



**Le projet du Suroît,
un recul environnemental
résultant de la psychose anti-hydroélectricité**

Mémoire déposé

au Bureau d'audiences publiques sur l'environnement

par Jean-François Lefebvre et Razi Shirazi,

du Groupe de recherche appliquée en macroécologie

(GRAMÉ)

le 4 octobre 2002

La justification du projet

Dans son plan d'approvisionnement d'électricité 2002-2011, approuvé par la Régie de l'énergie, Hydro-Québec Distribution (H-QD) prévoit qu'à partir de 2006, selon le scénario moyen, la demande québécoise excédera l'électricité patrimoniale qui s'établit à 165 TWh. Tout comme plusieurs autres intervenants auprès de la Régie de l'Énergie, nous avons souligné que les efforts en efficacité énergétique devraient être plus importants que ce qui était prévu alors par H-QD. Nous sommes toutefois convaincus que les efforts en efficacité énergétique, de manière réaliste, vont surtout permettre de ralentir la croissance de la demande. Il y a donc une certaine justification à augmenter la production électrique québécoise pour répondre à une demande domestique grandissante.

Le projet de la construction de la centrale du Suroît, une centrale alimentée par le gaz naturel exploitable en décembre 2006, est toutefois agencé dans une perspective manifeste de répondre aux besoins des marchés extérieurs. Dans ses soumissions en réponse au premier appel d'offre lancée au printemps 2002 pour garantir l'approvisionnement en électricité post-patrimoniale, H-QD n'a pas jugé utile d'inclure la centrale du suroît, en revanche, elle propose trois centrales hydrauliques¹.

En supposant que les trois projets hydrauliques soumis par Hydro-Québec Production soient retenus, ce qui serait, et de loin, la meilleure option en terme de choix environnemental, cette filière renouvelable comblerait au plus 950 MW sur les 1 200 MW de l'appel d'offre. Donc, au mieux, l'ajout de production d'origine thermique, laquelle constitue la quasi-totalité des offres venant du privé, serait quand même de 250 MW. Il s'en suivrait des retombées environnementales significatives, lesquelles seront plus importantes, évidemment, si une des soumissions hydrauliques n'était pas retenue.

Mentionnons que le processus d'évaluation de ce premier appel d'offre se fera sur la base du moindre coût, sans utiliser le moindre critère d'évaluation de l'impact environnemental des filières. Suite aux interventions de plusieurs intervenant, dont celui

¹ Voir Annexe I.

regroupant le Groupe de recherche appliquée en macroécologie et l'Union pour le développement durable, la Régie de l'Énergie a reconnu que le plus bas prix économique n'était pas nécessairement le plus bas coût social. La Régie a demandé à H-QD d'inclure certains critères environnementaux dans l'évaluation de futurs appels d'offres.

Les projets de centrales hydroélectriques actuellement en construction, d'après l'étude d'impact déposé par (H-QD) à la présente audience, permettent d'ajouter 2 222 MW puissance à celle produite en 2002. Les projets en demandes d'autorisation et à l'étude totalisent 1 775 MW additionnels (en excluant le Suroît). D'autres projets devraient pouvoir s'ajouter sous peu, notamment celui de Gull Island.

Le ralentissement dans le développement hydroélectrique des dernières années est responsable du fait que notre production excédentaire destinée à l'exportation est, actuellement, en nette régression. Il est aussi directement responsable de la venue du projet de la centrale du Suroît.

Mais les besoins internes québécois ne sont clairement pas à la base du projet du Suroît. On devrait donc comprendre de cette affirmation d'Hydro-Québec Production qui « propose le projet de centrale à cycle combiné du Suroît afin de profiter pleinement des occasions d'affaires rentables sur les marchés de gros au Québec et en périphérie² », que, dans ce cas-ci, ce sont surtout les marchés périphériques qui sont visés puisque les besoins domestiques sont déjà autrement satisfaits. Qu'Hydro-Québec Distribution cherche à saisir les occasions d'affaires qui s'offrent à elle est parfaitement cohérent avec ses objectifs corporatifs et tout à fait souhaitable pour la société québécoise, mais alors que cela se fasse à la lumière de choix avisés.

Selon le GRAME, les besoins et les marchés en électricité « propre » sont tels qu'aucun projet d'énergie renouvelable ne devrait avoir à « justifier » sa production, un critère que ne devrait surtout pas servir à rejeter ce type de projet, ou à ralentir son évaluation

² Étude d'impact sur l'environnement, page 2-2.

environnementale, laquelle devrait porter exclusivement sur l'impact environnemental du projet.

Ce n'est pas le cas de la centrale du Suroît.

Le Suroît versus le développement durable

Cette centrale de 900 MW, bien que d'une des technologies les plus performantes au monde pour la filière des turbines à gaz (efficacité de 58 %), consommerait quelque trois millions de m³ de gaz par jours pour les 25 à 30 prochaines années. Elle rejetterait 2,45 millions de tonnes d'équivalent CO₂ de gaz à effet de serre (GES) par an, ce qui représente 2,8 % des émissions annuelles totales du Québec. Elle émettrait également de nombreuses substances toxiques notamment du dioxyde de soufre, responsable des pluies acides, du benzène, du toluène, un puissant solvant organique cancérigène, etc.

En effet, la croissance de la demande énergétique n'est pas propre au Québec, elle s'intègre plutôt à l'intérieur d'une tendance nord américaine. Dans ce contexte, le Québec, grâce à ses grandes potentialités hydroélectriques, est en mesure de produire d'énormes quantités d'électricité à des coûts très faibles et avec un impact environnemental largement inférieur à celui des centrales thermiques. Il jouit ainsi d'un considérable avantage concurrentiel qu'il se doit de saisir pour favoriser son développement. Cependant, pour qu'il y ait gain réel de richesses, la croissance économique ne peut se faire que dans une perspective soutenable, c'est-à-dire lors qu'elle intègre tous les coûts qui lui sont liés, tant économiques qu'environnementaux et sociaux. C'est ce qui se définit par le développement durable : " un développement qui répond aux besoins du présent sans compromettre la capacité des générations futures de répondre aux leurs³". Selon Dansereau et Drapeau (1998)⁴, le respect du développement durable en matière énergétique demande que l'on favorise :

³ COMMISSION DES NATIONS UNIES SUR L'ENVIRONNEMENT ET LE DÉVELOPPEMENT (1988). Notre avenir à tous. Éditions du Fleuve, Montréal, 454 p.

1. la réduction de la consommation totale d'énergie
2. la réduction des gaz à effet de serre
3. l'efficacité énergétique
4. le remplacement des énergies non renouvelables par des énergies renouvelables
5. le respect des ententes internationales
6. le choix de filières ayant le moins d'impacts négatifs globaux sur la biosphère
7. l'évaluation publique des projets et des programmes
8. la planification en fonction d'un horizon de deux ou trois générations
9. l'équité.

La construction du Suroît, sous un tel regard et dans un État qui dispose d'importantes potentialités en terme de production hydroélectrique, et dans une moindre mesure éolienne, des filières énergétiques reconnues pour être propres et renouvelables⁵, est inacceptable voire embarrassant. Elle est embarrassante parce qu'elle se traduit par la croissance marquée d'une filière polluante au Québec, et inacceptable car elle témoigne d'un défaitisme face aux difficultés rencontrées pour développer une filière propre, l'hydroélectricité.

Il faut aussi se poser la question de la qualité de l'usage du gaz comme sources énergétique dans ce projet. En effet, la technologie retenue pour le Suroît, une centrale électrique des plus performantes alimentée au gaz, permet d'obtenir une efficacité de

⁴ DANSEREAU, P. et J.-P. DRAPEAU (1995). Déclaration de principes pour une politique énergétique qui respecte le concept du développement durable. Mémoire pour le Débat national sur l'énergie, Union pour le développement durable, Québec, 5 p.

DANSEREAU, P. ET J.-P. DRAPEAU (1998). "La seule option: une politique énergétique axée sur le développement durable". In: GENDRON, C. ET J.-G. VAILLANCOURT (1998) L'énergie au Québec. Quels sont nos choix? Éditions Écosociété, Montréal, pp. 171-174.

⁵ Voir l'annexe II.

58 %. Le gaz naturel, s'il est utilisé directement pour le chauffage, dépendamment de l'équipement emprunté, peut atteindre environ 90 % d'efficacité.

En d'autres termes, s'il faut faire le Suroît pour profiter des marchés d'exportation, pourquoi ne pas utiliser directement le gaz dans le chauffage, pour libérer de l'hydroélectricité? Notons que là encore, l'utilisation de l'hydroélectricité plutôt que le chauffage direct au gaz naturel permettrait d'émettre 11 fois moins de GES (et 13 fois moins si l'hydroélectricité permet de remplacer du mazout).

Nous présentons à l'annexe II le document intitulé « *Comparative environmental analysis of power generation options*, chapitre 3 du rapport : *International Energy Agency (2000) Hydropower Agreement – annex III, Vol. II, Main Report*.

L'Agence internationale de l'énergie (AIE) y démontre que la filière des centrales au gaz naturel est un deuxième choix, lorsqu'il n'y a pas de potentiel de développement d'énergies renouvelables, ce qui est loin d'être le cas au Québec.

Finalement, nous désirons amener votre attention au tableau 20 (p. 81) de l'annexe II, lequel souligne que les centrales thermiques imposent des impacts macroécologiques qui dépassent les enjeux sur les écosystèmes locaux et affectent l'ensemble des écosystèmes ainsi que la diversité biologique (via les précipitations acides et les changements climatiques).

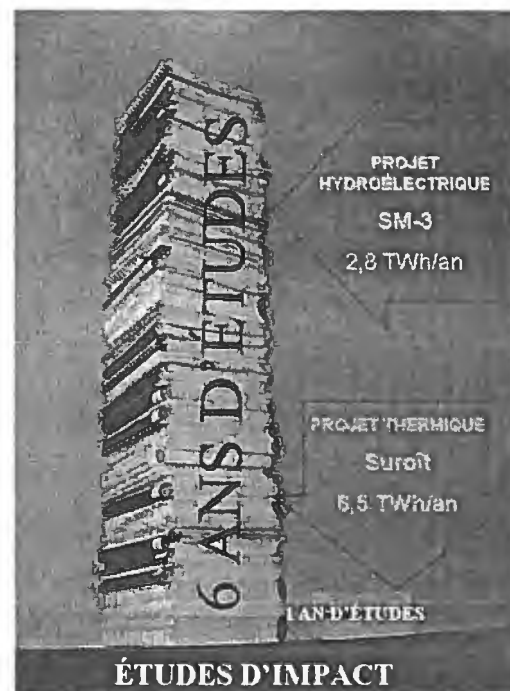
Comment sommes-nous arrivés là? Pour la prise en compte de l'impact macroécologique des projets

H-QD, tout en admettant que l'hydroélectricité constituerait une meilleure source d'approvisionnement, s'arrête sur l'option thermique en invoquant les « inconvénients, dont celui d'exiger de plus longs délais de réalisation, en particulier pour les installations de grande envergure », relatifs à la filière hydroélectrique.

Outre les questions proprement techniques, deux raisons principales expliquent cette lenteur de réalisation dont il est fait mention. La première réside dans une fausse et persistante croyance, véhiculée par certains écologistes et lobbies, contre les vertus écologiques de l'hydroélectricité (vertus que démontre une lecture attentive du rapport de l'AIE déposé en annexe). La deuxième, corollaire de la première, relève de la lourdeur administrative du processus réglementaire relatif à l'approbation des projets hydroélectriques.

À gauche, le résultat des 6 années d'études d'impact requises pour répondre aux exigences pour une centrale hydro-électrique devant produire 2,8 TWh/an (Sainte-Marguerite-3).

À droite, l'étude produite en un an qui est demandée pour une centrale thermique de 6,5 TWh/an (le Suroît).



L'argument invoqué par H-Q est fondé sur des problèmes réels, mais il est insuffisant pour expliquer une abdication devant les priorités environnementales de notre société.

Un deuxième choix qui devrait mis de côté au profit du premier choix

Les bonnes performances, en terme d'émissions de GES du Québec sont redevables en grande partie à sa production hydroélectrique. Le Premier ministre du Canada, M. Jean

Chrétien, s'est officiellement engagé à déposer, d'ici Noël 2002, un projet de Loi sur la ratification du protocole de Kyoto.

La ratification du Protocole de Kyoto donnera un message clair : la réduction de l'impact énergétique global et planétaire de notre société doit être maintenant considéré en priorité.

Cela pénalisera les producteurs d'énergie de source fossiles, particulièrement le mazout et le charbon, tout en favorisant le gaz naturel, mais surtout les énergies renouvelables.

Toute source additionnelle d'énergie fossile devra impliquer l'achat de droits d'émission. Par cette acquisition de droits d'émissions, l'entreprise qui augmentera ses émissions devra financer, dans une autre entreprise, une réduction d'émissions proportionnelle. Évidemment, un projet de l'importance du Suroît induira une pression à la hausse sur le coût de ces permis jusqu'à ce qu'ils atteignent le prix du marché international.

H-Q prétend qu'après Kyoto, elle pourra bénéficier d'hypothétiques crédits de GES obtenus pour sa production hydroélectrique passée et les employer pour couvrir les émissions du Suroît. Rien n'est moins sûr. En effet, notre engagement au Kyoto signifiera qu'il y aura un plafond à la quantité de GES que nous pourrions émettre.

Ce plafond s'établira, en moyenne durant la période de 2008 à 2012, à 94 % de nos émissions de 1990. Nos performances passées constitueront un avantage en ce qu'elles diminueront l'effort à faire, mais elle ne nous dispenseront en rien de notre engagement.

Le fait qu'HQ ait réellement réduit ses émissions (en réduisant l'utilisation de la centrale de Tracy) pourrait lui valoir quelques droits d'émissions additionnels, mais qui ne couvriraient probablement au mieux le tiers des émissions prévues à la centrale.

Dans le cadre du Kyoto, le seul moyen d'augmenter ses émissions de GES est donc d'acheter des crédits de réduction. Cela peut se faire par un échange de permis dans la même compagnie, dans le même pays ou sur les marchés extérieurs. Inversement, en diminuant ses émissions, il est possible de les vendre. Le Suroît aurait pu être employé à

cette fin si les États-Unis n'avaient pas rejeté Kyoto et pourrait l'être avec les provinces voisines. Effectivement, par rapport à la électricité américaine qui est très majoritairement produite au mieux par les centrales au gaz naturel, et au pire au mazout ou au charbon, la nôtre aurait eu le double avantage d'être peu coûteuse et plus propre. En l'exportant, on n'aurait pas augmenté nos émissions de GES et on aurait aidé nos voisins du sud à faire baisser les leurs. Dans l'état actuel des choses, bien qu'exporter notre électricité aux États-Unis est toujours souhaitable économiquement et sur le plan de l'environnement, vu qu'elle remplacera des filières plus polluantes, elle ne constitue pas un atout pour l'atteinte des objectifs de Kyoto.

Pour ce qui est des autres provinces, l'exportation d'hydroélectricité demeure, de toute façon un premier choix qui nous semble encore possible.

Conclusion et recommandations

Force est donc de constater qu'aller de l'avant avec ce projet de centrale thermique sera un choix peu judicieux et incohérent avec la politique énergétique québécoise. Au Québec, la construction d'une centrale thermique, loin de constituer une priorité, est un pas en arrière. En matière énergétique, des priorités existent. C'est vers elles que les efforts devraient être dirigés.

Une des premières serait d'accroître les efforts pour la réhabilitation de l'hydroélectricité et contre la désinformation dont cette importante filière renouvelable a été victime. Des mesures d'accélération du processus administratif concernant l'évaluation des projets hydroélectriques, sans pour autant nuire à la qualité des travaux et examens à effectuer, est également fortement souhaitable. La levée de ces barrières, difficilement justifiables et basées sur une approche microécologique qui néglige les enjeux globaux, permettra à la production hydroélectrique, tant pour les besoins internes qu'extérieurs, de poursuivre son développement.

Tout en devant refuser le projet du Suroît, le BAPE doit s'engager à réviser le processus d'évaluation des projets hydroélectriques, notamment en harmonisant les démarches fédérale et provincial, afin de réduire les délais d'approbation.

Dans le contexte des nouvelles ententes de partenariat, particulièrement avec les Cris et les Inuits, il faut miser sur le développement des énergies renouvelables du Québec, incluant l'hydroélectricité et l'éolien.

Il est également nécessaire de contribuer massivement à augmenter les efforts en efficacité énergétique.

Le Québec a su se distinguer comme une société fortement conscientisé et alerte en égard aux préoccupations environnementales. Le débat sur le projet de centrale à cycle combiné du Suroît lui offre une nouvelle occasion de le démontrer.

Annexe I

Annexe II

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.

TECHNICAL REPORTS IN THIS SERIES

Hydropower Upgrading Task Force (Annex 1)

Guidelines on Methodology for Hydroelectric Turbine Upgrading by Runner Replacement – 1998 (available to non-participants at a cost of U.S. \$1,000 per copy)

Guidelines on Methodology for the Upgrading of Hydroelectric Generators – to be completed in May 2000

Guidelines on Methodology for the Upgrading of Hydropower Control Systems – to be completed in 2000

Small-scale Hydropower Task Force (Annex 2)

Small-scale Hydro Assessment Methodologies – to be completed in May 2000 (available to non-participants on request)

Research and Development Priorities for Small-scale Hydro Projects – to be completed in May 2000 (available to non-participants on request)

Financing Options for Small-scale Hydro Projects – to be completed in May 2000 (available to non-participants on request)

Global database on small hydro sites available on the Internet at: www.small-hydro.com

Environment Task Force (Annex 3)

Survey on Positive and Negative Environmental and Social Impacts and the Effects of Mitigation Measures on Hydropower Development – 2000 (available to non-participants on request)

A Comparison of the Environmental Impacts of Hydropower with those of Other Generation Technologies – 2000 (available to non-participants on request)

Legal Frameworks, Licensing Procedures, and Guidelines for Environmental Impact Assessments of Hydropower Developments – 2000 (available to non-participants on request)

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

Volume 1: Summary and Recommendations
Volume 2: Main Report
Volume 3: Appendices
– 2000 (available to non-participants on request)

Hydropower and the Environment: Effectiveness of Mitigation Measures – 2000 (available to non-participants on request)

Education and Training Task Force (Annex 5)

All of the following reports are available on the Internet at www.annexv.iaea.org (some reports may consist of more than one volume)

Summary of Results of the Survey of Current Education and Training Practices in Operation and Maintenance – 1998 (available to non-participants on request)

Development of Recommendations and Methods for Education and Training in Hydropower Operation and Maintenance – 2000 (available to non-participants on request)

Survey of Current Education and Training Practice in Hydropower Planning – 1998 (available to non-participants on request)

Structuring of Education and Training Programmes in Hydropower Planning, and Recommendations on Teaching Material and Reference Literature - 2000 (available to non-participants on request)

Guidelines for Creation of Digital Lectures – 2000 (available to non-participants on request)

Evaluation of Tests – Internet-based Distance Learning – 2000 (available to non-participants on request)

Brochure

A brochure is available for the general public. Entitled "Hydropower – a Key to Prosperity in the Growing World", it can be found on the Internet (www.usbr.gov/power/data/data.htm) or be obtained from the Secretary. (address on the inside back cover)

TABLE OF CONTENTS

ACKNOWLEDGMENTS	ix
PREFACE	1
INTRODUCTION	5
1 CLASSIFICATION OF HYDROPOWER PROJECTS	11
1.1 Hydropower and Electricity Supply	11
1.2 Types of Hydroelectric Projects	14
1.2.1 Run-of-River-Type Projects	16
1.2.2 Reservoir Type Projects	17
1.2.3 Pumped-Storage Type	18
1.2.4 Small, Mini and Micro Projects	19
1.2.5 Upgrading Projects	21
1.2.6 River Diversion Projects	22
1.2.7 Multipurpose Projects	23
1.3 Conclusion	25
References	26
2 TRENDS IN HYDROPOWER DEVELOPMENT	27
2.1 The Playing Field	27
2.2 Restructuring of Electricity Markets Worldwide	28
2.2.1 Restructuring – A Global Phenomenon	28
2.2.2 The Electricity Sector – Then and Now	28
2.2.3 Characteristics of the Restructured Markets	29
2.2.4 Consequences for Hydropower and the Environment	30
2.3 Trends in Planning	31
2.3.1 Old Approach	31
2.3.2 New Approach	32
2.4 Increased Role of Private Developers	34
2.4.1 Trends for the Financial Viability of Hydropower Projects	35
2.4.2 Emerging Conflicts Between Economic and Financial Planning	37
2.4.3 Improved Optimization of Projects in System Context	37
2.4.4 Improved Probabilistic Investment Analysis and Risk Avoidance Tools	38
2.4.5 Decrease in Comprehensive Field Investigations	38
2.5 Environmental Trends	39
2.5.1 Trend to Integrate Environmental Assessment (EA) into the Planning and Design of Hydropower Projects	39
2.5.2 Trend to Quantify Environmental Costs and Benefits	39
2.5.3 Growing Recognition of Hydropower as a Means to Limit Global Warming	41
2.6 Trends in Design	42
2.6.1 Design of Hydropower Infrastructures	42

2.6.2	Design Tools	44
2.6.3	Design Work by Utilities, Contractors and Manufacturers	44
2.6.4	Quality Insurance by Independent Panel of Experts	44
2.7	Trends in Construction	45
2.7.1	Overall Project Management	45
2.7.2	Inclusion of Resettlement and Environmental Mitigation	45
2.7.3	Influx of Workers	45
2.7.4	Monitoring by Independent Panel of Experts	45
2.7.5	Training of Operator Personnel	45
2.8	Trends in Operation	45
2.8.1	Project Operation and Maintenance	45
2.8.2	Project Operation During Abnormal Events	46
2.8.3	Outsourcing Operation and Maintenance	46
2.8.4	Safety Inspections	46
2.8.5	Monitoring of Environmental and Social Impacts	46
2.9	Rehabilitation and Upgrading of Existing Dam Projects	46
2.9.1	Review of Safety	46
2.9.2	Upgrading Existing Dam Projects	46
2.10	Long Term Trends	47
2.10.1	Increasing Importance of Water Rights	47
2.10.2	Increasing Difficulty for Vulnerable People to Pay for Water	47
2.10.3	Prospects for Pumped Storage Plants	47
2.11	Summary Table on Trends	47
2.12	Conclusions	49
	References	50
3	COMPARATIVE ENVIRONMENTAL ANALYSIS OF POWER GENERATION OPTIONS	51
3.1	Introduction	51
3.2	Methodological Issues Related to the Comparison of Power Generation Systems	51
3.2.1	Potential Uses of Life-Cycle Assessment (LCA)	51
3.2.2	Main Atmospheric Issues Covered by Life-Cycle Assessments	53
3.2.3	Reliability of Generation Systems, a Criteria for Rigorous Comparisons	53
3.2.4	Main Types of Electricity Generation Systems Considered	55
3.2.5	Evaluation of Windpower Electric Service and its Impacts on Backup Options	56
3.3	Results of Life-Cycle Assessments	57
3.3.1	Life-Cycle "Energy Payback Ratio"	57
3.3.2	Contribution to Climate Change: Life-Cycle Greenhouse Gas (GHG) Emissions	60
3.3.3	Land Requirements	64
3.3.4	Contributions to Acid Precipitation: Life-Cycle Sulfur dioxide (SO ₂) and Nitrogen Oxide (NO _x) Emissions	67
3.3.5	Contributions to Photochemical Smog: Life-Cycle NO _x Emissions and Volatile Organic Compounds (VOC)	72
3.3.6	Emissions of Particulate Matter (PM)	75
3.3.7	Emissions of Mercury (Hg)	77

3.4	Integration of Life-Cycle Environmental Impacts	79
3.4.1	Integration of Impacts on Human Health	79
3.4.2	Integration of Impacts on Biodiversity	80
3.5	Conclusions on Main Issues	82
	References for Tables 9 to 17	84
4	REVIEW OF THE MOST EFFECTIVE MITIGATION MEASURES	87
4.1	Introduction	87
4.2	Biophysical Issues	87
4.2.1	Reservoir Impoundment	87
4.2.2	Loss of Biological Diversity	91
4.2.3	Reservoir Sedimentation	92
4.2.4	Modifications to Water Quality	93
4.2.5	Modifications to Hydrological Regimes	95
4.2.6	Barriers for Fish Migration and River Navigation	96
4.3	Socioeconomic Issues	98
4.3.1	Involuntary Displacement	98
4.3.2	Public Health Risks	100
4.3.3	Impacts on Vulnerable Minority Groups	103
4.3.4	Sharing of Development Benefits	104
	References	107
5	ETHICAL CONSIDERATIONS	109
5.1	Value Systems	109
5.1.1	Differing Views of Human Relations	109
5.1.2	Ethics of Conviction, Ethics of Responsibility, Ethics of Discourse	110
5.2	Learning from Experience	111
5.2.1	Water, a Precious Resource	111
5.2.2	Dams Have Improved Living Conditions	112
5.2.3	Dams Have Harmed Watersheds and Scattered Communities	112
5.3	Ethical Dilemmas	112
5.3.1	Protection of Nature and Satisfaction of Essential Human Needs	112
5.3.2	Distribution of Wealth	114
5.3.3	Rights of Affected People	114
5.3.4	Diversity of Rules and Cultural Differences	115
5.4	Ethical Principles	116
5.4.1	Entrusting and Stewardship (responsible management)	116
5.4.2	Participatory Decision Making	117
5.4.3	Prudence and Control	117
5.4.4	Fairness and Justice	117
5.4.5	Optimality	118
5.5	Conclusions	119
	References	120

6	LEGAL AND REGULATORY FRAMEWORK	121
6.1	Introduction	121
6.2	Method and Objectives	122
6.2.1	Review of Literature Assessing Environmental Impact Assessment Processes	122
6.2.2	Principles of International Environmental Law and Sustainable Development	122
6.2.3	Five Common Ethical Principles as a Common Ground for Analysis	122
6.3	Analysis, Findings and Assessment of Legal Mechanisms	123
6.3.1	Policy Level	124
6.3.2	Project Planning Stage	126
6.3.3	Implementation Stage	134
6.3.4	Operation Stage	135
6.3.5	Upgrading, Relicensing and Decommissioning Stages	136
6.4	Conclusions	137
6.4.1	General Remarks	137
6.4.2	Governments	138
6.4.3	Non-Governmental Organizations	138
6.4.4	Proponents	139
	References	140
7	SUMMARY AND RECOMMENDATIONS	143
7.1	Introduction	143
7.2	Lessons Learned	144
7.2.1	Recent Trends in Hydropower Development	144
7.2.2	Comparative Environmental Analysis of Power Generation Options	145
7.2.3	Comparative Life-cycle Environmental Performance of Hydropower	147
7.2.4	Environmental and Social Impacts of Hydropower: State of Knowledge and Challenges	149
7.2.5	Ethical Considerations	152
7.2.6	Legal and Regulatory Frameworks and Decision-making Issues	154
7.3	Recommendations	155
	Recommendation # 1	
	Energy Policy Framework	156
	Recommendation # 2	
	Decision-making Process	158
	Recommendation # 3	
	Comparison of Hydropower Project Alternatives	162
	Recommendation # 4	
	Improving Environmental Management of Hydropower Plants	167
	Recommendation # 5	
	Sharing Benefits with Local Communities	170

TABLE

1: Average Size of Hydro Reservoir per Unit of Capacity	20
2: Trends in the Planning of Hydropower Projects	33
3: Competitiveness of Hydro	36
4: Summary of Trends in the Electricity Business and the Environment.....	47
5: Potential Uses of LCAs	52
6: Summary of Atmospheric Issues and Pollutants Involved	53
7: Ancillary Services Related to Electricity Supply Options	54
8: Main Generation Systems Considered, with their Expected Level of Service	55
9: Life-Cycle Energy Payback Ratio	58
10: Major Greenhouse Gases Affecting Assessment of Energy Systems	61
11: Life-Cycle Greenhouse Gas Emissions (kt eq. CO ₂ /TWh)	62
12: Land Requirements (km ² /TWh/y)	66
13: Life-Cycle SO ₂ Emissions (t SO ₂ /TWh)	68
14: Life-Cycle NO _x Emissions (t NO _x /TWh)	70
15: Life-Cycle NMVOC Emissions (t/TWh)	74
16: Life-Cycle Total Particulate Matter Emissions (t/TWh)	76
17: Mercury Emissions at Plant (kg Hg/TWh)	78
18: Chain of Effects Between Each Pollution and Human Health	79
19: Main Systems, with Final Impacts on Human Health	80
20: Main Energy Systems, with Final Impacts on Biodiversity	81
21: Synthesis of Environmental Parameters for Energy Options (Life-cycle Assessment)	83
22: Legal Instruments Associated with the Policy Level	124
23: Detailed Description of a Project	126
24: Screening	127
25: Class Assessment	127
26: Terms of Reference and Scoping	128
27: Common Assessment	129
28: Public Participation and Public Hearing	130
29: Mandatory Deadlines/Time Frame of the Process	131
30: Inter-Agency Committee	132
31: Approval of the EA by Government Authorities	132
32: Authorization of Project by Government Authorities	133
33: Legal Instruments Associated with Implementation	134
34: Legal Instruments Associated with Operations	135
35: Legal Instruments Associated with Upgrading, Relicensing and Decommissioning	136
36: Synthesis of Environmental Parameters for Electricity Options	148

FIGURE

1: 1973 and 1995 Fuel Shares of Electricity Generation, Worldwide	6
2: Principle of a Hydropower Plant	11
3: Example of daily change in electricity demand for nine electric power companies, 1975-1995, Japan	12
4: Example of annual change in electricity demand for nine electric power companies, 1967-1995, Japan	12
5: Cross-section of the Kitinen river in northern Finland	17
6: Context for Hydropower Development	27
7: Short-term Variations in Wind Production	56

PHOTO

1: Tadami Power plant – a low head project in Japan	14
2: Altadammen – a high head project in Norway	14
3: Pesqueru – a run-of-river project in Spain	14
4: Orellana – a reservoir project in Spain	14
5: Brisay – a single purpose project in Québec, Canada	14
6: Freudenau – a multipurpose project in Vienna, Austria	14
7: A large hydropower reservoir: Suvanto, Finland	15
8: A mini hydro project: Kotaway in Indonesia	15
9: Kamaushi – a low head run-of-river power station in Japan	16
10: Nore power station – a high head run-of-river plant in Norway	16
11: River flow and run-of-river production, Rivière-des-Prairies in Québec, Canada	17
12: Numappara – a pumped-storage plant in Japan	19
13: Small weir in reduced-flow river, Norway	23

The views presented in this report do not necessarily represent the views
of the International Energy Agency, nor the governments represented therein.

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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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., SO₂) 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.

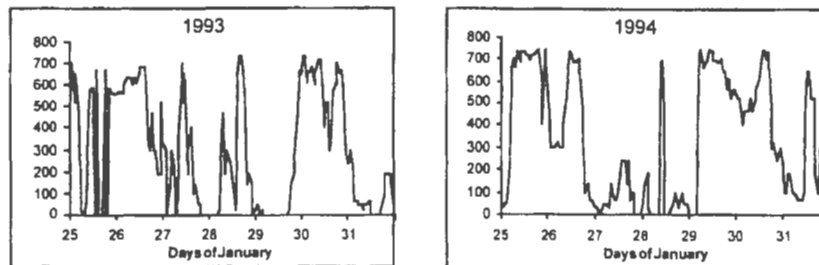
Since LCA focuses on energy produced, this means that systems designed mainly or exclusively to add capacity cannot be included fairly. For example, a project designed to increase the capacity of a hydropower plant may not increase the energy produced and would therefore have an infinite level of environmental 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)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	World	Europe			Asia
		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 ¹	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	<ol style="list-style-type: none"> 1 Calculated from cited data. Do not include all the life cycle, only the production of a photovoltaic 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 CO₂ removal, 2nd & 3rd for conventional and advanced technologies. 					

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

Electricity Generation Options (classified by level of service)	North America					Comments
	USA, Cornell U., Pimentel et al., 1994	USA, FTI, U. of Wisconsin-Madison, White & Kulinski, ¹¹ 1999	Canada, Enviro-science Inc., Bélanger, ¹² 1995	Canada, Hydro-Québec, Peisajovich, 1997	Canada, U. of Guelph, Gingerich and Hendrickson, ¹⁵ 1993	
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 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 & Kulinski 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.
<p>8 Includes reservoirs for other uses (flood control, drinking water, storage, irrigation).</p> <p>9 Energy plantation.</p> <p>10 1994 or earlier turbines on a favorable site. Do not include O & M.</p> <p>11 Wind project sizes ranging from 2 turbines (1.2 MW total; EPR 17) to 143 turbines (107 MW total; EPR 39).</p> <p>12 Energy plantation. Value calculated for a transportation distance of 40 km.</p> <p>13 Mean of 3 large projects in Quebec.</p> <p>14 Beauharnois (Quebec) power plant.</p> <p>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).</p>						

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 CO₂ 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 CO₂ equivalent. This means that CO₂ 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 CO₂. In LCAs, each greenhouse gas is converted to an equivalent of CO₂ 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 ₂ O	310
Perfluoromethane	CF ₄	6 500
Perfluoroethane	C ₂ F ₆	9 500

CO₂ and CH₄ are directly related to energy systems and included in most studies. Any combustion will produce CO₂ and commercial natural gas is composed of 95% CH₄. 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 CO₂ is currently available and variations in emissions depend mainly on the efficiency of plants.

Table 11: Life-Cycle Greenhouse Gas Emissions (kt eq. CO₂/TWh) (1/2)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	World		Europe					Asia
		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 ¹¹	18 ¹³
Diesel	555 to 883		624/883 ^{1a}	555 ⁹		778			
Base load options with limited flexibility									
Hydropower run-of-river	1 to 18	9 ²						2 ¹¹	18 ¹³
Bituminous coal: modern plant	790 to 1 182		823 to 1074 ^{1a}	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 ²	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	17 to 118	17 to 27 ³							
Biomass: Forestry waste combustion	15 to 101	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:	<ol style="list-style-type: none"> 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%. 								
UF: use factor									
UCPTE: <i>Union pour la coordination de la production et du transport de l'électricité</i>									
GHG: greenhouse gas									

Table 11: Life-Cycle Greenhouse Gas Emissions (kt eq. CO₂/TWh) (2/2)

Electricity Generation Options (classified by level of service)	North America							Comments
	USA, FTI, U. of Wisconsin, White & Kudnski, ¹⁶ 1999	USDOE, Argonne National Laboratory, ¹⁷ 1992	USA, NDCEE, ¹⁸ 1997	Canada, Hydro-Québec, a: Gagnon 1999 & b: Béjanger, 1998	Canada, FFCC, 1995	Canada, SEEDA, 1994	USEPA, AP-42, 1998 & 1999	
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 ²¹ (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 Biomass: Forestry waste combustion						118 ²⁰ 15 / 101 ²¹		Values highly dependent on wood quality and on conditions of exploitation (transportation distance, etc.).
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.
	<p>16 CO₂ emissions only. Wind project sizes ranging from 2 turbines (1.2 MW; high emissions) to 143 turbines (107 MW; low emissions).</p> <p>17 200 kW, thermal efficiency 40 – 60%, life 5 y.</p> <p>18 200 kW, thermal efficiency >40%, 85% if heat is recovered.</p> <p>19 GHG emissions from reservoir included from preliminary research. (Data is site specific, not averaged.)</p> <p>20 Poplar plantation (Data is site specific, not averaged.)</p> <p>21 1st value for soft wood waste, 2nd for loggin residue, both excluding emissions at plant. (Data is site specific, not averaged.)</p> <p>22 Class 7 & 6 wind sites. (Data is site specific, not averaged.)</p> <p>23 Thermal efficiency 35%.</p> <p>24 Medium-volatile bituminous, thermal efficiency 35%.</p> <p>25 Thermal efficiency 35%.</p> <p>26 Thermal efficiency 45%.</p>							

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 km²/TWh/y is required for waste disposal, multiplied by 30000 years, applied to 30 years of generation, the factor would increase from 0,5 km²/TWh/y to 100 km²/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* (km²/TWh/y)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	World		North America				Comments
		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	
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 ¹			110	Values represent total reservoir area, not flooded area. Values highly dependent on site characteristics. 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		1 10 MW/km ² , with a UF of 25% and 95% availability.						
Lat. Am.: Latin America		2 Matane (Canada) project, includes a reserved edge zone.						
* Data for each year of production, life-span have no effect on factors.		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 (SO₂) 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 SO₂, 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 SO₂ 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 SO₂

When looking at the next table on SO₂ emissions, the reader should keep in mind that SO₂ 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 SO₂ 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 SO₂ emissions. But these technologies have been implemented only in a few countries such as Japan.

Table 13: Life-Cycle SO₂ Emissions* (t SO₂/TWh) (1/2)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	World		Europe				North America
		IEA, "Benign Energy?" 1998	ETSU, UK, IER and Enco, 1995	Switzerland, PSI, Dones et al., 1996	UK, ETSU, Bates, ⁷ 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 ⁴	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 ⁴		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 :		<ol style="list-style-type: none"> 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. 						
<p>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</p> <p>* Most of life cycle SO₂ 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 SO₂ are indicated in this table.</p>								

Table 13: Life-Cycle SO₂ Emissions (t SO₂/TWh) (2/2)

Electricity Generation Options (classified by level of service)	North America (cont'd)				Comments
	Canada, SECD, 1994	Canada, FFCC, 1995	Canada, Theoretical calculations, Bélanger, 1999	USEPA, AP-42, 1998 & 1999	
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 ¹¹	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)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	World		Europe				North America
		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 ¹						
Bituminous coal: modern plant	700 to 5 273+		1 000/700 ⁴	1 400 ¹	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 ⁴	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 ¹						
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 ¹		150 ¹				
Acronyms:		<ol style="list-style-type: none"> 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 UCPTC countries in 2005-2015. 9 3 kW. 10 Transmission and distribution included. 						
<p>FGD: flue-gas desulfurization SCR: selective catalytic reduction UCPTC: Union pour la coordination de la production et du transport de l'électricité</p> <p>* 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.</p>								

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

Electricity Generation Options (classified by level of service)	North America (cont'd)					Comments
	USDOE, Argonne National Laboratory, 1992	Canada, Hydro-Québec, Gagnon, 1999a	Canada, SECD, 1994	Canada, FFCC, 1995	USEPA, AP-42, 1998 & 1999	
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 ¹⁴ (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.
	<p>11 Poplar plantation. (Data is site specific, not averaged.)</p> <p>12 1st value for soft wood waste, 2nd for loggin residue. (Data is site specific, not averaged.)</p> <p>13 Class 7 & 6 wind sites. (Data is site specific, not averaged.)</p> <p>14 Thermal efficiency 35%.</p> <p>15 Thermal efficiency 45%.</p> <p>16 Thermal efficiency 42%.</p>					

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 SO₂ and NO_x, coal, oil and diesel based generation systems are important contributors to acid precipitation.

Biomass has a low emissions factor for SO₂ 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 SO₂, 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)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	Europe			North America			Comments
		Switzerland, PSI, Dones et al., 1996	UK, ETSU, Bates, ¹ 1995	Germany, ÖKO Inst., Fritsche, 1992	USA, NDCEE, ² 1997	Canada, FFCC, 1995	Canada, SECCA, 1994	
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								
Biomass: Forestry waste combustion	89+						89 ⁵ (plant only)	Values highly dependent on wood quality and on conditions of exploitation (transportation distance, etc.).
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.
		<ol style="list-style-type: none"> 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)

Electricity Generation Options (classified by level of service)	Range of Life-Cycle Values	World		Europe		North America			Comments
		IEA, "Benign Energy?" 1998	ETSU, UK, IER and Enco, 1995	UK, ETSU, Bates, ⁵ 1995	Germany, ÖKO Inst., Fritzsche, 1992	USA, NDCCE, 1997	USDOE, Argonne National Lab., 1992	Canada, SEEDA, 1994	
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 ⁴	
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 ⁶						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.

- 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)

Electricity Generation Options (classified by level of service)	Range of Values	Europe		North America			Comments
		Switzerland, PSI, Dones et al., 1996	Canada, Hydro-Québec, Gagnon, ⁷ 1999b	Canada, Lui et al. Canadian Electricity Ass., 1994	USEPA, 1997	USEPA, AP-42, 1998 & 1999	
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 ¹	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 ¹	2 ⁴	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	0,5 to 2				0,5 / 1,4 ⁷	2 ¹⁰	
Biomass: Forestry waste combustion							
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	<ol style="list-style-type: none"> 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) <p>Means of measured values. Wide range due to variable Mercury concentrations in fuel and control systems:</p> <ol style="list-style-type: none"> 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. <p>Mean of measured values at 28 facilities burning bituminous coal (11), subbituminous coal (15) and lignite (2), with different control systems:</p> <ol style="list-style-type: none"> 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 ₂ SO ₄ 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 O ₃) → →	→ →	Direct toxic/carcinogenic 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	<ul style="list-style-type: none"> • Main issue: breach of dams • Risks from water-borne diseases, particularly when there is irrigation
Diesel	<ul style="list-style-type: none"> • Climate change • Acid precipitation • Photochemical smog • Particulate matter
Base load systems with some flexibility	
Hydropower run-of-river	<ul style="list-style-type: none"> • Main issue: breach of dams
Coal	<ul style="list-style-type: none"> • Climate change • Acid precipitation • Photochemical smog • Particulate matter • Toxic metals
Heavy oil	<ul style="list-style-type: none"> • Climate change • Acid precipitation • Photochemical smog • Particulate matter
Nuclear	<ul style="list-style-type: none"> • Radioactive substances
Natural gas turbines	<ul style="list-style-type: none"> • Climate change • Acid precipitation • Photochemical smog
Intermittent systems that need a backup production	
Windpower	<ul style="list-style-type: none"> • Depends on which backup system is used (oil or hydro)
Solar photovoltaic	<ul style="list-style-type: none"> • 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 scales⁴: 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. Franklin⁵ equally proposes that the protection of biodiversity be focused upon ecosystems, and not on individual habitats.

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	<ul style="list-style-type: none"> • Barriers to migratory fish • Loss of terrestrial habitat • Change in water quality • Modification of water flow 	X X X X		
Diesel	<ul style="list-style-type: none"> • Climate change • Acid precipitation 	X X	X	X
Base load systems with some flexibility				
Hydropower run-of-river	<ul style="list-style-type: none"> • Barriers to migratory fish 	X		
Coal	<ul style="list-style-type: none"> • Climate change • Acid precipitation • Mining and transportation of coal 	X X X	X	X
Heavy oil	<ul style="list-style-type: none"> • Climate change • Acid precipitation 	X X	X	X
Nuclear	<ul style="list-style-type: none"> • Radioactive substances 	X		
Natural gas turbines	<ul style="list-style-type: none"> • Climate change • Acid precipitation 	X X	X	X
Intermittent systems that need a backup production				
Windpower	<ul style="list-style-type: none"> • Risks for some species of birds • Depend on which backup system is used (oil or hydro) 	X (?)	(?)	(?)
Solar photovoltaic	<ul style="list-style-type: none"> • 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)	NM VOC 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		190 to 212	
Biomass: Forestry waste combustion	27	15 to 101	0,9+	12 to 140	701 to 1 950	89+	217 to 320	0,5 to 2
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	

References for Tables 9 to 17

- Argonne National Laboratory. 1992 (Consulted July 2nd, 1999). "Technology Summary A.7 : Fuel Cells". Technical Data summarized for the U.S. Department of Energy. <http://www.energyanalysis.anl.gov/a-fossil.htm>, pp. 13-14.
- DWTMA. 1997. *The Energy Balance of Modern Wind Turbines*. Windpower Note, No. 16. 16 pages.
- Bates, J. 1995. *Full Fuel Cycle Atmospheric Emissions and Global Warming Impacts from UK Electricity Generation*. ETSU-R-88, Harwell, 37 p. + App.
- Bélanger, C. 1995. *Analyse environnementale des options de production utilisant la biomasse forestière*. Prepared by Enviro-science inc. for Hydro-Québec, 42 p.
- Bélanger, C. 1998. "Cycles de vie du gaz naturel et du charbon – Fiches techniques". Hydro-Québec. Data compilation from many authors, mult. pag.
- Dones, R. et al. 1996. *Project GaBE : Comprehensive Assessment of Energy Systems – Environmental Inventories for Future Electricity Supply Systems for Switzerland*. Paul Scherrer Institut, PSI Bericht Nr. 96-07, 141 p.
- EEE, UK and Enco. 1995. "ExternE – Externalities of Energy, Vol. 6: Wind & Hydro". European Commission, EUR 16525 EN.
- ETSU, UK and IER, D. 1995. "ExternE – Externalities of Energy, Vol. 3: Coal & Lignite and Vol. 4 : Oil & Gas". European Commission, EUR 16522 EN and EUR 16523 EN.
- Fritsche, U. 1992. "TEMIS – A computerized tool for energy and environmental fuel & life cycle analysis – Current status and perspectives". ÖKO-Institut e.V., Darmstadt/Freiburg, Expert Workshop on life-cycle analysis of energy systems, Methods and experience. Paris, France, May 21-22 1992, pp. 103-111.
- FFCC. 1995. "Full Fuel Cycle Emission Analysis for Existing and Future Electric Power Generation Options in Alberta, Canada". Full Fuel Cycle Consortium, 62 p.
- Gagnon, L. and J.F. van de Vate. 1997. *Greenhouse gas emissions from hydropower – The state of research in 1996*. Hydro-Québec and IAEA, Energy Policy, Vol. 25, No. 1, pp. 7-13.
- Gagnon, L. 1999a. Hydro-Québec, Strategic Planning Unit, Internal report.
- Gagnon, L. 1999b. Hydro-Québec, Strategic Planning Unit. Estimate of reservoir Mercury emissions based on study by N. Thérien et K. Morrison.
- Gingerich, J. and O. Hendrickson. 1993. "The theory of energy return on investment: A case study of whole tree chipping for biomass in Prince Edward Island". *The Forestry Chronicle*, Vol. 69, No. 3, pp. 300-306.
- Gipe, Paul. 1995. (Consulted July 8th 1999). "Overview of Worldwide Wind Generation". <http://keynes.fb12.tu-berlin.de/luftraum/konst/overview.html>.
- Godish, T. 1997. *Air Quality*. Lewis Publishers, 3rd Edition, 448 p.
- International Energy Agency. 1998. *Benign energy? The environmental implications of renewables*. OCDE, 122 pages + Appendix (<http://www.iea.org/tech/pubs/>).

Kivisto, A. 1995. *Energy payback period and carbon dioxide emissions in different power generation methods in Finland*. Lappeenranta University of Technology, Finland. Paper presented at the symposium: Into the Twenty-First Century : Harmonizing Energy Policy, Environment, and Sustainable Economic Growth, 18th International Association for Energy Economics International Conference, Washington DC, July 5-8.

Lehrhofer, J. 1995. "Energy parameters : definitions and data". Graz University of Technology, Austria. Paper presented at the symposium : Assessment of greenhouse gas emissions from the full energy chain for nuclear power and other energy sources, International Atomic Energy Agency, Vienna, 26-28 September. (Working material).

Lui, P.Y et al. 1994. *Étude du transport atmosphérique, de la transformation et des retombées du mercure*. Report prepared by Ontario Hydro Technologies for the Canadian Electricity Association. Report no 9237 G 950.

National Defense Center for Environmental Excellence (NDCEE). 1997. "Environmental Security Technology Certification Program (ESTCP) Validation Tasks – Phase II : Fuel Cell – Task 5 : DOD Guidebook for Evaluating Fuel Cell Technology". 47 pages + appendix.

Peisajovich, A.. 1997. *Étude de cycle de vie de l'électricité produite et transportée au Québec*. Direction principale Communication et Environnement, Hydro-Québec, 156 p. + Appendix.

Pimentel, D. et al. 1994. "Renewable energy: Economic and environmental issues". Cornell University, Ithaca NY. *BioScience*. Vol. 44 No. 8, September, pp. 536-547.

Quick, R. and J. Poy. 1998. *Demonstration of a Phosphoric Acid Fuel Cell Power Plant at an Ontario Hydro Facility*. Canadian Electric Association Projet No. 9333 G 1016, Prepared by Ontario Hydro Technologies.

SECDA. 1994. *Levelized cost and full fuel-cycle environmental impacts of Saskatchewan's electric supply options*. Saskatchewan Energy Conservation and Development Authority, Technology Group, SECDA Publication No. T800-94-004, 59 p.

Uchiyama, Y. 1996. *Life cycle analysis of electricity generation and supply systems, Net energy analysis and greenhouse gas emissions*. Central Research Institute of the Electric Power Industry, Japan. Paper presented at the symposium: Electricity, health and the environment: comparative assessment in support of decision making, International Atomic Energy Agency, Vienna, 16-19 October.

USEPA. 1997. *Locating and Estimating Air Emissions From Sources of Mercury and Mercury Compounds*. Office of Air Quality, Planning and Standards, EPA-454/R-97-012, multiple pag.

Vladu, I.F. 1995. *Energy chain analysis for comparative assessment in the power sector*. IAEA, Electricity, Health and the Environment: Comparative Assessment in Support of Decision Making, Vienna, 16-19 october. pp. 293-322.

World Energy Council (WEC). (Consulted July 8th, 1999). "Chapter 13 : Wind Energy – Commentary". http://www.worldenergy.org/wecgeis/members_only/registered/open.plx?file=publications/default/current_ser/wind.stm.

White, S.W. and G.L. Kulcinski. 1999. *Net Energy Payback and CO₂ Emissions From Wind-Generated Electricity in the Midwest*. Fusion Technology Institute, University of Wisconsin-Madison. Report prepared for Energy Center of Wisconsin, 72 p.