Energy and Environmental Advantages of Cogeneration with Nuclear and Coal Electrical Utilities

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Abstract: The use of electrical-utility cogeneration from nuclear energy and coal is examined for improving regional energy-resource utilization efficiency and environmental performance. A case study is presented for a large and diverse hypothetical region which has nuclear and coal facilities in its electrical utility sector. Utility-based cogeneration is determined to reduce significantly annual use of uranium and coal, as well as other fossil fuels, and related emissions for the region and its electrical-utility sector. Reductions in greenhouse gas emissions are significant, indicating that utility-based cogeneration has a role in combating climate change.

Keywords: Cogeneration, combined heat and power, emissions, efficiency, coal, nuclear energy

1. Introduction

A case study is presented in which the potential benefits are investigated of cogeneration (or combined heat and power) using the facilities of electrical utilities in a hypothetical region. Cogeneration involves the simultaneous production of thermal and electrical energy, with the main advantage being that less input energy is consumed than would be required to produce the same products in separate processes. Additional benefits often include more economic, safe and reliable operation, and reduced emissions (Rosen, 1998). The latter is primarily attributable to reduced energy consumption and the use of modern technologies in large, central installations. The reduced emissions of greenhouse gases can be significant, allowing cogeneration to contribute to mitigating climate change.

The case study considers the potential impact of utility-based cogeneration in the hypothetical region, relative to the situation with very limited cogeneration, with the objective of determining the possible annual benefits derivable from utility-based cogeneration. The hypothetical region is assumed to have the following characteristics:

- a diverse economy, including many types of industry with a range of heating needs,
- a large population (approximately 10 million),
- an electrical-utility sector that predominantly uses uranium and coal in thermal power plants, and hydroelectric plants,
- a large land area (over 200,000 square kilometers), with the population and industry spread over it, so that energy needs are geographically dispersed rather than concentrated in a small area, and
- a varying climate, with temperatures reaching 30°C in summer and -30°C in winter, so that heating and cooling are likely required.

Nuclear and fossil-fuel thermal power plants form the basis of most cogeneration systems. In thermal power plants, a fossil fuel or uranium resource is converted to heat in the form of steam or hot gases, which is then converted in part to electricity. The remaining heat is rejected as waste to the environment. Cogeneration systems are similar to thermal power plants, but some of the generated heat is delivered as a product, often as steam or hot water, usually with reduced electricity production. Cogeneration efficiencies based on electrical and thermal products can exceed 80% (Rosen, 1998). Cogeneration applications can vary in size, from single buildings to utility-scale facilities.

2. Cogeneration

There are many types of cogeneration systems, and applications exist throughout the world. Most of these are based on fossil-fuels. A cogeneration system is normally selected to match thermal and electrical demands.

Numerous cogeneration advances have been reported, e.g., residential total energy systems incorporating cogeneration (Gusdorf et al., 2008). Cogeneration has been proposed based on coal gasification and solid oxide fuel cells (Ghosh and De, 2006). Trigeneration (i.e. cogeneration with cooling as a third product) has also been assessed (Teopa Calva et al., 2005) as have its potential for integrating beneficially with district energy (Emho, 2003). The cogeneration of heat and electricity from CANDU nuclear power plants has been considered (Burnstaple and Tong, 1984). The latter report is consistent with a past opportunity for utility-based cogeneration promoted in Ontario, Canada (Ontario Hydro, 1984). The electrical utility stated that large supplies of heat in the form of steam or hot water are available at several of its stations around the province, at as high as 230°C for nuclear and 510°C for coal-fired stations.

Cogeneration plants have been analysed thermodynamically using energy (Misa et al., 2007) and exergy (Kanoglu et al., 2007; Dincer and Rosen, 2007), as have related technologies such as district heating and cooling (Rosen et al., 2005; Kanoglu et al., 2007; Dincer and Rosen, 2007; Rosen et al., 2005). Design criteria have been identified for distributed cogeneration plants (Bertaa et al., 2006), and the synthesis of industrial utility systems has been examined for cost-effective decarbonisation (Varbanov et al., 2005). The optimal design of gas turbine cogeneration plants was recently studied (Yokoyama and Ito, 2006), as have economic factors, like demand charges and their impact on the optimization of cogeneration dispatch in deregulated energy markets (Coffey and Kutrowski, 2006). Utility/cogeneration inter-tie electrical protection has also been studied (Rifaat, 1995).

2.1. Electrical-Utility Facilities

The hypothetical region is assumed to utilize a mix of energy sources for its electricity generation, including nuclear energy and coal. Hydraulic energy may be used, but is not considered in this case study because it can not be used for cogeneration. For the electrical generation stations considered here, the efficiency based on electrical energy is assumed to be 37% for coal-fired plants and 30% for nuclear plants, based on a previous report (Rosen, 1998). The largest energy loss is the heat rejected from the condensers in cooling water. Thus, efficiency can be markedly improved for both types of plants if the thermal energy rejected by the condensers is used, i.e., if cogeneration is implemented.

Many cogeneration systems are possible based on coal and nuclear electrical stations. A significant degree of flexibility exists in the current system for utility-based cogeneration within both individual station units and multiple unit stations. In addition, many enhancements of the existing system are possible using advanced cogeneration technologies.

Many existing electrical generation and cogeneration systems utilize natural gas as fuel, and natural gas-based cogeneration systems may play an important role in future utility-based cogeneration. The importance of natural gas is in part related to its relatively low greenhouse gas emissions, compared to other fossil fuels. Nonetheless, the present work concentrates on coal and uranium, the fuels assumed used in the utility sector of the hypothetical region.

2.2. Prior Assessments of Utility Cogeneration

Investigations of the energy, environmental, health, and economic benefits of utility-based cogeneration have been carried by the author for Ontario, Canada, focusing on annual assessments (Rosen, 1994; Hart and Rosen, 1994) as well as cumulative assessments over time periods of decades (Rosen and Le, 1994). In addition related techno-economic studies have been reported (Diener and Cain, 1993; FVB/Eltec, 1993; MacRae, 1992; Rogner, 1993).

Analyses like the one reported here have been performed for similar technologies, e.g., a comparison of environmental and health impacts of electrical power generation, including nuclear-based processes (Rashad and Hammad, 2000). Options for nuclear energy beyond electricity, including the provision of heating, have been investigated (Soutworth et al., 2007) and are important given the predictions for increased nuclear energy use (Rogner et al., 2008a, 2008b; Cleveland, 2008; Toth, 2008).

3. Thermal Demands and Markets

Two main heat demands can normally be satisfied through cogeneration:

- residential, commercial and institutional (RCI) processes (e.g. space and water heating), which require relatively low-temperatures heat. Note that cogenerated heat can also be used to drive absorption chillers for space cooling, and that district heating (using a central heat supply to meet a region’s heat demands) and has been applied extensively in the RCI sector.
- industrial processes (e.g. heating, drying, melting, boiling), which require heat at varied temperatures. Thermal energy-intensive industries include chemical, petrochemical and metal processing, fertilizer and cement production, pulp and paper processing, manufacturing and construction.

Potential markets in a region for utility-cogenerated thermal energy, which exist mainly in the RCI and industrial sectors, are a portion of the total thermal-energy demands. These markets depend on many factors, both technical and non-technical.

Heat characteristics and availability: The quantity, supply rate and temperature of supplied heat must satisfy all demand requirements and, in addition, the system must be able to accommodate actual variations in heat-demand parameters (quantity, temperature, etc.). In this area, cogenerated heat from nuclear plants is usually at a lower temperature and thus less valuable than that from fossil-fired plants. Furthermore, heat must be available when it is in demand, either by cogenerating when heat is demanded or storing the heat during periods between its generation and utilization.

Distance: Users and suppliers of thermal energy must be located within a suitable distance. Given nuclear plants tend to be few, large and separated by large distances, rather than spread out geograhpically, the potential contributions are lower for nuclear- than fossil-derived heat.

Infrastructure, attitude and economics: An overall infrastructure and relevant technologies must exist for all cogeneration steps (heat supply, distribution, storage, utilization). In addition, a positive attitude towards cogeneration is needed by all stakeholders (suppliers, distributors, users). Furthermore, the economics for cogeneration options normally need to be competitive with or superior to the economics for non-cogeneration options. This statement presumes a traditional economic approach, but the inclusion of externalities such as environmental costs can substantially increase the economic competitiveness of cogeneration, and policy reasons (e.g., environmental) can render cogeneration alternatives desirable even if not economically competitive.

4. Cogeneration Scenarios

Six scenarios are considered in which the effects of implementing electrical utility-based cogeneration are examined for the region. The scenarios are assessed by evaluating changes in such quantities as energy consumption and environmental emissions. To better understand the behaviour of the electrical-utility sector, the regional effects of cogeneration for the scenarios are separated out for this sector.

4.1. Base Case

Annual data for the region and its electrical-utility sector, against which the scenarios are assessed, are provided for

- energy requirements for heating (Fig. 1),
- energy use for the region (Fig. 2), including primary and secondary (electricity),
- energy use for the electrical-utility sector (Fig. 3),
- environmental material emissions (Table 1).
- environmental non-material emissions (Table 2).

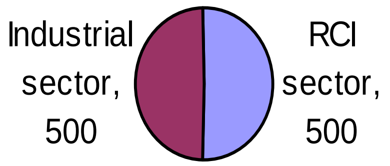

Fig. 1. Annual energy requirements in the region for heating, by sector (PJ).

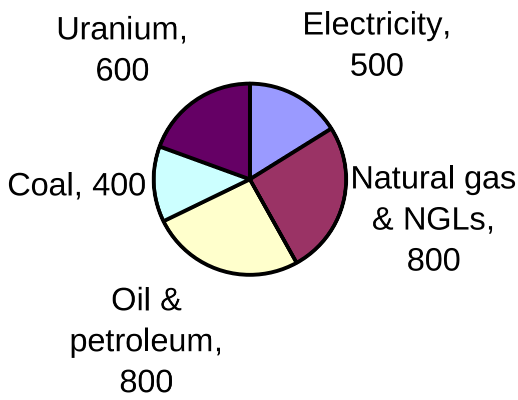

Fig. 2. Annual energy use in the region (PJ). NGLs denotes natural gas liquids. Uranium energy is taken to be heat delivered by fission.

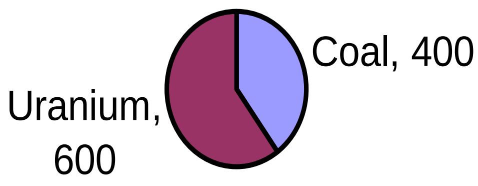

Fig. 3. Annual energy use in the region's electrical-utility sector (PJ). Uranium energy is taken to be heat delivered by fission. Hydraulic energy use is omitted.

Table 1. Annual material emissions (kilotons) for the region and its electrical-utility sector

	SO_2	NO_X	CO_2	CO	Particulates	V.O.C.[a]	Spent uranium
Region	1400	600	150,000	3500	800	800	1
Utility sector	300	100	30,000	10	10	1	1

[a] V.O.C. denotes volatile organic compound.

Table 2. Annual non-material emissions for the region and its electrical-utility sector

	Thermal pollution[a] (PJ)	Radiation[b] (10^{15} Bq)
Region	600	10
Utility sector	600	10

[a] Thermal pollution is heat emitted to bodies of water that cause appreciable temperature rises.
[b] Radioactive emissions from non-nuclear-energy sources are not included, e.g., radioactivity in coal-station stack gases.

4.2. Scenarios

Six cogeneration scenarios are considered in which the use of heat from basic or advanced utility-based cogeneration networks supplies some of the heat demands of the RCI and/or industrial sectors (Table 3). The scenarios are intended to span possible wide range of market penetration for utility-based cogeneration, with Scenarios A and C assuming the least penetration and Scenario F assuming the most.

Table 3. Descriptions of the electrical utility-based cogeneration scenarios

Scenario	Type of utility-based cogen. network	Sector receiving utility-cogen. heat	Proportion of sector heat demands met via utility-based cogen.
A	Basic	RCI	Small
B	Advanced	RCI	Large
C	Basic	Industrial	Small
D	Advanced	Industrial	Large
E	Basic	RCI and industrial	Small
F	Advanced	RCI and industrial	Large

The scenarios consider two cogenerated-heat users: the RCI and industrial sectors. Heat demands are equally divided between these sectors quantitatively (Fig. 1), but exhibit qualitative differences:

- RCI heat demands are almost exclusively for low-temperature heat for space and water heating, and
- industrial heat demands are for various tasks and, based on data reported elsewhere, 20% are at low (<125-150°C), 30% at medium (between 125-150°C and 400-500°C) and 50% at high temperatures (>400-500°C).

The scenarios consider two hypothetical utility-based cogeneration networks: basic and advanced. The basic network is founded on a current network of thermal electrical stations having little cogeneration, with only minor cogeneration modifications implemented in some nuclear and coal stations. The advanced network consists of a modified network, where some multi-unit stations are separated and located near heat demands, and where advanced cogeneration technologies are used along with current-technology thermal stations modified for cogeneration. For the advanced network, government intervention through legislation and incentives to promote cogeneration is assumed sufficient to result in significant market penetration for cogeneration and the perception of cogeneration as a conventional. Thermal storage is used in both networks, especially for coal stations, which operate much more intermittently than nuclear stations.

For both utility-based cogeneration networks (Rosen, 1998):

- overall efficiencies are taken to be 85% for nuclear and coal cogeneration,
- electrical efficiencies (in %) are approximated by the expressions $32-(0.11)T$ for nuclear cogeneration and $40-(0.074)T$ for coal cogeneration, where T denotes the cogenerated-heat temperature (in °C), and
- thermal efficiencies are given by the differences between the corresponding overall and electrical efficiencies.

In all scenarios, half of the cogenerated heat is used to offset electricity provided by the electrical utility to users for heating. The other half of the cogenerated heat is used to offset the non-electrical utility energy resources (e.g., natural gas and oil) used by others for heating. Also, 33% of the cogenerated heat is assumed to be produced from coal and 67% from nuclear energy. These are presumed to be the same proportions from which electricity is generated from them. To supplement the cogenerated electricity, current-technology non-cogenerating coal and nuclear generating stations are used, again in the same proportions as cited above.

4.3. Thermal Demands Met via Cogeneration

The portions of the heat demands met by utility-cogenerated heat are estimated using the factors in section 3. It is assumed for the RCI sector that

- utility-cogenerated heat temperatures permit for all scenarios 100% of the heat demands to be satisfied, as they are all at low temperatures,
- 35% of heat demands are within a servicable distance of the cogeneration plant for scenario A, and 60% for scenario B, and
- 25% of potential users find the infrastructure, attitude, economic conditions favourable enough to use cogenerated heat for scenario A, and 65% for scenario B.

Similarly, it is assumed for the industrial sector that

- utility-cogenerated heat temperatures permit 100% of low- and medium-temperature industrial heat demands to be satisfied for scenarios C and D, and 30% of high-temperature demands for scenario C and 40% for scenario D,
- 30% of low-, 23% of medium- and 15% of high-temperature demands are located within a servicable distance of the cogeneration plant for scenario C, while the corresponding values are 60%, 45% and 30% for scenario D, and
- 40% of potential users find the infrastructure, attitude, economic conditions favourable enough to use cogenerated heat for scenarios C and D.

Consequently, the six scenarios considered can be quantitatively described as follows:

A a basic utility-based cogeneration network supplies a small portion (10%) of the annual heat demand of the RCI sector;
B an advanced utility-based cogeneration network supplies a significant portion (40%) of the annual heat demand of the RCI sector;
C a basic utility-based cogeneration network supplies a small portion (5%) of the annual heat demand of the industrial sector;
D an advanced utility-based cogeneration network supplies a significant portion (10%) of the annual heat demand of the industrial sector;
E a basic utility-based cogeneration network supplies the portions of the heat demands for the RCI and industrial sectors referred to in scenarios A and C, respectively; and
F an advanced utility-based cogeneration network supplies the portions of the heat demands for the RCI and industrial sectors referred to in scenarios B and D, respectively.

5. Results and Discussion

Results for the scenarios are presented for the region, including the RCI and industrial sectors, and its utility sector, where cogeneration occurs.

5.1. Region

The thermal energy needs supplied by cogeneration in the RCI and industrial sectors are presented in Table 4. Note that the percentage values in that table apply to the columns, e.g., values in the second column in Table 4 provide the percentage of the total heat demand in the RCI sector met via cogeneration.

Table 4. Percentage of annual heat demand met by cogeneration, by sector[a]

Scenario	RCI	Industrial	RCI and industrial
A	10	0	5
B	40	0	20
C	0	5	3
D	0	10	5
E	10	5	10
F	40	10	30

[a] Percentage values apply to columns.

Table 5. Percentage reductions in regional energy use[a]

Scenario	Electricity	Natural gas & NGLs[a]	Oil & petroleum	Coal	Uranium	Tot.
A	5	3	0.5	20	7	5
B	25	10	2.0	40	30	17
C	3	1	0.3	10	3	3
D	6	2	0.6	20	5	5
E	8	4	0.7	20	9	6
F	30	15	2.6	40	35	21

[a] NGLs denotes natural gas liquids.

Table 6. Percentage reductions in regional emissions[a]

Scenario	Material emissions						Non-material emissions		
	SO_2	NO_X	CO_2	CO	Particulates	V.O.C.	Spent uranium	Thermal pollution	Radiation
A	5	3	4	1	1	1	7	20	7
B	14	9	12	3	2	2	30	70	30
C	5	3	3	1	1	0	3	10	3
D	7	4	5	1	1	1	5	10	5
E	7	4	5	1	1	1	9	20	9
F	18	12	15	4	2	3	35	80	35

[a] Notes on V.O.C., thermal pollution and radioactive emissions are as in Tables 1 and 2.

The scenario assessment results are provided in the form of percentage annual reductions in the region for energy use (Table 5) and environmental emissions (Table 6), in which each percentage change is relative to the corresponding base-case value. The key point demonstrated is that energy use and environmental emissions decrease for the region for all scenarios. Also, regional electricity-generation requirements decrease for all scenarios. Most of the regional environmental benefits are associated with reductions in the use of coal and other fossil fuels, rather than nuclear energy, but a portion of the benefits are due to substitution of uranium for fossil fuels. The reductions observed in environmental effects for each scenario are significant.

Two key regional results (highlighted subsequently in Table 10) for each scenario follow:

- electricity consumption decreases by between 3% for low penetration of utility-based cogeneration and 30% for high penetration, reducing regional electrical generation correspondingly, and
- emissions of carbon dioxide decrease by 3% to 15%, demonstrating that utility-based cogeneration can conribute to mitigating climate change.

5.2. Electrical-Utility Sector

The percentage of coal and uranium that are used for cogeneration in coal and nuclear power plants, respectively, are listed in Table 7.

Table 7. Percentage of utility fuel used for cogeneration

Scenario	Coal	Uranium
A	10	10
B	80	50
C	6	5
D	10	2
E	20	10
F	100	50

Percentage reductions in the region's electrical utility-sector are presented for energy use (Table 8) and emissions (Table 9). Electricity, natural gas and NGLs, oil and petroleum and others are not shown in Table 8 because the use of each in the utility sector does not change for the cogeneration scenarios. The key observation in Tables 8 and 9 is that energy use and environmental emissions decrease for the electrical-utility sector for all scenarios. Most of the reductions observed for all scenarios in environmental effects for the utility sector are significant and are mainly associated with reductions in the use of coal. A portion of the benefits are due to a substitution of uranium for fossil fuels.

Table 8. Percentage reductions in regional energy use in utility sector

Scenario	Coal	Uranium	Total
A	20	7	10
B	40	30	30
C	10	3	6
D	20	5	10
E	20	9	13
F	40	35	40

Table 9. Percentage reductions in regional emissions by utility sector

Scenario	Coal-related emissions[a]	Uranium-related emissions[b]	Thermal pollution[c]
A	20	7	20
B	40	30	70
C	10	3	10
D	20	5	10
E	20	9	20
F	40	35	80

[a] Includes emissions of SO_2, NO_X, CO_2, CO, particulates and V.O.C.s.
[b] Includes emissions of spent uranium and radiation.
[c] Attributable to both uranium and coal use.

Three key results (see Table 10) for each scenario for the electrical-utility sector are that utility-based cogeneration permits reductions of

- 10% to 40% in coal use and coal-related emissions,
- 3% to 35% in uranium use and related emissions, and
- 10% to 40% in carbon dioxide emissions.

6. Closing Remarks

Some important regional and utility-sector results for each scenario are highlighted in Table 10. The case study suggests that electrical utility-based cogeneration in a region could be beneficial in that, for the same services delivered, cogeneration permits increased efficiency and reduced energy consumption and related emissions, and can substitute nuclear energy for other fuels. This conclusion presumes that cogeneration can be implemented at the region's thermal power stations and that potential markets for utility-cogenerated heat exist in the region in the RCI and industrial sectors. It would therefore be worthwhile for regions like the hypothetical one considered here to investigate with their electrical utilities and other relevant parties options for cogeneration.

Table 10. Percentage reductions in key parameters for the region and its electrical-utility sector

	Regional parameters		Electrical-utility sector parameters		
Scen-ario	Elec. use	CO_2 emis-sions	Coal use	Uran-ium use	CO_2 emis-sions
A	5	4	20	7	20
B	25	12	40	30	40
C	3	3	10	3	10
D	6	5	20	5	20
E	8	5	20	9	20
F	30	15	40	35	40

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