1-2018

A complementary Cyber-Human Systems framework for Industry 4.0 Cyber-Physical Systems

Matthew Krugh
Clemson University

Laine Mears
Clemson University, mears@clemson.edu

Follow this and additional works at: https://tigerprints.clemson.edu/auto_eng_pub

Part of the [Automotive Engineering Commons](#)

Recommended Citation

Please use the publisher's recommended citation.

This Article is brought to you for free and open access by the Automotive Engineering at TigerPrints. It has been accepted for inclusion in Publications by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

MSEC2014-xxxx

PLANT-LEVEL ENERGY SUPPLY ANALYSIS AND OPTIMIZATION IN ENERGY, ECONOMIC AND ENVIRONMENT

Lujia Feng
Clemson University
Department of Automotive
Engineering
Greenville, South Carolina, USA

Laine Mears
Clemson University
Department of Automotive
Engineering
Clemson, South Carolina, USA

Qilun Zhu
Clemson University
Department of Automotive
Engineering
Greenville, South Carolina, USA

Cleveland Beaufort
BMW Manufacturing Co.
Greer, South Carolina, USA

Joerg Schulte
BMW Manufacturing Co.
Greer, South Carolina, USA

KEYWORDS

Plant Level Energy Supply, Optimization, Energy Management System, Parameter Analysis, Energy, Economic, and Environment.

ABSTRACT

Increasing attention has recently been drawn to the energy consumption of the manufacturing process. Manufacturers are facing challenges from society of reducing emissions and operating more efficiently because of rising raw material prices and energy costs. Manufacturers are trying to balance among the total energy, economic and environmental targets simultaneously, a strategy that can be self-conflicting at times. This paper focuses on the objective optimizations of a plant-level energy supply system, and describes how a multi-objective optimization strategy can be effectively formulated for making the best use of energy delivered to the manufacturing process. An example from an automotive assembly manufacturer is described.

INTRODUCTION

Increasing energy prices, more restrictive policies [1], and the maintenance of positive public image are forcing industries to pay closer attention to their energy use. Research in manufacturing energy use has developed in two distinct paths. One topic focuses on the energy demand reduction [2], which

includes the study of energy conservation in manufacturing processes; another branch of researchers are investigating the improvement of the energy supply system, such as the study of renewable energy sources, efficient energy conversion and delivery technologies, and optimal energy operation strategies.

Plant-level manufacturers are chosen as the study objective in this paper because of their relative independence in energy strategy setting; in reality, the plant-level manufactures are generally regarded as the decision maker. Various energy sources as a result of the various manufacturing processes and working environment maintenance technologies are normal requirements to consider in energy strategy setting. Though with a relatively smaller initial investment, purchasing all desired energy forms directly from a supplier is typically not pragmatic nor cost reasonable. In the majority of cases, some on-site energy transformation equipment is employed. Some energy conversion systems are also enhanced to be more energy efficient by applying co-generation [3]. Generally, the combined heat and power (CHP) cogeneration system improves the energy efficiency from traditionally 30% to encouragingly 70%. And the introduction of the absorption chiller, which produces chilled water from hot water, to co-generation, is making the whole system even more efficient [4, 5]. For the consolidation of energy management, a centralized energy management department is individually located above the production processes in terms of energy utility [6]. A centralized energy management system receives energy inputs

from the suppliers and outputs to production departments. Systematically, multiple-input and multiple-output (MIMO) is a general form for energy conversion and delivery within the centralized energy center. An example of energy center with three inputs and five outputs is shown in Figure 1.

Figure 1: CENTRALIZED ENERGY MANAGEMENT SYSTEM

Figure 1 illustrates a MIMO energy management system. Electricity, natural gas and landfill gas are used as three energy source inputs to the energy center. Electricity, natural gas, hot water, chilled water and compressed air are the five outputs of the energy center. The hot water circulated back from energy outputs to the absorption chiller for chilled water production should not be taken as an energy output, nor energy input. The cogeneration system in the energy center burns gas (natural or supplied from renewable sources such as landfill gas) and generates two forms of energy – electricity and hot water. The capacity of the cogeneration system is defined as the maximum fuel input rate. Hot water can also be produced from boilers to convert the combustion gas (natural gas and/or landfill gas) chemical energy to thermal energy. Air compressors and centrifugal chillers transform the electricity into compressed air and chilled water respectively. From here we can define the energy conversion as a process of changing energy form and quality; energy pass-through, a process of delivery energy in the same form and quality, is also considered. A centralized energy management system includes both energy conversion and pass-through. Figure 1 is a relatively complex general system; not every manufacturer has or needs all of the energy inputs and outputs here; it is also possible that other energy sources are applied. Photovoltaics (PV) is no longer a rare technology used for energy gathering. However, unstable energy sources like PV are not considered for this paper.

Initial equipment investment, and later maintenance and upgrade are inevitable in a centralized energy management system. Optimization based on the economic analysis of

lifetime investment is a worthy topic of study. On the other hand, how to take full advantage of existing systems to operate to a desired target and balance among energy consumption, economics and environment at the same time, is another stimulating question asked by both researchers and manufacturers. The optimization algorithms developed in this paper consider the situation that all the equipment has already depreciated its initial investment and later upgrade fee.

The optimization developed in this paper is based on minimum time period of one day. Constraints from the equipment dynamic capacity are more critical in shorter period optimization, such as by-hour or by-minute. This paper is more intend to analyze the situation for behavior over a longer period, and to consider the existence of an energy storage system. We also assume the sudden energy demand change, such as the impulsive energy demand shift caused by large manufacturing facility shuts down or turns on, will not alter the energy supply or conversion equipment operation strategy in such a short time.

In the processes of energy conversion and pass-through, auxiliary power is unavoidable. To simplify the problem and avoid the effects from various auxiliary specifications, energy consumption discussed in this paper only refers to the energy demand from the manufacturing processes, i.e., the energy consumption within the boundary of energy center of Figure 1 is excluded. The major plant energy consumption is affected by many factors, such as the weather condition, working environmental settings, productivity, and equipment efficiencies. The energy demand mentioned in this paper refers to the energy consumed in the manufacturing process. Instead of reducing energy demand during the manufacturing process and working environment maintenance, the energy supply system optimization can provide suggestions to energy conversion and pass through strategies under different manufacturing and environmental conditions.

Optimal targets – energy, economic and environment are individually described, and a multi-objective optimization is described. A case study from automotive assembly plant is provided for illustration, and a key parameters analysis based on prospective scenarios is developed.

LITERATURE REVIEW

A large body of research been developed on industrial energy consumption. It is reported that the overall energy consumption in industry accounts for 37% of all end-user sector shares of the world's total delivered energy [7]. Azadeh et al. proposed a data envelopment analysis (DEA) optimization model for energy intensive manufacturing sectors and emphasis on the structure importance of national energy consumption [8]. They pointed out that development in different manufacturing sectors will lead to alternative energy structures. As one major part of the industrial energy consumer, optimization approaches

to minimize the energy usage, economic cost, and greenhouse gases (GHGs) have been developed.

For plant-level manufacturers, equipment investment is a big decision that needs to be supported by sound analysis. Internal rate of return and payback time are used to analyze the economic optimization in manufacturing energy investment. Méndez-Piñero and Colón-Vázquez [9] focused on cost optimization of the replacement of existing systems by using internal rate of return (IRR) to minimize the energy consumption in the HVAC, compressed air and lighting system. Payback time assessments were deployed in renewable energy equipment and building investment like solar photovoltaic system [10], cogeneration unit [11], and building retrofitting and construction [12, 13]. In addition to investment evaluation, energy audits usually play a key role in energy efficiency determination and related decision-making. Patrick et al. gave an example from foundry furnaces investment to prove how economic optimization changed the traditional energy audition based decision-making [14]. Furthermore, modern manufacturers have established energy simulation models to monitor their manufacturing processes. Mardan et al. stated the combination steps of discrete-event simulation and energy system optimization. A case study was used to show how these two tools benefit each other and achieve the optimal and feasible results [15].

On the other hand, energy supply optimization concentrates on the energy delivery and conversion. Voll et al. proposed an approach for optimal energy distribution. The approach of Voll and his colleagues applied an energy conversion hierarchy to classify the conversion technologies, and resulted in a superstructure-free synthesis and expandable framework [16]. Research on energy supply system optimization focuses on weights of the reduction of the energy consumption, cost and associated emissions. Industrial energy distribution multi-objective optimization is developed by Buoro et al. to target the economic and environmental goals by applying mixed integer linear programming model. As Buoro and his colleagues claimed, different optimal solutions can be obtained by adjusting the weights in objectives of economic and environment [17]. This results effectively in a single-objective solution. In Fubara et al.'s paper, three types of CHP systems are analyzed and compared under cost and energy driven operation strategies. They found the application of micro-CHP will result in lower cost but higher energy usage [18].

However, the energy optimization supply of the plant-level manufacturer without changing the manufacturing processes, nor working environment, has not been discussed deeply. Unlike the traditional manufacturers, who use single or straightforward energy source(s) from supplier, current manufacturers are trend to have their own on-site energy conversion, storage and delivery system [19] to fulfill the requirement for multiple, stable energy sources supply. Except

for the electricity and thermal energy, modern manufacturers are also looking for energy forms like cooling, compressed air, and clean renewable energy. One of the challenges for the energy optimization in manufacturing supply system is the estimation of energy demand from process lines. Though Herrmann and his colleagues contended an energy oriented simulation concept in their paper [20], researchers are still looking for inexpensive ways to predict energy demand. Another challenge in the development of energy optimization at the plant-level manufacturer is the usually ignored fact of basic conflict among energy, economic and environment optimal operation.

MODEL ESTABLISHMENT

Single Objective Optimization

Optimization models are established according to Figure 1. The outputs of the energy center are the inputs of manufacturing major plant (see Figure 2). The energy center is our research object, which provides the energy supply to the major plant. While the energy supply to energy center refers to energy directly from utility suppliers.

Figure 2: SIMPLIFIED ENERGY INPUTS AND OUTPUTS SCHEMA

The energy center processes energy from suppliers and passes desired forms and amount of energy to the major plant. Equipment efficiencies and energy conversion ratios are represented as an energy-equipment coefficient and all together denoted in the 5×7 matrix C as shown below. The coefficient matrix C relates the output energy with energy center equipment. It contains the energy produced (positive) in energy center and energy inputs to equipment (negative). Equipment efficiency is the efficiency of equipment in producing certain types of energy forms. For example, the efficiency of cogeneration to produce hot water is about 40% and the efficiency to produce electricity is approximately 30%. The conversion ratio has a similar concept as the efficiency, which represents as the energy variation ratio in output energy and input energy to the equipment. The difference is that the conversion ratio can be larger than 1. For example, the conversion ratio (i.e. coefficient-of-performance, COP) [21] of absorption represents the fraction of energy dismissed from the chilled water relative to thermal energy put into the chiller. And since the energy pass through is defined as the fixedness of energy form and quality, the conversion ratio for all pass through energy is 1. If energy is the input of energy center equipment, which means energy from suppliers is consumed in the energy center, the energy-equipment coefficient should be negative (e.g., the coefficient of electricity to compressed air is -1.). Generally, one form of energy center output comes from

multiple energy input approaches, (e.g., chilled output of energy center is the summation of chilled water input from the absorption chiller and centrifugal chiller.) the energy output equals the summation of the product of coefficients and equipment energy consumption (X_j), and demand should be no less than the outputs of energy center (i.e., $D_i \leq \sum_j C_{i,j} X_j$, $i = 1, 2, 3$). Representing in matrix form:

$$\begin{bmatrix} \text{Electricity} \\ \text{Hot water} \\ \text{Chilled water} \\ \text{Natural Gas} \\ \text{Compressed Air} \end{bmatrix} \leq \begin{bmatrix} \square & \dots & \square \\ \vdots & \ddots & \vdots \\ \square & \dots & \square \end{bmatrix} \begin{bmatrix} \text{Co generation} \\ \text{Boiler} \\ \text{Absorbtion Chiller} \\ \text{Centrepital Chiller} \\ \text{Air Compressor} \\ \text{Pass through Gas} \\ \text{Pass through Electricity} \end{bmatrix}$$

D C X

C – 5×7 Coefficient matrix,

X – 7×1 Equipment/Energy center consumption vector,

D – Energy demand vector 5×1

Matrix X is a 7×1 Equipment/energy center consumption vector. It is represented as the form of energy, and in units of MWh. Aside from major plant demand, constraints also come from capacity. Constraints from equipment lower bound and upper bound can be defined by the matrix X : $LB \leq X \leq UB$.

In addition, the transfer function T is used to transform the energy consumed by equipment to energy from suppliers, as

$$\begin{bmatrix} \text{Electricity} \\ \text{NG} \\ \text{LFG} \end{bmatrix} = \begin{bmatrix} \square & \dots & \square \\ \vdots & \ddots & \vdots \\ \square & \dots & \square \end{bmatrix} \begin{bmatrix} \text{Co generation} \\ \text{Boiler} \\ \text{Absorbtion Chiller} \\ \text{Centrepital Chiller} \\ \text{Air Compressor} \\ \text{Pass through Gas} \\ \text{Pass through Electricity} \end{bmatrix}$$

S T X

T – 3×7 Transfer matrix (transfer equipment/energy center consumption vector X to supply vector S),

S – 3×1 Energy supply vector.

Instead of minimizing each of the energy forms from suppliers, targets are set to minimize the sum. With all the definitions, a single objective optimization algorithm can be written:

Optimization objective: $\min (f \cdot S)$

Subject to: $D < C \cdot X$

$LB \leq X \leq UB$

f – Objective coefficient vector.

Single objective optimization is proposed through defining different objective coefficients and keeping all other matrices

and vectors the same. When the supply vector is processed in the unit of MWh, $f = [1 \ 1 \ 1]$ converts the individual energy forms into energy optimization objective – total energy supply. And simply setting the objective coefficient vector to desired factors, optimization objective varies accordingly. $f = [\frac{\$ of electricity}{MWh}, \frac{\$ of Natural Gas}{MWh}, \frac{\$ of Landfill Gas}{MWh}]$ is the form of the objective coefficient vector for economic optimization; and $f = [\frac{kg emission of electricity}{MWh}, \frac{kg emission of Natural Gas}{MWh}, \frac{kg emission of Landfill Gas}{MWh}]$ is the form of the objective coefficient vector for environmental optimization.

Multi-objective Optimization

Linear scalarization for the objective parameters can be used for multi-objective optimization. Objective weights ω_n are set as the scalarization parameters. n represents the targets of three single optimizations $n = 1 - \text{Energy}; 2 - \text{Economic}; 3 - \text{Environment}$.

The multi-objective optimization problem becomes:

$$\begin{aligned} \text{Optimization objective: } & \min \sum_{n=1}^3 (\omega_n \cdot f_n \cdot S) \\ \text{s. t. } & D < C \cdot X \\ & LB \leq X \leq UB \\ & 0 \leq \omega_n \leq 1 \\ & \sum_{n=1}^3 \omega_n = 1 \end{aligned}$$

CASE STUDY

A case study from a typical automotive assembly plant is developed to illustrate the optimization process and results. The automotive assembly plant consists of vehicle panel welding, body panting, and parts assembly for a mid-sized vehicle. Three major departments are the body shop, paint shop and assembly shop. Compressed air is used on process lines. Electricity, hot water, chilled water are used for both manufacturing processes and working environment maintenance. Pass-through natural gas is only delivered to the paint shop for the processes temperature maintenance.

Assume the optimization is developed on a daily basis. The average demand of energy forms to the three departments is shown in the Figure 3; the daily total energy demand is about 1425MWh. The lower and upper bound of equipment used for the optimization study is shown in Table 1.

Figure 3: ENERGY DEMAND FORMS DISTRIBUTION

Table 1: EQUIPMENT ENERGY INPUTS LOWER AND UPPER BOUND

[MWh]	Lower Bound	Upper Bound
Co-generation	0	1000
Boiler	0	400
Absorption Chiller	0	30
Centrifugal Chiller	0	60
Air Compressor	0	60
Pass Through Gas	0	Infinity
Pass Through Electricity	50	Infinity

The lower bound is assumed as the situation when the plant is shut down and the only electricity consumption is to make sure the plant and its facilities are maintained at idle. The upper bound is assumed as the equipment and supply capacity. The unit price of each energy form is the approximate value, equipment efficiencies and conversion ratios are provided by the automotive assembly plant. The environmental coefficient of electricity and natural gas refer to carbon dioxide emission factors from U.S. Energy Information Administration. And the listed value for renewable energy – landfill gas, is calculated through the heat value as:

$$\text{Emission factor of landfill gas} = \text{emission factor of natural gas} \times \frac{HHV_{LFG}}{HHV_{NG}}$$

The optimization objective coefficient vector is defined in Table 2.

Table 2: OBJECTIVE COEFFICIENT

	Electricity	Natural Gas	Landfill Gas
Energy	1	1	1
Economic [\$/MWH]	55	20	10

Environment [kg CO ₂ /MWh]	690	181	90.5
---------------------------------------	-----	-----	------

Three optimal targets yield three distinct results. As Table 3 shows, the results of minimum cost in US dollars, and minimum environment impact in carbon dioxide emission reached unanimous results. The energy optimization results in a higher cost and carbon dioxide emission, while the economic and environment optimization ends up higher energy consumption.

Table 3: OPTIMIZATION RESULTS

	Supply [MWh]	Cost [\$]	Emission [kg CO ₂]
Energy [MWH]	1,654	37,623	413,440
Economic [\$]	1,730	36,150	390,600
Environment [kg CO ₂]	1,730	36,150	390,600

Different optimization results yield diverse operation suggestions. For a plant that wants to save energy and lower the MWh energy per produced vehicle, optimization suggests use less cogeneration but more electricity; nonetheless, the optimization results of economic and environment suggests use more cogeneration and absorption chillers.

Multi-objective optimization for this plant is developed by setting different weight to three targets. The results show it tends to achieve the same outcomes as the single optimization of economic or environment, unless the weight given to target of energy is set to approximately 1.

PARAMETER ANALYSIS

Parameter analyses are discussed in this section in different scenarios and only the important outcomes and significant effects are shown. All the following analyses are based on the data used in the case study.

Emission Factor

If the source of the electricity is clean and has extremely low emission (e.g., the electricity is from nuclear power plant), the result of environmental optimization is the same as the energy optimization. Figure 4 shows the nonlinear relationship between the total carbon dioxide emission and a continuously change in the electricity emission factor. Interestingly, the larger the emission factor of the electricity, the smaller the total emission. Because when the emission factor of electricity is higher, optimization result suggest the less use of electricity and higher conversion of cogeneration system.

Figure 4: EFFECT OF ELECTRICITY EMISSION FACTOR ON THE TOTAL CARBON DIOXIDE EMISSION

Demand

Assume the original data used for demand is the plant running in a 2 shifts working load. It is common for the manufacturer to reduce the shifts for holidays and less production planned days. In single- shift days, we cut the energy demand in half and keep the energy forms distribution as indicated in Figure 3.

Table 4: EFFECTS OF DEMAND ON ENERGY SUPPLY

Supply [MWh]	Energy		Economic		Environment	
	2 Shifts	1 Shift	2 Shifts	1 Shift	2 Shifts	1 Shift
Electricity	379.5	189.8	330.0	57.5	330.0	57.5
Natural Gas	400.0	200.0	400.0	200.0	400.0	200.0
Landfill Gas	875.0	437.5	1000.0	858.3	1000.0	858.3

As Table 4 shows, the energy supply drops by 50% as the demand is reduced by 50%. Nevertheless, the operation strategies do not change as much as the demand changes in the optimization of economics and environment. The cogeneration system still runs at a high capacity and the electricity purchased from the suppliers has dropped dramatically.

Table 5: SUPPLY ENERGY, COST AND EMISSION UNDER THREE SINGLE OPTIMIZATIONS

	Supply [MWh]	Cost [\$]	Emission [kg CO ₂]
Energy [MWh]	1,655	37,623	413,440
Economic [\$]	1,730	36,150	390,600
Environment [kg CO ₂]	1,730	36,150	390,600

Table 5 shows that though the energy demand from the process lines is cut in half, it is difficult to reduce the cost and emission by the same amount. Considering the energy used per vehicle, or energy cost per vehicle, or emission per vehicle, it is more reasonable for a plant to maintain running under as high a process line utility as possible.

Another consideration is the change of energy demand caused by weather condition. As mentioned in the previous section, hot water and chilled water are partially used for the working temperature maintenance. On cold days, the plant will need more hot water and less chilled water to heat the plant; and in hot days, the demand on hot water and chilled water will be inverse. In order to observe the full variation, the upper bounds of the analysis are also changed to fulfill the demand (increasing the upper bound of boiler and centrifugal chiller).

Figure 5: EFFECTS OF DEMAND CHANGE FROM WEATHER CONDITION ON THE ENERGY SUPPLY (OPTIMIZATION TARGET: ENERGY [MWh])

As the weather gets colder, the demand on the hot water will increase, and the demand on the chilled water decrease. Figure 5 describes the trend of three supplied energy sources as a result of energy optimization. Before the hot water demand reaches 400MWh, the supply electricity and landfill gas have a linear decrease and increase trend respectively. When the hot water demand reaches 400MWh, the capacity of cogeneration limits the yield of hot water, and boiler use of natural gas to create the remaining hot water is necessary. The supply electricity has a slower decreasing trend, because the cogeneration system can no longer produce electricity while the centrifugal chillers keep consuming electricity. Overall, the total supply energy increases as the weather gets cold, and the total energy cost has a decreasing trend before the hot water demand reaches 400MWh and increasing trend after the 400MWh (see Figure 6).

This implies manufacturers need to consider about the plant location in terms of energy consumption and cost.

Figure 6: EFFECTS OF DEMAND CHANGE FROM WEAHTE CONDITION ON THE TOTAL ENERGY SUPPLY AND TOTAL ENERGY COST (OPTIMIZATION TARGET: ENERGY [MWH])

Economic and environment optimizations show the same results as the change of demand on the hot water and chilled water.

Figure 7: EFFECTS OF DEMAND CHANGE FROM WEAHTE CONDITION ON THE ENERGY SUPPLY (OPTIMIZATION TARGET: COST [\$])

Figure 7 shows cost optimization of the energy forms supply trends resulting from the effects of hot water demand change due to the weather condition. Unlike the energy optimization, cost optimization suggests the operation of cogeneration always be maintained at full capacity, and to purchase as little electricity as possible. As the demand of hot water increases, the boilers begin generation by using natural gas at the point of 375MWh hot water demand (in the case of the example plant, landfill gas is not used in boilers). The total supply energy and total energy cost share the same trends (see Figure 8).

Figure 8: EFFECTS OF DEMAND CHANGE FROM WEAHTE CONDITION ON THE TOTAL ENERGY SUPPLY AND TOTAL ENERGY COST (OPTIMIZATION TARGET: COST [\$])

Efficiency

It is common for the thermal and electrical efficiencies of the cogeneration system to degrade after years of operation [22].

Figure 9: EFFECTS OF EFFICIENCY OF CO-GENERATION SYSTEM ON SUPPLY ENERGY (OPTIMIZATION TARGET: ENERGY [MWH])

Figure 9 shows how the efficiency of the cogeneration system affects the energy supply by setting energy as the optimization target – higher the efficiency, lower landfill gas and electricity is required.

However, in the scenario of cost as the target, the operation strategy is different. Figure 10 illustrates that the cogeneration system always runs in full capacity and the electricity supply will decrease with higher cogeneration efficiency.

Figure 10: EFFECTS OF EFFICIENCY OF CO-GENERATION SYSTEM ON SUPPLY ENERGY (OPTIMIZATION TARGET: COST [\$])

The variation of other equipment efficiency does not have such a strong effect on the supply energy and operation strategies, and is not discussed here.

Bound

From the cost optimization and some points of the energy optimization, the upper bound of the cogeneration limits the optimization result. Bound analysis, especially upper bound analysis, provides suggestions for equipment selection and investment.

Figure 11: EFFECTS OF CO-GENERATION SYSTEM UPPER BOUND ON SUPPLY ENERGY (OPTIMIZATION TARGET: ENERGY [MWh])

Figure 11 and Figure 12 illustrates the effects of cogeneration system upper bound on the optimization results. Target energy optimization uses more cogeneration system as a smaller upper bound until the demand of hot water is fulfilled, while the target cost optimization always uses the cogeneration system at its full capacity.

Figure 12: EFFECTS OF EFFICIENCY OF CO-GENERATION SYSTEM ON SUPPLY ENERGY (OPTIMIZATION TARGET: COST [\$])

Cost

The energy supply unit prices vary from place to place and time to time. Unit supply energy price analyses are reported in this section.

Figure 13: EFFECTS OF LANDFILL GAS UNIT PRICE ON THE SUPPLY ENERGY COST

Figure 14: EFFECTS OF ELECTRICITY UNIT PRICE ON THE SUPPLY ENERGY COST

Figure 13 and Figure 14 show how electricity and landfill gas unit price affect the purchase of supplied energy. When both energy unit prices vary together, the effects on the total supply energy cost are shown in Figure 15.

Figure 15: EFFECTS LANDFILL GAS AND ELECTRICITY UNIT PRICE ON TOTAL SUPPLY ENERGY COST

Efficiency and Demand

The coupled effect from efficiency and demand are studied in this section.

Figure 16: EFFECTS OF COGENERATION SYSTEM EFFICIENCY AND HOT WATER DEMAND ON TOTAL ENERGY SUPPLY

The total supply energy is affected by both energy demand and cogeneration system efficiencies. The coupled effect from both sides is illustrated in Figure 16 and Figure 17. High cogeneration system efficiency, small hot water demand, larger cold water demand will lead to a smaller energy consumption and cost.

Figure 17: EFFECTS OF COGENERATION SYSTEM EFFICIENCY AND HOT WATER DEMAND ON TOTAL SUPPLY ENERGY COST

CONCLUSION

A relatively complex three energy form input and five energy form outputs, MIMO system is used to study the energy supply system of a major manufacturing plant. Both single objective optimizations and linearly-scaled multi-objective optimization are described in this paper. Energy, economic and environment effects from energy use are analyzed, and shown to be in conflict. A case study from an automotive assembly plant is provided. Key parameter analysis based on possible scenarios is developed, and suggestions on the equipment operation, plant location selection and manufacturing working load schedule are made.

FUTURE WORK

Three major aspects can be developed to improve the value of the current work. First, a day ahead or longer energy demand forecasting would be very promising by combining with the optimization developed in this paper; how much energy will be needed tomorrow, and how can we plan the generation accordingly? Operation strategies can be scheduled ahead to achieve the most desired optimization results. Second, consumption evaluation of the energy center and delivery system can contribute to the assessment of influences from strategy variation. Third, equipment, construction and labor cost of energy management should be considered in the further development of the economic analysis and initial investment.

ACKNOWLEDGMENTS

The authors would like to thank BMW Manufacturing Co. for their project sponsorship and access to the manufacturing facility.

REFERENCES

- [1] Dixon, R. K., McGowan, E., Onysko, G., and Scheer, R. M., 2010, "US Energy Conservation and Efficiency Policies: Challenges and Opportunities," *Energy Policy*, **38**(11) pp. 6398-6408.
- [2] Bruzzone, A. A. G., Anghinolfi, D., Paolucci, M., and Tonelli, F., 2012, "Energy-aware Scheduling for Improving Manufacturing Process Sustainability: A Mathematical Model for Flexible Flow Shops," *CIRP Annals - Manufacturing Technology*, **61**(1) pp. 459-462.
- [3] Zarnikau, J., and Reilley, B., 1996, "The Evolution of The Cogeneration Market in Texas," *Energy Policy*, **24**(1) pp. 67-79.
- [4] Marques, R. P., Hacon, D., Tessarollo, A., and Parise, J. A. R., 2010, "Thermodynamic Analysis of Tri-generation Systems Taking into Account Refrigeration, Heating and Electricity Load Demands," *Energy and Buildings*, **42**(12) pp. 2323-2330.
- [5] Tassou, A., Chaer, I., Sugiarta, N., Ge, Y.-T., and Marriott, D., 2007, "Application of Tri-generation Systems to The Food Retail Industry," *Energy Conversion and Management*, **48**(11) pp. 2988-2995.
- [6] Ngai, E. W. T., Chau, D. C. K., Poon, J. K. L., and To, C. K. M., 2013, "Energy and Utility Management Maturity Model for Sustainable Manufacturing Process," *International Journal of Production Economics*, **146**(2) pp. 453-464.
- [7] Abdelaziz, E. A., Saidur, R., and Mekhilef, S., 2011, "A Review on Energy Saving Strategies in Industrial Sector," *Renewable and Sustainable Energy Reviews*, **5**(1) pp. 150-168.
- [8] Azadeh, A., Amalnick, M. S., Ghaderi, S. F., and Asadzadeh, S. M., 2007, "An Integrated DEA PCA Numerical Taxonomy Approach for Energy Efficiency Assessment and Consumption Optimization in Energy Intensive Manufacturing Sectors," *Energy Policy*, **35**(7) pp. 792-806.
- [9] Méndez-Piñero, M. I., and Colón-Vázquez, M., 2013, "Economic Analysis of Alternatives for Optimizing Energy Use in Manufacturing Companies," *Energy Economics*, **40** pp. 146-154.
- [10] Peng, J., Lu, L., Yang, H., 2013, "Review on Life Cycle Assessment of Energy Payback and Greenhouse Gas Emission of Solar Photovoltaic Systems," *Renewable and Sustainable Energy Reviews*, **19** pp. 255-274.
- [11] Goortani, B. M., Mateos-Espejel, E., and Paris, J., 2010, "Integration of A Cogeneration Unit into A Kraft Pulping Process," *Applied Thermal Engineering*, **30**(17-18) pp. 724-729.
- [12] Huang, Y., Niu, J., and Chung, T., 2012, "Energy and Carbon Emission Payback Analysis for Energy-efficient Retrofitting in Buildings - Overhang Shading Option," *Energy and Buildings*, **44** pp. 94-103.
- [13] Bourrelle, S. J., Andresen, I., and Gustavsen, A., 2013, "Energy Payback: An Attributional and Environmentally Focused Approach to Energy Balance in Net Zero Energy Buildings," *Energy and Buildings*, **65** pp. 84-92.
- [14] Thollander, P., Mardan, N., and Karlsson, M., 2009, "Optimization as Investment Decision Support in A Swedish Medium-sized Iron Foundry – A Move Beyond Traditional Energy Auditing," *Applied Energy*, **86**(4) pp. 433-440.
- [15] Mardan, N., and Klahr, R., 2012, "Combining Optimisation and Simulation in An Energy Systems Analysis of a Swedish Iron Foundry," *Energy*, **44**(1) pp. 410-419.
- [16] Voll, P., Lampe, M., Wrobel, G., and Bardow, A., 2012, "Superstructure-free Synthesis and Optimization of Distributed Industrial Energy Supply Systems," *Energy*, **45**(1) pp. 424-435.
- [17] Buoro, D., Casisi, M., Nardi, A. D., Pinamonti, P., and Reini, M., 2013, "Multicriteria Optimization of A Distributed Energy Supply System for An Industrial Area," *Energy*, **58** pp. 128-137.
- [18] Fubara, T. C., Cecelja, F., and Yang, A., 2013, "Modelling and Selection of Micro-CHP Systems for Domestic Energy Supply: The Dimension of Network-wide Primary Energy Consumption," *Applied Energy*, **114** pp. 327-334.
- [19] Müller, E., Poller, R., Hopf, H., and Krones, M., 2013, "Enabling Energy Management for Planning Energy-efficient Factories," *Procedia CIRP*, **7** pp. 622-627.
- [20] Herrmann, C., Thiede, S., Kara, S., and Hesselbach, J., 2011, "Energy Oriented Simulation of Manufacturing Systems – Concept and Application," *CIRP Annals - Manufacturing Technology*, **60**(1) pp. 45-48.
- [21] Naguib, R., 2011, "The Changing Landscape of Chillers' Energy Efficiency," *Energy engineering*, **108**(4) p. 1-25.
- [22] Kurz, R., and Brun, K., 2009, "Degradation of Gas Turbine Performance in Natural Gas Service," *Journal of Natural Gas Science and Engineering*, **1**(3) pp. 95-102.