricity to the facility was known for temporary (even a split-of-a-second) service disruption. Every disruption of service (even a very short one) was causing the gambling machines in the casino to malfunction. These malfunctions could lead to expensive repair costs. Some electronics needed to be replaced after every disruption of power. There was downtime as well as unnecessary repair work.

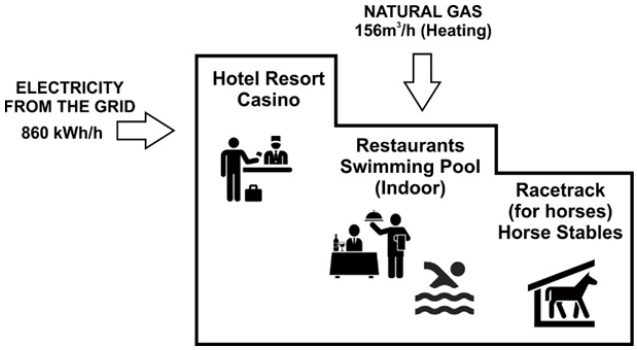


Fig. 1 Utility consumption prior to Combined Heat and Power System

A team of five students supervised by faculty was asked to find a solution to the problem. A practical problem like this allowed the students to apply classroom knowledge to a real-world application [5]. Students also had the opportunity to learn the skills needed to work as a team member. Involvement in the project allowed the students to cross-reference and apply theoretical knowledge gained in courses previously taken [6, 7]. Students were

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highly motivated while establishing professional contacts and building up their resumes [8]. The team of students suggested the *combined heat and power* system as method of correcting the problem.

LITERATURE ANALYSIS

Problem-based learning is one of the most effective teaching methods [9, 10] and more and more often it is also becoming an element of assessment by accreditation committees of technical faculties [11].

Adderley, et.al. (1975) [12] were the first to define project-based learning as having the following characteristics.

- projects involve the solution of a problem; often, though not necessarily, set by the student(s)
- projects involve initiative by the student or group of students, and necessitate a variety, of educational activities,
- projects commonly result in an end product (e.g., thesis, report, design plans, computer program and model),
- work often goes on for a considerable length of time,
- teaching staff are involved in an advisory, rather than authoritarian, role at any or all of the stages – initiation, conduct and conclusion.

The implemented project meets the requirements of the project (PBL) and is an active form of teaching focused on the student. The course project is characterized by student autonomy, constructive research, goal setting, collaboration, communication and reflection within real-world practices.

Heat and Power (CHP*)* is also known as co-generation [13]. Heat is normally a byproduct of electricity generation. In most cases, heat and power are generated separately greenhouse gas emissions [14, 15, 16]. CHP makes it possible to generate heat and power simultaneously. This increases the coefficient of performance and reduces the amount of greenhouse gas emissions [17]. These CHP systems are a suitable alternative for commercially secluded buildings. CHP integrated into these buildings is a growing and economically justified alternative [18, 19, 20]. The project was completed as a part of the project-driven curriculum. Involvement in the project provided the students with valuable industrial experience and helped them learn the skills required to be part of multidisciplinary teams. The topic selected for the project was suitable for teaching engineering students a comprehensive approach to engineering design.

COMPARATIVE ANALYSIS OF DIFFERENT TECHNICALLY POSSIBLE SOLUTIONS

Four different solutions for supplying electric power to the hotel, resort and casino have been identified.

1. Using the electric energy from the grid as well as natural gas (for heating) [21, 22],
2. Onsite combined heat and power system for generating electricity and heat [23, 24],
3. Installing a 1 MW wind turbine and a 1 MW solar array [25, 26, 27, 28],
4. Regional (bigger in size) combined heat and power cogeneration system [29, 30].

SWOT analysis [31, 32, 33, 34] of the four technically possible solutions is listed in Table 1.

Table 1

SWOT analysis of different solutions

Solution	Strengths (S)	Weaknesses (W)	Opportunities (O)	Threats (T)
1. Using the electric energy from the grid and natural gas (for heating).	No need to maintain electric power generator and internal combustion engine,	Periodical disruption of electric power. High utility cost by buying electricity and natural gas.	No need for capital investment.	High greenhouse gas emissions.
2. Onsite combined heat and power system for generating electricity and heat.	Lower utility cost by paying only for natural gas. No periodical disruption of electric power.	Need to maintain internal combustion engine and electric generator.	Lower greenhouse gas emissions. No need to work with other partners.	Need for capital investment to install the system.
3. Installing a 1MW wind turbine and a 1MW solar array.	No periodical disruption of power.	Dependency on wind or sun.	Totally renewable source of energy. Zero emission of greenhouse gases.	Very high cost of initial investment. Need for extra land to accommodate the installation.
4. Regional (bigger in size) combined heat and power cogeneration system.	No periodical disruption of electric power. No need to maintain an internal combustion engine and electric generator.	Need for costly transmission of electric power and heat.	Lower emission of greenhouse gases.	Very high initial investment. Secluded location of hotel, resort and casino. Need for more partners involved in the project.

Based on the SWOT analysis of the four different solutions, the decision was made to install an onsite heat and power system. This solution has the largest number of strengths (S) and opportunities (O) and the smallest amounts of weaknesses (W) and threats (T).

RESEARCH METHODOLOGY

The research described in this article was conducted by a team of students under the supervision of the Engineering faculty. The students were conducting mainly theoretical research and analysis of different technically possible solutions to provide a reliable source of electric power as well as heating and air conditioning to the hotel, resort and casino. The students were analyzing the data related to energy usage at the resort, hotel and casino. Many onsite inspections were conducted to take measurements and analyze the feasibility of different solutions. SWOT analysis was conducted, and the results were discussed with the client. The student team was also researching different available heat and power systems. The detailed specification of the CHP system based on the prioritized consumer specification was prepared and submitted to the potential supplier of the system. After the system was selected, the detailed documentation related to installation and maintenance were prepared.

SELECTION OF THE POWER GENERATION SYSTEM

The challenging step in the project was the selection of a commercially available CHP system. Based on the power capacity requirement of 860 kW, the Dresser-Rand CHP generator fueled by natural gas was selected. This unit provides 860 kW electric power working at an efficiency of 34.7%. A large amount of heat will be generated and utilized for space heating as well as heating domestic water, a swimming pool and dehumidifying the air in the hotel and casino. The heat is being harvested from the cooling system of the internal combustion engine powering the generator. Approximately 721 kW of heat is being harvested by installing a liquid-to-liquid heat exchanger. There are commercially available heat exchangers of that size. In addition, there is a significant amount of heat that can be harvested by installing a gas-to-liquid heat exchanger using the heat from exhaust gases.

The amount of heat that can be recovered from this type of exhaust system is 480 kW. The total amount of heat to be recovered from the engine cooling and exhaust system is approximately 1200 kW (Fig. 2). The student team decided to keep the modifications when purchasing the generator and heat exchanger to a minimum. This allows for a reduced cost of disruptions. The financial analysis of the suggested design needed to be performed to calculate the return on the initial investment.

The selection of commercially available water turbines and electric generators was conducted based on selected product criteria and consumer expectations.

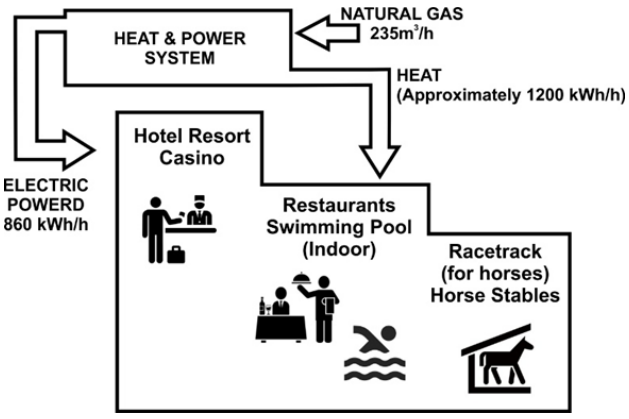


Fig. 2 Utility consumption after *combined heat and power system* installation

The following steps were followed in this procedurę:

1. Determining the quantifiable (measurable) product criteria based on brainstorming and reviewing product specifications. The following criteria have been selected.
   C1. Grid independent system
   C2. Generator powered by natural gas
   C3. Liquid-cooling system of the engine
   C4. Power generators compatible with heat exchangers
   C5. Cost factor
   C6. Reliability factor
   C7. Minimal downtime for maintenance
   C8. Low cost of maintenance
   C9. Low vibration and noise levels
   C10. Low greenhouse gas emissions
   C11. High efficiency of the liquid-to-liquid heat exchanger
   C12. Cost of the liquid-to-liquid heat exchanger
   C13. High efficiency of gas-to-liquid heat exchanger
   C14. Cost of the gas-to-liquid heat exchanger
2. Specifying consumer expectations using the Likert Scale [35, 36]:
   1) Practically unimportant criterion
   2) Not important criterion
   3) Important criterion
   4) Very important criterion
   5) Most important criterion
3. Determining the weights of the criteria.

The weights of the criteria were determined using the Likert Scale as well as the fuzzy Saaty Scale (Table 2).

Table 2
Weights of criteria assessments

Assessment of Importance	Assessment in the Likert Scale	Fuzzy Saaty Assessment Scale
Practically unimportant	1	1, 1, 1
Not important	2	1.5, 2, 2.5
Important	3	2.5, 2, 3.5
Very important	4	3.5, 4, 4.5
Most important	5	4.5, 5, 5.5

Source: Based on [36].

After processing the assessments, it is necessary to develop a combined fuzzy decision matrix as shown in the following formula [37]:

$$\tilde{x}_{ij}=(a_{ij}, b_{ij}, c_{ij}),$$

$$a_{ij} = \min_k\{a_{ij}^k\}, b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ij}^k, c_{ij} = \max_k\{c_{ij}^k\},$$

where:

a – fuzzy rating, left,

b – fuzzy middle rating,

c – fuzzy rating on the right,

K – customer,

i, *j* = 1, 2, …, *n*.

4. Selection of the criteria.

The importance of the selected criteria is shown in Table 3.

Table 3

Importance of individual criteria

Criteria	Mark	a	b	c
Grid independent system	C1	4.5	4.95	5.5
Generator powered by natural gas	C2	4.5	4.90	5.5
Liquid-cooling system of the engine	C3	3.5	4.05	4.5
Power generators compatible with heat exchangers	C4	3.5	4.02	4.5
Cost factor	C5	3.5	3.90	4.5
Reliability factor	C6	3.5	4.02	4.5
Minimal downtime for maintenance	C7	2.5	3.12	3.5
Low cost of maintenance	C8	2.5	3.10	3.5
Low vibration and noise levels	C9	2.5	3.05	3.5
Low greenhouse gas emissions	C10	2.5	3.12	3.5
High efficiency of the liquid-to-liquid heat exchanger	C11	2.5	3.10	3.5
Cost of the liquid-to-liquid heat exchanger	C12	2.5	2.90	3.5
High efficiency of gas-to-liquid heat exchanger	C13	2.5	2.93	3.5
Cost of the gas-to-liquid heat exchanger	C14	2.5	2.95	3.5

Based on the selected criteria and their importance, the company manufacturing the turbines (and the generator) have been contacted. Based on the provided criteria the company has submitted a proposal. The proposal satisfied the specified criteria and was accepted for implementation.

HEAT RECOVERY AND USE

The internal combustion engine powering the electric generator produces a large amount of heat. That heat is being harvested by two heat exchangers as shown in Figure 3.

Liquid-to-liquid heat exchanger is using heat generated by cooling the engine. The gas-to-liquid heat exchanger is extracting heat from exhaust gases. The exhaust gases are being cooled to approximately 120°C. Cooling the exhaust below the temperature of boiling water may require a stainless-steel exhaust system because of extensive corrosion. The temperature of the water supplied by both heat exchangers is approximately 90°C.

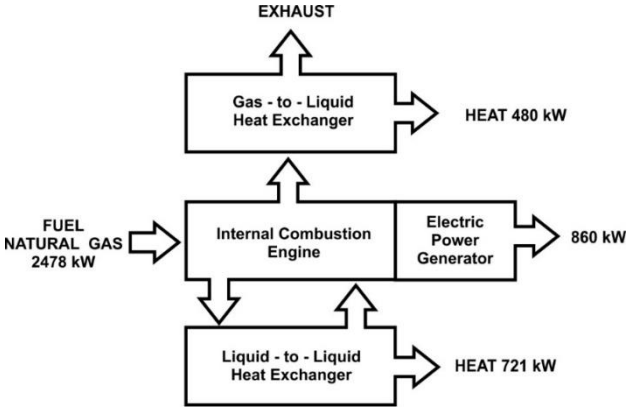


Fig. 3 Schematic drawing of the combined heat and power system

The water is being used for the following purposes.

- Space heating of the resort, hotel, casino and restaurants,
- Heating the domestic water to be used in the resort, hotel, casino, restaurants, etc.,
- Heating the swimming pool in the resort and hotel,
- Dehumidifying the air in the summer to improve the air quality.

The combined heat and power system is a sufficient source of electric power and heat for the entire facility.

ANALYSIS OF THE COST EFFECTIVENESS

The installation of the combined heat and power system resulted in a reduction of the utility costs. The utility cost decreased from 136 dollars/hour to 75.20 dollars/hour (Table 4).

Table 4

Utility cost before and after installation of a Combined Heat and Power System (CHP)

Utility	Cost before Installation	Cost after Installation
Electricity	Consumption: 860 kWh/h Average Cost: 0.1 dollars/kWh Estimated total cost: 86 dollars/hour	Electricity is generated by CHP system
Natural Gas	Consumption: 156 m^3/hour Average cost: 0.32 dollars/m^3 Estimated total cost: 50 dollars/hour	Consumption: 235 m^3/hour Average cost: 0.32 dollars/m^3 75.20 dollars/hour
Total Cost	Combined total cost of utilities (electricity and gas) 136 dollars/hour	Total cost of utilities (Gas only) 75.20 dollars/hour

This resulted in a saving equal to 60.80 dollars/hour. As a result, the annual saving is 532600 dollars/year. The annual cost of maintenance of the CHP system will be approximately 30000 dollars/year. After the substitution of the maintenance fee, the annual saving will be 502600 dollars/year. The cost of the initial outlay of the project is $2.9 M. The life expectancy of the system is 10 years.

FINANCIAL ANALYSIS OF THE PROJECT

This engineering project requires a substantial investment ($2.9M). The funding for this project will be secured through a bank loan. The weighted average cost of capital (*WACC*) for this project is the cost of credit after tax incentives.

$$WACC = K_{dT}$$

where:

K_{dT} – cost of the credit after tax incentive (tax incentive lower the interest rate)

$$K_{dT} = K_d(1 - T)$$

where:

K_d – cost of credit (5% for this project)

T – corporate tax rate (28% for this project)

Substituting numerical values:

$$K_{dT} = 0.05(1 - 0.28) = 0.036 = 3.6\%$$

Therefore,

$$WACC = 0.036 = 3.6\%$$

The financial profitability of the project can be assessed by calculating the following indicators:

- Net present value (NPV),
- Internal rate of return (IRR),
- Profitability index (PI),
- Return on investment,

(Number of years needed for the full return on the investment)

- Discounted rate of investment.

(Number of years needed for the full return on the investment considering the discounted income)

The most important indicators of the profitability of the investment are the net present value (*NPV*) and the internal rate of return (*IRR*).

The net present value (*NPV*) of the project is the discounted income minus the initial investment. *NPV* can be calculated using the following equation.

$$NPV = CF_0 + \frac{CF_1}{(1+WACC)} + \frac{CF_2}{(1+WACC)^2} + \cdots + \frac{CF_n}{(1+WACC)^n}$$

where:

CF_0 = initial investment

WACC = cost of capital

CF_1, CF_2, ……. CF_n – incomes in different years

If,

NPV > 0 (The investment is a good investment)

NPV < 0 (The investment is a bad investment)

Net present value represents the growth of the company's assets. Therefore, the objective is to maximize the *NPV*.

Assuming the present cost of electricity and natural gas, the annual profit is $ 502600.

Table 5 shows the discounted income for the first ten years of operation of the Combined Heat and Power System. (The income is discounted based on the cost of capital).

The calculated *NPV* after ten years is $1427756. The return on investment was calculated to be 5.8 years. The discounted return on investment was calculated to be 6.2 years.

Table 5

Discounted annual income

Year of Operation	Factor Discounting the Income $1/(1 + WACC)^n$	Discounted Income (CF_n)
1	0.965	$485009
2	0.931	$467921
3	0.899	$451837
4	0.867	$435754
5	0.837	$420676
6	0.807	$405598
7	0.779	$391525
8	0.752	$377955
9	0.725	$364385
10	0.700	$351820

Internal rate of return (IRR) represents the return received by the company on the project investment. IRR needs to be higher than the cost of capital. Internal rate of return can be calculated by solving the following equation:

$$PV = CF_0 + \frac{CF_1}{(1 + IRR)} + \frac{CF_2}{(1 + IRR)^2} + \cdots + \frac{CF_n}{(1 + IRR)^n}$$

where:

CF_0 – initial investment,

CF_1, CF_2,…….CF_n – annual income received from investment.

Substituting the numerical values and solving the equation for *IRR*, the internal return rate was calculated to be *IRR* = 0.07 (7%). The internal rate of return (7%) is much higher than the cost of capital.

Profitability index (*PI*) is the ratio of the total income divided by the initial expense. The profitability index can be calculated using the following formula:

$$PI = \frac{\frac{CF_1}{(1+WACC)} + \frac{CF_2}{(1+WACC)^2} + \cdots + \frac{CF_n}{(1+WACC)^n}}{CF_0}$$

Substituting the numerical values, the profitability index was calculated to be *PI* = 1.48. The profitability index indicates that for each $1 investment the company assets increased by $1.48.

CONCLUSIONS

The PBL method in academia is currently attracting more and more attention. Known as teaching based on solving a real problem, "resulting from practice", it is more and more often used, especially at technical universities. At the heart of the PBL method is a non-trivial problem/task that students solve in team projects, supported by a faculty. Learning and solving the "real world" problem happens simultaneously. The student project described in the article was a successful energy-efficient alternative to the traditional grid system. Investment in a combined heat and power system has proven to be a low risk and high return-rate investment. The project was completed as a capstone design assignment incorporated into the Engineering curriculum as a part of the project-driven approach to Engineering education. The project was successful in sparking students' interest as well as increasing students' motivation. It also allowed the students to establish professional contacts. These skills, supporting life-

long self-education, are useful for entry into and for staying in the labor market. The application of the PBL method in practice proves that it shapes "design thinking" as well as developing the creativity and innovation of students. PBL to be introduced at the university, requires good cooperation with the environment, adequate infrastructure and preparation of teachers. The most important element of the PBL method is the student, whose task is to learn how to look for and select the necessary information to solve the given problem. PBL assumes a different role of teacher than in traditional teaching – the teacher does not dictate what the student is to learn or what sources to use. The role of the teacher in the PBL method is to design an appropriate set of task situations, which will be a simulation of problems that the student may encounter in their future professional life.

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Wes Grebski
ORCID ID: 0000-0002-4684-7608
Pennsylvania State University
Professor Emeritus
76 University Drive
Hazleton, PA 18202, USA
e-mail: wxg3@psu.edu

Robert Ulewicz
ORCID ID: 0000-0002-5694-4284
Czestochowa University of Technology
Faculty of Management
ul. J.H. Dąbrowskiego 69, 42-201 Częstochowa, Poland
e-mail: robert.ulewicz@pcz.pl