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Energy Policy 30 (2002) 1267–1278

ENERGY POLICY

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Life-cycle assessment of electricity generation options: The status of research in year 2001

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Abstract

This article presents the environmental impacts of electricity generation systems, based on life-cycle assessments (LCAs). These assessments normally include impacts from extraction, processing and transportation of fuels, building of power plants and generation of electricity.

The LCAs show that the following options have an excellent performance: hydropower (run-of-river and with reservoir), nuclear energy and windpower.

Hydropower with reservoir does have high land requirements, but in spite of this, it is possible to conclude that it has the highest performance, if we consider 2 factors not always included in LCAs: firstly, reservoirs can provide secondary benefits such as irrigation or flood control; and secondly, hydropower has a high operating flexibility that can improve the reliability of electricity supply.

Keywords: Electricity; Life-cycle; Environment; Impact

1. Methodology

This article presents a summary of comparative studies on the environmental impacts of electricity generation systems. It is based on numerous life-cycle assessments (LCAs) carried out around the world over the last decade.

A life-cycle assessment is an environmental assessment of all of the steps involved in creating a product. Its goal is to give an all inclusive picture of the environmental impacts of products, by taking into account all significant "upstream" and "downstream" impacts. In the power sector, the assessment should include extraction, processing and transportation of fuels, building of power plants, production of electricity and waste disposal.

This article focuses mainly on *biophysical* impacts that can be quantified. Social issues are not discussed. Since they are important for hydropower development, they are addressed in other articles of this journal.

This comparison of power generation systems can be considered "generic", because it presents a general overview of environmental impacts that can be "normally" expected. Some impacts can be greater or smaller, according to site specific conditions or mitigation measures. These "generic" comparisons can be useful for decision-makers, for the following reasons:

- Policy decisions are often needed *before* site specific information is available. These "generic" comparisons will guide these decisions.
- Many debates on energy systems do not consider the impacts of entire energy systems, such as the extraction and processing of fossil fuels. This article will try to include issues of the entire energy system.
- In many assessments, the *reliability* of electricity supply is often neglected. This essential consideration will be integrated as much as possible in this article.
- At the planning level for power generation systems, the "generic" data is not a substitute for careful

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0301-4215/02/$ - see front matter
PII: S0301-4215(02)00088-5

analysis of site specific conditions. Nevertheless, it can provide an indication of which impact may require the most mitigation efforts.

1.1. Potential uses of life-cycle assessment

Life-cycle assessment (LCA) can also be designed to meet different purposes. It can be used to assess a product, a commercial or future technology. In this article, the results were selected with the following criteria:

- The performance of modern commercial technologies is presented. Performance of old technologies may be very different.
- The short-term performance is presented, not the expected future performance.
- The size of plants was not considered.
- Typical conditions for North America or Europe were generally used.

1.2. The exceptional case of hydropower

Results for hydropower should be used with care because hydropower is highly site-specific. Since it is impossible to predefine one "best commercial technology" for hydropower, results of studies are largely based on the average characteristics of current installed capacity (and not of future projects which may not be known in sufficient detail). Moreover, the assessment of hydropower may differ widely depending if projects are multi-purpose projects or not. A purpose such as irrigation requires larger reservoirs, negatively affecting a large number of environmental resources, and lead to water losses, which reduce potential power generation.

To make a fair comparison among electricity generation systems, the assessment of hydropower should only include projects without irrigation, or else parameters should be corrected to attribute impacts to each purpose. In reality though, this is not done, and for hydropower, most studies ignore the other purposes of such facilities, therefore overestimating the environmental impacts.

1.3. Main atmospheric issues covered by LCAs

Table 1 is a reminder of the main atmospheric issues that can be targeted by life-cycle assessments. It is important to note that many LCAs produce an inventory of emissions for each energy system, without trying to give an actual description of the final environmental impacts of these emissions. This is due to the fact that final environmental impacts can be extremely variable, depending upon geography and other sources of pollution.

1.4. Reliability of generation systems, a criteria for rigorous comparisons

The comparative analysis of power generation systems could be made per unit of capacity (e.g. comparing systems that produce 100 MW). But some power plants are used at full capacity for most of the year, while others are not available for such a high use factor. Therefore, comparisons of systems based upon installed capacity would often be inappropriate. The amount of energy produced (kWh) is a much better base for comparisons. It is adopted for most LCAs. However, the reader must remember that even comparisons per kWh do not take into consideration two major issues:

- The other purposes of hydropower reservoirs, such as irrigation and flood control.
- The reliability of electricity supply.

The storage of electricity in large quantities is very expensive, so the reliability of electricity supply must be achieved by producing electricity exactly at the same time it is consumed. If this balance is not maintained, frequency fluctuations will result, with major impacts on electrical equipment, such as computers or appliances. The following list presents some "ancillary" services required to provide reliable electricity:

- Voltage control: to maintain transmission-system voltages within required ranges.
- Regulation: to maintain minute-to-minute generation/load balance.
- Operating reserve: to be able to immediately correct generation/load imbalances.
- Load following: where generation can meet the hour-to-hour and daily variations in load.
- System black-start capability: the ability of a generating unit, after a blackout, to go from a shutdown condition to an operating condition without assistance from the electrical grid.

Generation options are not all equally capable of providing such services. Reliable electricity networks cannot depend only on "must-run" systems such as nuclear energy or on intermittent systems such as wind power. In comparison, hydropower with reservoirs has a high "level of service" because it can provide all the services to maintain this balance. Oil or diesel fired plants can also provide much flexibility, notably because large quantities of fuel can be easily stored.

But comparative analysis rarely considers the ancillary services provided by hydropower or oil. This would be difficult, because it is impossible to assign a "quality" to each kWh. However, comparisons should consider the fact that some forms of generation are intermittent (e.g. wind) and constantly require a "backup" system to

Table 1
Summary of atmospheric issues and pollutants involved

Issue	Type of impacts	Precursor pollutants and main sources
Acid rain: formation of sulfuric and nitric acid	Regional impacts on lakes, forests and materials	*SO_2*: sulfur dioxide, from smelters, combustion of coal or oil, and from processing of natural gas *NO_x*: nitrogen oxides, from transportation (mainly) or any combustion
Photochemical smog: formation of ozone and other toxic pollutants in the lower atmosphere	Affects human health at local and regional level	*NO_x*: nitrogen oxides, from transportation (mainly) or any combustion
	Reduces productivity of agriculture	*VOCs*: volatile organic compounds, from transportation, refineries, oil and wood heating
Greenhouse gases	Climate change affecting agricultural and forest productivity, and increasing the likelihood of extreme events such as hurricanes, floods and droughts	*CO_2*: carbon dioxide, from fossil fuel combustion and destruction of forests
		CH_4: methane, from livestock, paddy fields, landfill sites, extraction, transportation and distribution of natural gas, extraction of oil and coal

compensate for fluctuations. For intermittent production systems, two approaches can be used to compare systems fairly.

- They can be analyzed in combination with a typical backup system, providing the same reliability as other "stand-alone" systems. The assessment of a combination of systems is a technical challenge, but it can be done, as shown in the article entitled "Adding wind energy to hydropower".
- If the assessment does not consider the required backup, it should be recognized clearly that the assessment is not at the same level as other "stand-alone" systems.

1.5. Main types of electricity generation systems

Considering that the levels of service of electricity generation systems vary greatly, we will regroup systems based on their ability to meet demand fluctuations. Table 2 presents the main systems considered, with their characteristics.

2. Results of life-cycle assessments

2.1. Greenhouse gas emissions

2.1.1. Environmental issues

The Intergovernmental Panel on Climate Change has produced a *Summary for policymakers* on the impacts of climate change (IPCC, *Climate Change 2001: Impacts, Adaptation and Vulnerability*, pp. 7 and 14). It considers that the following impacts are "likely" or "very likely":

- "More intense precipitation events: Increased floods, landslide, avalanche, and mudslide damage"
- "Increased summer drying over most mid-latitude continental interiors and associated risk of drought"
- "Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities"
- "Intensified droughts and floods associated with El Nino events in many different regions"
- "Sea-level rise and an increase in the intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia"

2.1.2. Understanding the studies on greenhouse gas emissions

Because of the potential impacts of climate change, many studies have focused on assessing greenhouse gas emissions of energy systems. These studies produced data on emissions of "CO_2 equivalent". This means that CO_2 and other greenhouse gases have been included in the assessment. But other greenhouse gases have different effects on the climate and may have a different atmospheric life span. To take into account these differences, the IPCC has produced a set of "global warming potential" indicators, relative to CO_2. In life-cycle assessment studies, each greenhouse gas is converted to an equivalent of CO_2 and added to the

Table 2
Main generation systems, with expected level of service

Electricity generation systems	Comments on reliability and flexibility of electricity production
Systems capable of meeting base load and peak load	
Hydropower with reservoir	High reliability and flexibility Many run-of-river plants have a reservoir upstream, and therefore can be considered as having reservoirs
Diesel	High reliability and flexibility
Base load systems with less flexibility	
Natural gas combined cycle turbines	Mostly base load with high technical flexibility, but high use factors are needed to buy gas at low price, which reduces flexibility
Coal	Mostly base load with some flexibility
Heavy oil	Mostly base load with some flexibility
Hydropower run-of-river	Mostly base load with low flexibility
Biomass	Mostly base load with low flexibility
Nuclear	Base load only, almost no flexibility
Intermittent systems that need a backup production (no flexibility)	
Wind power	Needs a backup system with immediate response, generally hydropower with reservoir
Solar photovoltaic	Needs a backup system with immediate response, such as hydropower with reservoir or diesel

inventory. For example, a gram of CH_4 has a *global warming potential* of 23, relative to a gram of CO_2 (over a 100-year period).

CO_2 and CH_4 are directly related to energy systems and included in most studies. Any combustion will produce CO_2 and commercial natural gas is composed of 95% CH_4. Other greenhouse gases may not be included, because of the low volumes involved in energy systems.

In Fig. 1, results vary according to whether studies considered best available commercial technology or average technology. For fossil fuels, no commercial scrubbing of CO_2 is currently available and variation in emissions depends mainly on efficiency of plants.

2.1.3. Main findings concerning greenhouse gas emissions

Run-of-river hydropower has the highest performance among all systems, followed closely by another group with similar emission factors: nuclear, reservoir based hydropower and wind power. However, the issue of level of service is not included in this ranking. Run-of-river hydropower (without an upstream reservoir), as well as nuclear energy, have low electricity generation flexibility, while wind power is intermittent. These three energy systems require a backup system which may be fossil fuel, thereby increasing significantly the final emissions factor of the overall electricity system.

Coal (modern or old plant) has clearly the highest emission factor, with twice the emissions of natural gas combined cycle.

The chosen emission factors for hydropower, with reservoir or run-of-river, are typical of boreal conditions, with a life span of 100 years (some studies use 50 years). One source of greenhouse gas emissions is the decay of flooded biomass. The assessment of these emissions is site specific, depending upon different factors: First, the area of reservoir per kWh can vary according to topography. Second, the amount of flooded biomass, per unit of area, can vary by a factor of 5 (500 t/ha for tropical forest versus 100 t/ha for boreal climate). For projects with an average size of reservoir per kWh, in boreal or mountain regions, hydropower has an emissions factor approximately 60 times lower than modern coal-fired generation.

Scientific uncertainties are relatively low for most of these results. Nevertheless, uncertainties persist for biomass and hydropower:

- The system with the highest level of uncertainty is biomass. This depends upon one key issue that needs to be resolved. If a forest or plantation is used to produce energy, does it store carbon permanently in soils?
- For greenhouse gas emissions from decaying biomass in hydropower reservoirs, uncertainties still persist. For reservoirs in boreal or mountain regions, the amount of flooded biomass is small. Because of this, it is unlikely that future research will arrive at higher emission factors than those reported in Fig. 1. For reservoirs in tropical environments, emission factors could be higher, but would depend on many site-specific conditions. Some studies did not consider emissions from reservoirs in the assessment of hydropower.

2.1.4. Future performance of energy systems concerning greenhouse gas emissions

For global issues such as climate change, expectations concerning potential reductions from future technologies

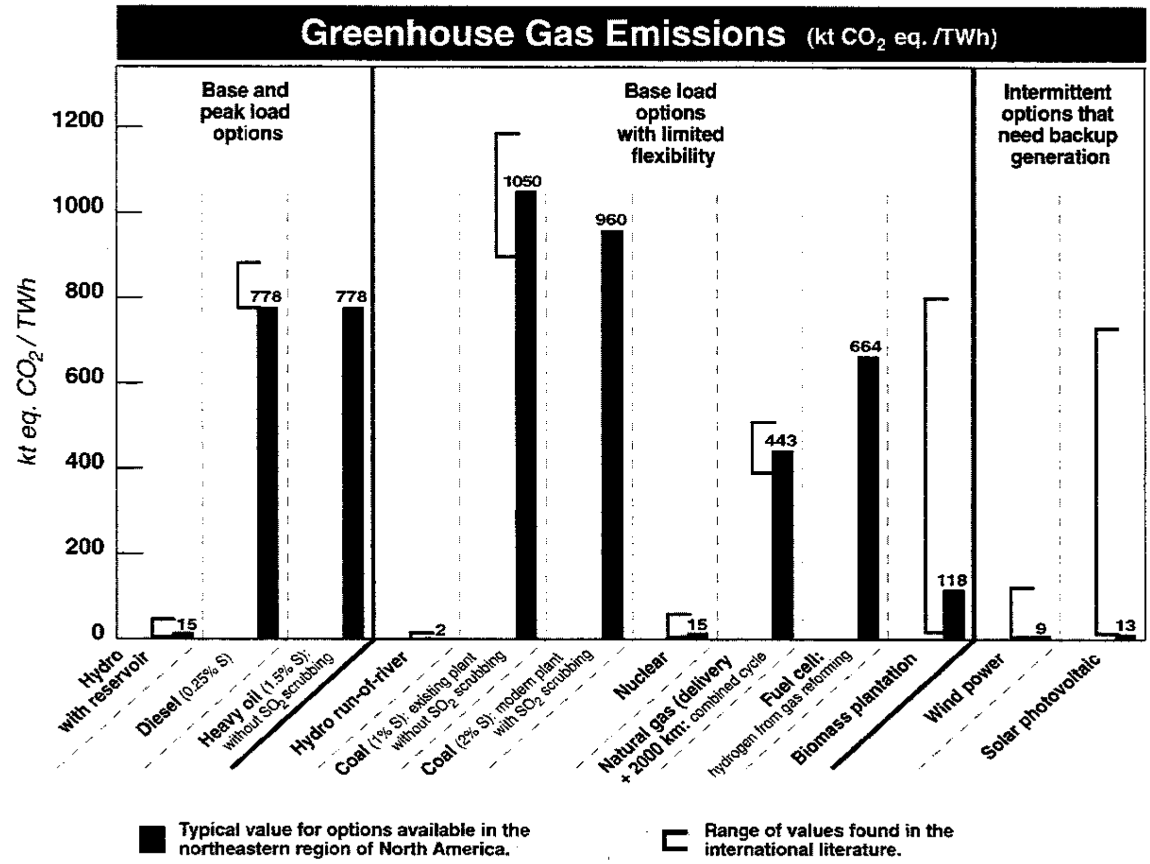

Fig. 1.

are high because many studies look at only one stage of the life-cycle. But life-cycle assessment does show that these expectations are exaggerated. This is simply due to the fact that some technologies emit less greenhouse gas emissions at one stage of their life-cycle, but more at other stages. Examples of this situation are numerous:

- Alternative fuels such as ethanol from crops produce lower emissions at combustion (than oil) but emissions related to producing the crops offset these benefits.
- A similar case is fuel cells, which emit virtually nothing in their operation, but the production of their fuel (hydrogen reforming from natural gas) will increase their greenhouse gas emission factors to a higher level than natural gas turbines.
- Another technology for which expectations are high is carbon sequestration. But "scrubbing" of CO_2 emissions from flue gas is a huge task. For pollutants such as sulfur, the benefits of scrubbing technologies can be justified by the fact that the waste generated by these technologies are manageable. It is different for CO_2 emissions because the carbon responsible for CO_2 emissions represent more than 50% of the coal, compared to averages of 1% or 2% sulfur for coal. Capturing all this carbon and pumping it in deep underground reservoirs is technically possible, but will involve huge amounts of energy, pollution and expenditures. Its relative benefits should therefore be much less than expected.

As a consequence, in the next few decades, it is unlikely that major technologies will be developed to solve the climate change issue. Energy efficiency measures and renewable energy development should remain the best options to reduce greenhouse gas emissions.

2.2. *Acid precipitation*

2.2.1. *Environmental issues*

Acid precipitation is still a major issue in many parts of the world. Even in North America where programs have reduced emissions, specialists consider that current level of SO_2 and NO_x emissions still affect the productivity of many lakes, rivers and forests. Nevertheless, it is difficult to establish a direct link between atmospheric emissions and ecosystem impacts. Moreover, the vulnerability of forests varies significantly according to the types of soils involved.

In sum, it is impossible to establish a direct link between one type or one source of emission and the

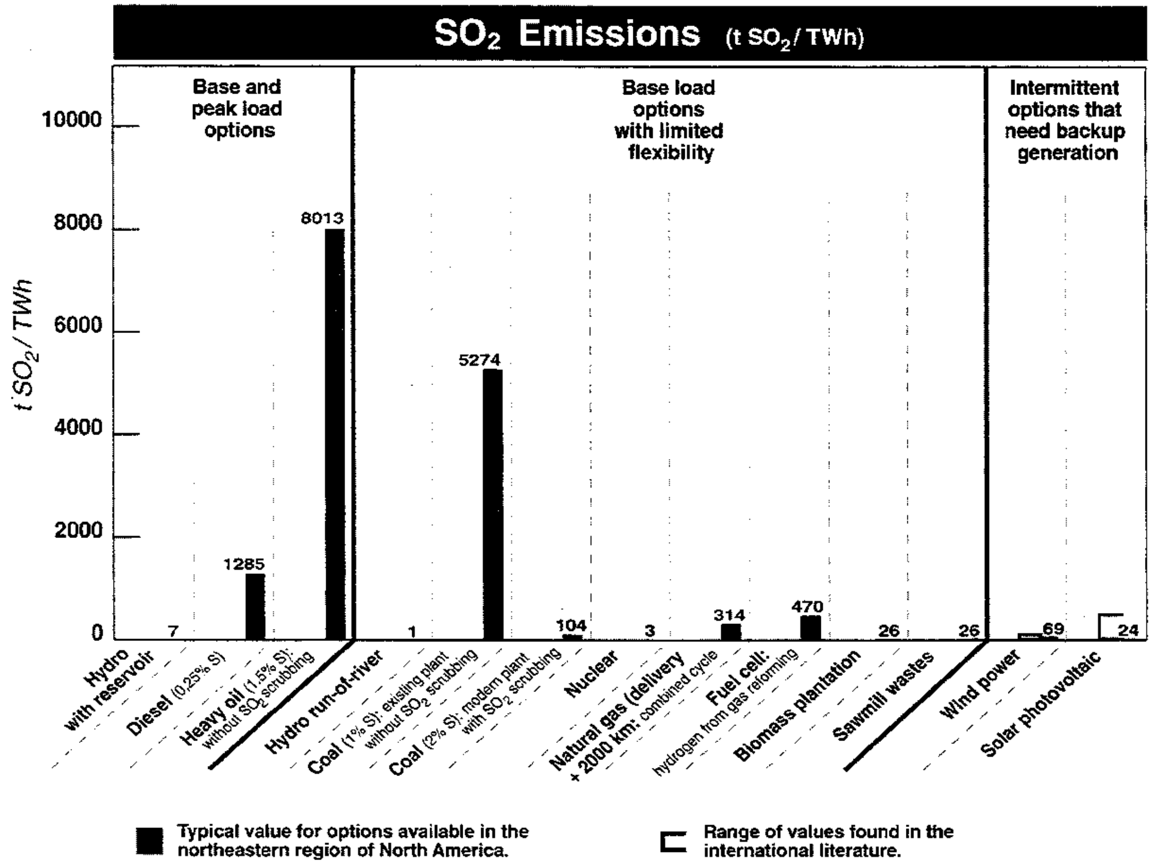

Fig. 2.

ultimate environmental damage caused by atmospheric emissions. The emission factors presented in the following figures must therefore be considered as indicators of "potential" impacts.

In the case of forest productivity, impacts of pollutants are numerous and sometimes indirect (Godish, 1997, p. 108-112):

- Acid will tend to remove some essential nutrients from soils (K, Ca, Mg).
- Acid may mobilize toxic metals such as aluminum, which can damage roots.
- Adding nitrogen, the main nutrient of plants, may create an unbalance in resources and make trees more vulnerable to diseases and frost. Impacts of other atmospheric pollution must be also considered.
- Photochemical smog can damage the leaves.
- Climate change may increase heat stress or intensity of droughts.

2.2.2. *Understanding the studies on SO_2 emissions*

Figs. 2 and 3 present the results of studies concerning the two major precursors of acid precipitation:

- The main precursor is SO_2, which leads to the formation of sulfuric acid.
- The other precursor is NO_x, which leads to the formation of nitric acid (before contributing to the formation of acid precipitation, NO_x can also be involved in other chemical reactions, causing smog).

When looking at Fig. 2, the reader should keep in mind that SO_2 emissions can vary significantly, according to the following factors for each fossil fuel:

- For coal, the sulfur content can vary from 0.5% to 5% and even more in exceptional cases.
- For oil, average sulfur content in light oil/diesel is about 0.2% and 2% for heavy oil, but these percentages can vary significantly from one region to another.
- Commercial natural gas has virtually no sulfur, because it is removed in processing plants after extraction. Depending upon sulfur concentrations and regulations, this process can create high or low SO_2 emissions.
- There is a wide variety of technologies to reduce emissions at plant, with different performance. Some commercial scrubbing technologies that are currently available are capable of removing about 90% of SO_2 emissions. But these technologies have not been

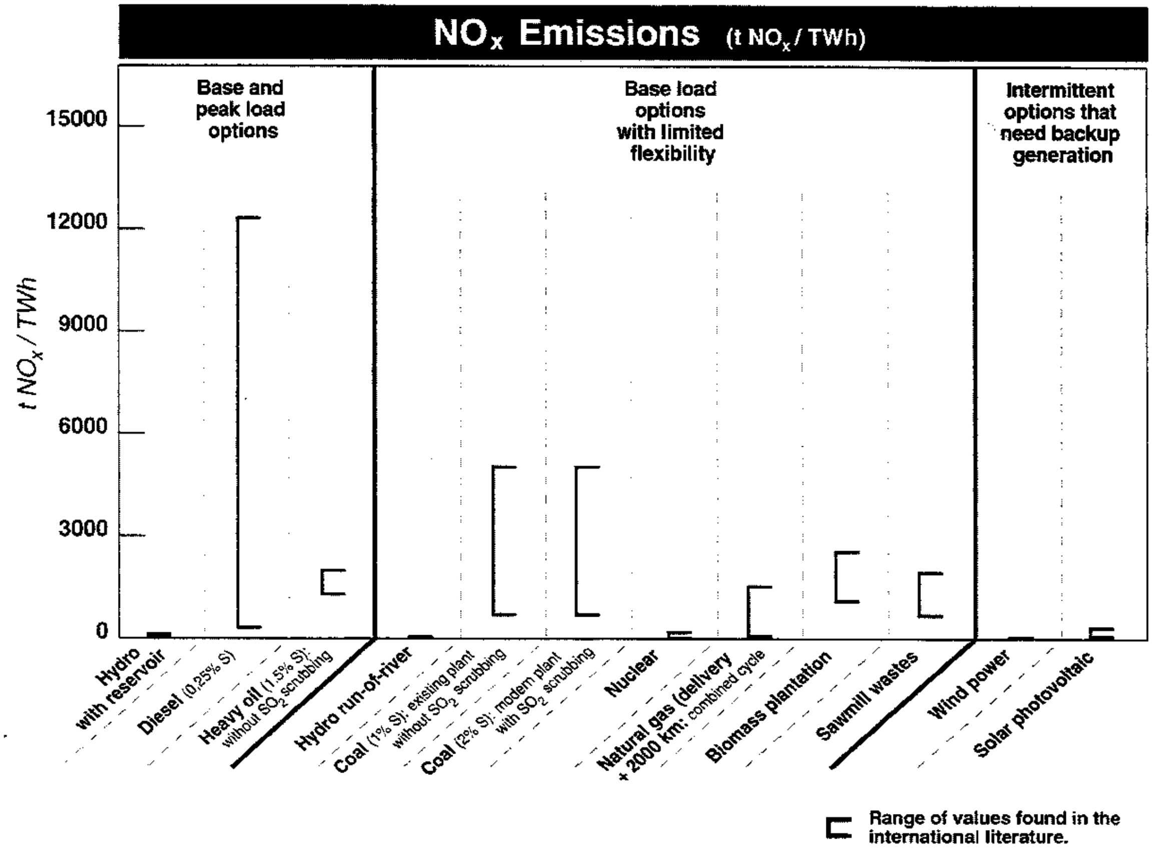

Fig. 3.

widely implemented. It is therefore normal that studies arrive at a wide range of results.

2.2.3. Understanding the studies on NO_x emissions

Studies on NO_x emissions can also arrive at a wide range of results, but these variations are more dependent upon combustion technology than on fuel:

- Most NO_x emissions are caused by the fact that oxygen is required for any form of combustion and that the main source of oxygen is ambient air, which is composed of 79% nitrogen (N). Therefore, the conditions of combustion are the main determinant in the level of NO_x emissions.
- Technologies that involve compression of air, such as diesel engines, will normally produce high level of NO_x emissions.
- The main exception to the "combustion rule" is coal, where significant amounts of nitrogen are also part of the fuel, thereby increasing NO_x emission factors.

2.2.4. Main findings concerning acid precipitation

- Emission factors for hydropower and nuclear energy are hundreds of times less than those of coal-based power generation systems without scrubbing. Considering SO_2 and NO_x, coal, oil and diesel based generation systems are important contributors to acid precipitation.
- Biomass has a low emissions factor for SO_2 but a very high factor for NO_x. It is therefore a significant source of acid precipitation.
- Natural gas, when considering the processing of fuel and NO_x emissions, can also be a significant source of acid precipitation.
- The benefits of wind power (intermittent) are dependent upon network conditions and more difficult to assess. If wind power reduces the use of oil-fired plants (which can be used to compensate for wind fluctuations), this would result in a reduction in net emissions; however, in some cases, wind power may increase the use of oil-fired plants (as backup).

2.2.5. Future performance of energy systems concerning acid precipitation

The main sources of SO_2 are coal and oil-fired power plants. For these options, scrubbing technologies already exists to reduce emissions by more than 90%, but these technology are costly and reduce the efficiency of plants. Another option is to burn oil or coal that has a low sulfur content, but again this is more costly, often requiring longer transportation. In summary, the issue is

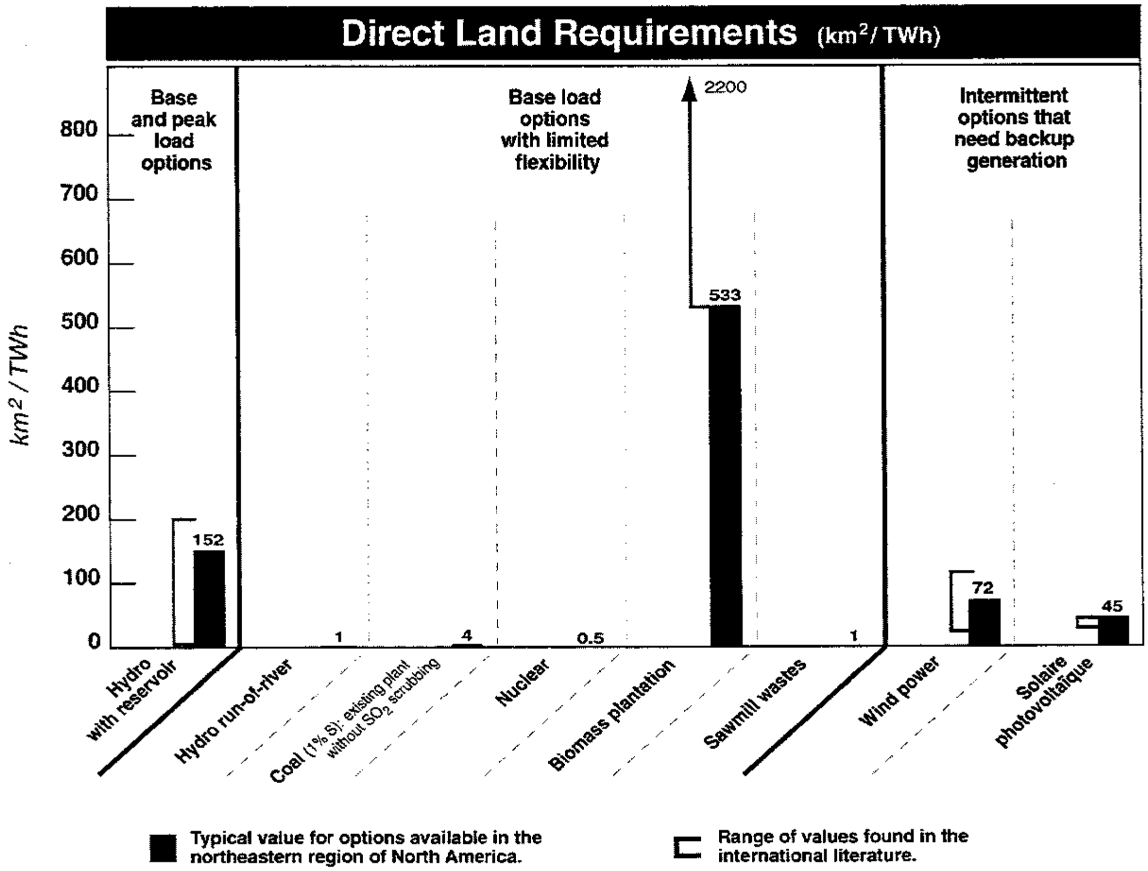

Fig. 4.

economic, and future performance of oil and coal generation will be dependent on policy initiatives, not on new technology.

It is difficult to predict if future policy will require more emission reductions in North America, but according to recent ecological studies, more reductions are required. Even after Canadian and American SO_2 reduction plans are implemented in 2010, 800 000 km^2 in Canada will still receive more than the critical load of 8–20 kg of sulfates per hectare per year (Environment Canada). Above this level, aquatic and forest productivity is seriously reduced.

2.3. Land requirements

2.3.1. Environmental issues

This issue will gain importance in the future for many reasons:

- With population growth, more land is required for farms, cities and industries, and land for other uses is becoming scarce.
- Emerging renewable sources of energy, such as wind or solar power require large land areas.
- Alternative sources of biofuels, such as ethanol from crops, require very large areas of farmland.

The values in Fig. 4 are representative of different energy systems everywhere in the world. All electricity generation systems affect land use, either directly or indirectly. Examples include:

- For hydropower, the transformation of forests/land into aquatic ecosystems.
- For coal, the large areas affected by mining activities and fallout of acid rain.
- For biomass, the area of forests that are exploited.

2.3.2. Understanding the studies on land requirements

This type of assessment must be considered with caution, because it does not consider the intensity of the impact, nor the degree of compatibility of generation options with other land use. Moreover, the data in Fig. 4 considers only the direct use of land. It does not consider indirect impacts, such as losses related to climate change (e.g. losses of land due to increase in sea levels).

The results for hydropower vary significantly because of site-specific conditions. Results are for projects designed mainly for power generation. In many countries, such as the United States, most reservoirs were created for purposes of irrigation and water supply. Many of these reservoirs involve small or no power generation and would have even higher land use factors per TWh.

For fossil fuels, very little data exists and some upstream activities are not considered. For example, surface mining of coal would require much more land than underground mining, but the data does not allow for such distinctions.

2.3.3. Main findings concerning land requirements

- Nuclear energy has the lowest land requirements, if we do not consider the land required for long-term waste disposal. The inclusion of this use of land would seriously increase the land requirements, because a small area of land is needed, but for many thousands of years. For example, if 0.1 km/TWh is required for waste disposal, multiplied by 30 000 years, applied to 30 years of generation, the factor would increase from 0.5 km/TWh to 100 km/TWh).
- Biomass plantation is the system that requires the most land per unit of energy. Other renewable sources (hydropower, wind power and solar power) have similar high land requirements, which can vary significantly according to site-specific conditions. Data on hydropower is based on the total area of reservoirs, not the flooded areas which would necessarily be smaller (before impoundment, rivers and lakes already occupy a significant area).
- Available data concerning coal show that it requires much less land than any renewable source of energy. But this is an assessment based on direct land requirements only (by power plants and mining activities). Indirect "use" of land, related to fallout of atmospheric emissions or related to the impacts of climate change, are not included in the data. These areas are huge and can multiply the land "use" factors of fossil fuels.

To show the order of magnitude of this indirect land "use", it is possible to calculate a factor of land modified by acid rain. Even after Canadian and American SO_2 reduction plans are implemented in 2010, 800 000 km^2 in Canada will still receive more than the critical load of 8–20 kg of sulfates per hectare per year (Environment Canada). Above this level, aquatic and forest productivity is seriously reduced.

If we consider that all coal-fired plants in the region (500 TWh/yr) are responsible for this excess, it means that each TWh of coal generation reduces ecosystem's productivity over 1600 km^2. This is 10 times the highest area used by existing hydropower.

2.3.4. Future performance of energy systems concerning land requirements

For all options, it is unlikely that technological development will lead to serious reductions in land use. For coal and oil, it would be possible to reduce areas affected by acid precipitation, but no new technology is required to achieve that. For hydropower, the size of reservoir is more and more an issue. Projects in the planning stage in Canada include reservoirs which are about 5 times smaller than existing ones (per unit of energy).

At first sight, future development of renewable sources could be constrained by land requirements. But this issue is specific to each project, because compatibility with other land uses will differ widely. The constraints will depend on many factors:

- population density;
- compatibility of a project with other land use such as recreation, forestry or agriculture;
- and for hydropower, the need for other uses of water, such as irrigation, water supply or flood control.

One key issue will be competition with food production, but most renewable projects have little negative impacts on agriculture:

- For windpower, the land around the windmills can still be used for agriculture.
- Solar energy can be developed on rooftops or arid areas without agriculture.
- Hydropower can be developed in mountainous or cold climate, and hydro reservoirs can improve food production through irrigation.

One future energy option could however be severely limited by land use: biomass plantations for energy production (either direct burning of biomass or conversion to fuel such as ethanol). In this case, there is direct competition with farmland.

2.4. Energy payback ratio

2.4.1. Definition

For each power generation system, the "energy payback" is the ratio of energy produced during its normal life span, divided by the energy required to build, maintain and fuel the generation equipment.

2.4.2. Environmental issues

If a system has a low payback ratio, it means that much energy is required to maintain it and this energy is likely to produce many environmental impacts. For fossil fuels, it means environmental impacts at extraction, transportation and processing of fuels. For renewable sources, it means environmental impacts at building the facility. If an option has a ratio of close to one, it means it consumes almost as much energy as it produces, so it should never be developed.

2.4.3. *Understanding the studies on energy payback*

In the recent context of climate change commitments, life-cycle assessments have focused mainly on greenhouse gas emissions from energy systems. These assessments are essential. However, these emissions can vary dramatically according to their context. For example, if a system utilizes aluminum as a building material, the assessment will vary greatly whether the aluminum smelters use hydropower or electricity from coal.

Because the "energy payback ratio" is less affected by upstream choices of energy supply, it has the advantage of minimizing the fluctuation when evaluating greenhouse gas emissions. It should therefore be considered as one of the most reliable indicators of environmental performance. This indicator minimizes fluctuations in results of studies, but it does not eliminate them. The data in Fig. 5 show that renewable energies can have very large variations. This is due to variable site-specific conditions (topography for hydro, quality of the wind, intensity of solar radiation for solar energy).

2.4.4. *Main findings concerning "energy payback ratios"*

Hydropower clearly has the highest performance, with energy payback ratios of 205 and 267 compared to fossil fuel systems with typical ratios of 5 to 7. These figures, 205 for hydro with reservoir and 267 for run-of-river, are for projects in Quebec, assessed over a period of 100 years.

In Fig. 5, wind power, for the best wind sites, also has a very good performance (ratio of 80). However, this ratio is overestimated because the calculations did not consider the need for backup capacity to compensate for wind fluctuations.

Biomass can also have a good performance (ratio of 27), when electricity is produced from forestry wastes. But when trees are planted for the purpose of producing electricity, the ratio is much lower (about 5), because these biomass plantations require high energy inputs. For these two biomass options, the distance between the source of biomass and the power plant must be short, otherwise the energy payback ratio drops to very low values.

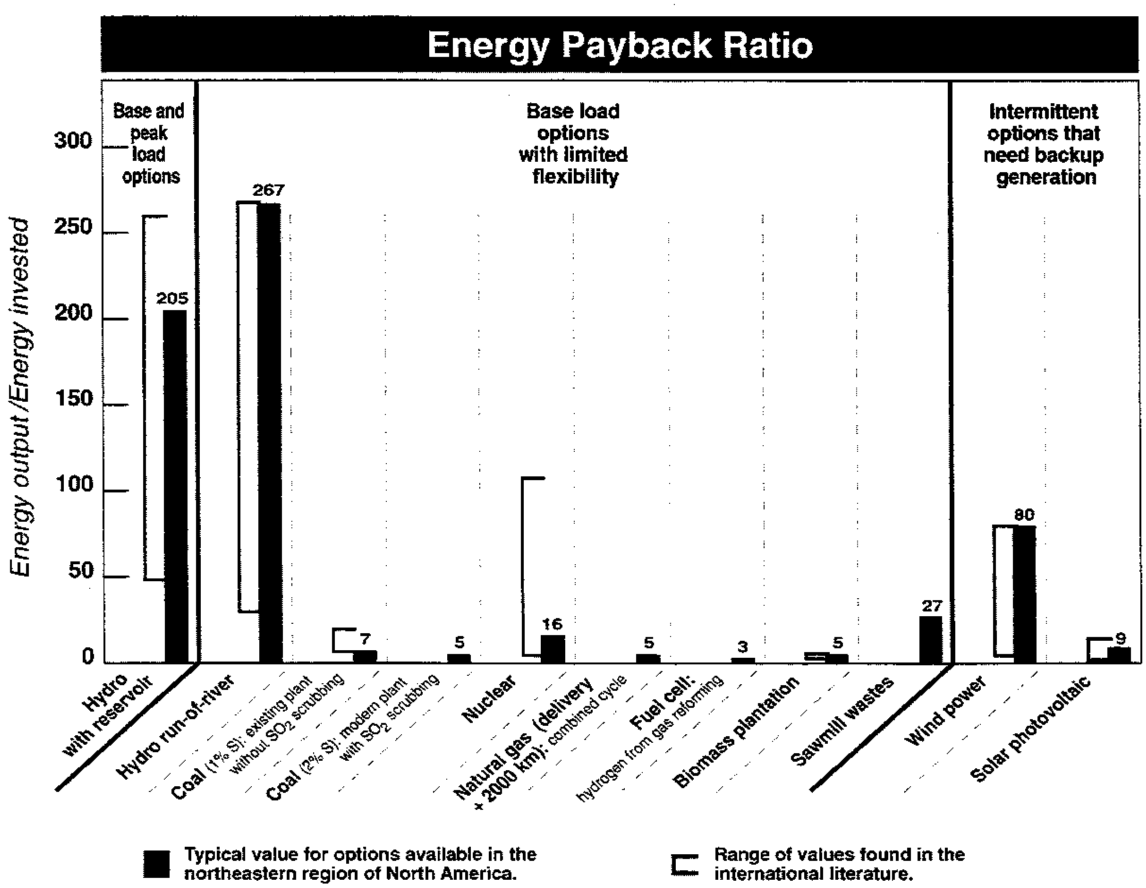

Fig. 5.

Table 3
Other atmospheric emissions from energy options (some data is not life-cycle assessment)

Generation options (classified by level of service)	NMVOC emissions (t/TWh)	Particulate matter emissions (t/TWh)	Mercury emissions (kg Hg/TWh)
Options capable of meeting base load and peak load			
Hydropower with reservoir		5	
Diesel	1570	122–213	
Base load options with limited flexibility			
Natural gas c.c. turbines	72–164	1–10	0.3–1
Bituminous coal: modern	18–29	30–663	1–360
Lignite: old plant		100–618	2–42
Heavy oil: no scrubbing	22		2–13
Hydropower run-of-river		1–5	
Biomass combustion	89	190–320	0.5–2
Nuclear		2	
Intermittent options that need a backup production			
Wind power		5–35	
Solar photovoltaic	70	12–190	

For natural gas generation, the ratio of 5 is relatively low, mainly because of the energy spent in transportation of gas over 2000 km. Gas generation situated near extraction and processing plants has a much higher performance.

For coal-fired generation, distance also has an effect but the performance can be affected by scrubbing of air pollution. The lower payback ratio of 5 is due to scrubbing of SO_2, which requires resources such as lime that must be extracted and delivered.

2.4.5. Future performance of energy systems concerning the payback ratio

Fossil fuels already have low energy payback ratios and these will be declining over the next decades. This is due to multiple factors:

- As the best fossil reserves are depleted, they tend to be replaced by wells that require a higher energy investment (located in far away regions or under the sea).
- Other considerations may involve selecting resources that are located at greater distances. For example, transportation of coal by train in the US has increased in the last decade because users tend to select Western low sulfur coal.
- In the future, there will be more energy wasted in fossil-fueled power plants to reduce emissions. Scrubbing of SO_2 can reduce the overall efficiency of coal generation. If capture and sequestration of CO_2 becomes commercially available, this will involve spending huge amounts of energy in the operation of scrubbing and disposal equipment. It is relevant to note that sulfur is about 1% of coal while carbon is more than 50% of the coal. If SO_2 scrubbing has such an impact on the overall efficiency, it is possible to question the eventual feasibility of CO_2 scrubbing.

2.5. Other atmospheric emissions

2.5.1. Health issues

The previously discussed emission factors concerned climate change and acid precipitation. Other types of air emissions have more direct and local effect on health. These are particulate matter, toxic metals (such as mercury) and non-methane volatile organic compounds (NMVOC) that contribute directly to smog formation.

Table 3 presents the range of values for these emissions. Analysis of this table must me done carefully, because much of the data is direct emissions from plants (not life-cycle assessment). Despite this, we can see that hydropower, windpower, nuclear energy and natural gas have excellent performances compared to oil, coal or biomass combustion.

2.5.2. Comparing mercury contamination

Since the creation of some hydro reservoirs is known to release mercury in the food chain, it is possible to compare the intensity of this phenomenon, relative to coal or oil-fired mercury emissions, which contaminate the food chain of thousands of lakes.

For the LaGrande hydropower complex in Northern Quebec, modelling has been done to estimate the amount of mercury that is returned to the watershed after flooding. When we consider this phenomenon over many years and the electricity produced, a factor of 0.07 kg Hg/ TWh can be calculated. Per unit of energy, the typical emission factor for coal is 200 times higher. Moreover, studies have shown that about half of the mercury that is released by hydro reservoirs is mercury that was emitted by coal-fired plants and smelters in the previous decades.

2.6. Conclusion

Results from comparative analysis show that hydropower and windpower have an excellent performance. The excellent performance of hydropower becomes more obvious when we consider associated benefits that are not included in most LCAs:

- The multi-purpose character of reservoirs, which can provide flood control, irrigation, drinking water... .
- Because of its operating flexibility, hydropower can increase the reliability of electricity supply.

Nuclear energy also has an excellent performance. Some groups will remain opposed to this option because of radioactive wastes and concerns about catastrophic accidents, but these issues are difficult to include in LCAs.

The performance of natural gas generation is much better than coal or oil-fired generation, but it has high emissions, relative to renewable sources of energy. Its performance is affected negatively when it is delivered over long distances.

Coal clearly has the worst performance on most criteria: emissions of greenhouse gases, SO_2, NO_x, volatile organic compounds, particulates, toxic metal and land requirements when indirect factors are considered. Its energy payback ratio can be decent, but only if there is no scrubbing and minimal transportation.

References

Godish, T., 1997. Air Quality, 3rd Edition. Lewis Publishers, New York, 448pp.