Implementing Agreement For Hydropower Technologies And Programmes

Par

INTERNATIONAL ENERGY AGENCY

Extrait de L'Annexe III

“Hydropower and the Environment: Present Context and Guidelines for Future Action”

Subtask 5 Report

VOLUME II: Main Report, 2000.

Pièce GRAME-2, doc.2

INTERNATIONAL ENERGY AGENCY

IMPLEMENTING AGREEMENT FOR
HYDROPOWER TECHNOLOGIES
AND PROGRAMMES

ANNEX III

HYDROPOWER AND THE ENVIRONMENT:

PRESENT CONTEXT AND GUIDELINES FOR FUTURE ACTION

Subtask 5
Report

VOLUME II:
Main Report

May 2000

3 COMPARATIVE ENVIRONMENTAL ANALYSIS OF POWER GENERATION OPTIONS

3.1

INTRODUCTION

This chapter presents a summary of the results 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.

This summary focuses mainly on *biophysical* impacts which can be quantified. Social issues are not discussed in the present chapter. But since they are important for hydropower development, they are addressed in other sections of this report.

The comparison of power generation systems can be considered "generic", because it presents a general overview of environmental impacts that can be "normally" expected. Some of the discussed 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 political debates on energy systems do not consider the environmental impacts of entire fuel processes, including "upstream" of plants (such as extraction of fossil fuels) and "downstream" of plants (such as waste disposal). This summary 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 chapter (this issue is not normally included in LCAs).

- At the planning level for power generation systems, the "generic" data is not a substitute for detailed analysis of site specific conditions. Nevertheless, it can provide an indication of which impact may require the most mitigation efforts.

The following section (3.2) will discuss the methodological issues related to the comparison of power generation systems. This discussion is important in order to understand the underlying assumptions and limitations associated with this type of research. Section 3.3 will then present the results for each "quantifiable" environmental impact and section 3.4 will present a summary of potential impacts with regards to qualitative issues such as biodiversity and human health.

3.2

METHODOLOGICAL ISSUES RELATED TO THE COMPARISON OF POWER GENERATION SYSTEMS

3.2.1

Potential Uses of Life-Cycle Assessment (LCA)

A life-cycle assessment is an environmental assessment of all of the steps involved in creating a product. Its goal is to avoid giving a wrong picture of products, by including any significant upstream and downstream impact. In the power sector, the assessment should include extraction, processing, transportation of fuels, building of power plants, production of electricity, waste disposal, refurbishment and decommissioning. In practice however, some steps such as decommissioning may not be studied in detail.

Life-cycle assessment can also be designed to meet different purposes. Understanding the purpose of such studies is essential to understand their results. The following table describes some of these purposes and how they affect the basic parameters of assessments.

Table 5: ***Potential Uses of LCAs***

Purpose of life-cycle assessment	Definition and scope of technology that is assessed	Period concerned	Examples of application
1. Performance assessment of an entity or activity	Existing power plants, even if outdated	Actual or past performance	Environmental performance reports of entities
2. Performance of specific projects, in an integrated resource plan	• Site of project is known • Modern commercial technologies • Consideration of the size of each project	Expected short-term performance	Entities strategic planning, which must consider the specific regional context where projects would be implemented
3. Generic assessment of the performance of energy systems	**• Modern commercial technologies** **• No consideration of size of plants**	**Expected short-term performance**	**The present report, where exceptional context is not considered and typical parameters are used.**
4. Performance assessment of future systems	Technologies in development	Expected long-term performance	Assessment of future technologies, based on expected development of technology

In this report, the results presented apply mainly to purpose no. 3 and occasionally to purpose no. 4 (for fuel cells). For commercial technologies, decision-makers should have relative confidence in LCA, but should be very careful in checking if data concern similar contexts (e.g., same type of coal with same level of combustion technology).

For future technologies, uncertainties are greater (for example, for fuel cells, it is difficult to define the energy chain and probable efficiency in producing hydrogen). Despite this, LCA is an essential practice for new technologies, because LCAs have constantly shown that new technologies will produce less environmental benefits than originally expected (e.g., the reduction in emissions from the use of ethanol in gasoline is partly offset by emissions in the production of ethanol).

The 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 affects a large number of environmental resources and leads to water losses, which reduce potential power generation. To make a fair comparison of 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.

3.2.2
Main Atmospheric Issues Covered by Life-Cycle Assessments

The following table 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 (e.g., SO_2) for each energy system, without trying to give an actual description of the final environmental impacts of these emissions (e.g., the impact of acid precipitation). This is due to the fact that final environmental impacts can be extremely variable, depending upon geography and other sources of pollution.

Table 6: ***Summary of Atmospheric Issues and Pollutants Involved***

Issue	Type of impacts	Precursor pollutants	Main sources
Acid rain Formation of sulfuric and nitric acid	Regional impacts on lakes, forests and materials	**SO_2:** sulfur dioxide	Smelters; combustion of coal, oil and diesel fuel; extraction of gas
		NO_x: nitrogen oxides	Mainly transportation, any combustion
Photochemical smog Formation of ozone and other toxic pollutants in the lower atmosphere	Affects human health at local and regional level. Reduces productivity of agriculture	**NO_x:** nitrogen oxides	Mainly transportation, any combustion
		VOCs Volatile organic compounds	Transportation, refineries, oil, wood heating
Particulate matter Very small particles have a direct effect on lungs	Significant effects on human health, particularly on asthmatics	**PM10** matter with diameter of less than 10 microns	Diesel, wood and coal combustion
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	All fossil fuels and the destruction of forests
		CH_4: methane	Livestock, paddy fields, landfill sites, extraction of natural gas, oil and coal, transportation and distribution of natural gas

3.2.3
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 1000 MW). However, 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, which is a complex issue.

Since electricity is very difficult or expensive to store in large quantities, the reliability of electricity supply must be achieved by supplying electricity exactly at the same time as 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 table presents some "ancillary" services required to provide reliable electricity. Generation options are not all equally capable of providing such services.

Table 7: ***Ancillary Services Related to Electricity Supply Options***

Service	Description
Reactive supply and voltage control	The injection or absorption of reactive power from generators to maintain transmission-system voltages within required ranges
Regulation	The use of generation equipped with governors and automatic-generation control to maintain minute-to-minute generation/load balance within the control area to meet NERC control-performance standards
Operating reserve – spinning	The provision of generating that is synchronized to the grid and is unloaded, that can respond immediately to correct for generation/load imbalances caused by generation and transmission outages and that is fully available within 10 minutes
Operating reserve – supplemental	The provision of generating capacity and curtailable load used to correct for generation/load imbalances caused by generation and transmission outages and that is fully available within 10 minutes
Energy imbalance	The use of generation to correct for hourly mismatches between actual and scheduled transactions between suppliers and their customers
Load following	The use of generation to meet the hour-to-hour and daily variations in system load
Backup supply	Generating capacity that can be made fully available within one hour; used to back up operating reserves and for commercial purposes
System black-start capability	The ability of a generating unit to go from a shutdown condition to an operating condition without assistance from the electrical grid and to then energize the grid to help other units start after a blackout occurs

Source: Eric Hirst Consulting, Internet site.

Reliable electricity networks cannot depend only on "must-run" systems such as nuclear energy or on intermittent systems such as windpower.

In comparison, hydropower with reservoirs has a high "level of service" because it can provide all the "ancillary" services required 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 LCAs rarely consider 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 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 (assessment includes the impacts of the backup).
- 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.

The assessment of a combination of systems in Integrated Resource Planning is a technical challenge, but it can be done.

3.2.4
Main Types of Electricity Generation Systems Considered

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

Table 8: ***Main Generation Systems Considered, with their Expected Level of Service***

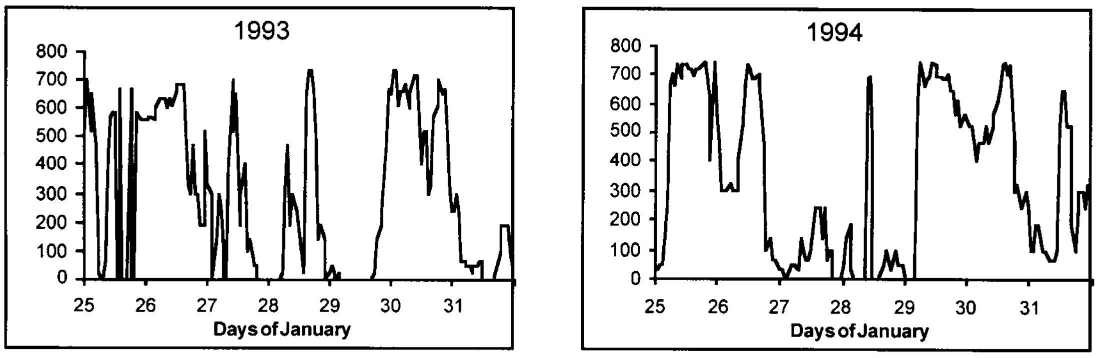
Electricity Generation Systems	Comments on reliability and flexibility of electricity production
Systems capable of meeting base load and peak load	
Hydropower with reservoir	High reliability and flexibility. Many run-of-river plants can rely on upstream reservoir, and therefore can be considered as having reservoirs.
Diesel	High reliability and flexibility.
Base load systems with less flexibility	
Natural gas combined cycle turbines	Mostly base load with technical flexibility, but constant 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.
Systems designed to meet peak load	
Increased capacity on existing hydropower	Designed to add capacity, without adding energy.
Pumped-storage hydropower	Designed to add capacity, while reducing total energy.
Light Oil: single cycle turbines	Adds capacity and energy. Generally low use factor.
Intermittent systems that need a backup production, (no flexibility)	
Windpower	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.

Since LCA focuses on energy produced, this means that systems designed mainly or exclusively to add capacity cannot be included fairly. For example, a project designed to increase the capacity of a hydropower plant may not increase the energy produced and would therefore have an infinite level of environmental impact per kWh (impacts would be divided by zero kWh). These systems will therefore not be included in this report.

3.2.5
Evaluation of Windpower Electric Service and its Impacts on Backup Options

A common misconception is that on a windy site, the wind blows and blows without stopping. In fact, even on a site with a high windpower potential, the wind blows and stops frequently on a short time basis, as shown in the figure below.

Figure 7: ***Short-term Variations in Wind Production***



(Analysis with hourly wind speed data on an excellent class 5 wind site, in Québec, Canada.)

Yearly windpower fluctuations can also be important. In the case of Québec, windpower simulations were run, with 8 years of wind data for two excellent sites (Hydro Review, Vol. XVII, No. 4, August 1998 and article submitted to Energy Policy). In the best year, for 37% of the time, wind production would have been less than 20% of installed capacity. In the worst year, for 60% of the time, production would have been less than 20% of capacity. These simulations show that both short-term and long term fluctuations should be expected.

However, it is generally assumed that large electricity networks have other sources of generation to compensate for such windpower fluctuations. In most cases, this assumption is valid, but adding wind farms to a network has impacts on other generation. So windpower must be evaluated in combination with its backup production option(s).

Wind fluctuations happen quickly and backup options must be able to increase their generation almost instantly. As a consequence, the most likely backup are oil or coal fired, or often hydropower which is very flexible.

If Backup is Provided by Fossil Fuels

If windpower is backed up by oil or coal plants, these plants cannot be used to produce at close to their maximum capacity and must have "spinning reserve" to be able to increase generation rapidly. In some cases, this means that oil or coal plants may have to operate at lower efficiency than otherwise, in order to be ready to compensate for wind generation instability. Therefore, on a per kWh basis, the thermal plants may be slightly more polluting because of windpower. This issue should be part of the assessment of windpower.

Nevertheless, in a network dominated by fossil fuel generation, windpower development is still environmentally justified because it can seriously reduce emissions. However, this benefit can be slightly less than normally expected.

If Backup is Provided by Hydropower

When windpower is developed, backup capacity must be available or be built, which applies to hydropower or to any other backup. With respect to environmental issues, a hydro backup is different from a thermal backup, because hydropower plants can reduce and increase generation with minimal efficiency losses and no emissions.

The development of windpower can have indirect environmental impacts by affecting river flows. In the Québec context, simulations indicate that the main concern is related to periods when river flows are at their lowest, in summer, when hydropower demand is also low at around 10000 MW (from a network with maximum capacity of 35000 MW).

If 3000 MW of windpower are installed, on each summer windy day, the flow of these rivers would have to be reduced seriously (or if minimum river flows are legally required, unproductive water spillage would be required).

Conclusion

Windpower has indirect economic costs. Because it has only intermittent energy to offer and no reliable capacity, either ancillary services have to be bought or additional backup capacity is required. The fact that extra capacity is already built and available does not eliminate the backup costs, because in open markets, this existing available capacity can be used to sell electricity at a higher price during peak hours.

It is important to note that some impacts of windpower on electricity networks are proportional to the installed capacity, relative to the size of the network (10 MW of wind in a 500 MW network having similar effect as 100 MW of wind in a 5000 MW network). For projects that are relatively small, the impacts are small in absolute terms but they are not eliminated. The impacts are only more difficult to perceive, but they still exist.

Depending of circumstances, the assessment of windpower should include the following issues.

- If ancillary services are bought to compensate for windpower fluctuations, part of the life-cycle environmental impacts of backup options should be included.

- If the backup option is fossil fueled, the effect on emissions should be accounted for. Because of wind fluctuations, it might not be possible to run the fossil fueled plant within the best conditions (efficiency losses, frequent shut downs and start-ups).

- If the backup option is hydropower, the effects on river flows should be investigated.

Environmental impacts of the required backup must be included in a complete assessment of windpower. This does not mean that windpower development is not justified from an environmental point of view. Even including the impacts of backup options, there are many instances where windpower could seriously reduce air emissions, notably by reducing the use of oil and coal.

3.3

RESULTS OF LIFE-CYCLE ASSESSMENTS

This sections presents the results of LCAs for most quantifiable parameters covering issues such as atmospheric emissions, land requirements and occupational health. For each parameter, we present a range of results from studies carried out in different countries.

3.3.1
Life-Cycle "Energy Payback Ratio"

Environmental Issues

For each power generation system, the "energy payback ratio" is the ratio of energy produced during its normal life span, divided by the energy required to build, maintain and fuel the generation equipment. It is an indirect indicator of environmental impact. If a system has a low payback ratio, it means that much energy is required to maintain it and it is likely to have more environmental impacts than a system with a high payback ratio.

Understanding the Results of Studies

In the recent context of climate change commitments, life-cycle assessments have focused mainly on greenhouse gas emissions of energy systems. These assessments are essential. However, the emissions can vary dramatically according to their context. For example, if a system utilizes aluminum as a building material, the assessment will vary greatly if 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 these fluctuations. It should therefore be considered as one of the most reliable indicator of environmental performance.

If this indicator minimizes some fluctuations in study results, it does not eliminate them. The data in the following table shows that payback ratios do not vary much for fossil fuels, but vary significantly for renewable energies. This is due to variable site conditions (topography for hydro, quality of the wind, intensity of solar radiation for solar energy).

Table 9: ***Life-Cycle Energy Payback Ratio (1/2)***

		World	Europe			Asia
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**IEA, "Benign Energy?" 1998**	**Finland, Lappeenranta U. of Tech., Kivisto, 1995**	**Denmark, DWTMA, 1997**	**Austria, Graz U. of Tech., Lehrhofer,[4] 1995**	**Japan, CRIEPI, Uchiyama, 1996**
Options capable of meeting base load and peak load						
Hydropower with reservoir	48 to 260				56 to 260 20 to 1 600 MW UF 42 to 64% life 50 y	50 [5] 10 MW UF 45%
Diesel						
Base load options with limited flexibility						
Hydropower run-of-river	30 to 267				30 to 60 20 to 50 MW UF 68% life 50 y	50 [5] 10 MW UF 45%
Bituminous coal: modern plant	7 to 20		11 [2]	9		7/17 to 20 [6,7]
Brown coal: old plant						
Heavy oil without scrubbing	21					21
Nuclear	5 to 107		7 to 12		17	24 to 107 [6]
Natural gas combined cycle turbines	14		14[3]			
Large fuel cell (nat. gas to hydrogen conversion)						
Biomass: Energy plantation	3 to 5					
Biomass: Forestry waste combustion	27					
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)						
Windpower	5 to 39		35 UF 22%	26 to 34 600 kW UF 21 to 26% life 20 y	7 to 33 0,01 to 3 MW UF 8 to 51% life 20 y	6 100 kW UF 20%
Solar photovoltaic	1 to 14	2 to 14 [1]	2 30 kW UF 10%		1 to 4 300 kW UF 11% life 20 y	5 1 MW UF 15%

Acronyms :

UF:	use factor
EPR:	energy payback ratio
O & M:	operation and maintenance

1 Calculated from cited data. Do not include all the life cycle, only the production of a photovaltaic module.

2 Coal imported from Russia & Poland. (Values calculated from data.)

3 Natural gas imported to Finland from Russia.(Values calculated from data.)

4 Wide range of values for hydro is explained by the project sizes (20 & 1 600 MW) and for wind by the average wind speeds (5,5 & 7 m/s).

5 No distinction between run-of-river and reservoir.

6 Imported resources.

7 1st value for CO_2 removal, 2nd & 3rd for conventional and advanced technologies.

Table 9: ***Life-Cycle Energy Payback Ratio (2/2)***

	North America					
Electricity Generation Options (classified by level of service)	**USA, Cornell U., Pimentel et al., 1994**	**USA, FTI, U. of Wisconsin-Madison, White & Kulcinski,[11] 1999**	**Canada, Enviro-science inc., Bélanger,[12] 1995**	**Canada, Hydro-Québec, Peisajovich, 1997**	**Canada, U. of Guelf, Gingerich and Hendrickson,[15] 1993**	**Comments**
Options capable of meeting base load and peak load						
Hydropower with reservoir	48 [8] includes reservoirs designed for other uses			205 [13]		Refurbishment instead of dismantling can almost double the ratios. Values highly dependent on site characteristics.
Diesel						
Base load options with limited flexibility						
Hydropower run-of-river				267 [14]		Refurbishment instead of dismantling can almost double the ratios. Values highly dependent on site characteristics.
Bituminous coal: modern plant	8	11				
Brown coal: old plant						
Heavy oil without scrubbing						
Nuclear	5	16				
Natural gas combined cycle turbines						
Large fuel cell (nat. gas to hydrogen conversion)						
Biomass: Energy plantation	3 [9]		5			Values highly dependent on wood quality and on transportation distance. Use of wood wastes produced at in a short distance from plant gives a high EPR compared to large energy plantations.
Biomass: Forestry waste combustion					27	
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)						
Windpower	5 [10] UF 35%	17 to 39 343 to 750 kW UF 24 to 35 life 20 to 30 y				Values highly dependent on turbine capacity, life, and site use factor. The main energy requirement is related to material production, followed by O & M (White & Kulcinski 1999). Values do not consider the energy investments required for backup production.
Solar photovoltaic	9 UF 21% life 20 y					Values highly dependent on sun exposure. Values do not consider the energy investments required for backup production options.

[8] Includes reservoirs for other uses (flood control, drinking water, storage, irrigation).

[9] Energy plantation.

[10] 1994 or earlier turbines on a favorable site. Do not include O & M.

[11] Wind project sizes ranging from 2 turbines (1,2 MW total; EPR 17) to 143 turbines (107 MW total; EPR 39).

[12] Energy plantation. Value calculated for a transportation distance of 40 km.

[13] Mean of 3 large projects in Quebec.

[14] Beauharnois (Quebec) power plant.

[15] Whole tree chipping (poor quality, mainly pole-sized spruce). Includes engine and hydraulic oil. Main energy input is related to transportation of the chips to the burning facilities (240 km round trip).

Main Findings Concerning "Energy Payback Ratios"

Reservoir based hydropower clearly has the highest performance: its energy payback ratio varies between 48 and 260, while those of systems based on fossil fuels are in a range of 7 to 21. The advantage of hydropower is in fact greater than this when we consider two other aspects.

- The lowest factors for hydropower include projects that were designed for irrigation. Even with this multiple use, hydropower still performs better than any other system.

- Some of the calculations were made with a life-span of 50 years for hydropower. Some experts consider that a life span of 100 years should be used for hydropower, with one replacement of turbines. In this case the payback ratios would be almost doubled.

In the table, windpower, for the best wind sites, also has a high energy payback ratio. However, this ratio is overestimated because the calculations did not consider the need for backup capacity to compensate wind fluctuations. As shown previously (in section 3.2.3), the level of service of windpower is very low, even when many wind sites are spread out over a large territory.

For biomass, the energy payback ratio varies between 3 and 27. This variation is explained by differing contexts: biomass plantations created exclusively for electricity generation (low factors, because they require many energy input) or else the use of waste biomass in an industry such as pulp and paper (high factors).

In the case of fossil fuels, energy payback ratios are and 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 rate of energy investment (located in far away regions or under the sea).

- Environmental 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 spent or wasted in fossil-fired power plants, in order to reduce emissions. Scrubbing of sulfur reduces the efficiency of a plant. 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.

3.3.2

Contribution to Climate Change: Life-Cycle Greenhouse Gas (GHG) Emissions

Environmental Issues

The Intergovernmental Panel on Climate Change makes the following comments on the environmental impacts of climate change (IPCC, 1996, p. 6-7).

- "Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places...

- Sustained rapid climate change could shift the competitive balance among species and even lead to forest dieback..."

- "Models project an increase in sea level of about 50 cm from the present to 2100."

- "Future unexpected, large and rapid climate system changes... are by their nature, difficult to predict. This implies, that future climate changes may also involve 'surprises'."

Understanding the Results of Studies

Because of these potential impacts, many studies have focused on assessing GHG emissions of energy systems. These studies produce 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. To take into account these differences, the IPCC has produced a set of "global warming potential" indicators, relative to CO_2. In LCAs, each greenhouse gas is converted to an equivalent of CO_2 and added to the inventory (see following table).

Table 10: ***Major Greenhouse Gases Affecting Assessment of Energy Systems***

Species	**Chemical formula**	**Global warming potential per kg over 100 years (IPCC,1996)**
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Perfluoromethane	CF_4	6 500
Perfluoroethane	C_2F_6	9 500

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. However, considering their global warming potential, they could affect significantly the results.

In the next table on GHG emissions, 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 variations in emissions depend mainly on the efficiency of plants.

Table 11: ***Life-Cycle Greenhouse Gas Emissions (kt eq. CO_2/TWh) (1/2)***

		World		Europe					Asia
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**IEA, "Benign Energy?" 1998**	**a: ETSU, UK and IER and b: EEE, UK and Enco, 1995**	**Switzerland, PSI, Dones et al., 1996**	**Finland, Lappeenranta U. of Tech., Kivisto, 1995**	**UK, ETSU, Bates,[11] 1995**	**Austria, IAEA, Vladu, 1995**	**Germany, ÖKO-Inst., Fritsche, 1992**	**Japan, CRIEPI, Uchiyama, 1996**
Options capable of meeting base load and peak load									
Hydropower with reservoir	2 to 48	4 to 15[1]						2[12]	18[13]
Diesel	555 to 883		624/883[6]a	555[9]		778			
Base load options with limited flexibility									
Hydropower run-of-river	1 to 18	9[2]						2[12]	18[13]
Bituminous coal: modern plant	790 to 1 182		823 to 1074[7]a	1 081[8]	894	1 082	790	1 021	859 to 991[14]
Lignite: old plant	1147 to 1272+		1 147 a					1 162	
Heavy oil without scrubbing	686 to 726+								686
Nuclear	2 to 59			12[8]	10 to 26	4	35	59	2 to 21[14]
Natural gas combined cycle turbines	389 to 511		407 a	390[9]	472	453	480	456	
Large fuel cell (nat. gas to hydrogen conversion)	290+ to 520+								
Biomass: Energy plantation Biomass: Forestry waste combustion	17 to 118 15 to 101	17 to 27[3] 29[4]							
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)									
Windpower	7 to 124	7 to 9	9 b		14			11	124[15]
Solar photovoltaic	13 to 731	107 to 211[5]		731[10]	95			30	126

Acronyms :

UF:	use factor
UCPTE:	*Union pour la coordination de la production et du transport de l'électricité*
GHG:	greenhouse gas

1 Large scale hydro. Estimated emissions from construction and reservoir.
2 Small hydro (< 10 MW), not necessarily run-of-river.
3 1st value for the forestry residue fuel cycle, transportation of 100 km round-trip, 2nd and 3rd value for energy crops cycle in different countries.
4 Excluding emissions at plant.
5 Range of data includes different cell types, roof mounted.
6 1st value for combine cycle base load plant, 2nd for gas turbine peak load plant.
7 1st value for integrated gas combined cycle, 2nd for atmospheric fluidized bed combustion.
8 Values for Austria in 1990.
9 Projected values for UCPTE countries in 20005-2015.
10 3 kW.
11 Transmission and distribution included.
12 No emission accounted from reservoir.
13 No distinction is made between run-of-river and reservoir type of hydropower.
14 Advanced and conventional technology.
15 100 kW turbines with a UF of 20%.

Table 11: ***Life-Cycle Greenhouse Gas Emissions (kt eq. CO_2/TWh) (2/2)***

	North America							
Electricity Generation Options (classified by level of service)	**USA, FTI, U. of Wisconsin, White & Kucinski,[16] 1999**	**USDOE, Argonne National Laboratory,[17] 1992**	**USA, NDCEE,[18] 1997**	**Canada, Hydro-Québec, a: Gagnon 1999 & b: Bélanger, 1998**	**Canada, FFCC, 1995**	**Canada, SECDA, 1994**	**USEPA, AP-42, 1998 & 1999**	**Comments**
Options capable of meeting base load and peak load								
Hydropower with reservoir				10 to 30 a		48 [19]		Refurbishment instead of dismantling can almost reduce emissions by 50%. Values highly dependent on site characteristics.
Diesel							704 [23] (plant only)	
Base load options with limited flexibility								
Hydropower run-of-river						1		Refurbishment instead of dismantling can almost reduce emissions by 50%. Values highly dependent on site characteristics.
Bituminous coal: modern plant	974			913 b	910	1 182	1 029 [24] (plant only)	
Lignite: old plant							1 272 [25] (plant only)	
Heavy oil without scrubbing							726 [23] (plant only)	
Nuclear	15					2		
Natural gas combined cycle turbines				511 b	433	389	407 [26] (plant only)	
Large fuel cell (nat. gas to hydrogen conversion)		290 to 520 (plant only)	378 (plant only)			353		
Biomass: Energy plantation						118 [20]		Values highly dependent on wood quality and on conditions of exploitation (transportation distance, etc.).
Biomass: Forestry waste combustion						15 / 101 [21]		
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)								
Windpower	9 to 20					11 / 38 [22]		Values highly dependent on turbine capacity, life, and site use factor. Values do not consider emissions from required backup production.
Solar photovoltaic						13		Values highly dependent on sun exposure. Values do not consider the emissions from required backup production.

16 CO_2 emissions only. Wind project sizes ranging from 2 turbines (1,2 MW; high emissions) to 143 turbines (107 MW; low emissions).
17 200 kW, thermal efficiency 40 – 60%, life 5 y.
18 200 kW, thermal efficiency >40%, 85% if heat is recovered.
19 GHG emissions from reservoir included from preliminary research. (Data is site specific, not averaged.)
20 Poplar plantation (Data is site specific, not averaged.)
21 1st value for soft wood waste, 2nd for loggin residue, both excluding emissions at plant. (Data is site specific, not averaged.)
22 Class 7 & 6 wind sites. (Data is site specific, not averaged.)
23 Thermal efficiency 35%.
24 Medium-volatile bituminous, thermal efficiency 35%.
25 Thermal efficiency 35%.
26 Thermal efficiency 45%.

Main Findings Concerning Greenhouse Gas Emissions

In the preceding table, 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 windpower.

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 both have low electricity generation flexibility, while windpower is intermittent. These three energy systems all require a backup system which may be based on fossil fuels, thereby increasing significantly the final emissions factor of these options.

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

The emission factors of hydropower, with reservoir or run-of-river, would be much lower if we use a life-span of 100 years (many studies use 50 years).

The assessment of hydropower with reservoirs can be site-specific, depending upon two factors: first, the amount of flooded biomass per hectare can vary by a factor of 5 (500 t/ha for tropical forest versus 100 t/ha for boreal climate) and affect emissions from reservoirs; second, the area of reservoir per kWh can vary according to topography. For projects with an average size of reservoir per kWh, in boreal or mountain regions, hydropower has an emissions factor approximately 20 to 60 times lower than 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 GHG emissions from decaying biomass in hydropower reservoirs, uncertainties still persist. For reservoirs in boreal or mountain regions, the amount of flooded biomass is small and because of this, it is unlikely that future research will arrive at higher emission factors than those reported in the table on GHG emissions. For reservoirs in tropical environments, emission factors could be higher, but would depend on many site-specific conditions. Many studies do not consider emissions from reservoirs in the assessment of hydropower.

3.3.3
Land Requirements

All electricity generation systems use large areas of land. These land “requirements” can be considered as an indirect indicator of some environmental impacts. Examples of these various types of impacts include:

- for hydropower, the transformation of forests/land into aquatic ecosystems
- for coal, the use of large areas for mining activities
- for biomass, the area of forests that is exploited.

Understanding the Results of Studies

This type of assessment must be considered with prudence, because it does not consider the intensity of the impact. Moreover, the data in the following table considers only the direct use of land. It does not consider indirect impacts, such as losses related to climate change (ex. losses due to increase in sea levels).

The results for hydropower vary significantly because of site-specific conditions. The figures are for projects designed mainly for power generation. In some countries, such as the United States, most reservoirs were created for purposes of irrigation and water supply. Many of these reservoirs involve very little 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.

Main Findings Concerning Land Requirements

Nuclear energy clearly 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 (if 0,1 km^2/TWh/y is required for waste disposal, multiplied by 30000 years, applied to 30 years of generation, the factor would increase from 0,5 km^2/TWh/y to 100 km^2/TWh/y).

Despite the low diversity of available data concerning fossil fuel systems, the data show that they require much less land than any renewable source of energy. This is an assessment based on direct land requirements only. 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 could multiply the land “use” factors of fossil fuels.

Biomass plantations is the system that requires the most land per unit of energy.

Other renewable sources (hydropower, windpower and solar power) have similar land requirements, which can vary significantly according to site-specific conditions. Data on hydropower is based on area of reservoirs, and not on flooded areas which would be necessarily smaller.

Table 12: ***Land Requirements* (km^2/TWh/y)***

		World		North America				
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**World Energy Council, 1999**	**Canada & Austria, Hydro-Québec & IAEA, Gagnon & van de Vate, 1997**	**USA, Cornell U., Pimentel et al., 1994**	**USA, Gipe, 1997**	**Canada, Enviro-science inc., Bélanger,[6] 1995**	**Canada, SECDA, 1994**	**Comments**
Options capable of meeting base load and peak load								
Hydropower with reservoir	2 to 152 projects designed production for energy		Québec: 152 Finland: 63 Switzerland: 2 China: 24 Sweden: 25 Africa: 639 Asia: 41 Lat. Am.: 105	750 [3]			110	Values represent total reservoir area, not flooded area. Values highly dependent on site charasteristics. Multi-purpose reservoirs increase land requirements.
Diesel								
Base load options with limited flexibility								
Hydropower run-of-river	0,1						0,1	
Bituminous coal: modern plant	4			4				
Lignite: old plant								
Heavy oil without scrubbing								
Nuclear	0,5			0,5 [4]				
Natural gas combined cycle turbines								
Large fuel cell (nat. gas to hydrogen conversion)								
Biomass: Energy plantation	533 to 2200			2 200		533		Values highly dependent on wood quality and conditions of exploitation (transportation distance, etc.).
Biomass: Forestry waste combustion	0,9+						0,9 [7] (plant & waste storage only)	
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)								
Windpower	24 to 117	48 [1]	72 [2]	117 [5]	24 to 71		65 / 29 [8]	Values highly dependent on turbine capacity, life, and site use factor. Values do not consider land requirements for backup production.
Solar photovoltaic	27 to 45			27			45	Values highly dependent on sun exposure. Values do not consider land requirements for backup production.

Acronyms :

UF: use factor
Lat. Am.: Latin America

* Data for each year of production, life-span have no effect on factors.

1 10 MW/km^2, with a UF of 25% and 95% availability.
2 Matane (Canada) project, includes a reserved edge zone.
3 Includes reservoirs for other uses (flood control, drinking water, storage, irrigation).
4 Does not consider long-term storage of nuclear wastes.
5 1994 or earlier turbines, assuming a 35% UF.
6 Energy plantation (15 dry t/ha/y).
7 Crop or logging residues and softwood waste. (Data is site specific, not averaged.)
8 Data for 30 MW / 75 MW. (Data is site specific, not averaged.)

3.3.4

Contributions to Acid Precipitation: Life-Cycle Sulfur Dioxide (SO_2) and Nitrogen Oxide (NO_x) Emissions

Environmental Issues

The following two tables 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 – This issue is discussed in the next section).

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.

In the case of forest productivity, impacts of pollutants are numerous and sometimes indirect (Godish, p. 108-12):

- 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 (next section) can damage the leaves

- climate change may increase heat stress or intensity of droughts.

Finally, the vulnerability of forests vary significantly according to the types of soils involved. In sum, it is impossible to establish a direct link between one type of emission and the ultimate environmental damage caused by such an emission. The emission factors presented in the following tables must therefore be considered as indicators of "potential" impacts.

Understanding the Results of Studies on SO_2

When looking at the next table on SO_2 emissions, the reader should keep in mind that SO_2 emissions may 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 performances. Some commercial scrubbing technologies that are currently available are capable of removing about 90% of SO_2 emissions. But these technologies have been implemented only in a few countries such as Japan.

Table 13: ***Life-Cycle SO_2 Emissions* (t SO_2/TWh) (1/2)***

		World		Europe				North America
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**IEA, "Benign Energy?" 1998**	**ETSU, UK, IER and Enco, 1995**	**Switzerland, PSI, Dones et al., 1996**	**UK, ETSU, Bates,[9] 1995**	**Austria, IAEA, Vladu, 1995**	**Germany, ÖKO-Inst., Fritsche, 1992**	**Canada, Hydro-Québec, Gagnon, 1999a**
Options capable of meeting base load and peak load								
Hydropower with reservoir	5 to 60	9 to 60 [1]						5
Diesel	84 to 1 550				1 550			
Base load options with limited flexibility								
Hydropower run-of-river	1 to 25	25 [2]						
Bituminous coal: modern plant	700 to 32 321+		1 100/200[6]	1 510 [7]	1 490		700	
Lignite old plant	600 to 31 941+		668				600	
Heavy oil without scrubbing	8 013 to 9 595+							
Nuclear	3 to 50				50			
Natural gas combined cycle turbines	4 to 15 000+			155 [8]		300		
Large fuel cell (nat. gas to hydrogen conversion)	6							
Biomass: Energy plantation	26 to 160	90 to 160 [3]						
Biomass: Forestry waste combustion	12 to 140	140 [4]						
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)								
Windpower	21 to 87	15 to 87	87					
Solar photovoltaic	24 to 490	220 to 490 [5]		230				

Acronyms :

FGD : flue-gas desulfurization
SCR : selective catalytic reduction
UF: use factor
UCPTE: *Union pour la coordination de la production et du transport de l'électricité*
Therm. eff.: thermal efficiency

* Most of life cycle SO_x emissions from fossil fuel fired plants are emitted from the fuel combustion at generation plants. These emission factors are highly influenced by the power plant either with FGD and SCR facilities or without them. As a result, wide range of values for SO_x are indicated in this table.

[1] Large scale hydro.
[2] Small hydro (< 10 MW), not necessarily run-of-river.
[3] Values for energy crops cycle in different countries.
[4] Value for the forestry residue fuel cycle, transportation of 100 km round-trip
[5] Range of data includes different cell types, roof mounted.
[6] 1st value for integrated gas combined cycle, 2nd for atmospheric fluidized bed combustion.
[7] Values for Austria in 1990.
[8] Projected values for UCPTE countries in 2005-2015.
[9] Transmission and distribution included.

Table 13: ***Life-Cycle SO_2 Emissions (t SO_2/TWh) (2/2)***

	North America (cont'd)				
Electricity Generation Options (classified by level of service)	**Canada, SECDA, 1994**	**Canada, FFCC, 1995**	**Canada, Theoretical calculations, Bélanger, 1999**	**USEPA, AP-42, 1998 & 1999**	**Comments**
Options capable of meeting base load and peak load					
Hydropower with reservoir	7				Refurbishment instead of dismantling can almost reduce emissions by 50%. Values highly dependent on site characteristics.
Diesel			84 / 836[13]	1 285[18] (plant only)	
Base load options with limited flexibility					
Hydropower run-of-river	1				Refurbishment instead of dismantling can almost reduce emissions by 50%. Values highly dependent on site characteristics.
Bituminous coal: modern plant	1 783	1 018	373 / 1 726[14]	2 637 to 32 321[19] (plant only)	
Lignite old plant			4 347 / 31 941[15]	2 764 to 8 293[20] (plant only)	
Heavy oil without scrubbing			8 013[16]	9 595[21] (plant only)	
Nuclear	3				
Natural gas combined cycle turbines	4	413	1 500 / 15 000[17]	2[22] (plant only)	
Large fuel cell (nat. gas to hydrogen conversion)	6				
Biomass: Energy plantation	26[10]			4 to 81[23] (plant only)	Values are highly dependent on wood quality and on conditions of exploitation (transportation distance, etc.).
Biomass: Forestry waste combustion	12 / 29[11]				
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)					
Windpower	21 / 69[12]				Values highly dependent on turbine capacity, life, and site use factor. Values do not consider emissions from required backup production.
Solar photovoltaic	24				Values highly dependent on sun exposure. Values do not consider the emissions from required backup production.

10 Poplar plantation. (Data is site specific, not averaged.)

11 1st value for soft wood waste, 2nd for loggin residue. (Data is site specific, not averaged.)

12 Class 7 & 6 wind sites. (Data is site specific, not averaged.)

13 If 0,17% S in diesel and 32% thermal efficiency at plant, and with 90% scrubbing. (Not life cycle.)

14 If 0,5 and 5% S in coal, 35% thermal efficiency at plant and with 90% scrubbing. (Not life cycle.)

15 If 0,5 and 5% S in coal and 30% thermal efficiency at plant. (Not life cycle.)

16 If 1,5% S in oil and 32% thermal efficiency at plant. (Not life cycle.)

17 If 0,5 and 5% H2S in gas and 45% therm. effi. at plant with 95% removal during purification. (Not life cycle.)

18 Thermal efficiency 35% and 0,25% S.

19 Thermal efficiency 35% and 0,5 & 5% S.

20 Thermal efficiency 35% and 1% S.

21 Thermal efficiency 35% and 2% S.

22 Thermal efficiency 45%.

23 Thermal efficiency 42%.

Table 14: ***Life-Cycle NO_x Emissions* (t NO_x/TWh) (1/2)***

		World		Europe				North America
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**IEA, "Benign Energy?" 1998**	**ETSU, UK, IER and Enco, 1995**	**Switzerland, PSI, Dones et al., 1996**	**UK, ETSU, Bates,[10] 1995**	**Austria, IAEA, Vladu, 1995**	**Germany, ÖKO-Inst., Fritsche, 1992**	**USA, NDCEE, 1997**
Options capable of meeting base load and peak load								
Hydropower with reservoir	3 to 42	3 to 13 [1]						
Diesel	316+ to 12 300				12 300			
Base load options with limited flexibility								
Hydropower run-of-river	1 to 68	68 [2]						
Bituminous coal: modern plant	700 to 5 273+		1 000 / 700 [6]	1 400 [7]	2 928	1 050	700	
Lignite: old plant	704 to 4 146+		704				800	
Heavy oil without scrubbing	1 386+							
Nuclear	2 to 100				15		100	
Natural gas combined cycle turbines	13+ to 1 500		13 (plant only)	280 [8]	494	1 500	800	
Large fuel cell (nat. gas to hydrogen conversion)	0,3+ to 144							0,3 to 14 (plant only)
Biomass: Energy plantation	1 110 to 2 540	1 110 to 2 540 [3]						
Biomass: Forestry waste combustion	701 to 1 950	1 950 [4]						
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)								
Windpower	14 to 50	20 to 36	36					
Solar photovoltaic	16 to 340	200 to 340 [5]		150 [9]				

Acronyms :

FGD : flue-gas desulfurization
SCR : selective catalytic reduction
UCPTE: *Union pour la coordination de la production et du transport de l'électricité*

* Most of life cycle NO_x emissions from fossil fuel fired plants are emitted from the fuel combustion at generation plants. These emission factors are highly influenced by the power plant either with FGD and SCR facilities or without them. As a result, wide range of values for NO_x are indicated in this table.

[1] Large scale hydro.
[2] Small hydro (<10 MW), not necessarily run-of-river.
[3] Values for energy crops cycle in different countries.
[4] Value for the forestry residue fuel cycle, transportation of 100 km round-trip.
[5] Range of data includes different cell types, roof mounted.
[6] 1st value for integrated gas combined cycle, 2nd for atmospheric fluidized bed combustion.
[7] Values for Austria in 1990.
[8] Projected values for UCPTE countries in 2005-2015.
[9] 3 kW.
[10] Transmission and distribution included.

Table 14: ***Life-Cycle NO_x Emissions (t NO_x/TWh) (2/2)***

	North America (cont'd)					
Electricity Generation Options (classified by level of service)	**USDOE, Argonne National Laboratory, 1992**	**Canada, Hydro-Québec, Gagnon, 1999a**	**Canada, SECDA, 1994**	**Canada, FFCC, 1995**	**USEPA, AP-42, 1998 & 1999**	**Comments**
Options capable of meeting base load and peak load						
Hydropower with reservoir		11	42			Refurbishment instead of dismantling can almost reduce emissions by 50%. Values highly dependent on site characteristics.
Diesel					316 to 758 [14] (plant only)	
Base load options with limited flexibility						
Hydropower run-of-river			1			Refurbishment instead of dismantling can almost reduce emissions by 50%. Values highly dependent on site characteristics.
Bituminous coal: modern plant			1 235	919	1 225 to 5 273 [14] (plant only)	
Lignite: old plant					995 to 4 146 [14] (plant only)	
Heavy oil without scrubbing					1 386 [14] (plant only)	
Nuclear			2			
Natural gas combined cycle turbines			459	416	256 to 944 [15] (plant only)	
Large fuel cell (nat. gas to hydrogen conversion)	< 110 (plant only)		144			
Biomass: Energy plantation			1 396 [11]		268 to 1 460 [16] (plant only)	Values highly dependent on conditions of exploitation (transportation distance, etc.).
Biomass: Forestry waste combustion			701 / 1 380 [12]			
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)						
Windpower			14 / 50 [13]			Values highly dependent on turbine capacity, life, and site use factor. Values do not consider emissions from required backup production.
Solar photovoltaic			16			Values highly dependent on sun exposure. Values do not consider the emissions from required backup production.

[11] Poplar plantation. (Data is site specific, not averaged.)

[12] 1st value for soft wood waste, 2nd for loggin residue. (Data is site specific, not averaged.)

[13] Class 7 & 6 wind sites. (Data is site specific, not averaged.)

[14] Thermal efficiency 35%.

[15] Thermal efficiency 45%.

[16] Thermal efficiency 42%.

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

Understanding the Results of Studies on NO_x

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.

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 both 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 windpower are dependent upon network conditions and more difficult to assess. If windpower reduces the use of oil fired plants (which themselves can compensate for wind fluctuations), there would result a reduction in net emissions; however, in some cases, implementation of windpower may increase the use of oil-fired plants (as backup).

3.3.5

Contributions to Photochemical Smog: Life-Cycle NO_x Emissions and Volatile Organic Compounds (VOC)

Environmental Issues

Volatile organic compounds are complex molecules of hydrocarbon, which contribute, in conjunction with NO_x, to numerous chemical reactions in the lower atmosphere. Such reactions are accelerated by sunlight and are the source of increased levels of tropospheric – or low level – ozone and of other toxic/carcinogenic chemicals (Godish, 97, p. 38-42). The main sources of smog come from the transportation sector.

Standards for tropospheric ozone are regularly exceeded in many large cities and neighboring regions, with significant health impacts. Moreover, the ozone "cloud" can persist for many days, and damage forests and crops.

Emissions factors for NO_x are presented in the previous section. Considering that NO_x emissions are responsible for both smog and acid precipitation is not a "double-counting" mistake. This is due to the fact that NO_x emissions are used as a catalyst in the formation of ozone, but the nitrogen oxide molecules are not eliminated from the atmosphere. These molecules are then involved in slower chemical reactions that will produce nitric acid. So if conditions are favorable (e.g.: a hot sunny day and the presence of VOCs), NO_x emissions can contribute both to the formation of ozone and of nitric acid.

When the nitrogen returns to the ground as nitric acid, it can lead to other impacts such as the formation of excess nitrogen in forest soils, which in turn can affect the balance of nutrients needed by trees. Or else the nitrogen can be washed out into lakes and rivers, with potential effects on aquatic life.

As with SO_2, it is impossible to establish a direct link between NO_x and VOC emissions and the relative impacts of air pollutants. To create serious smog problems, many conditions are required: sunlight, heat and relatively high concentrations of NO_x and VOCs. Because of this, the actual health impacts can be totally different depending upon conditions. The location of fossil fueled power plants is a key issue relative to this environmental problem.

Understanding the Results of Studies on Emissions of "Non-Methane Volatile Organic Compounds" (NMVOC)

The following table presents the results of studies on "non-methane volatile organic compounds" (NMVOC). The exclusion of methane is required because even if it can be considered as a volatile organic compound, it is much less "reactive" than other VOCs, thereby contributing very little to the formation of tropospheric ozone.

Main Findings Concerning Photochemical Smog

Emissions factors for hydropower and nuclear energy are hundreds of times less than those of fossil fuels based power generation systems.

Any form of combustion can contribute significantly to smog if it is located in a region with many other sources.

Table 15: ***Life-Cycle NMVOC Emissions (t/TWh)***

		Europe			North America				
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**Switzerland, PSI, Dones et al., 1996**	**UK, ETSU, Bates,[1] 1995**	**Germany, ÖKO Inst., Fritsche, 1992**	**USA, NDCEE,[2] 1997**	**Canada, FFCC, 1995**	**Canada, SECDA, 1994**	**USEPA, AP-42, 1998 & 1999**	**Comments**
Options capable of meeting base load and peak load									
Hydropower with reservoir									
Diesel	1 570		1 570						
Base load options with limited flexibility									
Hydropower run-of-river									
Bituminous coal: modern plant	18 to 29		29			18		7 to 19 [3] (plant only)	
Lignite: old plant									
Heavy oil without scrubbing	22+							22 [3] (plant only)	
Nuclear									
Natural gas combined cycle turbines	72 to 164	96	132	100		164	72	37 [4] (plant only)	
Large fuel cell (nat. gas to hydrogen conversion)	65				31 (plant only)		65		
Biomass: Energy plantation	89+							89 [5] (plant only)	Values highly dependent on wood quality and on conditions of exploitation (transportation distance, etc.).
Biomass: Forestry waste combustion									
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)									
Windpower									Values do not consider the emissions from required backup production.
Solar photovoltaic	70	70							Values highly dependent on sun exposure. Values do not consider the emissions from required backup production.

1 Transmission and distribution included.

2 Methane emissions might be included in value.

3 Thermal efficiency 35%. (Total organic compounds)

4 Thermal efficiency 45%. (Total organic compounds)

5 Thermal efficiency 42%. (Total organic compounds)

3.3.6
Emissions of Particulate Matter (PM)

Environmental Issues

A small portion of fuels like coal and heavy oil is not combustible ("ash content"). This leads to emissions of particulate matter. Such emissions can also be caused by incomplete combustion of fossil fuels or by transformation of sulfur emissions.

Particulate matter is often referred to as PM10, meaning of a size of less than 10 microns. Recent studies have focused on very small particles (PM5), because the smaller particles seem to have much more effects on respiratory health.

Standards for particulate matter are regularly exceeded in large cities. The main sources of particulate matter are generally coal combustion and diesel fuel used in the transportation sector.

Compared to other pollutants, there is a more direct link between the concentration of PM10 and respiratory health.

Understanding the Results of Studies on Particulate Matter Emissions

The following table presents the results of life-cycle analysis. Results vary greatly for coal, depending on combustion and scrubbing technologies.

Main Findings Concerning Particulate Matter

Coal and biomass have very high emission factors, compared to other options.

Without scrubbing technologies, the emissions from coal and biomass can be hundreds of times higher than emissions from the full cycle of hydropower or natural gas turbines.

Windpower and solar photovoltaic have significant emissions during the manufacture of materials.

Table 16: **Life-Cycle Total Particulate Matter Emissions (t/TWh)**

		World		Europe		North America			
Electricity Generation Options (classified by level of service)	**Range of Life-Cycle Values**	**IEA, "Benign Energy?" 1998**	**ETSU, UK, IER and Enco, 1995**	**UK, ETSU, Bates,[6] 1995**	**Germany, ÖKO Inst., Fritsche, 1992**	**USA, NDCEE, 1997**	**USDOE, Argonne National Lab., 1992**	**Canada, SECDA, 1994**	**Comments**
Options capable of meeting base load and peak load									
Hydropower with reservoir	5							5	
Diesel	122 to 213+			122		213 (plant only)			
Base load options with limited flexibility									
Hydropower run-of-river	1 to 5	5 [1]						1	
Bituminous coal: modern plant	30 to 663+		160 / 30 [5]	190	100	663 (plant only)		185	
Lignite: old plant	100 to 618		618		100				
Heavy oil without scrubbing									
Nuclear	2			2				2	
Natural gas combined cycle turbines	1 to 10+			1		10 (plant only)			
Large fuel cell (nat. gas to hydrogen conversion)	2 to 6+					6 (plant only)	4 (plant only)	2	
Biomass: Energy plantation	190 to 212	190 to 210 [2]						212 [7]	Values highly dependent on wood quality and on conditions of exploitation.
Biomass: Forestry waste combustion	217 to 320	320 [3]						217/254 [8]	
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)									
Windpower	5 to 35	5						35	Values do not consider the emissions from required backup production.
Solar photovoltaic	12 to 190	140 to 190 [4]						12	Values highly dependent on sun exposure. Values do not consider the emissions from required backup production.

1 Small hydro (<10 MW), not necessarily run-of-river.
2 Values for energy crops cycle in different countries.
3 Value for the forestry residue fuel cycle, transportation of 100 km round-trip.
4 Range of data includes different cell types, roof mounted.
5 1st value for integrated gas combined cycle, 2nd for atmospheric fluidized bed combustion.
6 Transmission and distribution included.
7 Poplar plantation; Assumption of a sustainable harvest.
8 1st value for soft wood waste, 2nd for loggin residue.

3.3.7
Emissions of Mercury (Hg)

Environmental Issues

Mercury is present in the natural environment because volcanoes are a major source of airborne Mercury. Over the last decades however, anthropogenic sources of Mercury have exceeded natural sources. The main anthropogenic sources are coal and oil combustion, metal smelters and waste incinerators. Because of these activities, concentration of Mercury in Northern soils have doubled or tripled in the last decades.[1]

Hydropower is also concerned with the issue of Mercury. After flooding, the organic matter in reservoirs stimulates the activity of bacteria that turn inorganic Mercury into organic Mercury via methylation In its organic form, Mercury is assimilable in the food chain. Monitoring of reservoirs in Canada and Finland has demonstrated that Mercury accumulation in fish peaks after five to ten years and decreases thereafter, returning to normal in 20 to 30 years.[2]

Mercury can be ingested by local populations when fish is a part of their diet. Long-term exposure to toxic levels of methylmercury can translate into health problems. However, monitoring of this health issue is simple and mitigation is possible by controlling fish consumption (as it is done in Northern Québec).

Understanding the Results of Studies on Mercury Emissions

The following table does not show the results of life-cycle analysis. For fossil fuels and biomass, the data is for direct emissions at the plant only. For coal, it is normal to have a large range of emission factors because the Mercury content of coal varies substantially among coal types, at different locations in the same mine, and across geographic regions.

For hydropower, the factor produced in the table is not based on emissions: it is an estimate of Mercury that was returned to the biota after the creation of the reservoirs of the La Grande complex in Northern Québec.[3]

Main Findings Concerning Mercury Emissions

Among energy options, coal is clearly the largest emitter of Mercury. Heavy oil, biomass and natural gas also have significant emission factors, but these factors are several times smaller than typical factors for coal.

Per unit of energy, the rate of methylation of Mercury in hydro reservoirs is about 200 times less than typical emission factors of coal. Moreover, a portion of the Mercury that is returned to the biota by reservoirs came from fossil fuel combustion.

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[1] M.Lucotte et al., “Anthropogenic mercury enrichment in remote lakes of Northern Quebec”, *Water, Air and Soil Pollution* 80:467-76, 1995.

[2] J.-F. Doyon, R. Schetagne, 1999, *Réseau de suivi environnemental du complexe La Grande 1997-98.*

[3] N. Thérien and K. Morrison, “Calculated Fluxes of Mercury to Fish in the Robert-Bourassa Reservoir”, *Mercury in the Biogeochemical Cycle,* Springer, 1999, p. 259-72.

Table 17: ***Mercury Emissions at Plant (kg Hg/TWh)***

		Europe	North America				
Electricity Generation Options (classified by level of service)	**Range of Values**	**Switzerland, PSI, Dones et al., 1996**	**Canada, Hydro-Québec, Gagnon,[2] 1999b**	**Canada, Lui et al. Canadian Electricity Ass., 1994**	**USEPA, 1997**	**USEPA, AP-42, 1998 & 1999**	**Comments**
Options capable of meeting base load and peak load							
Hydropower with reservoir	0,07		0,07				Net accumulation of total Mercury in biota, over a 6 year period after flooding.
Diesel							
Base load options with limited flexibility							
Hydropower run-of-river							
Bituminous coal: modern plant	1 to 360			103 to 360[3]	1 to 131[4]	14[8]	Concentrations of Mercury in coal are highly variable, from region to region and even within a single stream. Emissions at plant also depend on the presence and efficiency of emissions control systems.
Lignite: old plant	2 to 42				2 to 42[5]	23[8]	Concentrations of Mercury in coal are highly variable, from region to region and even within a single stream. Emissions at plant also depend on the presence and efficiency of emissions control systems.
Heavy oil without scrubbing	2 to 13			13[3]	2[6]	3[8]	
Nuclear							
Natural gas combined cycle turbines	0,3 to 1	0,3[1]				1[9]	
Large fuel cell (nat. gas to hydrogen conversion)							
Biomass: Energy plantation Biomass: Forestry waste combustion	0,5 to 2				0,5 / 1,4[7]	2[10]	
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)							
Windpower							
Solar photovoltaic							

Acronyms :

UCPTE: *Union pour la coordination de la production et du transport de l'électricité*
ESP: electrostatic precipitator

1 Projected value for UCPTE countries in 2010, thermal efficiency 57%.
2 Estimate based on study by N. Thérien & K. Morrison. 50 years of hydro production used in estimate.
3 Thermal efficiency 35%. (Theoretical calculations)

Means of measured values. Wide range due to variable Mercury concentrations in fuel and control systems:
4 Thermal efficiency 35%, with & without control.
5 Thermal efficiency 35%, with control.
6 Thermal efficiency 35%, typical emissions.
7 Thermal efficiency 42%, with ESP /without control.

Mean of measured values at 28 facilities burning bituminous coal (11), subbituminous coal (15) and lignite (2), with different control systems:
8 Thermal efficiency 35%.
9 Thermal efficiency 45%.
10 Thermal efficiency 42%.

3.4

INTEGRATION OF LIFE-CYCLE ENVIRONMENTAL IMPACTS

In the previous section (3.3), life-cycle environmental impacts were examined according to each major category of quantifiable impacts (e.g., GHG emissions, land area used, SO_x and NO_x emissions...). This, however, does not present the reader with a clear picture of the final effect of all of these categories of impacts. This section will try to present a wider view of cumulative life-cycle impacts of energy systems on human health.

The previous section also did not address some significant environmental issues that are difficult to quantify. One of these is the effect of hydro and biomass power generation on biodiversity. This is discussed further in section 3.4.2.

To describe cumulative environmental impacts, it is necessary to examine the various links between electricity generation and the “final health” of humans or ecosystems. This is also discussed further in the next two sections.

3.4.1
Integration of Impacts on Human Health

The cumulative impacts on human health are mostly related to atmospheric emissions. These are summarily described in the following table.

Table 18: ***Chain of Effects Between Each Pollution and Human Health***

First level pollution	Second level pollution	Third level pollution	Final impact on human health
SO_2 NO_x → →	→ Formation of acid H_2SO4 HNO_3 →	→ Washout of toxic metals (Al) from soils to rivers →	Impact on respiratory health Absorption of these metals by humans (through the food chain)
VOC → + NO_x →	→ Photochemical smog formation (notably 03) →	→ →	Direct toxic/carcigonic effects High toxicity
GHGs: CO_2 CH_4 →	Climate change →	Increased frequency of extreme events: floods / droughts →	Direct impact on the health of affected populations
Particulate matter	→	→	Direct impact on respiratory health
Toxic metals such as Mercury →	Contamination of soils, rivers and lakes →	→	Absorption of these metals by humans (through the food chain)

The next table presents, for each power generation system, the main health issues, including which chains of effects are relevant.

Table 19: ***Main Systems, with Final Impacts on Human Health***

Systems	Source of final significant impacts on human health
Systems capable of meeting base load and peak load	
Hydropower with reservoir	• Main issue: breach of dams • Risks from water-borne diseases, particularly when there is irrigation
Diesel	• Climate change • Acid precipitation • Photochemical smog • Particulate matter
Base load systems with some flexibility	
Hydropower run-of-river	• Main issue: breach of dams
Coal	• Climate change • Acid precipitation • Photochemical smog • Particulate matter • Toxic metals
Heavy oil	• Climate change • Acid precipitation • Photochemical smog • Particulate matter
Nuclear	• Radioactive substances
Natural gas turbines	• Climate change • Acid precipitation • Photochemical smog
Intermittent systems that need a backup production	
Windpower	• Depends on which backup system is used (oil or hydro)
Solar photovoltaic	• Depends on which backup system is used (oil or hydro)

3.4.2
Integration of Impacts on Biodiversity

Biodiversity issues are difficult to summarise because they can be expressed at many different geographical levels: a local pond, a river, a region, a biome or the planet. LCAs of energy systems must therefore clarify at which level an impact can become a biodiversity issue.

One author, Reed F. Noss, suggests that the assessment of biodiversity aspects be carried out according to three distinct scales[4]: within habitat, between habitat (including the "edge effect") and regional. The focus should be on ecosystems, and more specifically on preserving a network of ecosystems. Other authors also focus on the protection of ecosystems. J. Franklin[5] equally proposes that the protection of biodiversity be focused upon ecosystems, and not on individual habitats.

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[4] Reed F. Noss, "A Regional Landscape Approach to Maintain Diversity", *BioScience*, vol. 33 no. 11, p. 700-6.

[5] Jerry F. Franklin, "Preserving Biodiversity: species, ecosystems or landscapes?", *Ecological Applications*, 3(2), 1993, p. 202-5.

For the generic assessment of energy systems (see following table), we will use the three following levels to assess potential biodiversity impacts:

- local and regional ecosystems: the various habitats directly affected by a project
- biomes: the largest ecological units, generally defined according to dominant vegetation
- genetic diversity at world level: the protection of endangered species.

For many energy systems, impacts on local and regional ecosystems may be site-specific. This is true for hydropower, but also for some fossil fuel based power generation. For example, the impacts of acid emissions will vary significantly according to ecological conditions. Any generalization must therefore be treated with care. Moreover, habitat modifications do not necessarily result in a loss of biodiversity. Even if hydropower does change terrestrial ecosystems into aquatic ecosystems, these new ecosystems may be very productive.

Table 20: ***Main Energy Systems, with Final Impacts on Biodiversity***

Generation Systems	**Source of final significant impacts on biodiversity**	**Local and regional ecosystems**	**Biomes**	**Genetic diversity** at world level
Systems capable of meeting base load and peak load				
Hydropower with reservoir	• Barriers to migratory fish • Loss of terrestrial habitat • Change in water quality • Modification of water flow	X X X X		
Diesel	• Climate change • Acid precipitation	X X	X	X
Base load systems with some flexibility				
Hydropower run-of-river	• Barriers to migratory fish	X		
Coal	• Climate change • Acid precipitation • Mining and transportation of coal	X X X	X	X
Heavy oil	• Climate change • Acid precipitation	X X	X	X
Nuclear	• Radioactive substances	X		
Natural gas turbines	• Climate change • Acid precipitation	X X	X	X
Intermittent systems that need a backup production				
Windpower	• Risks for some species of birds • Depend on which backup system is used (oil or hydro)	X (?)	(?)	(?)
Solar photovoltaic	• Depend on which backup system is used (oil or hydro)	(?)	(?)	(?)

3.5

CONCLUSIONS ON MAIN ISSUES

Even if social issues are important for many projects, including hydropower, they are not addressed in this chapter for the following reasons.

- Social issues are extremely variable from one project to another.

- "Generic" comparisons of systems are useful at the policy level where specific projects may not be known.

- The nature and importance of residual social impacts depend largely upon the nature and extent of mitigation and compensation programs, which may vary significantly from one project to another (or from one country to another).

Obviously, social issues must be integrated into the decision-making process. This process is discussed at length in the following chapters. Moreover, the comparison of energy systems on the basis of LCAs does not eliminate the need for political arbitration. This is due to the fact that many impacts are impossible to compare directly (e.g., local land use issues for hydropower or biomass energy plantations versus the management of radioactive wastes for nuclear power versus global and regional atmospheric issues for coal, oil and natural gas generation).

The different levels of impacts (e.g., global, regional and local) may be a good criteria to define priorities. Modifications to a global biochemical cycle (such as the carbon cycle) will ultimately produce important impacts on human health and biodiversity. Compared to local issues, such a global change is likely to be the source of more impacts. Carrying out environmental assessments on the basis of such levels of priority would clearly favor any renewable energy source over the various forms of fossil fuel power generation.

It is more difficult to give an overall conclusion on nuclear energy. Some groups will remain opposed to its development because of the issue of radioactive wastes. However, LCAs remain very favorable to this energy system.

Table 21 on the next page presents a summary of life-cycle impacts.

To conclude on the performance of hydropower, it is important to note that most comparisons of systems are unfair to hydropower for the following reasons.

- The multi-purpose character of reservoirs increase their environmental impacts, while the related benefits are often neglected.

- The reliability and flexibility that hydropower provides to the electricity network is often forgotten.

- Since "best available technology" is not an appropriate concept for hydropower, comparisons tend to compare statistics of old hydropower projects with new recent thermal power projects.

However, despite this "structural" negative bias, hydropower still comes out ahead of other energy systems in most comparisons.

Table 21: ***Synthesis of Environmental Parameters for Energy Options (Life-cycle Assessment)***

Electricity Generation Options (classified by level of service)	**Energy Payback Ratio**	**Greenhouse Gas Emissions** (kt eq. CO_2/TWh)	**Land Requirements** (km^2/TWh/y)	**SO_2 Emissions** (t SO_2/TWh)	**NO_x Emissions** (t NO_x/TWh)	**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	48 to 260	2 to 48	2 to 152 projects designed for energy production	5 to 60	3 to 42		5	0,07 methylmercury in reservoirs
Diesel		555 to 883		84 to 1 550	316+ to 12 300	1 570	122 to 213+	
Base load options with limited flexibility								
Hydropower run-of-river	30 to 267	1 to 18	0,1	1 to 25	1 to 68		1 to 5	
Bituminous coal: modern plant	7 to 20	790 to 1 182	4	700 to 32 321+	700 to 5 273+	18 to 29	30 to 663+	1 to 360
Lignite: old plant		1 147 to 1 272+		600 to 31 941+	704 to 4 146+		100 to 618	2 to 42
Heavy oil without scrubbing	21	686 to 726+		8 013 to 9 595+	1 386+	22+		2 to 13
Nuclear	5 to 107	2 to 59	0,5	3 to 50	2 to 100		2	
Natural gas combined cycle turbines	14	389 to 511		4 to 15 000+	13+ to 1 500	72 to 164	1 to 10+	0,3 to 1
Large fuel cell (nat.gas to hydrogen conversion)		290+ to 520+		6	0,3+ to 144	65	2 to 6+	
Biomass: Energy plantation	3 to 5	17 to 118	533 to 2 200	26 to 160	1 110 to 2 540	89+	190 to 212	0,5 to 2
Biomass: Forestry waste combustion	27	15 to 101	0,9+	12 to 140	701 to 1 950		217 to 320	
Intermittent options that need a backup production (such as hydro with reservoir or oil-fired turbines)								
Windpower	5 to 39	7 to 124	24 to 117	21 to 87	14 to 50		5 to 35	
Solar photovoltaic	1 to 14	13 to 731	27 to 45	24 to 490	16 to 340	70	12 to 190	

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