Exergy as a Tool for Sustainability

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Abstract: Although we conventionally use energy analysis to assess energy systems, exergy analysis has many advantages. Exergy analyses provide useful information, which can directly impact process designs and improvements because exergy methods help in understanding and improving efficiency, environmental and economic performance as well as sustainability. Exergy’s advantages stem from the fact that exergy losses represent true losses of potential to generate a desired product, exergy efficiencies always provide a measure of approach to ideality, and the links between exergy and both economics and environmental impact can help develop improvements. Exergy analysis also provides better insights into beneficial research in terms of potential for significant efficiency, environmental and economic gains. An illustration of nuclear power generation and of a country’s energy system and its electrical utility sector helps clarify the benefits and advantages of exergy. Exergy analysis should prove useful to engineers, scientists, and decision makers.

Key-Words: exergy, sustainability, efficiency, energy conservation, entropy, environment, economics, nuclear power

1 Introduction

We conventionally assess energy systems using energy, which is based on the first law of thermodynamics which states the principle of energy conservation. But energy analysis has many weaknesses that can be overcome with an alternative thermodynamic analysis method.

Exergy analysis, based on the second law, has several advantages over energy analysis. For instance, more meaningful efficiencies are evaluated with exergy analysis since exergy efficiencies always measure approach to ideality, while inefficiencies are better described with exergy analysis in terms of magnitude, type, cause and location. Exergy methods can also play a role in improving environmental and economic performance. When all facets of exergy are taken together, it is observed that exergy is a powerful tool for understanding and improving the sustainability of processes and systems, and helping achieve sustainable development.

For these reasons and others, exergy analysis has been increasingly applied over the last several decades, to improve efficiency, economic and environmental performance and, ultimately, sustainability. Exergy analysis can be applied to assess and improve energy systems, as well as other systems like ecological systems. In this article, we examine the role of as a tool for sustainability, with the objective of increasing appreciation and utilization of exergy methods.

Here, we describe exergy and its application through exergy analysis. The breadth of energy systems assessed with exergy analysis is presented. The ties between exergy and economics, the environmental implications of exergy and the links between exergy and sustainability are described. Finally, an illustrative example of applications of exergy analysis is presented for nuclear power generation, first as an isolated process and then as a component of a country and its electrical utility sector.

2 Exergy Analysis

Exergy analysis [1-9] involves the application of exergy concepts, balances and efficiencies to evaluate and improve energy and other systems. Exergy flows through at all points in a process or system are examined. Many suggest that devices are best evaluated and improved using exergy analysis with or in place of energy analysis.

Energy analysis has inherent difficulties as it considers only quantities of energy and ignores energy quality, which is continually degraded during real processes. Exergy analysis overcomes many of these problems.

Many exergy applications have been reported over several decades, and extensive bibliographies assembled, including Goran Wall’s compilation at http://exergy.se. In addition, a journal devoted to exergy, International
Journal of Exergy, was established several years ago by Inderscience. Applications of exergy reported include:

- Conventional and alternative electricity generation.
- Engines and combustion.
- Transportation, e.g., land, air and water.
- Heating and cooling and cogeneration.
- Petrochemical processing and fuels production.
- Chemical processes, e.g., distillation and desalination.
- Metallurgical processes, e.g., smelting.
- Energy storage, e.g., in batteries and thermal storages.

2.1 Exergy

Exergy is defined as the maximum work which can be produced by a flow or system as it is brought to equilibrium with a reference environment, and can be viewed as a measure of energy usefulness or quality. Exergy is consumed during real processes due to irreversibilities, and conserved during ideal processes.

Exergy quantities are evaluated relative to a reference environment [1-12], which has zero exergy and is in stable equilibrium, with all parts at rest relative to one another. Chemical reactions can not occur between environmental components. The reference environment acts as an infinite system (a sink and source for heat and materials), and experiences only internally reversible processes in which its intensive state (i.e., temperature $T_o$, pressure $P_o$, chemical potentials $\mu_{ioo}$ for each of the $i$ components present) remains constant. These properties in part determine the exergy of a flow or system.

2.2 Exergy balances and efficiencies

An energy balance for a system may be written as

\[
\text{Energy input} - \text{Energy output} = \text{Energy accumulation}
\]

where energy inputs and outputs cross system boundaries and energy accumulation occurs within the system. With the principles of energy conservation and entropy non-conservation, an exergy balance can be written:

\[
\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation}
\]

The main difference is that, unlike energy, exergy, a measure of energy quality or work potential, is consumed. Exergy consumption is proportional to entropy creation due to irreversibilities.

Exergy efficiency increases are subject to theoretical limitations, which identify the maximum attainable, and practical limitations, which further limit efficiency.

Theoretical limitations establish an upper limit. To assess the potential for increased efficiency, theoretical limits must be clearly understood. Lack of clarity on this issue has in the past often led to confusion, in part because energy efficiencies generally are not measures of how nearly the performance of a process or device approaches the theoretical ideal. The consequences of such confusion can be very significant. For example, resources have at times been directed towards increasing the energy efficiencies of devices that in reality were efficient and had little potential for improvement, while devices have not been targeted for improved efficiency, even though the difference between the actual and maximum theoretical efficiencies, which represents the potential for improvement, has been large.

Practical limitations acknowledge that no process can be ideal. And that the goal when selecting energy sources and utilization processes is not to achieve maximum efficiency, but rather to achieve an optimal trade-off between efficiency and such factors as economics, sustainability, environmental impact, safety and societal and political acceptability. This optimum is dependent on many factors, which can be altered to favour increased efficiency via government financial incentives for efficient technologies and disincentives for low-efficiency alternatives through special taxes and regulations.

3 Extensions of Exergy

Exergy concepts can be applied beyond thermodynamics.

3.1 Exergy and environmental impact

Exergy applications are increasing in environment and ecology. Many suggest that the impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed with exergy. Although the exergy of an energy form or a substance is a measure of its usefulness, exergy is also a measure of its potential to cause change. The latter point suggests that exergy may be, or provide the basis for, an effective measure of the potential of a substance or energy form to impact the environment.

The most appropriate link between the second law of thermodynamics and environmental impact has been cited as exergy, in part because it is a measure of the departure of the state of a system from that of the environment [1,10-12]. The exergy of a system depends on the states of both
the system and the environment. This departure is zero only when the system is in equilibrium with its environment.

Relations between exergy and the environment may reveal the underlying fundamental patterns and forces affecting changes in the environment, and help efforts to address environmental damage. Tribus and McIrvine [13] suggest that performing exergy analyses of the natural processes occurring on the earth could form a rational foundation for ecologically planning because it would indicate the disturbance caused by large-scale changes. The author introduced relationships between exergy and environmental impact [12], which are illustrated approximately in Fig. 1 as a function of process exergy efficiency.

3.1.1 Degradation
A material found in nature or created artificially, which is in a state of disequilibrium with the environment, can be defined as a resource [14]. Resources have exergy because of this disequilibrium, and resource degradation reduces their inventory and thus is a form of environmental damage. Resources are usually valued for their reactivity (e.g., fuels) or composition (e.g., ores).

More generally, exergy is fundamentally a measure of order, so the exergy of an ordered system is greater than that of a disordered one. The destruction of order is a form of environmental damage, with the exergy difference of the systems measuring (i) the exergy (and order) destroyed when the order is lost, and (ii) the minimum work required to convert the disordered system to the ordered one (i.e., to clean up). In reality, more than this minimum work, which only applies if a reversible clean-up process is employed, is required.

The environmental impact associated with resource degradation can be reduced through increased efficiency. Also, since the earth is an open system subject to a net influx of exergy from the sun, environmental damage can be reduced by utilizing solar radiation instead of degrading other resources.

3.1.2 Emissions
The exergy with waste emissions carries the potential for environmental damage in that such exergy, by being out of stable equilibrium with the environment, represents a potential to cause change. When emitted to the environment, this exergy represents a potential to change the environment. Usually, emitted exergy causes a change which is harmful, such as damage to structures, compromised health, and interference with the net input of exergy via solar radiation to the earth (e.g., global warming).

To reduce waste exergy emissions, it would be advantageous to have air-pollution ratings in which the air-pollution cost for a fuel is determined as either the cost to remove the pollutant, or the cost to society of the pollution. The latter could be implemented as a tax which would be levied if pollutants are not removed from effluent flows, or in other ways.

3.2 Exergy and economics
In energy systems analysis and design, techniques are often used which combine scientific disciplines (especially thermodynamics) with economics to achieve optimum designs. For energy systems, costs are conventionally based on energy, but many [15-21] suggest costs are better distributed among outputs based on exergy. Exergy applications with economics are increasing, in books [e.g., 1,15,16], critical reviews and comparisons and elsewhere [e.g., 21].

Methods of performing exergy-based economic analyses have evolved and are referred to as thermoeconomics, second-law costing, exergoeconomics, etc. These techniques recognize that exergy, not energy, is the commodity of value in a system, and assign costs and/or prices to exergy-related variables. These techniques usually help determine the appropriate allocation of economic resources so as to optimize the
design and operation of a system, and/or the economic feasibility and profitability of a system (by obtaining actual costs of products and their appropriate prices).

Tsatsaronis [21] identifies four main types of analysis methods, depending on which of the following forms the basis of the technique: (i) exergy-economic cost accounting, (ii) exergy-economic calculus analysis, (iii) exergy-economic similarity number, and (iv) product/cost efficiency diagrams.

### 3.3 Exergy and sustainability

The economic, environmental and other aspects of exergy extend to sustainability. Increasing efficiency usually reduces environmental impact and also has sustainability implications as it lengthens the lives of existing resource reserves. Although increasing efficiency generally entails greater use of materials, labor and more complex devices, the additional cost may be justified by the resulting benefits.

In fact, the term “energy crisis,” used to imply an unsustainable supply of energy, would seem meaningless because we have large quantities of energy around us although much is of qualities too low to be useful. The term “exergy crisis” would more appropriately reflect what the lay person is concerned about: an unsustainable supply of high-quality energy resources [22].

The author feels that those working in energy systems and the environment require an understanding of exergy and the insights it can provide into efficiency, economics, environmental impact and sustainability, and that policy makers also need to appreciate exergy because energy policies increasingly play an important role in addressing sustainability issues [23-25].

### 4 Illustration: Nuclear Power Generation

Energy and exergy analyses are applied to nuclear power generation, based on the Pickering Nuclear Generating Station [26]. Operated by the provincial electrical utility, Ontario Power Generation (formerly Ontario Hydro), in Ontario, Canada since 1971, the station, has a net unit electrical power output of approximately 500 MW. Other data are presented in Table 1. This illustration, based on a prior investigation [27], clearly illustrates how exergy analysis allows process inefficiencies to be better pinpointed than energy analysis, and efficiencies to be more rationally evaluated. Consequently, the illustration identifies areas where the potential for performance improvement is high, and trends that may aid in the design of future stations. The results compare well with those from exergy analyses of other thermal power plants [28].

The following steps are applied for energy and exergy analyses of nuclear power generation:

- Divide the process into the desired number of sections, depending on the detail and information sought.
- Perform mass and energy balances and determine basic quantities (e.g., heat) and properties (e.g., pressure).
- Select a reference-environment model, accounting for the process and information desired.
- Evaluate energy and exergy values.
- Determine exergy balances and exergy consumptions.
- Select and evaluate appropriate measures of merit.
- Interpret results, and draw appropriate conclusions and recommendations for design changes, retrofits, etc.

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>Flow</th>
<th>Mass (kg/s)</th>
<th>Energy (MW)</th>
<th>Exergy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat from nuclear fission</td>
<td>Heat</td>
<td>1763</td>
<td>1763</td>
<td></td>
</tr>
<tr>
<td>Heavy water from reactor</td>
<td>7724</td>
<td>9548</td>
<td>2984</td>
<td></td>
</tr>
<tr>
<td>Main boiler steam (H₂O)</td>
<td>814</td>
<td>2227</td>
<td>862</td>
<td></td>
</tr>
<tr>
<td>Condenser cooling water</td>
<td>24073</td>
<td>1107</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Moderator cooling water</td>
<td>1957</td>
<td>90</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Generator/transformer waste heat</td>
<td>11</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity for pumps</td>
<td>19</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross electrical output</td>
<td>542</td>
<td>542</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.1 Process description

A single unit of the station has four main sections:

- **Steam Generation.** Heat is produced and used to generate and reheat steam. Natural uranium is fissioned in the presence of a moderator to produce heat, which is transferred from the reactor to the boiler in the Primary Heat Transport Loop. The flow rate of pressurized heavy water (D₂O) in that loop is 7724 kg/s. The D₂O is heated from 249°C and 9.54 MPa to 293°C and 8.82 MPa in the nuclear reactor. Light-water steam (815 kg/s at 4.2 MPa and 251°C) is produced in the boiler and transported through the secondary heat transport loop. Spent fuel is removed from the reactor, and heat generated in the moderator rejected.

- **Power Production.** The steam from the Steam Generation section passes through a series of turbine
and 2.5 MW in the calandria tubes) and transferred to the shield, 0.1 MW in the dump tank, 2.4 MW in the calandria produced in other reactor components (1.1 MW in the moderator, 2.6 MW is transferred from the rate of heat rejection by the moderator cooler, 82 MW is actually observes for each unit that, of the 90 MW assumed produced in the moderator. The power utility energy input. All heat rejected by the moderator cooler is net heat produced by uranium is considered the main occurrence at the reference-environment temperature and the temperature of about 880°C produced (i.e., the thermal neutron flux-weighted average efficiencies discussed subsequently. If, alternatively, fissioning uranium is assumed theoretically so high that the energy and exergy of the heat can be considered equal. This assumption has a major effect on the exergy efficiencies discussed subsequently. If, alternatively, fission heat is at the temperature at which it is actually produced (i.e., the thermal neutron flux-weighted average temperature of about 880°C), the exergy of the heat is about 75% of the energy. Thus efficiency definitions for nuclear power generation used here follow nuclear industry conventions, but these efficiency definitions are inadequate because they are based on the heat released from the uranium rather than its energy or exergy content.

4.3 Results and discussion

4.3.1 Efficiencies and losses

Exergy consumptions for devices are listed, according to process sections, in Table 2. Figures 2 and 3 illustrate the net energy and exergy flows and exergy consumptions for the four main process sections.

An overall energy efficiency is evaluated as

Energy efficiency = Net electricity out/Energy in

and an overall exergy efficiency as

Exergy efficiency = Net electrical exergy out/Exergy in

Fission heat is the only input source of energy or exergy for the station, and the energy and exergy efficiencies are both 30%. Nonetheless, these efficiencies differ markedly for many station sections. In the Steam Generation section, exergy consumptions account for 1027 MW or 83% of the total exergy losses (47 MW in the boiler, 9 MW in the moderator cooler, 1 MW in the heavy-water pump, and 970 MW in the reactor). The energy and exergy efficiencies for the Steam Generation section, considering the increase in energy or exergy of the water as the product, are 95% and 42%, respectively, so this section thus appears significantly more efficient based on energy than exergy. This discrepancy implies that although 95% of the input energy is transferred to the preheated water, the energy is degraded as it is transferred. In the condensers, much energy enters (1125 MW for each unit), of which close to 100% is rejected, and little exergy enters (44 MW for each unit), of which about half is rejected and half internally consumed. Thus, energy implies erroneously that most losses in electricity-generation potential are associated with condenser heat rejection, while exergy demonstrates that the condensers are responsible for little of these losses (see Figs. 2-3). This discrepancy arises because heat is rejected by the condensers at a near-environment temperature. In the Power Production and Preheating sections, energy losses are small (less than 10 MW total), and exergy losses were moderately small (about 150 MW in the Power Production section and 20 MW in the Preheating section) and almost entirely associated with internal consumptions.
Figure 2. Simplified energy diagram for a nuclear power generation unit, indicating net energy flow rates (MW) for flows. Flow widths are proportional to energy flow rates. Station sections shown are Steam Generation (S.G.), Power Production (P.P.), Condensation (C.), and Preheating (P.). Flows shown are electrical power (P), heat input (Q) and heat rejected (Q_r).

Figure 3. Simplified exergy diagram for a nuclear power generation unit, indicating net exergy flow rates for flows and consumption rates (negative values) for devices (in MW). Flow widths are proportional to exergy flow rates, and shaded regions to exergy consumption rates. Other details are as in Figure 3.

The 970 MW exergy consumption rate in the reactor can be further understood by hypothetically breaking down the processes within it [27]: moderator heating (8% of the reactor exergy consumption), heating of the fuel pellets (to their maximum temperature of approximately 2000°C) (22%), transferring heat within the fuel pellets to the surface of the pellets (at approximately 400°C) (51%), transferring heat from the surface of the fuel pellets to the cladding surface (at 304°C) (8%), and transferring heat from the cladding surface to the primary coolant and then to the preheated boiler feedwater to produce steam (10%).

The assessment yields several illuminating insights. First, although nuclear power generation energy and exergy efficiencies are similar, energy analysis does not systematically identify the location and cause of process inefficiencies, while exergy analysis does. Specifically, energy losses are associated with emissions (mainly heat rejected by condensers), and exergy losses primarily with consumptions (mainly in the reactors). Second, since devices with the largest thermodynamic losses have the

Table 2. Breakdown by section and device of exergy consumption rates for a unit of a nuclear power generating station

<table>
<thead>
<tr>
<th>Section/device</th>
<th>Exergy consumption rate (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Generation</td>
<td>1027</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>56</td>
</tr>
<tr>
<td>Pump</td>
<td>1</td>
</tr>
<tr>
<td>Power Production</td>
<td>143</td>
</tr>
<tr>
<td>Turbines</td>
<td>117</td>
</tr>
<tr>
<td>Generator</td>
<td>6</td>
</tr>
<tr>
<td>Transformer</td>
<td>6</td>
</tr>
<tr>
<td>Condensation</td>
<td>25</td>
</tr>
<tr>
<td>Preheat</td>
<td>21</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>20</td>
</tr>
<tr>
<td>Pumps</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>1216</td>
</tr>
</tbody>
</table>
largest margins for efficiency improvement, efforts to increase the efficiencies of nuclear power generation should focus on the reactors. Third, the use of heat rejected by condensers only increases the exergy efficiencies by a few per cent.

Note that the step in which heat is generated by fissioning uranium is assumed outside the nuclear reactor boundary. The overall energy and exergy efficiencies could be significantly different if this step were considered. Then, the energy and exergy of the fresh and spent nuclear fuel would be required. The exergy of nuclear fuel is not agreed upon. Researchers usually only deal with the heat delivered by nuclear fuels, and most argue that the exergy of nuclear-derived heat is equal or nearly equal to the exergy because the heat can potentially be produced at very high temperatures. Nevertheless, the potential of spent uranium is significant, as it is highly radioactive and releases significant quantities of heat for many years. These factors impact on the exergy and energy performance, and should be taken into account in efforts to improve efficiencies.

4.3.2 Environmental impact
The exergy-environment relations described previously are illustrated for nuclear power generation:

- Order and resource degradation occur during the exergy consuming conversion of uranium to less ordered spent fuel. Although a degree of resource degradation is unavoidable for a real process, increased exergy efficiency can reduce the degradation. In the extreme, if the process in the example were made thermodynamically ideal by increasing the exergy efficiency from 30% to 100%, uranium use and the related emissions would each decrease by about 70%.
- Waste exergy emitted with waste heat to the atmosphere and lake represents a potential to impact the environment. Concern exists regarding thermal pollution in bodies of water, and exergy-based insights into environmental-impact potential of such phenomena could improve our understanding.

4.3.3 Economics
The example helps illustrate that costs are better distributed among outputs if cost accounting is based on exergy because it often is a consistent measure of economic value (i.e., a large quantity of exergy is often associated with a valuable commodity) while energy is only sometimes a consistent measure of economic value. In previous studies for the coal, oil and nuclear power generation [19], thermodynamic and economic data for mature devices identified correlations between capital costs and thermodynamic losses for devices. The existence of such correlations likely implies designers knowingly or unknowingly incorporate exergy recommendations into process designs indirectly. Several findings followed from the analysis of the relations between thermodynamic losses and capital costs for devices in modern power generation:

- A significant parameter is the ratio of thermodynamic loss rate (energy and exergy) to capital cost, with a correlation observed between capital cost and exergy loss rate, but not energy loss rate. The variation in thermodynamic-loss-rate-to-capital-cost ratio values for different devices is large when based on energy loss, and small when based on exergy loss.
- Devices in modern power generation appear to conform approximately to a particular value of the thermodynamic-loss-rate-to-capital-cost ratio (based on exergy loss), which reflects the “appropriate” trade-off between exergy losses and costs in successful designs.

5 Illustration Extended: Nuclear Power in the Context of a National Energy System
Where it is used, nuclear power generation is a component of a country’s electrical utility sector, which is a part of the national economy. Here, the illustration is extended by considering the efficiency of energy utilization in Canada and its utility sector using energy and exergy analyses reported previously [29]. The energy-utilization efficiency of a country and its sectors can be clarified with exergy. This assessment allows nuclear power generation to be seen in a broader context.

5.1 Sector analyses
The main energy resources used in Canada are coal, petroleum, natural gas, nuclear energy and hydraulic energy. Renewable energy resources (e.g. wind, solar, wave, tidal) are neglected since present use is minor. The utility sector includes processes for electricity generation from these energy sources. The other three main sectors are residential-commercial, transportation and industrial.

In the electricity generation analyses, several simplifications are made. The hydraulic source is taken to be the change in kinetic and potential energy of flowing water (even though coal equivalents are often used to represent hydraulic energy inputs). As in the previous section, the nuclear source is assumed to be nuclear-derived heat at a temperature so high that its energy and
exergy are equivalent. Also the reference-environment model from the previous section is used, but with a temperature of 25°C (except where noted).

5.2 Results and discussion

5.2.1 Utility sector

For the different types of electricity generation, Table 3 lists energy and exergy efficiencies, which are equal, and the quantities of electricity generated and energy inputs. Using data from Table 3, the mean overall energy and exergy efficiencies for the utility sector are found to be equal at 53%. Fossil fuel and nuclear electricity generation have efficiencies below the sector mean.

Table 3. Efficiencies of Canada and its main sectors

<table>
<thead>
<tr>
<th>Sector</th>
<th>Energy Efficiency (%)</th>
<th>Exergy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential-commercial</td>
<td>73</td>
<td>14</td>
</tr>
<tr>
<td>Industrial</td>
<td>72</td>
<td>43</td>
</tr>
<tr>
<td>Transportation</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Electrical utility</td>
<td>53</td>
<td>53</td>
</tr>
<tr>
<td>Overall</td>
<td>51</td>
<td>24</td>
</tr>
</tbody>
</table>

5.2.2 Comparison of sectors and the country

The efficiencies for the overall Canadian economy and its main sectors are compared in Table 4. The energy efficiencies range from 18 to 73% and the exergy efficiencies from 14 to 53%. The most efficient sectors on energy and exergy bases are different, and the utility sector is observed to be relatively efficient. The residential-commercial sector exhibits the greatest differences for energy and exergy evaluations. The most significant differences between energy and exergy efficiencies are attributable to heating processes. For example, the overall exergy efficiency of the residential-commercial sector (14%) is much lower than the overall energy efficiency (73%) because high-quality energy (i.e., high exergy) sources are used for low-quality energy (i.e., low exergy) demands. The higher exergy efficiency of the industrial sector is mainly attributable to the high temperatures required for most industrial heating (∼400°C) compared to residential-commercial heating (∼25°C). The industrial sector thus utilizes relatively more of the quality or work potential of fuels.

The energy data if Table 4 indicate that nearly 50% of the total energy consumed in Canada is converted to useful energy for end uses, and that the transportation and utility sectors cause the most energy wastes. The exergy-flow diagram differs markedly from the energy diagram in that only 24% of Canadian exergy consumption is converted to useful exergy for end uses, with the residential-commercial and industrial sectors causing the greatest wastes. Thus, energy analysis indicates a more limited margin for efficiency improvement than exergy analysis. Yet only exergy analysis indicates the real margin for improvement. By using exergy rather than energy analysis, therefore, energy-utilization efficiency in the country is more clearly illuminated, and more rational allocations of energy-related research are made.

The results agree with analyses of other countries [30].

Table 4. Generation data for utility and industrial sectors

<table>
<thead>
<tr>
<th>Electrical generation mode</th>
<th>Energy flows (PJ)</th>
<th>Efficiencies (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated electricity³</td>
<td>Input electricity</td>
<td>Exergy electricity</td>
</tr>
<tr>
<td>Hydroelectric²</td>
<td>1000</td>
<td>1176</td>
</tr>
<tr>
<td>Nuclear</td>
<td>230</td>
<td>767</td>
</tr>
<tr>
<td>Fossil³</td>
<td>293</td>
<td>916</td>
</tr>
</tbody>
</table>

¹ Hydraulic and nuclear generation occur in the utility sector, while 262 PJ of fossil generation is in the utility sector and the remainder in the industrial sector.
² Hydraulic energy is taken to be the change in kinetic and potential energy of flowing water.
³ The contribution by different fossil fuels is 91% coal, 7% petroleum and 2% natural gas.

6 Conclusions

Exergy analyses provide useful information, which can have direct implications on process designs and improvements. Exergy methods help in understanding and improving not only efficiency, but also environmental and economic performance as well as sustainability. In part, these advantages of exergy stem from the fact that exergy losses, unlike energy losses, represent true losses of the potential to generate a desired product from inputs, and exergy efficiencies, unlike energy efficiencies, always provide a measure of approach to the theoretical upper limit. The ties of exergy to economics and environmental impact can also be used to improve energy systems.

Exergy analysis also provides better insights into beneficial directions for research, in terms of potential significant efficiency, environmental and economic gains, than energy analysis. For example, focusing research on process areas with low exergy efficiencies directs effort to areas with the largest margins for efficiency improvement.
Exergy typically suggests improvement efforts should concentrate more on exergy consumptions rather than emissions. Of course, such other factors as health, safety, and socio-political implications also affect decisions. The illustration of an exergy analysis of nuclear power generation and of a country and its electrical utility sector helps clarify the benefits and advantages of exergy.

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References:
Heat Exchanger Exergoeconomic Lifecycle Cost Optimization

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Abstract: Considering lifecycle cost analysis during the design phase of thermal systems gives the design effort more worth. Furthermore thermodynamic exergetic optimization is proven to be useful method for determining the most lifecycle cost optimal design of thermal systems for given thermodynamic constraint. The most thermodynamic efficient heat exchanger design basing on first low analysis may not be the most lifecycle economic one. Nevertheless including the second law (exergetic) analysis in the lifecycle cost optimization technique will definitely result in a thermodynamic efficient and lifecycle most economic heat exchanger design. In this study lifecycle cost optimization procedure for shell and tube heat exchanger has been developed. The total cost includes initial and operating cost presents the objective function for the optimization procedure. The study searches for the optimum, if they exist, by doing the different parametric study based on both sizing and the rating problem. Cost of the heat exchanger has been optimized basing on different constraints, like length, shell diameter etc.

Keywords: heat exchanger, operating cost, optimization, entropy generation, exergy destruction, thermodynamics.

Nomenclature:

\( m_H \) Hot fluid mass flow rate (shell side)
\( m_C \) Cold fluid mass flow rate (tube side)
\( v_C \) Specific volume of cold fluid (Tube side)
\( v_H \) Specific volume of hot fluid (shell side)
\( \Delta E_{H,T} \) Rate of exergy change due to temperature of the hot fluid
\( \Delta E_{H,P} \) Rate of exergy change due to pressure drop of the hot fluid
\( \Delta E_H \) Total rate of exergy change of hot fluid
\( T_{Hout} \) Hot fluid outlet temperature
\( T_{Hin} \) Hot fluid inlet temperature
\( T_{Cin} \) Cold fluid inlet temperature
\( T_{Cout} \) Cold fluid outlet temperature
\( \Delta P_H \) Hot fluid pressure drop (shell side)
\( \Delta P_C \) Cold fluid pressure drop (Tube side)
\( \text{exf}_2 \) Exergy flow outside (Hot fluid)
\( \text{exf}_1 \) Exergy flow inside (Hot fluid)
\( \text{exf}_3 \) Exergy flow inside (cold fluid)
\( \text{exf}_4 \) Exergy flow outside (cold fluid)
\( C_{pH} \) Specific heat of hot fluid
\( C_{pC} \) Specific heat of cold fluid
\( T_o \) Environmental temperature
\( \Delta E_C \) Total rate of exergy change of cold fluid
\( \dot{E}_{XD} \) Exergy destruction rate
\( \dot{E}_{X_{\text{q},j}} \) Exergy due to heat source
\( \dot{E}_{Xe} \) Outlet exergy
\( \dot{E}_{xi} \) Inlet exergy
\( W_{cv} \) Exergy due to work
\( \text{ex}_i \) Exergy at inlet
\( \text{ex}_e \) Exergy at exit
\( n_p \) Number of tubes in one pass
\( L \) Length of heat exchanger
\( N_p \) Number of passes
\( C_T \) Tube cost per meter
\( D_s \) Shell diameter
\( P_{pt} \) Tube side pumping power
\( P_{ps} \) Shell side pumping power
\( P_p \) Total pumping power
\( C_E \) Cost of electricity per kWh
\( C_{py} \) Pumping cost per year
\( C_{dy} \) Exergy destruction cost per year
\( N \) Heat exchanger life (years)
\( I \) Inflation rate
\( P_T \) Pitch
\( C \) Clearance between adjacent tubes