CASE STUDY IN INDUSTRIAL ECOLOGY: REGIONAL UTILITY-BASED COGENERATION

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Summary

This article presents a case study in industrial ecology illustrating the benefits of regional utility-based cogeneration. The concept of industrial ecology, and the related methodologies of life-cycle assessment and design for the environment, are reviewed, and their relation to sustainable development described. The case study assesses six scenarios in which utility-based cogeneration is implemented in the province of Ontario, Canada using the facilities of the main provincial electrical utility. The scenarios are examined both on an annual basis and on a cumulative basis spanning 20 years. The scenarios assume utility-based cogeneration satisfies portions of the heat demands of the residential-commercial-institutional and/or the industrial sectors. We show that the

implementation of utility-based cogeneration in Ontario offers significant opportunities to reduce annual and cumulative energy use and related emissions, and to provide economic benefits for the province and its electrical utility. Because of this, it would seem worthwhile for Ontario, and other regions in the world, to investigate appropriate options for utility-based cogeneration, and to develop and implement plans that will achieve optimal regional benefits. The decision as to which option(s) to implement is complex and must ultimately be group-based, as actual implementation efforts involve many stakeholders (governments, utilities, customers, and others) whose competing interests can lead to conflicting views. In addition, there are often many barriers to regional utility-based cogeneration that require joint efforts to overcome. Regardless of implementation details, utility-based cogeneration as discussed in this case study adheres to the philosophy of industrial ecology in moving towards sustainable development. Finally, anticipated future trends relating to the case study are discussed.

1. Introduction

Industrial ecology provides an important approach for achieving sustainable development. Through the industrial ecology approach, technology and society develop while addressing environmental concerns in an "appropriate" manner. Such a merging of technology and environment is a critical consideration in the development of life support systems.

Industrial ecology strives to achieve a balance between uncontrolled and unplanned development and a return to low-technology ways of the past. Different people and societies usually identify different appropriate balance points. The implementation of industrial ecology usually involves many parties, each of whom often have differing, and sometimes competing, interests. Thus, the undertaking of industrial-ecology measures inherently involves group decisions and often requires conflict resolution.

In this article, a case study in industrial ecology is presented which investigates the potential benefits of regional cogeneration using the facilities of the local electrical utility. The region considered is Ontario, Canada, and both annual and cumulative benefits are considered, relative to the business-as-usual situation where cogeneration is applied only in a very limited manner in Ontario. Cogeneration allows heating and electrical services to be provided with significantly lower energy-resource use and environmental emissions than would occur using separate processes for heating and electricity generation. As these benefits can be notable, cogeneration can contribute significantly towards the achievement of sustainable development, particularly when it is applied on a regional scale using the local electrical-utility infrastructure.

2. Industrial Ecology

In their 1995 book *Industrial Ecology*, Graedel and Allenby define industrial ecology as: the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution.

With an industrial ecology approach, one seeks optimum cycles and processes for using material and energy resources, while satisfying environmental constraints and financial and other desires as much as possible.

The industrial ecology approach views systems and activities in concert with the environment, rather than in isolation, and provides a systems or overall perspective. The overall life cycle for a product or process is considered within the industrial ecology framework, i.e., a life cycle assessment approach is taken (see Section 2.1). The name industrial ecology arises from the analogy and links between the processes and cycles encountered within industry and the environmental cycles and processes within the discipline of ecology.

Industrial ecology is in part based on the following expression, which provides an approximate measure of environmental impact:

Environmental impact = (Population) % (Wealth/person in population) % (Environmental impact per unit wealth) (1)

Consider the right hand side of this equation. The first term, population, is expected to grow, with correspondingly increased demands for both resources and waste sinks. The degree of population growth to be expected is difficult to predict, as there are many factors that affect it. On the one extreme, there may be unmanaged population growth, which, given the limited carrying capacity of the Earth, will likely lead to severe problems that will ultimately cause population levels to decrease in unpredictable manners due to disasters, famines, etc. On the other extreme, population growth may be curtailed through overt measures to constrain it, although such measures are not likely to achieve successfully significant reductions in population growth. Efforts to control environmental impact often strive for managed population growth within which sustainable levels of development can be achieved.

The second term, wealth per person, can be evaluated in several ways, including Gross Domestic Product (GDP) per capita for a country or region. This term varies with location, time, and other factors, but tends to increase (usually due to human desires for higher standards of living).

The third term, environmental impact per unit wealth, depends on the availability and deployment of environmental impact reduction technologies. This term is mainly technically based, and its reduction offers the most hope for achieving sustainable development by offsetting the environmental-impact increases associated with increases in the first and second terms.

Thus, industrial ecology seeks to permit sustainable economic and cultural development with moderate population growth, relying in large part on technical advances and managed development that achieves a balanced compromise between the following two extreme alternatives:

a) Return to low-level technology, with the corresponding consequences of trying to change society so that it returns to past ways. A reduction in technology use would likely yield a corresponding reduction in resource use and waste emissions.

However, this scenario is highly unrealistic, given the desire of most developed countries to improve their standards of living, and the desire of countries with emerging economies to achieve the living standards observed in more developed countries.

b) Unmanaged development, such as is seen in many areas at present, with unlimited population growth and few environmental constraints. This approach likely leads eventually to major societal disruptions and potentially catastrophic events.

It is sometimes inferred that the industrial ecology approach leads to "correct" solutions to environmental and sustainable-development problems. This reasoning can be misleading as truly correct solutions are subjective and infrequently are obtainable. Rather, optimal solutions are normally sought, where the determination of the optimum usually involves trade-offs among different factors and constraints (each of which has an importance dependent on the weighting attributed it). Thus, industrial ecology helps provide an optimal solution through an approach considered by many to be rational and comprehensive.

The industrial ecology approach allows both anticipated and unexpected trends to be dealt with because it is:

- proactive, as opposed to reactive
- designed in, rather than added on
- flexible, not rigid
- comprehensive, encompassing, and systems-oriented, rather than insular

Most industrial ecology approaches incorporate the concepts of life cycle assessment and design for environment, and are directed towards sustainable development. These topics are therefore discussed in the next three subsections.

2.1 Life Cycle Assessment

Life cycle assessment (LCA) is a method for analyzing and improving the environmental impact of processes and systems, considering the full life cycle of the product or service. LCA is an important component of industrial ecology.

LCA normally involves a definition of the scope and boundaries for the assessment to be undertaken, and the following three distinct steps:

- Identification and quantification of the associated environmental impacts. The environmental burdens associated with a product, process or activity are evaluated by identifying and quantifying the inputs and the environmental emissions. The inputs include all energy and material resources (e.g., water, air, chemicals), and the outputs include products as well as solid, liquid, gaseous and energy wastes. The inputs and outputs are considered for all steps in the life of the product or process, including the pre-use, use and post-use phases.
- Assessment of the effects of the environmental impacts. For each environmental impact identified in step 1, the effects are determined (quantitatively if possible),

and the importance of each ascertained. This step is often challenging and imprecise, as many different views and interpretations are usually possible.
- Improvement of environmental performance through appropriate modifications. Opportunities to effect improvements in environmental performance are identified and evaluated, and implemented where appropriate (taking into account other decision-making considerations as well). This step involves finding the best opportunities and is often the most challenging of all LCA steps. The development of measures to improve environmental performance is sometimes referred to as design for the environment (DFE), which is discussed in the next section.

The precision and objectivity is different for each of the steps in LCA. The first step, although often time consuming, mainly involves data acquisition and is normally the most straightforward and objective. The second step is less precise and involves greater subjectivity, as assessments of the effects and importance of environmental impacts vary and are often debated. The third step usually is subjective and involves substantial choices, as views on the most appropriate ways to improve environmental performance often vary spatially, temporally and among different companies and individuals.

LCA provides a systems perspective, which helps in efforts to prioritize the many aspects of complex environmental situations (e.g., the nature and magnitude of problems and the best solutions).

LCA normally addresses the entire life cycle of a product or process, including the following life stages:

- extraction and processing of raw materials and other resources
- manufacturing
- transportation, distribution and storage
- use and re-use
- maintenance
- recycling
- final disposal

As LCA is often complex and extensive, the breadth of assessments are sometimes constrained in terms of their scope and/or the system boundaries considered. For instance, one may choose to limit the scope of an assessment and focus on only emissions, or even one type of emission (e.g., greenhouse gases), rather than consider all environmental impacts. Also, one may limit the boundaries of an assessment to only examining the device and its operation, or one may leave the scope broad and consider all phases in the life cycle. The case study considered in this article, as explained subsequently, focuses on the utilization phase of the life cycle. In general, the analysis is more straightforward but the results are less useful when the scope and boundaries of an assessment are limited, while the analysis is more complex but the results more comprehensive when the scope and boundaries are left broad.

Specific LCA methodologies based on the concepts discussed in this section are mainly in their infancy, although the first step is the furthest advanced in most methodologies. The types of LCA methodologies that exist vary greatly, ranging from qualitative and general, to quantitative, detailed and comprehensive.

2.2 Design for the Environment

Design is the act of creating a product or process to provide a service, often to satisfy a need, and usually involves many steps. Numerous factors are considered in design, including ability to meet purpose, safety, economics, customer/user satisfaction, manufacturability, materials and equipment requirements, efficiency, reliability, lifetime, legal/regulatory compliance, and environmental impact and concerns. The last factor, environmental impact and concerns, includes resource use as well as emissions and other forms of pollution. The inclusion of environmental impact and concerns in design is often referred to as design for the environment (DFE), which often forms the third step in LCA.

DFE involves considering environmental impacts and concerns in all parts of the design process, from the initial through to the final stages. DFE methods range from vague, non-rigorous and qualitative to detailed, specific and comprehensive. Many factors are considered in DFE, including the following:

- Materials selection. Materials that are abundant, non-toxic and recycled are often favored. By extension, efforts are often placed on leaving materials in a recyclable form after use.
- Structural design, including designing for minimum use of materials in products and processes.
- Usage patterns, which are especially important because the environmental impacts associated with use often are more significant than those for other stages in a product or process life cycle.
- Transportation. Both normal-operation concerns (e.g., transport energy use) and abnormal-operation concerns (e.g., accidental releases) are normally addressed.
- Storage, which can be of concern environmentally due to the risk of accidental emissions. Where toxic or hazardous substances are utilized, storage release risks can be reduced if the substances are produced only when required, rather than in advance and stored.
- Packaging. Environment-focussed preferences are often for no or minimal packaging, and for consumable, returnable, reusable, recyclable and made-from-recycled-materials packaging.
- Installation and removal. The installation of some products leads to environmental impacts, e.g., pipelines are often buried, and electrical distribution wires often traverse great distances.
- Reuse and recycling. Recycling is facilitated by minimizing the use of different materials and of toxic and hazardous materials, and is usually most effective when implemented early in the manufacturing chain.
- Energy utilization and selection. Energy-related DFE activities often are aimed at using environmentally benign and sustainable energy resources, and/or at increased efficiency.

Efficiency-improvement measures include improved monitoring, control and maintenance; recovery of waste material and heat; energy leak and loss prevention;

application of cogeneration, district heating and cooling and integrated energy systems; improved matching of energy supplies and demands; use of high-efficiency devices; and utilization of passive strategies and second-law analysis techniques to reduce energy use. The selection of energy resources can involve energy or fuel substitution (e.g., the use of heaters driven by natural gas rather than electricity). Environmentally preferred resources are usually those which (a) are renewable rather than non-renewable, (b) cause relatively lower environmental impacts, and (c) can be used with higher efficiency and more environmentally benign energy-conversion technologies.

The case study considered here focuses on the latter factor, energy utilization and selection. Of the efficiency-improvement measures listed in that point, the case study mainly addresses the following measures: cogeneration, district heating and cooling, integrated energy systems and waste heat recovery. Further, the case study indirectly considers energy-resource selection.
Some final comments on DFE are worth noting. First, DFE is best addressed during the initial stages of the design process, as it is usually easier to alter designs for better environmental performance in the initial phases of a design-development effort rather than as an afterthought. Second, DFE measures are often more effective and efficient when implemented in the initial steps of a process (e.g., it is often simpler and less expensive to reduce acid gas emissions by removing sulfur compounds from process feedstocks, than by adding capture and treatment steps to the end of a process or after emissions have left a facility). Third, the long lifetimes of many products and processes, often ranging from several years to several decades, make DFE decisions very important, as the impacts of such decisions persist for correspondingly lengthy durations.

2.3 Sustainable Development

Sustainable development has been defined and interpreted in numerous ways. One of the most often cited definitions is that given in the World Commission on Environment and Development’s 1987 report “Our Common Future” (commonly referred to as the Brundtland report), where sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

Clearly, many factors contribute to achieving sustainable development. For example, for development to be sustainable,

- it must satisfy the needs and aspirations of society,
- it must be environmentally and ecologically benign, and
- sufficient resources (natural and human) must be available.

The second point reinforces the importance of environmental concerns in sustainable development. Clearly, activities which continually degrade the environment are not sustainable over time, while those that have no or little negative impact on the environment are more likely to contribute to sustainable development (provided, of course, that they satisfy the other conditions for sustainable development).

The relation between sustainable development and the use of resources, particularly energy resources, is of great significance to societies. As this relation is most pertinent to the case study considered in this article, it is considered in more detail in the next two subsections.

2.3.1 Energy and Sustainable Development

A supply of energy resources is generally agreed to be a necessary, but not sufficient, requirement for development within a society. Societies, such as countries or regions, that undergo significant industrial and economic development almost always have access to a supply of energy resources. In some countries (e.g., Canada) energy resources are available domestically, while in others (e.g., Japan) they must be imported.

For development that is sustainable over long periods of time, there are further conditions that must be met. Principally, such societies must have access to and utilize energy resources that are sustainable in a broad sense, i.e., that are obtainable in a secure and reliable manner, safely utilizable to satisfy the energy services for which they are intended with minimal negative environmental, health and societal impacts, and usable at reasonable costs.

An important implication of the above statements is that sustainable development requires not just that sustainable energy resources be used, but that the energy resources be used efficiently. Through efficient utilization, society maximizes the benefits it derives from its energy resources, while minimizing the negative impacts (such as environmental damage) associated with their use. This implication acknowledges that most energy resources are to some degree finite, so that greater efficiency in utilization allows such resources to contribute to development over a longer period of time, i.e., to make development more sustainable. Even if one or more energy resources eventually become inexpensive and widely available, increases in energy efficiency will likely remain sought to reduce the associated environmental impacts, and the resource requirements (energy, material, etc.) to create and maintain systems to harvest the energy.

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Biographical Sketch

Dr. Marc A. Rosen is a professor in the Faculty of Engineering and Applied science at University of Ontario Institute of Ontario in Oshawa, Canada, where he served as founding dean for six years. He is also President Elect of the Engineering Institute of Canada. Dr Rosen was previously a professor in the Department of Mechanical Engineering at Ryerson Polytechnic University in Toronto, Canada. He recently completed a term as Department chair, and has served as Director of the Department's School of Aerospace Engineering. He has worked for such organizations as Imatra Power Company in Helsinki, Finland, Argonne National Laboratory outside Chicago, U.S.A. and the Institute for Hydrogen Systems, near Toronto. Dr. Rosen obtained a B.A.Sc. (1981) in Engineering Science, and a M.A.Sc. (1983) and Ph.D. (1987) in Mechanical Engineering, all from the University of Toronto. He is a registered Professional Engineer in Ontario, and a founding associate editor for " Exergy, An International Journal." Dr. Rosen is a fellow and Past President of the Canadian Society for Mechanical Engineering, vice president of its Thermo-Fluids Engineering Technical Division and a member of that society's journal Transactions of the CSME. With over 40 research grants and contracts and 170 technical publications, Dr. Rosen is an active teacher and researcher in thermodynamics (particularly second-law, or exergy, analysis), energy-conversion technologies (e.g., cogeneration, district energy, thermal storage, renewable energy), and the environmental impact of energy and industrial systems. Dr. Rosen has received many honors, including an Award of Excellence in Research and Technology Development from the Ontario Ministry of Environment and Energy in 1997, and the Sarwan Sahota/Ryerson distinguished scholar award in 1998.