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Energy, economy, and environment analysis and optimization on manufacturing plant energy supply system

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ABSTRACT

Increasing attention has recently been drawn to energy consumption in manufacturing plants. Facing the challenges from reducing emissions coupled with rising raw material prices and energy costs, manufacturers are trying to balance the energy usage strategy among the total energy consumption, economy, and environment, which can be self-conflicting at times. In this paper, energy systems in manufacturing environments are reviewed, and the current status of onsite energy system and renewable energy usage are discussed. Single objective and multicriteria optimization approaches are effectively formulated for making the best use of energy delivered to the production processes. Energy supply operation suggestions based on the optimization results are obtained. Finally, an example from an automotive assembly manufacturer is described to demonstrate the energy usage in the current manufacturing plants and how the optimization approaches can be applied to satisfy the energy management objectives. According to the optimization results, in an energy oriented operation, it takes 35% more in monetary cost; while in an economy oriented operation, it takes 17% more in megawatt hour energy supply and tends to rely more on the inexpensive renewable energy.

1. Introduction

Worldwide energy demand has continued increasing in the past decades. Every aspect of human activity – transportation, industrial, residential and commercial activities – requires rising support from energy. Fundamental to human development, energy could now also be harmful and restraining to sustainability. High expenses, unbalanced distribution and intensive demand leave energy-sparse countries fewer opportunities to advance technologically. Additionally, the correlation between the energy consumption and environmental degradation is well known – acid rain, deforestation, greenhouse effect, particle matter pollution, and similar negative environmental effects are examples. "Energy" is discussed as a problem, and a large body of research (and coupled enthusiasm) is directing expertise to solve this problem. This paper focuses on the energy supply to manufacturing plants.

Among the above-mentioned four end sectors, industrial activity is believed to be the most energy intensive. It is also reported that in recent years, more than one third of the energy produced in the US was consumed by industrial activity [1]. Manufacturing represents a significant contributor to this consumption. Compared with the large cost in production materials and labor, energy used to be considered in a minor role. However, manufacturers are facing a lot of pressure. Increasing energy price requires manufacturers to spend less [2]. More restrictive policies require them to use less energy per product [3]. Ascendant public environmental protection awareness demands plants to use more clean energy [4]. Manufacturers are now paying closing attention to their energy use.

Generally, research in the manufacturing energy system can be classified into two directions: energy demand and energy supply. A great number of studies have been made in reducing the energy demand in manufacturing systems, such as the improvement of process scheduling and machine power level adaptation. As the manufacturing systems get more complex, researches have be done to study the energy in the manufacturing flexibility [5]. The scheduling problem was specifically studied [6]. Machine power level energy efficiency was also well developed [7]. On the other hand, aside from recent attention to systemic intelligence such as smart grid and smart metering approaches, research into improving energy supply systems, particularly at the local industrial level, has seen less focus.

The plant level manufacturing system [8] is chosen as the study objective reported in this paper. It is a relatively independent system in energy operation, both from the supply/conversion side as

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Nomenclature

E	energy
η	efficiency
CE	energy cost
CM	maintenance cost
EF	emission factor
Ele	abbreviation for electricity
NG	abbreviation for natural gas
LFG	abbreviation for landfill gas
J	matrix of ones
ED	energy demand
S	supplied energy
P	purchased energy

Subscript

in	input
out	output
i	indicator of energy
j	indicator of equipment
k	indicator of objective
h	indicator of energy demand

well as demand. Considering the great amount of energy consumption in manufacturing plants, the decisions regarding supply strategy are of great importance. For example, the high peak electricity consumption of the plant is an utmost test to the local grid on its power reconfiguration capacity. On the other hand, the influences from both higher level (*e.g.*, strategy setting, policy in reducing the total carbon emission, or demand variations in an agile energy market) and lower level (*e.g.*, production schedule and weather effects) can also impact the decision made by the manufacturers.

Energy supply is the focus of this paper. Recently, manufacturing plants tend to have their own energy conversion and transmission systems to supply the energy demand for the main production lines. How to operate onsite energy conversion and transmission systems, how to cooperate the onsite system with the primary energy delivery from the utility companies, and how to achieve the best results in terms of energy, cost and emissions – these are the questions pursued in this paper by analyzing and optimizing the energy supply system in manufacturing plants. A case study from an automotive assembly plant is used to demonstrate the approaches, and show how the operation can be affected by both higher and lower level variability and decision makers' priorities. Compared with previous works, this work exam the energy conservation opportunities from the supply instead of consumption side, and clarify the savings from the energy, monetary cost, and environmental emission aspects.

2. Background

Pertinent background related to energy usage within the current manufacturing plant, especially the research on supply systems, renewable energy application, metering status, optimization approaches and U.S. energy prices are reviewed and discussed in this section.

2.1. Energy conversion and transmission

Purchasing all demand energy directly from the utility company requires only a small capital investment; but it is neither cost reasonable, nor pragmatic in the long term. To face the variable production conditions and changeable energy prices, plants are typically equipped with an onsite (*decentralized*) energy conversion and transmission system. While energy transmission is only to deliver the same forms and amount to the production lines, conversion involves changes in the energy forms and quantities. Typical energy conversion forms include combustion, electricity generation, air compression and thermal energy exchange. Representative examples of the energy conversion is given here. Combustible energy (such as coal, oil and natural gas) are burned in the combustion chamber to generate steam which rotates the turbine connected with an electrical generator. In this way, the chemical energy from the primary energy is converted to electricity. Traditional fired generation systems release the exhaust gas to the atmosphere; however a co-generation or tri-generation system will recover part of the thermal energy through heat exchange to create hot water or steam for later use. In this case, the thermal energy was also captured [9]. Other examples for chemical and thermal energy conversion, and electricity and thermal energy conversion are from the burners and chillers respectively. Usually, a burner/boiler will be onsite to supplement hot water/steam for production or building heating [10]. Chillers use electricity to generate chilled water, used for equipment and building cooling [11]. In the case of air compression, air compressors use electricity as energy input to compress air to a higher pressure for carrying energy to the shop floor [12]. Detailed energy modeling of these traditional energy conversion and transmission systems is relatively straightforward and well-studied [13].

2.2. Renewable energy

Apart from the geothermal and biomass energy, which have high requirements on the techniques and particular to location, solar and wind generation are two relative popular renewable energy sources for the manufacturing plants. However, compared with traditional energy supplies, solar and wind are relatively unstable.

Solar energy is used to provide high temperature as a process heat source, which has been increased use recently [14]. The electrical power from the PV solar panels depends on temperature and temperature. Researches use the MPPT (maximum power point tracker) to calculate the maximum power they can obtain from the sun:

$$P_S(G, \Delta T) = k_1 \cdot A_S \cdot G \cdot (1 - k_T \Delta T) \tag{1}$$

where P_S is the power from sun, A_S is the total area of the PV model (m^2), $\Delta T = T_c - T_{cref}$ is the temperature difference between the cell temperature T_c and the reference cell temperature T_{cref} (°C), k_T is the temperature coefficient, and k_1 is the PV module generation efficiency [15]. Solar irradiation G is often described in stochastic models to solve the problem of unstable availability of the solar input.

Wind power can be captured through coupled wind towers and turbines. The available wind generator power P_{out} can be expressed as a function of wind speed V_{wind}:

$$P_{out}(V_{wind}) = \begin{cases} P_{rated} \cdot \frac{(V_{wind}^k - V_{in}^k)}{(V_{in}^k - V_{rated}^k)} & \text{if } V_{in} \leqslant V_{wind} \leqslant V_{rated} \\ P_{rated} & \text{if } V_{rated} \leqslant V_{Wind} \leqslant V_{out} \\ 0 & \text{Otherwise.} \end{cases} \tag{2}$$