November 28, 2013

To whom it may concern:

In June of 2013, Manitoba Wildlands contracted Coldstream Consulting to conduct a life cycle assessment (LCA) of the proposed Keeyask Generation Station Project and to report the findings at the CEC public hearings. Coldstream proposed an LCA study that was based on the most applicable internationally accepted standards for LCA of civil engineering works and electricity production. Coldstream also developed Information Requests (IRs) to gather the required data for completion of the LCA study. As a part of the IRs, Coldstream developed a detailed data collection spreadsheet that requested data on each element in the Project Description.

The replies to the Round 1 IRs did not answer the specific requests that were made. Instead, Manitoba Hydro provided Manitoba Wildlands and Coldstream Consulting with a previously unpublished LCA study of the Keeyask Project. This LCA applied a streamlined approach in terms of the data that was used and the results that were calculated. The LCA study also employed a unique description of the project elements and the alignment of the scope of this document with the Project Description was not clear.

Coldstream Consulting then completed Round 2 IRs to attempt to align the LCA study with the Project Description. The replies to the Round IRs assured that the scope of the LCA was inclusive of all elements in the project description. At this point, a determination was made that it was impractical for Coldstream to complete an LCA study that aligned with the Project Description and was in conformance with the relevant standards as initially proposed. An alternative project was proposed in which Coldstream would complete a life cycle assessment protocol to guide future LCA efforts by Manitoba Hydro in developing the Environmental Impact Statement.

We applaud Manitoba Hydro's recognition that LCA is a useful tool for quantifying the environmental impacts of hydroelectric generation projects. We feel that future studies that are based on the proposed LCA protocol will provide greater return on investment by ensuring that the results allow conformance to EIS requirements.

Sincerely,

James Salazar and Matthew Bowick
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LIFE CYCLE ASSESSMENT (LCA) PROTOCOL FOR HYDROELECTRIC GENERATION STATION PROJECTS IN MANITOBA

Provided to the Clean Environment Commission
for the Keeyask Generation Project Proceedings

Prepared For:

MANITOBA WILDLANDS

Prepared By:

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November 28, 2013

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EXECUTIVE SUMMARY & ORGANIZATION OF PROTOCOL

This document is a proposed protocol for the use of life cycle assessment (LCA) as a tool to complete the Environmental Impact Statement (EIS) of proposed hydroelectric projects in the Province of Manitoba. The Canadian Environmental Assessment Agency (CEAA) EIS Guidelines and Keeyask Scoping Document, while not directly referring to LCA, both require impact calculations that are only possible with the completion of a database-driven LCA. Life cycle assessments of this nature are complex and should conform to the most relevant standards to ensure credibility with the public and scientific community. This protocol is thus based on internationally accepted standards for LCA of civil engineering works and electricity production.

PART I: TECHNICAL BACKGROUND INFORMATION

The first part of this protocol is a technical background document that defines industry best practice for LCA of hydroelectric projects.

CHAPTER 1: LIFE CYCLE ASSESSMENT METHODOLOGY

It is assumed that the reader has no prior experience with life cycle assessment methodology. A chapter on LCA methodology has been included which describes the basic framework and key issues that are addressed in the protocol. The four phases of LCA (goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation) are explained.

CHAPTER 2: LIFE CYCLE ASSESSMENT STANDARDS

Several key standards are applicable to this LCA protocol. The standards developed by the International Organization for Standardization (ISO) are the most universally accepted and are presented first. The protocol also references standards developed by the European Committee for Standardization (CEN) and product category rules (PCR) published by the International Environmental Product Declaration (EPD) System to further refine the ISO requirements.

Two guidance documents are presented for land use change impacts. The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories provides a general framework and formulae. The protocol developed by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the International Hydropower Association (IHA) for land-use change provides more specific long term guidance.

CHAPTER 3: HYDROELECTRIC GENERATION STATION LIFE CYCLE ASSESSMENT APPLICATIONS

Fulfilling the requirements of the EIS is one specific goal for hydroelectric generation LCA. This chapter presents a range of potential applications for LCA. Screening-level assessments are the least rigorous in terms of the scope and precision that is required. Communicating the results to the general public, as with the Environmental Impact Statement, increases the range of impacts that must be calculated for every element of the proposed project. A well-designed LCA may then serve as the basis for a Type III Environmental Product Declaration that may be used to market hydroelectricity internationally.

PART II: GUIDELINES FOR HYDROELECTRIC GENERATION STATION LIFE CYCLE ASSESSMENT AS PART OF AN ENVIRONMENTAL IMPACT STATEMENT

The second part of this protocol relates the standards-based LCA defined in Part 1 to the requirements of the Environmental Impact Statement. The four chapters in Part II define each of the four phases of an ISO-compliant LCA.

CHAPTER 4: REQUIREMENTS FOR LIFE CYCLE ASSESSMENT IN THE ENVIRONMENTAL IMPACT STATEMENT

The relevant portions of the Canadian Environmental Assessment Agency (CEAA) Environmental Impact Statement (EIS) Guidelines and Keeyask Scoping Document are presented to specify the requirements of the LCA. The EIS requirements dictate that the LCA includes a comprehensive accounting of air emissions and also includes water emissions, solid waste, and resource use. The requirements also call for the consideration of alternative means of electricity production which may be met with a literature review of previously published LCA studies.

CHAPTER 5: GOAL AND SCOPE DEFINITION

Based on the EIS requirements described in Chapter 4 and the standards presented in Part I, the goals and scope of the required LCA are defined. A recommended modular structure is presented that conforms to best practices and facilitates documentation.

CHAPTER 6: LIFE CYCLE INVENTORY

The life cycle inventory (LCI) phase is typically the most time and resource-intensive part of an LCA study. LCI data collection includes the surveying of quantity take-offs for constructed components and all activities caused by the construction, operation, and demolition of the facilities. The survey data is then imported into LCA-specific software, such as SimaPro[2] or GaBi[3], and linked to LCI databases for common materials, energy sources, and manufacturing processes. The current and projected landscape cover and associated emissions are also calculated in this phase. The modular structure presented in Chapter 5 and the organization of the Project Description are used to organize the LCI data collection.

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[2] http://www.pre-sustainability.com/simapro-lca-software
[3] http://www.gabi-software.com/

CHAPTER 7: LIFE CYCLE IMPACT ASSESSMENT

To maximize the value of the data that was gathered and accommodate the numerous project stakeholders, a wide range of impact indicators are recommended. The use of databases and LCA software in the life cycle inventory phase means the impact assessment phase is largely automated. Optional steps include grouping and weighting the individual results into a single index if the subjective elements are transparent.

CHAPTER 8: INTERPRETATION

The primary requirement of the EIS with regards to LCA is the documentation of the environmental impacts of the project that is largely met with the life cycle inventory and impact assessment described in Chapters 6 and 7. The EIS also requires mitigation strategies which may benefit from the use of LCA-based benchmarks and this process is described. Dynamic global warming representation is also proposed as a means to more fully understand the implications of the project's greenhouse gas emissions that includes significant amounts of methane. The limitations of the literature review as a comparison tool are also emphasized.

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LIST OF ABBREVIATIONS

CEAA	Canadian Environmental Assessment Agency
CEC	Clean Environment Commission
CEN	European Committee for Standardization
EN	European Standard
EIS	Environmental Impact Statement
EPD	Environmental Product Declaration
HGS	Hydroelectric Generation Station
HGS-LCA	Hydroelectric Generation Station Life Cycle Assessment
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
MH	Manitoba Hydro
PCR	Product Category Rules
SC	Sub-committee
SETAC	Society of Environmental Toxicology and Chemistry
TC	Technical Committee
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UNESCO	United Nations Educational, Scientific, and Cultural Organization

GLOSSARY OF TERMS

Based on ISO 14040/44:2006, ISO 21930:2007, ISO 14025:2006

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems

Characterization factor

Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator

Cradle-to-gate

A cradle-to-gate assessment considers impacts starting with extracting raw materials from the earth (the “cradle”) and ending at the plant exit “gate” where the product is to be shipped to the user. In-bound transportation of input fuels and materials to the plant is included. Out-bound transportation of the product to the user is not included. The use phase, maintenance and disposal phase of the product are also not included within the scope of a cradle-to-gate LCA.

Comparative assertion

Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function

Consumer

Individual member of the general public purchasing or using goods, property or services for private purposes

Elementary flow

Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation

Environmental aspect

Element of an organization's activities, products or services that can interact with the environment

Environmental impact

Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's environmental aspects

Environmental label / environmental declaration

Claim which indicates the environmental aspects of a product (3.11) or service

Functional unit

Quantified performance of a product system for use as a reference unit

Impact category indicator

Quantifiable representation of an impact category

Interested party

Person or body interested in or affected by the development and use of a Type III environmental declaration

Intermediate flow

Product, material or energy flow occurring between unit processes of the product system being studied

Life Cycle

Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal

Life Cycle Assessment (LCA)

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle

Life Cycle Impact Assessment (LCIA)

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product

Life Cycle Interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations

Product

Any good or service

Product category

Group of products that can fulfil equivalent functions

Product Category Rules (PCR)

Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories

Product system

Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product

Program operator

Body or bodies that conduct a Type III environmental declaration programme

Reference flow

Measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit

System boundary

Set of criteria specifying which unit processes are part of a product system

Third party

Person or body that is recognized as being independent of the parties involved, as concerns the issues in question

Transparency

Open, comprehensive and understandable presentation of information

Type III environmental declaration/Environmental product declaration (EPD)

Environmental declaration that provides quantified environmental data of a product, using predetermined parameters and, where relevant, additional environmental information (adapted from ISO 14025)

Type III environmental declaration programme

Voluntary programme for the development and use of Type III environmental declarations based on a set of operating rules

Verification

Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled

PART I: TECHNICAL BACKGROUND INORMATION

The first part of this protocol is a technical background document that defines industry best practice for *Life Cycle Assessment* (LCA) of hydroelectric projects.

Chapter 1 outlines the universally accepted methodological framework and requirements of LCA as stipulated in the *International Organization for Standardization* (ISO) standards 14040 and 14044.

Chapter 2 then summarizes the key aspects of other standards that apply directly to, or as a proxy for, Hydroelectric Generation Station LCA (HGS-LCA).

Chapter 3 presents some of the potential applications for HGS-LCA and discusses how differences in application influence the requirements of the LCA.

As a prescriptive protocol, this document uses technical language that is specific to the field. The reader is encouraged to move through Part I in its entirety before moving to Part II. If this is not possible, Chapter 1 provides a useful primer to explain the basic concepts of LCA. A glossary of terms and list of abbreviations has also been provided at the beginning of this document to be used as a reference.

CHAPTER 1: LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

Life cycle assessment, or LCA, generally refers to a “cradle-to-grave” approach for quantifying and interpreting environmental impacts associated with a product or service. “Cradle-to-grave” refers to all industrial processes from raw resource extraction through end of life. In quantifying the effects associated with each stage of the life cycle, LCA provides a comprehensive estimation of the cumulative environmental effects that are initiated by an economic decision - both upstream and downstream from the decision maker.

LCA as an analytical practice involves quantifying the energy and resource flows from nature (i.e. "inputs") as well as air, water, and land emissions back to nature (i.e. "outputs'). These flows, called *the life cycle inventory*, are quantified in terms of mass and energy balance relationships within industrial processes (calculated based on the law of conservation of energy and mass). The life cycle inventory is then related to the environmental impacts that they cause based on cause-effect models developed by scientists with expertise as to the drivers of sustainability issues (e.g. climate change experts, toxicologists, ecologists, etc.).

1.1 HISTORY OF LCA STANDARDIZATION

The history of LCA is important to consider in understanding the potential for its misuse and needing for standardization. Early LCAs were not conducive to replication as various methodologies were used to calculate material and energy flows and conversion to subsequent environmental impacts was often excluded. Many LCA studies were performed under marketing pressures and the manipulation of results by selective process and impact considerations meant that LCAs of the same products could arrive at drastically different conclusions. Based on this experience and a desire within the scientific community for comparability between studies, standards were established and a methodological framework emerged.

The *Society of Environmental Toxicology and Chemistry* (SETAC) made a major step toward standardization in 1993 when it published a *Code of Practice* (Consoli et al, 1993), which separated LCA into three distinct methodological phases: *Goal and Scope Definition*, *Life Cycle Inventory*, and *Life Cycle Impact Assessment*. These are described in detail in the following section (Section 1.2).

In the mid 1990’s, the *International Organization for Standardization* (ISO) sought to further define the practice. ISO established Subcommittee[5] 5 (SC 5), “Life Cycle Analysis”, of Technical Committee 207 (TC 207), “Environmental Management”, to author a new set of LCA standards. SC 5 published *ISO 14040: Environmental management - Life cycle assessment - Principles and framework* in 1997, which adopted the three phases established in the SETAC code and added *Interpretation* as a fourth. Between 1998 and 2000, requirements and guidelines of the methodological framework were subsequently published in the following standards:

[5] ISO Subcommittees and Technical Committees are chaired by a Secretariat and are tasked with the drafting of standards

- ISO 14041: Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis
- ISO 14042: Environmental management - Life cycle assessment - Life cycle impact assessment
- ISO 14043: Environmental management - Life cycle assessment - Life cycle interpretation

In 2006, ISO 14040 was revised and ISO 14041/14042/14043 were consolidated and revised as the new standard *ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines*. These two documents (ISO 14040:2006/14044:2006) are the universally accepted LCA standards that are currently in use.

1.2 THE LCA FRAMEWORK

The methodological framework presented in Figure 1 first appeared in ISO 14040:1997 and shows the logical relationship of the four LCA phases. The bi-directional arrows illustrate the iterative nature of LCA, a process by which the four phases are modified over the course of an assessment based on the interpretation of the findings in each phase.

Sections 2.2.1 through 2.2.4 outline some of the key concepts and requirements for each phase.

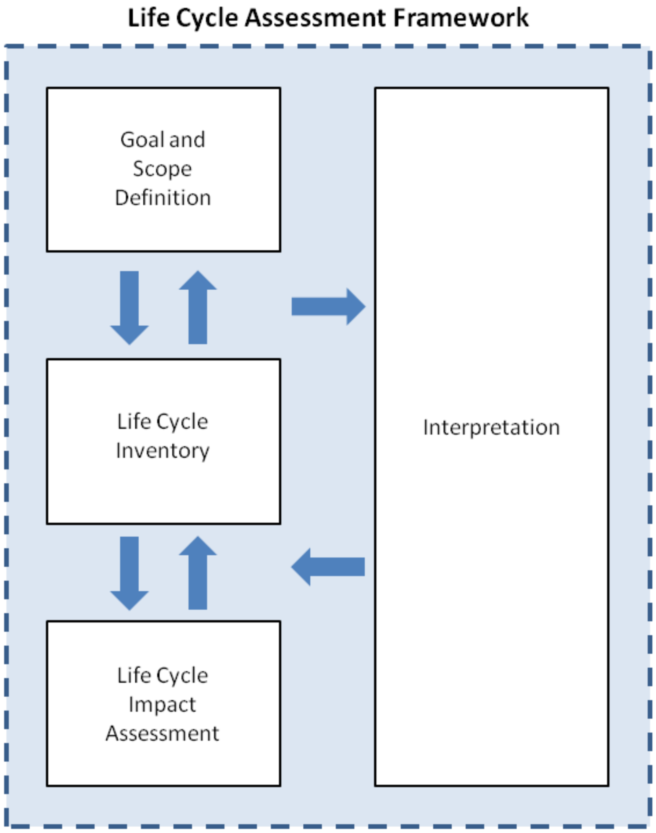

FIGURE 1: INTERNATIONAL STANDARD ISO 14040 FRAMEWORK FOR LIFE CYCLE ASSESSMENT

1.2.1 GOAL AND SCOPE DEFINITION

ISO 14040 identifies *Goal and Scope Definition* as a distinct phase of LCA as it has been recognized that the reasons for conducting a particular LCA influence the system models. ISO 14040 thus outlines the following four aspects of the goal definition that must be defined prior undertaking an LCA:

1. The intended application: how the LCA data will be used to inform greater sustainability objectives;
2. The reasons for carrying out the study: why an LCA is needed to fulfill information requirements;
3. The intended audience: to whom will the LCA results be communicated;
4. Comparative assertion: whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

According to ISO 14044, scope aspects to be defined in accordance with the established goals includes but is not limited to:

- The product system to be studied: the collection of processes occurring over the product life cycle included in study scope;
- The functional unit: the basis of comparison which can include a description of the product's functions, performance quality and duration, physical or spatial concerns;
- The system boundary: the demarcation between the product system of study and processes not in scope; evaluated based on mass, energy, and/or environmental significance cut-off criteria;
- Allocation procedures: the criteria by which inventory flows are partitioned between a process or the product system of study and one or more processes or other product systems; and can either be avoided, or based on physical relationships or other relationships such as economic value;
- LCIA methodologies and types of impacts: the methodologies by which life cycle inventory flows are to be evaluated;
- Interpretation to be used: the analyses to be conducted to ensure an accurate, credible study;
- Assumptions: includes the assumed scenarios required to model the life cycle of the product (e.g. fate of the product at end of life);
- Limitations: the exclusions from the analysis and uncertainty of the results that are calculated;
- Data quality requirements: the characteristics of the data needed to produce credible study results, including descriptions of age, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, and uncertainty;

The *functional unit* serves as the starting point for investigation into the *product system*. ISO 14044 defines a functional unit as “the quantified performance of a product system for use as a reference unit, i.e. it is the basis by which environmental information is reported and compared in an LCA". Functionality is typically derived from the use of multiple complimentary products that perform different functions. Thus, the life cycles of all the products and processes that are required for functionality combine to form the *product system* which is also referred to as the *object of assessment*.

1.2.2 LIFE CYCLE INVENTORY

In the *Life Cycle Inventory* (LCI) phase, data is collected for all of the material and energy flows of unit processes[6] determined to be within the system boundary of the product system.

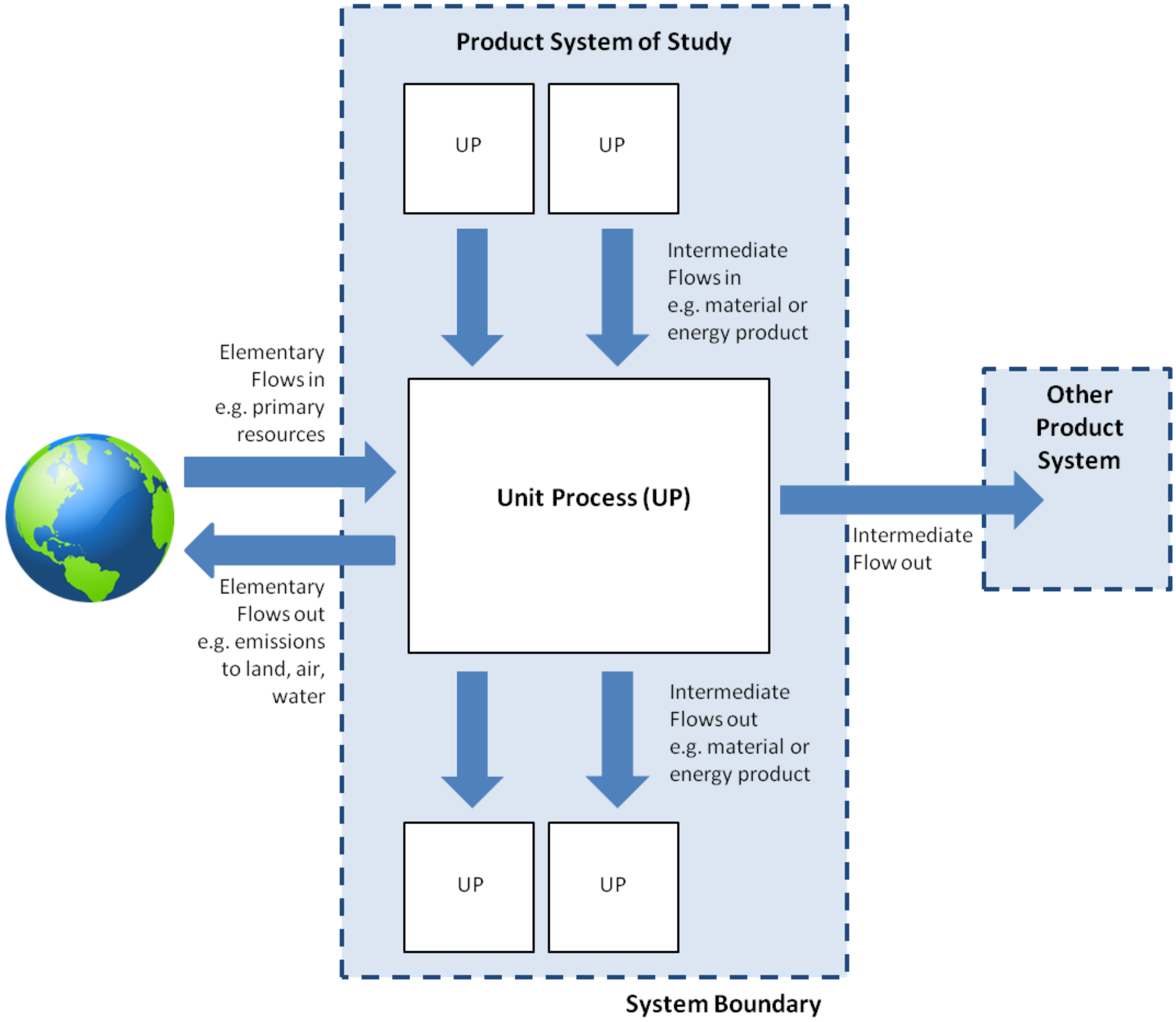

FIGURE 2: LIFE CYCLE FLOWS OF A UNIT PROCESS

Figure 2 presents a conceptual diagram of the flows of a unit process within the context of the product system. Flows that occur between processes that remain within the *technosphere*[7] are called

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[6] According to ISO 14044, a *Unit Process* is "the smallest element considered in the life cycle inventory analysis for which input and output data are quantified"

[7] The *technoshere* is that part of the physical environment which has been constructed or modified by humans.

intermediate flows (e.g. steel ingot inputs to a rebar manufacturer). Flows that cross the system boundary to or from earth are called *elementary flows*, and include raw material use (i.e. "inputs") and emissions to air, land, and water (i.e. "outputs"). The results of LCI are the cumulative totals of all elementary flows attributable to the product system. To calculate LCA results, all intermediate flows must be modeled back to their origin or fate in nature (or to their use in other product systems in which case *allocation* is applied to assign flows between the two product systems).

The LCI data collection is typically the most time consuming and resource intensive aspect of conducting an LCA and public and fee-based data sources are available for processes that are common to many products, particularly the production of commodities.

1.2.3 LIFE CYCLE IMPACT ASSESSMENT

In the *Life Cycle Impact Assessment* (LCIA) phase, the environmental impacts attributable to the product system are calculated. ISO 14040 specifies that all resource use, health consequences, and ecological consequences be grouped into impact categories to which an *impact category indicator*, or simply impact indicator, is calculated. The impact indicator value is found by multiplying the LCI values by *characterization factors* that relate the flows in the LCI to potential impacts.

Characterization factors are a second type of data that is available in the form of databases. These data sets are the result of specific modeling that relates emissions to environmental impacts (i.e. climate change models, toxicology estimates, etc.). Impact category indicators for which characterization factors have been published include global warming, stratospheric ozone depletion, acidification, aquatic eutrophication, terrestrial eutrophication, human toxicological effects, eco-toxicological effects, photo-oxidant formation, and abiotic resource depletion.

Optional elements of LCIA

ISO 14040/14044 recognizes that the optional step of *normalization* may help in interpreting LCA results. In normalization, the results are scaled based on the magnitude of the impact relative to the total amount of that impact that is caused by the economy as a whole. To normalize the result, the characterized impact indicator value is multiplied by a ratio that relates the potential impact to the per capita causation of that impact by an average person in a given year. Normalization does add uncertainty to the impact assessment results but helps identify which impact categories are significant in terms of the relative contribution to economy-wide impacts.

The normalized or non-normalized impact indicators may also be weighted based on the perception of their relative significance. Assigning weights is inherently subjective and may include valuation schemas that are specific to different types of results users. Weighting may be useful, however, because it allows the aggregation of numerous impact assessment results into one or a few metrics. Distilling the impact assessment results in this way allows the efficient consideration of results.

Weighting is most appropriate for internal decision making because this type of LCA weighs ease-of-use most heavily. Developing weighting factors for internal LCA use is also beneficial because it ensures a common valuation is applied by the various users of the LCA results. In all cases that weighting is used, ISO 14044 requires that the un-weighted impact assessment results are also presented along with the weights that are applied so that the results user may apply their own weighting and grouping. In the case of comparative assertions, ISO 14044 rejects the aggregation of impacts into weighted indices and requires a "sufficiently comprehensive set of category indicators".

1.2.4 INTERPRETATION

ISO 14040 distinguishes *Interpretation* as a distinct component of life cycle assessment. In this phase, the data and assumptions that critically influence the LCA results are examined in detail. The results are checked to ensure completeness and to test the sensitivity of assumptions made in the LCA. The boundaries and data quality are also checked to ensure consistency amongst materials. Finally, the results of the LCA study are described and reported in a manner that is meaningful to the proposed audience. This step should be given adequate attention as misinterpreted LCA results may result in less sustainable decision-making.

One fundamental concern of the interpretation phase is addressing the uncertainty that is present in the results. As with any data-intensive modeling, uncertainty in datasets ripples throughout the models and is often compounding. Calculating statistical uncertainty is atypical in LCA because this would require uniform and complete uncertainty reporting for all underlying LCI datasets. Life cycle inventory data is typically reported as an average or most likely scenario with no distribution given[8]. Despite this, partial uncertainty analysis is still potentially beneficial in recognizing significant deviation.

In the absence of statistical uncertainty estimation, *sensitivity analysis* is common to test the robustness of the LCA conclusions. Insignificant changes to the results in sensitivity analysis indicate the ability to exclude those alternatives as potentially contradictory to the conclusions of the study. Sensitivity analysis may also lead to the conclusion that some or even every result is strictly circumstantial.

Prior to the sensitivity analysis, it may be useful to first isolate the processes that have the potential to significantly influence results when the assumptions are changed. This allows the recognition of the modeling decisions that are critical to the results and makes possible the focus of greatest scrutiny to those found to be most significant. In *contribution analysis*, it may become clear that in a complex product system, consisting of hundreds of processes, that 95% or even 99% of the results are caused by just a few processes. Contribution analysis is also critical to identifying hotspots in the product system where mitigation efforts should be focused.

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[8] In cases in which uncertainty statistics are published, they are typically based on qualitative attributes that are assigned a numerical score, commonly referred to as a "pedigree matrix" approach

1.3 CRITICAL REVIEW

In LCAs that include a comparative assertion, ISO requires that a critical review be undertaken so that the conclusions of the study may be considered independent of any perceived biases of the LCA practitioner.

ISO 14044 notes that the critical review may be conducted by one or a panel of experts but does give preference to a critical review completed by a panel. ISO 14044 states “In order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public.”

ISO 14044 elaborates on the panel review by noting that “a critical review may be carried out as a review by interested parties. In such a case, an external independent expert should be selected by the original study commissioner to act as chairperson of a review panel of at least three members. Based on the goal and scope of the study, the chairperson should select other independent qualified reviewers. This panel may include other interested parties affected by the conclusions drawn from the LCA, such as government agencies, non-governmental groups, competitors and affected industries.”

1.4 LIMITATIONS

While LCA is a powerful tool for considering the impacts of decisions at a systems level, it is but one tool in the tool box that should be used for broader sustainability assessment. LCA is inherently limited by the use of generic LCI datasets that sacrifice spatial and temporal explicitness to be feasible. For example, there are no broadly accepted methods for inventorying “land use” in raw material extraction processes and as a result it is rarely calculated in LCA. Current research in LCA has made major strides in establishing accepted methodologies for inventorying land, water, waste, and flows that occur in different places and times. As a result, future LCI data will likely support this accounting and make such data available for life cycle impact assessment in LCA studies.

In addition to the limitations in LCI data, the LCIA phase must be somewhat spatially and temporally generic to aggregate the impacts of flows that occur throughout the life cycle.

The LCA practitioner must attempt to mitigate these uncertainties and communicate the limitations of the results to the intended audience.

CHAPTER 2: STANDARDS RELEVANT TO HYDROELECTRIC GENERATION STATION LCA

As noted in Section 1.1, the standards developed by ISO/TC 207/SC 5 (ISO 14040 and 14044) are the consensus standards for LCA practice. These standards, however, are only intended to serve as universal standards for LCA practice and are thus non-prescriptive in regards to the numerous modeling decisions required to complete an LCA. Figure 3 below and the rest of this chapter summarize the relationship between, and key aspects of, other published standards that apply directly to, or as a proxy for, *Hydroelectric Generation Station* (HGS) LCA.

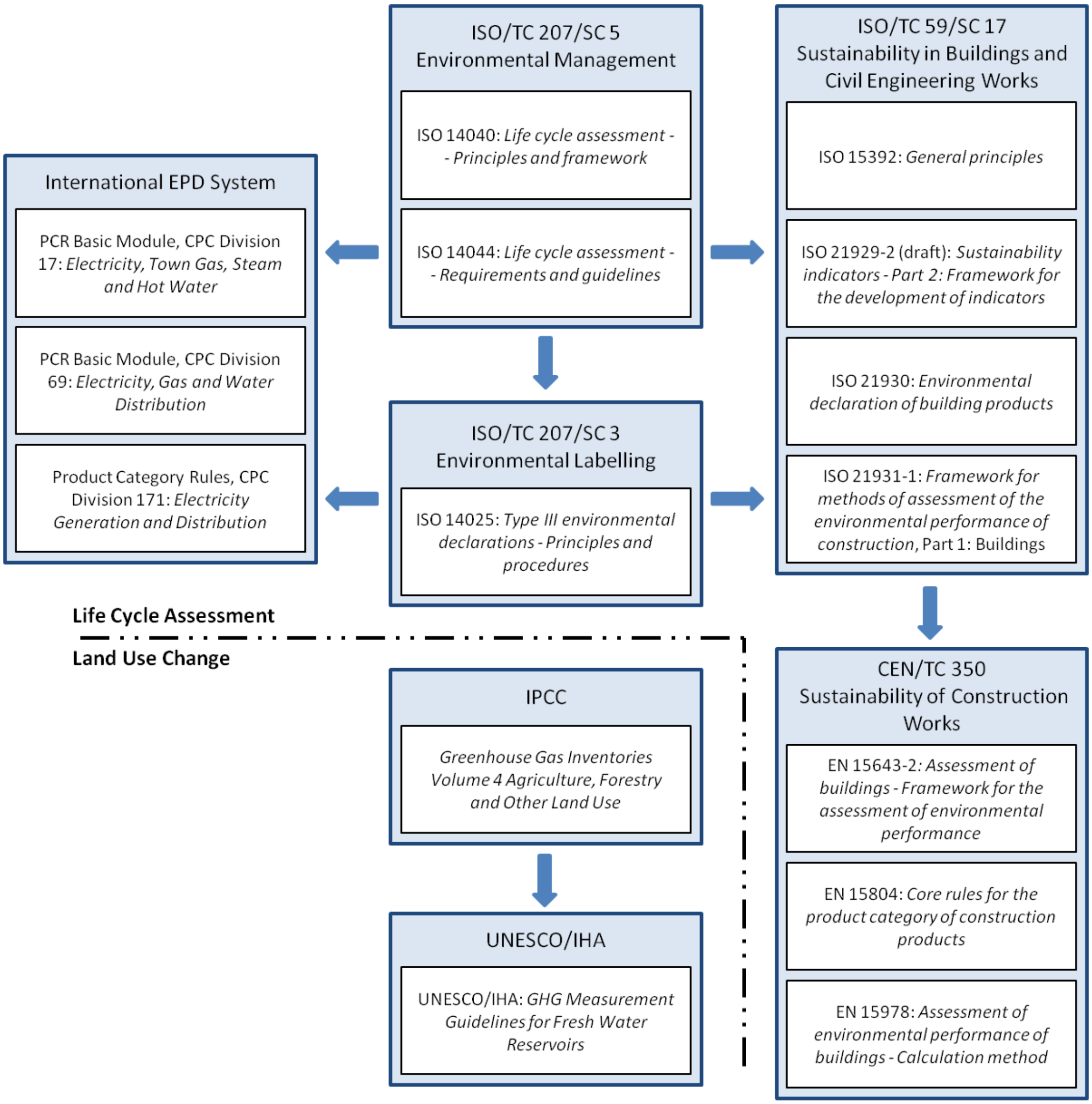

FIGURE 3: STANDARDS APPLICABLE DIRECTLY OR BY PROXY TO LIFE CYCLE ASSESSMENT OF HYDROELECTRIC GENERATION STATIONS

2.1 INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) STANDARDS

In addition to the standards developed by ISO/TC 207/SC 5 (ISO 14040 and 14044), ISO recognized that the wide range of potential applications for LCA requires sector-specific Technical Committees to further define LCA based on the expertise of professionals in that field. Section 2.1.1 summarizes the efforts to further standardize environmental product declarations while Section 2.1.2 summarizes efforts to define LCA of building and civil engineering works.

2.1.1 ENVIRONMENTAL PRODUCT DECLARATIONS (EPDS)

Type III Environmental Product Declarations (EPDs) are standardized documents that are increasingly being used to communicate the environmental performance of products. EPDs present quantified environmental data for products based on LCA that is conducted in accordance with sector-specific *Product Category Rules* (PCRs). PCRs define the common scoping elements and life cycle assumptions that are required to ensure that LCA results are comparable from one study to another.

ISO/TC 207/SC 3 published *ISO 14025: Environmental labels and declarations - Type III environmental declarations - Principles and procedures* to specify the application of the ISO 14040 series of standards in developing EPDs. ISO 14025 also outlines the procedures for establishing an EPD program and for developing PCRs. The key recognition in ISO 14025 is that interested parties with specific industry knowledge should be engaged to develop consensus scoping rules that EPD's in that product category must adhere to.

To date, more than 100 product category rules have been developed[10] and at least 10 different EPD programs have been established in North America[11].

2.1.2 SUSTAINABILITY IN BUILDING AND CIVIL ENGINEERING WORKS

ISO's Technical Committee (TC 59: Buildings and civil engineering works[12]) established Subcommittee 17 (SC 17: Sustainability in building and civil engineering works[13]) which has published several standards that further define the LCA framework. SC 17 initially focused on standards for buildings, as opposed to civil engineering works, as the spread of the green building movement worldwide was driving numerous building LCA studies without a harmonizing standard. SC 17 thus developed:

- ISO 15392: Sustainability in building construction, General principles
- ISO 21929-1: Sustainability in building construction, Sustainability indicators -- Part 1: Framework for the development of indicators and a core set of indicators for buildings

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[10] http://pcr-library.edf.org.tw/
[11] http://media.gednet.org/2013/05/2012_07_30_Report_PCR-in-the-US-Canada_Deliverable.pdf
[12] http://www.iso.org/iso/home/standards_development/list_of_iso_technical_committees/iso_technical_committee.htm?commid=49070
[13] http://www.iso.org/iso/home/standards_development/list_of_iso_technical_committees/iso_technical_committee.htm?commid=322621

- ISO 21930: Sustainability in building construction, Environmental declaration of building products
- ISO 21931-1: Sustainability in building construction, Framework for methods of assessment of the environmental performance of construction works, Part 1: Buildings

The evolution of standards published by SC 17 is such that ISO 15392 was first developed to define the application of sustainable development to the life cycle of buildings and other construction works. ISO 15392 "defines that sustainable development of buildings and other construction works bring(s) about the required performance with minimum adverse environmental impact, while encouraging improvements in economic, social (and cultural) aspects at local, regional and global levels".[14]

Upon the completion of this high-level framework, ISO 21929-1 was then developed to establish "a core set of indicators to take into account in the use and development of sustainability indicators for assessing the sustainability performance of new or existing buildings, related to their design, construction, operation, maintenance, refurbishment and end of life". ISO 21930 was then developed and complements ISO 21929 by establishing "a framework for and the basic requirements for product category rules as defined in ISO 14025 for type III environmental declarations of building products".[15] The purpose of ISO 21929-1, ISO 21930, and ISO 21931-1 can be summarized as follows:

- ISO 21929-1: criteria for building sustainability (environmental, economic, and social)
- ISO 21930: criteria, indicators, and reporting for LCA of building products
- ISO 21931-1: criteria and indicators for environmental sustainability of buildings

In 2013, SC 17 took the first step in expanding the suite of standards by addressing the specific sustainability issues of civil engineering works. SC 17 has recently completed the following draft that is now subject to public comment:

- ISO 21929-2.2: Draft on sustainability in buildings and civil engineering works - Sustainability indicators, Part 2: Framework for the development of indicators for civil engineering works

ISO 21929-2 mirrors ISO 21929-1 by providing the high level methodological basics under which a future standard (presumably ISO 21931-2) will be developed. In the absence of a specific standard that defines the framework for LCA of civil engineering works, we may draw many conclusions as to ISO's likely direction based on ISO 21929-2 and ISO 21931-1.

ISO 21929-2 defines the general sustainability principles that are of concern to interested parties of civil engineering works. ISO 21929-2 recognizes the following four environmental "issues of concern":

- Climate Change
- Depletion of Natural Resources

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[14] http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=40432
[15] http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=40435

- Environmental Pollution
- Biodiversity and Ecosystem

ISO 21929-2 also states that "when developing a system of environmental indicators of civil engineering works, the following environmental aspects shall be taken into consideration*":*

- Use of energy resources;
- Use of material resources, including production and management of wastes;
- Use of water;
- Land use;
- Emissions to air;
- Noise and vibrations;
- Emissions to water;
- Emissions to soil;
- Biodiversity of species and ecosystem;
- Landscape.

ISO 21929-2 indicates that ISO 21930 will be a common product-level standard for the construction materials that are used in both buildings and civil engineering works. ISO 21930 will thus provide specific guidance as to the underlying models on which an LCA of a civil engineering work should be developed. ISO 21930 provides an internationally accepted scope for decisions as to which LCIA categories should be supported for building sustainability metric analysis. ISO 21930 stipulates a number of mid-point LCIA characterization measures to be supported and, while not opposing end-point measures, dissuades their use until they are more internationally accepted. The measures advocated by ISO 21930 include:

- Climate change;
- Destruction of the stratospheric ozone layer;
- Acidification of land and water sources;
- Eutrophication;
- Formation of tropospheric ozone (photochemical oxidants);
- Depletion of non-renewable energy resources;
- Depletion of non-renewable mineral resources;

The indicators specified in ISO 29130 should be used to map the "environmental aspects" (e.g. sources) with four overarching areas of concern recognized in ISO 21929-2. Figure 4 shows the relationship between the requirements of ISO 21929-2 and the indicators of ISO 21930.

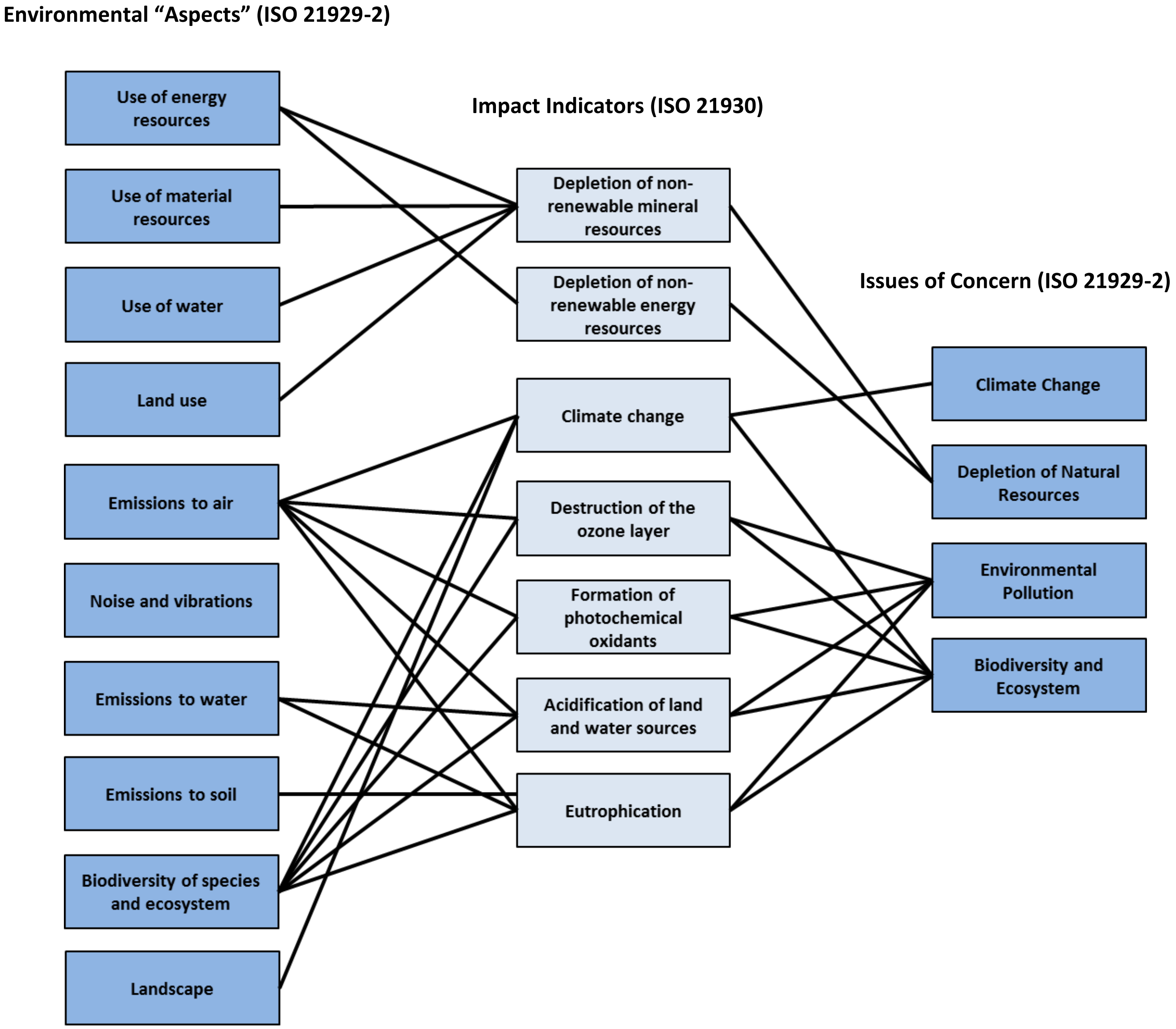

FIGURE 4: RELATIONSHIP BETWEEN ENVIRONMENTAL "ASPECTS" AND AREAS OF CONCERN FROM INTERNATIONAL STANDARD ISO 21929-2 AND INDICATORS SPECIFIED IN ISO 21930

The only environmental aspect not characterized under the impact indicators required by ISO 21930 is "noise and vibrations". No LCI datasets include this element as it is not a physical flow.

2.2 EUROPEAN COMISSION FOR STANDARDIZATION (CEN) STANDARDS

The ISO standards that have been described previously are considered an international consensus on LCA practice. The requirement of consensus, however, means that ISO does not address some of the modeling and reporting elements that are required for consistent LCA practice. The European Commission recognized the lack of harmonization and in 2005 established the *European Committee for Standardization* (CEN) Technical Committee 350 (TC 350) to address LCA and EPD standards for construction works[16]. CEN/TC 350 has since developed a series of standards to address environmental sustainability issues that mirror those developed by ISO. These are:

- EN 15643-2: Assessment of buildings - Framework for the assessment of environmental performance
- EN 15804: Core rules for the product category of construction products
- EN 15978: Assessment of environmental performance of buildings - Calculation method

Similar to ISO/TC 59/SC 17, CEN/TC 350 has initially focused on standards for buildings as opposed to civil engineering works. TC 350 has recently established Working Group 6 (WG 6) that will develop future standards specific to civil engineering works. The life cycle of a civil engineering work is, however, nearly identical to that of a building for the purpose of identifying life cycle stages and unit processes that should be included within the product system. Similar to the ISO standards suite described in Section 2.1, it is therefore expected that the CEN product level standard (EN 15804) will apply to both building (EN 15978) and forthcoming civil engineering works standards. EN 15978 requirements therefore serve as a useful indicator of what expected for civil engineering works.

The areas in which the CEN standards are particularly useful in supplementing ISO standards are the more detailed descriptions and modular structure of processes to be included in the system boundary and the environmental indicators to be reported.

Similar to ISO 21931-1, the system boundary of building projects according to EN 15978 is structured by the temporal flow of the building life cycle, i.e. *Product*, *Construction Process*, *Use*, and *End of Life* stages (see Figure 5 on Page 16). Each stage is comprised of *information modules*[17] labelled with alpha-numeric designations between "A1" through "C4"[18].

Accounting for the life cycle of a building is complete when all its constituent materials are either disposed of via landfill or incineration, or reach a state where they are no longer considered waste (e.g. a steel framing member ready for reuse). This allocation methodology is also known as the *Polluter Pays* principle. The benefit potential of materials and energy leaving the system boundary is optionally accounted in module "D".

[16] http://portailgroupe.afnor.fr/public_espacenormalisation/CENTC350/index.html
[17] *Information modules* are groups of processes that are similar in nature, e.g. material transport
[18] See EN 15978 for a comprehensive description of what is included in each module.

Table 1 presents the environmental indicators to be reported according to EN 15978 which encompass an array of LCIA and LCI results. The indicators also satisfy the requirements of the ISO 21900 series described in Section 2.1.

TABLE 1: ENVIRONMENTAL INDICATORS TO BE REPORTED ACCORDING TO EUROPEAN STANDARD (EN) 15978

Environmental Impacts
Global warming potential
Depletion of the stratospheric ozone layer
Acidification potential of land and water
Eutrophication potential
Formation potential of tropospheric ozone photochemical oxidants
Abiotic resource depletion potential for elements
Abiotic resource depletion potential of fossil fuels
Resource Use
Use of renewable primary energy excluding energy resources used as raw material
Use of renewable primary energy resources used as raw material
Use of non-renewable primary energy excluding resources used as raw material
Use of non-renewable primary energy resources used as raw material
Use of secondary material
Use of renewable secondary fuels
Use of non-renewable secondary fuels
Net use of fresh water
Waste Categories
Hazardous waste disposed
Non-hazardous waste disposed
Radioactive waste disposed
Output Flows Leaving the System
Components for re-use
Materials for recycling
Materials for energy recovery (not being waste incineration)
Exported energy

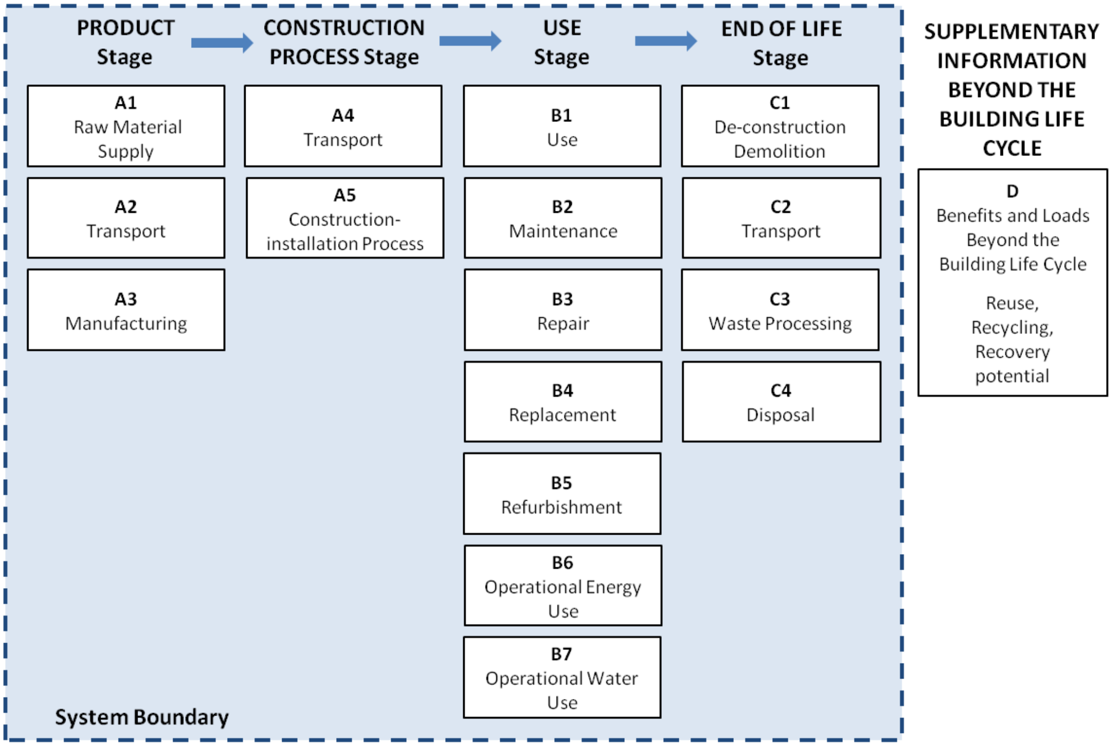

FIGURE 5: SCOPE AND MODULARITY FOR BUILDING LIFE CYCLE ASSESSMENT ACCORDING TO EUROPEAN STANDARD (EN) 15978

2.3 INTERNATIONAL EPD SYSTEM PRODUCT CATEGORY RULES

The *International EPD System* is an EPD program administered by the *Swedish Environmental Management Council* offering *"*a complete programme for any interested organisation in any country to develop and communicate EPDs according to ISO 14025:2006 and EN 15804:2012, carbon footprint of products according to ISO/TS 14067:2013, and supporting other environmental declaration programmes (i.e. national, sectorial, etc.) in seeking cooperation and harmonisation and helping organisations to broaden the use of their environmental declarations on an international market*"*[19]

The program contains a set of PCRs for products, classified according to the United Nations' *Central Product Classification* (CPC) system[20]. The hierarchical nature of the PCRs ensures not only consistency within product categories, but across different product categories as well. The PCRs are European in nature (i.e. they draw on European databases and impact assessment methodologies) and require adaptation to be applicable to the North American marketplace. Such adaptation is common in the building industry and typically replaces references to European LCI data and LCIA methods with specifications for the use of the USLCI database and TRACI LCIA method.

[19] http://www.environdec.com/en/The-EPD-system/#.UnvT0BBGY1k

[20] The CPC is a five digit classification system for goods and services. Available online at: http://unstats.un.org/unsd/cr/registry/cpc-2.asp

The International EPD System has developed the CPC three-digit level PCR *CPC 171: Electricity Generation and Distribution,* which draws on the following two-digit level *Basic Modules*[21]*:*

- CPC Division 17: Electricity, Town Gas, Steam and Hot Water
- CPC Division 69: Electricity, Gas and Water Distribution

PCR CPC 171 defines the scope requirements and impact indicators that must be reported for EPD's of electricity as a product. It differs from the building/project-level standards in that the functional unit is defined as the product output (1 kWh of electricity) and the scope that is required is specific to this functional unit.

According to the PCR, the system boundary of electricity generation and transmission/distribution projects is comprised of three information modules that are structured by the temporal flow of energy, i.e. production, conversion, and delivery (see Figure 6 on Page 20).

More specifically,

- The *Upstream Module* comprises environmental information on production and transportation of fuel and auxiliary substances, e.g. chemicals necessary for energy conversion.
- The *Core Module* comprises environmental information on the construction and operation of the energy conversion plant.
- The *Downstream Module* comprises environmental information on the transmission/distribution of the energy to the consumer.

All information modules include waste handling according to the polluter-pays allocation principle. For landfilled materials, the boundary is the final disposal; for materials that are recycled or reused, the boundary is at the gate of the scrap yard or collection site. Table 2 on the following page presents the environmental indicators to be reported according to the PCR, which, similar to EN 15978, encompass an array of LCIA and LCI results.

[21] Basic Modules do not themselves constitute PCRs and are intended as umbrella requirements for PCRs at higher levels (i.e. CPC three, four, or five digit levels).

TABLE 2: INDICATORS TO BE REPORTED ACCORDING TO ELECTRICITY PRODUCT CATEGORY RULES (CPC 171)

Resources for material production
Non-renewable resources
Renewable resources
Water use
Recycled resources
Resources for energy conversion
Non-renewable resources
Renewable resources
Recycled resources
Resources from technosphere
Remaining Intermediate flows
Potential Environmental Impact
Global warming potential
Ozone depletion potential
Acidification potential
Photochemical smog potential
Eutrophication potential
Life Cycle Inventory Emissions
LCI flows supporting the environmental impact categories
Radioactive isotopes in kBq
Biogenic CO2 (will not be included in GWP)
CO2 captured and sequestered or sold
Particle matter (PM)
Toxic substances
Oil to water and ground
Additional Information
Additional Environmental Information Not Based on LCA
Additional Environmental Information Based on LCA

Fuel-related Waste (non-radioactive) - to landfill
Ash
Gypsum
Other
Fuel-related Waste - to recycling or reuse
Ash
Gypsum
Other
Hazardous Fuel-related Waste – radioactive
Spent nuclear fuel
Uranium in spent nuclear fuel
Hazardous Fuel-related Waste – radioactive to final repository
High-level radioactive waste
Medium and low-level radioactive waste
Hazardous Waste - non-radioactive
To landfill
To incineration
To reuse
To recycling
Other waste
To landfill
To incineration
To reuse
To recycling

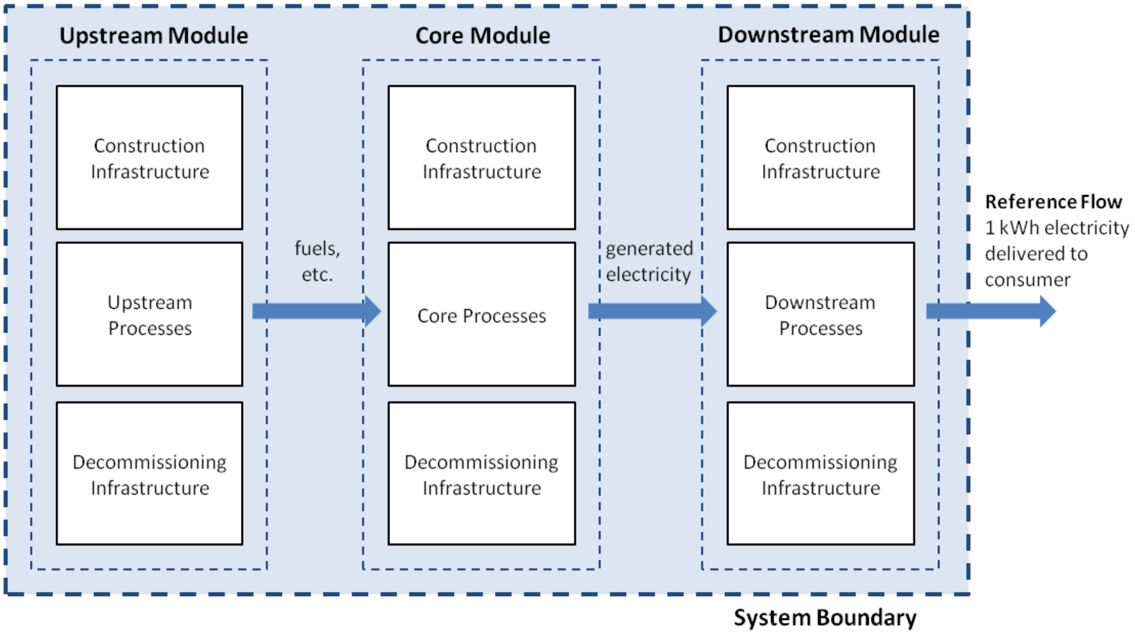

FIGURE 6: SCOPE AND MODULARITY OF LIFE CYCLE ASSESSMNET ON ELECTRICITY GENERATION AND DELIVERY ACCORDING TO ELECTRICITY PRODUCT CATEGORY RULES (CPC 171)

2.4 LAND-USE CHANGE GREENHOUSE GAS ESTIMATION

Infrastructure projects are known to cause significant greenhouse gas emissions due to temporary and permanent changes in the landscapes that they occupy. Both hydroelectricity generation and transmission cause land-use changes associated with flooding to create reservoirs and clearing for transmission lines and affected areas surrounding the dams.

The Intergovernmental Panel on Climate Change (IPCC), similar to ISO, represents the consensus of international research on accounting for global warming potential from land use change. In 2006, the IPCC published *Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and Other Land Use* that are particularly applicable to LCA of civil engineering works (IPCC, 2006).

In Appendix 2 of the 2006 guidelines, the IPCC presents a 3-tier methodology for estimating the greenhouse gas emissions from permanently flooded land. Under Tier 1, numerous default values and simplifying assumptions are provided while higher tier approaches require country-specific inventory and modeling but allow for more precise calculations. Tiers 1 and 2 require the estimation of diffusive emissions only. The Tier 3 method, based on detailed measurements, includes all relevant fluxes of carbon dioxide emissions from flooded lands. Tier 3 includes degassing emissions and considers the age, and the geographical location and the water temperature of the reservoir.

More specific guidance has been introduced in *GHG Measurement Guidelines for Fresh Water Reservoirs* published by the United Nations Educational Scientific and Cultural Organization (UNESCO) and the

International Hydropower Association (IHA). The UNESCO/IHA document *Greenhouse Gas Emissions from Freshwater Reservoirs* provides a detailed methodology to complete Tier 3 greenhouse gas estimations. The UNESCO/IHA protocol also provides guidance on the establishment of a monitoring system and the integration of field-measured greenhouse gas intensities with modeling results. Figure 7 appears in UNESCO/IHA (2011) and illustrates the various pathways of carbon dioxide and methane emissions that are caused by freshwater reservoirs.

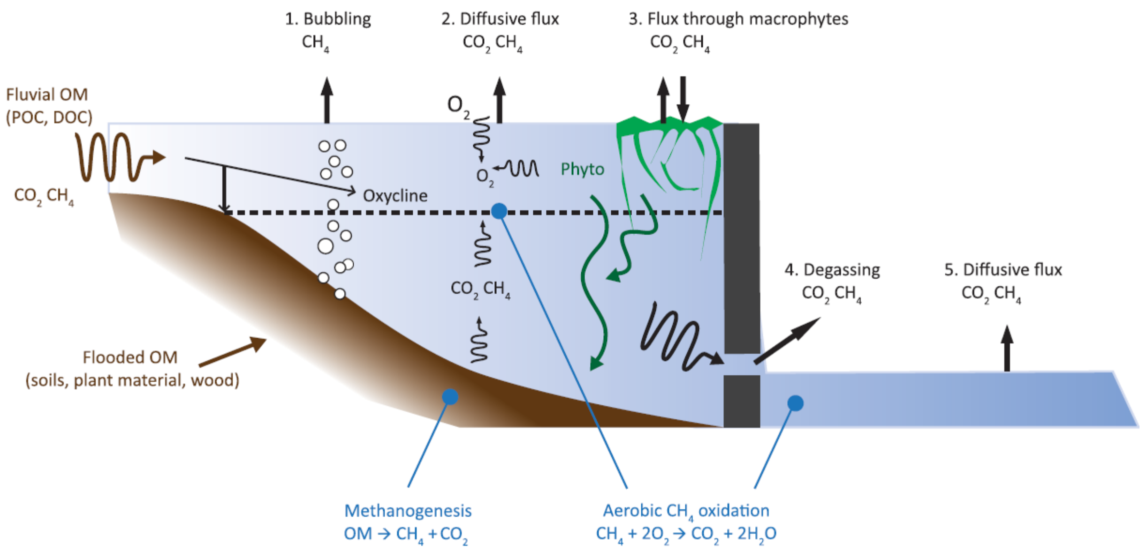

FIGURE 7: CARBON DIOXIDE AND METHANE PATHWAYS IN A FRESHWATER RESERVOIR WITH ANOXIC HYPOLIMNION (FIGURE 2.3 IN UNESCO/IHA 2011)

The pathways for emissions include (1) bubble fluxes (ebullition) from the shallow water; (2) diffusive fluxes from the water surface of the reservoir; (3) diffusion through the plant stems; (4) degassing just downstream of the reservoir outlet(s); and (5) increased diffusive fluxes along the river course downstream. Bubbling emissions are limited to shallow water (typically 0-10 m) and diffusive flux is the greatest contributor of reservoir emissions.

CHAPTER 3: HYDROELECTRIC GENERATION STATION LIFE CYCLE ASSESSMENT APPLICATIONS

This chapter presents some of the ways in which HGS-LCA studies may be used. The intent is to show the relationship between the defined goals of an LCA study and the quality of assessment required. The flexibility of LCA and range of potential stakeholders makes the clear definition of goals a critical component. The application, reasons, audience, and presence of comparative assertions all influence the breadth of the LCA's scope as well as the data quality rules and impact categories that must be considered.

Three types of LCA studies are illustrated in in Figure 8 to show the increasing requirements on their scope and the precision of the results that are calculated. The following three sections outline these types of LCAs and suitable applications for each.

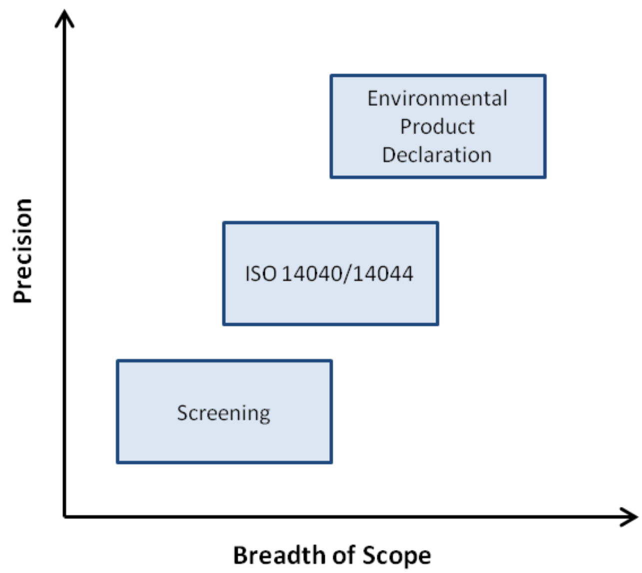

FIGURE 8: RELATIVE PRECISION AND BREADTH OF SCOPE REQUIRED FOR THREE TYPES OF LIFE CYCLE ASSESSMENT

3.1 SCREENING LIFE CYCLE ASSESSMENT

According to the *EeBGuide Guidance Document (Part B: Buildings)*[23] a screening LCA "may serve for an initial (quick) overview on the environmental impacts of a building or a product. With screening LCA, it is not possible to retrieve detailed results on the environmental performance of a building or a product and no comparative assertion can be based on it. This type of study yields an estimate on the

[23] The *EeBGuide Guidance Document Part B: Buildings* (available at http://www.eebguide.eu/), or "EeBGuide" is a European Commission funded guidance document for applying EN 15978 to building LCA studies within the framework of the *Energy Efficient Building Initiative*.

environmental performance, which can be helpful in the early design stages e.g. design draft by an architect or in early stages of a research project, e.g. to identify environmental hotspots that require an additional in-depth assessment".

At minimum, screening LCAs are conducted in accordance with the framework outlined in ISO 14040 (otherwise it would not constitute basic LCA), and additionally the requirements and guidelines of ISO 14044 to the extent that it is feasible given study resources and the defined study goals. In other words, screening LCA is generally conducted in accordance with the methodological principles of LCA, but is not intended to be in compliance with the ISO standards. Screening LCA reports should therefore not declare to be in conformance with ISO 14040/14044 when the study hasn't undergone the necessary rigor for compliance.

Table 3 presents two suitable applications for screening HGS-LCA.

TABLE 3: POTENTIAL SCREENING LIFE CYCLE ASSESSMENT APPLICATIONS

Intended Use	Reasons for Carrying Out Study	Intended Audience	Comparative Assertion
Internal decision-making, technology selection	To facilitate making high-level decisions about the choice of technology of new infrastructure projects by comparing two or more technologies (e.g. hydro vs. coal generation) at the feasibility phase.	MH management	Yes, critical review not required
Internal decision-making, infrastructure design	To [1] help prioritize mitigation efforts by recognizing environmental hotspots, and/or [2] provide quantitative impact estimates to weigh environmental trade-offs, and/or [3] determine the environmental preference of a material/product or construction assembly during design.	MH designers, project managers	No

The benefit of screening LCA is the flexibility it provides in making use of objective analysis at times when there is insufficient primary data and/or resources to produce an ISO-compliant study. Since a screening LCA would not have the requisite information to be credible for external use, it should only be used for internal decision-making. The goal of internal decision-making is the least burdensome because the scope of such an analysis may be limited to a particular sub-system or material sourcing decision with the results of the study least likely to be taken out of context.

3.2 ISO 14040/14044 LCA

An ISO 14040/14044 LCA study meets the requirements of the basic standards for LCA practice. Best industry practice dictates that HGS-LCA studies additionally consider the requirements of either the ISO 21000 standards series (see Section 2.1) or corresponding CEN standards (see Section 2.2).

While ISO-compliant LCA is more onerous than screening HGS-LCA in terms of breadth of analysis and precision, compliance means that it can be credibly used for more applications, including those that include third-party disclosure. In addition to internal decision making, some of the HGS-LCA applications this type of study can be used for by Manitoba Hydro are listed in Table 4.

TABLE 4: POTENTIAL INTERNATIONAL STANDARD ISO 14040/14044 LIFE CYCLE ASSESSMENT APPLICATIONS

Intended Use	Reasons for Carrying Out Study	Intended Audience	Comparative Assertion
Public stakeholder engagement	To provide holistic and quantitative metrics for the numerous criteria that different individual perspectives may assign to the concept of infrastructure "sustainability".	General public	No
Disclosure of generation station or supply mix	To demonstrate stewardship by providing transparency about the environmental impact of electricity generation.	Consumers and/or MH customers	No
Incorporation of results into LCI database	To provide the public information which can be used for other LCA studies in which the product systems includes Manitoba hydroelectricity as an input.	LCA practitioners	No
Marketing, technology comparison	To credibly demonstrate the environmental preference of a generation/transmission system relative to one or more competing technologies (e.g. hydro vs. coal generation).	Consumers and/or MH customers	Yes, critical review required

The first intended use noted in Table 4 (public stakeholder engagement) is akin to an HGS-LCA produced for an *Environmental Impact Statement* (EIS). Part II of this document is a best-practice protocol for such studies.

LCA studies are often publically disclosed for the purpose of transparency. This disclosure can also be in the form of an LCI database so that the data may be used in other LCA studies that include hydroelectricity as an input.

Technology comparison is the most burdensome in that LCA of multiple technologies must be completed with uniform data quality and methodology decisions under the scrutiny of a critical review panel. When conducting a comparative LCA, ISO 14044 requires the establishment of a peer-review panel with representatives from the various affected interests of the proposed study. This review panel should be convened at the inception of the LCA so that they may provide comments as to the goal and scope before the data collection begins. This is critical as the LCI data collection is the most resource-intensive portion of any LCA, and a review that takes place after the LCA has been completed might lead to redundant or unnecessary data collection and LCI modeling. The inclusion of the panel at the beginning of the LCA also aids in a collegial and collaborative atmosphere to the critical review.

3.3 ENVIRONMENTAL PRODUCT DECLARATIONS

As noted in Section 2.1.1, an EPD is essentially an executive summary of an LCA conducted according to a PCR. Additionally, critical reviews of the EPD and supporting LCA study are required. This process builds on an ISO-compliant study by including transmission effects and undergoes a second verification in addition to the LCA review. HGS EPDs are developed in compliance with ISO 14040/14044 and a relevant PCR such as the International EPD system's *PCR CPC 171* (see Section 2.3).

Some of the applications of HGS EPDs are listed in Table 5. It should be noted that an EPD is always intended to provide the public an environmental declaration of a single product (in this case an HGS) and is therefore not an avenue for comparative assertions[24] or a demonstration of design decision-making.

TABLE 5: POTENTIAL HYDROELECTRIC GENERATION STATION ENVIRONMENTAL PRODUCT DECLARATION APPLICATIONS

Intended Use	Reasons for Carrying Out Study	Intended Audience	Comparative Assertion
Disclosure of generation station or supply mix	To provide the highest quality data about the environmental impact of electricity generation.	Consumers and/or MH customers	No
Marketing	To provide a credible basis to make purchasing decisions in part based on environmental performance.	Consumers and/or MH customers	No

[24] In this case, it is the public's role to assess EPD results of competing products to evaluate relative environmental performance.

PART II: GUIDELINES FOR LIFE CYCLE ASSESSMENT AS PART OF AN ENVIRONMENTAL IMPACT STATEMENT

Part II of this document is a proposed set of best-practice guidelines for conducting a hydroelectric generation station LCA (HGS-LCA).

Chapter 4 provides the relevant portions of the Canadian Environmental Assessment Agency (CEAA) Environmental Impact Statement (EIS) Guidelines and Keeyask Scoping Document to outline the requirements of the LCA.

Chapter 5 defines the goals and scope based on the EIS requirements described in Chapter 4 and the standards presented in Part I.

Chapter 6 summarizes type of data that are required to complete the life cycle inventory model and how that data is linked to published databases in LCA software.

Chapter 7 lists the impact categories and corresponding models that should be used to produce the broad range of sustainability metrics required by the standards.

Chapter 8 concludes the protocol with a description of how the LCA results may be used to go beyond disclosure and influence decisions that mitigate impacts.

Part II draws heavily on the technical background information presented in Part I of this protocol. The reader is encouraged to refer back to relevant sections in Part I for technical clarifications as to LCA methodology (Chapter 1), standards (Chapter 2), and broader applications of HGS-LCA (Chapter 3).

CHAPTER 4: REQUIREMENTS FOR LIFE CYCLE ASSESSMENT IN THE ENVIRONMENTAL IMPACT STATEMENT

Proposed hydroelectricity generation projects in Manitoba are subject to both the provincial Environment Act[25] and the Canadian Environmental Assessment Act[26]. To comply with these statutes, the project proponent must prepare an *Environmental Impact Statement* (EIS) as defined in the EIS Guidelines published by the *Canadian Environmental Assessment Agency* (CEAA). The EIS must also comply with a Scoping Document developed by the project proponent.

The *CEAA EIS Guidelines* (Reference Number: 11-03-64144) for the Keeyask Generation Station and the *Keeyask Scoping Document* contain requirements that may only be met with LCA and LCA-based data. The requirements for the EIS are decribed in more detail in Sections 4.1-4.3 and can be summarized as follows:

1) **Detailed LCA:** A detailed LCA of the project that accounts for land, air, and water emissions. This LCA should document cumulative flows and impacts and facilitate benchmarking for procurement decisions.
2) **Literature Review:** A literature review (separate from the LCA) that considers LCA results of other generation technologies.

4.1 DETAILED LIFE CYCLE ASSESSMENT OF PROPOSED PROJECT

Section 5.3 of the CEAA Guidelines specifies that the EIS include detailed information as to the project's location, components, activities, and schedule. The requirements of the project description are also spelled out in more detail in Section 2.2 of the Scoping Document. The project description serves as the basis for the various supporting volumes of the EIS.

The requirements for the cumulative assessment of environmental impacts are described in more detail in the EIS Guidelines and Scoping Document, with particular emphasis on the impacts that are caused by the project on the existing environment. That said, several requirements in the EIS Guidelines may only be achieved through the use of LCA and meeting these are the focus of this protocol.

Section 2.3 of the Scoping Document requires that the EIS includes:

- *A description of atmospheric emissions, liquid emissions, and solid wastes, and plans to manage these emissions and wastes during construction;*
- *A description of i) fuel and dangerous and hazardous products and wastes and ii) plans to manage the fuel, products, and waste during construction.*

[25] http://web2.gov.mb.ca/laws/statutes/ccsm/e125e.php
[26] http://laws-lois.justice.gc.ca/eng/acts/C-15.2/

Section 8.1 of the EIS Guidelines elaborates on the requirements for air emissions accounting by requiring that the EIS include "an inventory of all potential sources of air contaminants and emissions from the proposed project: criteria air contaminants, air pollutants on the List of Toxic Substances in Schedule 1 of the Canadian Environmental Protection Act, 1999." The current list of Schedule 1 Toxic Substances[27] includes roughly 180 different substances including 44 different volatile organic compounds (VOC's). The LCI developed in the HGS-LCA for the EIS must thus include these emissions and secondary data sources must be comprehensive in nature and also include Schedule 1 Toxic substances. In addition to the air emissions inventory, the LCI data collection should also include liquid emissions, solid waste, fuel use, and hazardous waste as required by the Scoping Document.

Chapter 9 of the CEAA Guidelines outlines the requirements in calculating the environmental effects of the project. Chapter 9 stipulates that "the proponent shall identify the Project's likely adverse environmental effects during construction, operation, maintenance, decommissioning and reclamation of sites and facilities associated with the Project, and describe these effects using appropriate criteria".

Section 9.8 of the CEAA Guidelines specifies that the environmental effects should be cumulative. "Cumulative environmental effects are defined as environmental effects of a project, when considered in combination with the environmental effects of other past, present and reasonably foreseeable future projects or activities."

To conclude, the HGS-LCA must include a complete LCI accounting (particularly for air emissions), calculate environmental effects based on "appropriate criteria", and the results that are calculated must be cumulative to the project as defined in the project description.

4.2 CONSIDERATION OF ALTERNATIVES TO THE PROJECT

Section 5.2 of the CEAA Guidelines requires that the EIS includes "an analysis of alternatives to the Project which describe functionally different ways to meet the project need and achieve the project purpose where analyzed from the perspective of the proponent. Analysis of 'alternatives to' a project should validate that the preferred alternative is a reasonable approach to meeting the identified need and purpose." The CEAA Guidelines also requires that "the analysis in this section of the EIS should identify requirements of the proposed purchaser of the power to be produced by the Project."

The concepts of "alternatives to the project" are thus two-fold. First, the EIS Guidelines require that the EIS consider less impactful ways of completing the hydroelectric generation station project. This application is described in more detail in Section 4.3.

The second requirement, that the EIS consider alternatives from the perspective of the proposed purchaser expands the scope of the analysis to include other means of producing electric power that may be available to downstream customers.

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[27] http://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=0DA2924D-1&wsdoc=4ABEFFC8-5BEC-B57A-F4BF-11069545E434

The CEAA Guidelines provides conflicting requirements for the consideration of alternatives. On the one hand the CEAA states that the "analysis of alternatives to the Project should describe the process the proponent used to determine that the Project is viable (technical, social, cultural, economical and environmental)." These holistic criteria indicate that any LCA of alternative means of electricity production must be comprehensive in terms of the impact assessment categories that are included. The CEAA guidelines do recognize, however, that "at this stage of the process the level of analysis should reflect the more conceptual nature of the identified alternatives to the Project." This means that the assessment of the alternatives may not be subject to the same stringent requirements of the proposed project.

In the absence of a comprehensive LCA of all electricity generation technologies, the EIS could employ a literature review of LCA results. This literature review, however, should remain separate from the LCA of the proposed project so that the literature review results are not confused as comparative LCA results that ISO 14044 holds to the strictest of standards (e.g. conformance of system boundaries, data quality, impact assessment models, 'a sufficient range of impact assessment results', the scrutiny of a peer review panel, and other requirements outlined in Section 1.3). See Section 8.3 for more details on the interpretation of the LCA literature review.

4.3 ENVIRONMENTAL IMPACT MITIGATION

Section 9.2 of the CEAA Guidelines requires that "the EIS must consider measures that are technically and economically feasible and that would mitigate any significant adverse environmental effects of the Project. As a first step, the proponent is encouraged to use an approach based on the avoidance and reduction of the effects at the source. Such an approach may include modification of the design of the Project or relocation of project components".

Section 9.2 of the CEAA Guidelines goes further to require that the EIS "shall discuss the mechanisms it would use to require its contractors and sub-contractors to comply with these commitments and policies and with auditing and enforcement programs."

The detailed LCA of the proposed project should thus be structured so that the results are available throughout the environmental management team. LCA-based benchmarks should be developed to facilitate the implementation of LCA in decision making and is described in more detail in Section 8.1.

CHAPTER 5: GOAL AND SCOPE DEFINITION

5.1 GOAL DEFINITION

This section defines the goals based on the documentation elements from ISO 14044 and the requirements of the EIS recognized in Chapter 4:

Intended application(s)

To communicate the HGS's cumulative environmental impacts via the Environmental Impact Statement.

To facilitate impact mitigation through benchmarks in the proposed project as required in the Environmental Impact Statement.

Reasons for carrying out the study

The Manitoba Clean Environment Commission requires that the HGS proponent produce an Environmental Impact Statement for the purpose informing the public about the environmental implications of the HGS.

Intended audience

Participants of the Manitoba Clean Environment Commission's public hearings, future developers of LCA studies on Manitoba HGS, as well as the various project stakeholders and general public.

Comparative assertion

The LCA study is not a comparative assertion and therefore a critical review panel is not required.

5.2 OBJECT OF ASSESSMENT

For the purpose of this document, the *object of assessment* is a definition of what undergoes analysis, i.e. what aspects should be attributed to the HGS.

The HGS-LCA object of assessment should include all new generation station, transmission, transportation, and communication infrastructure related to the project, inclusive of associated land use change impacts and temporary works for construction seeking public approval via the EIS.

Since the EIS is an estimate of the environmental impact of a particular HGS (i.e. particular collection of infrastructure elements) seeking approval, the object of assessment may not account for all infrastructure that is attributable to it. The excluded infrastructure may include infrastructure that was, or is, in the process of being approved through another public-approval process. The most important example is downstream transmission and distribution infrastructure; while its construction is not seeking approval via the EIS in question, a percentage of the environmental burden is attributable to the HGS it services. Transmission infrastructure would need to be added to the project-level LCA to develop Type III Environmental Product Declarations (See Sections 2.3 and 3.3).

5.3 FUNCTIONAL UNIT

Since the intended use of the HGS-LCA is to inform the public of the estimated impacts associated with the proposed project, the following functional unit template should be used:

Infrastructure capable of providing consumers XXX kWh of electricity over the XXX year service life of the HGS.

In other words, the total accumulated life cycle results at the HGS scale are to be reported, rather than on a per-kWh basis (See Section 4.1 for language in the EIS requirements as to calculating cumulative impacts). As a secondary functional unit, the per-kWh results may be calculated and used as a point of reference to facilitate benchmarking (See Section 8.1).

5.4 SYSTEM BOUNDARY

The product system should include all life cycle processes forming the EN 15978 information modules (i.e. modules A1 through C4), and may optionally include module D as additional information (See Section 2.2 for a description of the modules). This recommendation reflects the fact that these information modules properly account for the processes occurring over the lifetime of an HGS.

Table 6 is a summary of the minimum recommended processes to be included within the system boundary of the HGS-LCA, and which information modules they belong to. Please note that Table 6 has been modified from EN 15978 for HGS-LCA applications, since the CEN standards for civil engineering works have not yet been published.

Additional information and recommendations regarding the selection of the system boundary is provided in subsequent sections.

TABLE 6: RECOMMENDED SYSTEM BOUNDARY FOR THE HYDROELECTRIC GENERATION STATION LIFE CYCLE ASSESSMENT

Life Cycle Stage	Information Module	Processes Included
Product	A1 Raw material supply	- primary raw resource extraction
	A2 Transport	- all materials transport up to manufacturing plant gate
	A3 Manufacturing	- manufacture of raw materials into products
Construction Process	A4 Transport	- material transport from manufacturing plant gate to site - construction equipment transport to and from site - worker transport to and from site
	A5 Construction-installation process	- on-site construction equipment energy and water use - all temporary infrastructure effects - production and construction process of ancillary materials[a] - production and construction process of waste materials - end of life of waste materials - land clearance effects[b]
Use	B1 Installed product in use	- emissions from installed products[c] - reservoir inundation effects[b]
	B2 Maintenance	- production and construction process of maintenance materials - end of life of waste materials
	B3 Repair	- production and construction process of repair materials - end of life of waste materials
	B4 Replacement	- production and construction process of replacement materials - end of life of waste materials
	B5 Refurbishment	- production and construction process of refurbishment materials - end of life of waste materials
	B6 Operational energy use	- operating energy use for facilities, reserve power - all ancillary materials effects[d]
	B7 Operational water use	- operating water and wastewater treatment for facilities
End of Life	C1 De-construction demolition	- on-site decommissioning equipment energy and water use - all temporary infrastructure effects - decommissioning phase worker transport to and from site - decommissioning equipment transport to and from site - production and construction process of ancillary materials
	C2 Transport	- material transport from site to disposal facility - material transport from site to location of end-of-waste state
	C3 Waste Processing	- all processes required for materials to each end-of-waste state
	C4 Disposal	- disposal facility equipment energy and water use - landfill effects - incineration effects

Table 6 footnotes on following page

Notes on Table 6:

[a] Construction Process and End of life stage ancillary materials include items such as shoring, formwork, and form release agents, i.e. materials that are required during construction and decommissioning activities, but do not form part of the infrastructure.

[b] The land use change impacts are included in A5 and B1 of this modular description of the system boundary for the sake of consistency. The land use impacts are anticipated to be significant in terms of the overall results and are calculated quite differently than the rest of the LCA results and thus will be reported separately.

[c] There is currently a lack of publically available LCA data on emissions from installed products during use, but it is recommended that at minimum SF_6 emissions from electrical switches be included.

[d] Operating energy ancillary materials may include oil, hydraulic liquids and/or fat, i.e. materials that are required in the electricity generation process, but are not fuels consumed to produce it.

5.5 LAND USE CHANGE

Pre-flood emissions from fire

Some hydroelectric projects (including the Keeyask GS) include a prescribed fire to remove woody debris from the flooding site aerobically so that the carbon is not anaerobically converted to methane after flooding. These impacts are included within the LCA under Module A5: Construction-installation process. They should also be reported separately in the LCA document and be interpreted to potentially mitigate emissions by selecting the least impactful clearing methods.

Post-flood emissions from diffusive flux

The remaining biogenic carbon is subject to aerobic and anaerobic decay. These impacts are included within the LCA under Module B1 Installed product in use. Similar to the land clearing impacts, they should also be reported separately in the LCA document and be interpreted to potentially mitigate emissions and to facilitate refinement with measured emissions.

5.6 TEMPORARY INFRASTRUCTURE EFFECTS

HGSs are unlike typical construction projects (e.g. buildings) in that the construction sites are often located in remotes areas and require significant temporary infrastructure during construction and decommissioning phases. Since the goal of HGS-LCA is to estimate the environmental impacts that are specifically attributable to the project, only additional impacts that are initiated by the HGS should be allotted to it.

To this point, the following characteristics influence decisions about the system boundary of temporary infrastructure:

- Temporary infrastructure (e.g. construction camps) may be used either [1] solely for the purpose of the HGS, or [2] re-used on other projects; this influences decisions about allotting the embodied effects (i.e. all information modules except B6 and B7) to the HGS.
- Temporary infrastructure may support either [1] construction of the HGS (e.g. work areas) or the workers (e.g. worker camps); this influences decisions about allotting the operational effects (i.e. information modules B6 and B7) to the HGS.

The following is recommended for allotting the embodied effects of temporary infrastructure to the HGS:

1. All embodied effects related to single-use temporary infrastructure should be included in the product system.
2. For re-used temporary infrastructure:
    a. All Construction Process and material-related Use stage effects should be included in the product system.
    b. Product and End of Life stage effects should be allotted to the HGS based on an economic allocation. This roughly translates to the percentage of time used by the HGS relative to the total time the infrastructure is estimated to be on all project sites over the course of its service life.

The following is recommended for allotting the operational effects of temporary infrastructure to the HGS:

1. All operational effects of temporary infrastructure that supports construction of the HGS (e.g. concrete mixing area) should be included in the product system.
2. The following operational effects of temporary infrastructure that supports HGS workers may be excluded from the product system, as it is assumed that differences between effects incurred on-site and effects that would otherwise be incurred at the primary residences of the workers is likely small, particularly in the context of the total HGS effects:
    a. Use of energy for hot water, appliances, and lighting;
    b. Use of potable water;
    c. Solid waste and wastewater generation.
3. It is assumed that the primary residences of the workers will require heating while they are at the worker camp and therefore the space heating of temporary infrastructure that supports HGS workers should be included in the product system.

5.7 WORKER TRANSPORTATION

Typical building LCA (e.g. as stipulated in EN 15978) does not account for the transportation of construction workers to and from site. This is justified since it is assumed that transportation effects would be incurred regardless of the construction of any single project. While the exclusion of HGS Use stage worker transportation is similarly justified, the following is recommended for Construction Process and End of Life stage worker transportation effects:

1. Transportation of workers in and around the site may be excluded from the product system since it is assumed that differences between the effects incurred on-site and those that would otherwise be incurred by the workers are likely small, particularly in the context of the total HGS effects.
2. Transportation of workers to and from their primary residences and the construction site should be included in the product system since these effects are likely significant and would not be incurred unless the HGS was being constructed.

5.8 CUT-OFF CRITERIA

Given the vast number of components (and hence materials) comprising a typical HGS project and the various processes each undergoes, it is not feasible to model the HGS in its entirety. To this end, ISO 14044 stipulates that certain elements may be excluded (i.e. cut) from a product system provided the mass, energy, or environmental relevance of such processes are considered.

The cut-off criteria of the LCA should conform to the following typical North American LCA practice:

- Mass: input and/or output flows that cumulatively account for than 1% of the total mass of the HGS may be excluded;
- Energy: input and/or output flows that cumulatively account for than 1% of the total energy use of the HGS may be excluded;
- Environmental relevance: if an input and/or output flow meets the mass and energy cut-off criteria noted above but is determined to account for more than 2% to any impact indicator (via secondary analysis), it shall be included in the system boundary.

A justification for excluding from scope any process that falls above the cut-off criteria should be provided and addressed in the limitations section of the LCA report.

5.9 SYSTEM BOUNDARY REPORTING

Given the vast number of components comprising a typical HGS project and the various processes each undergoes, complete and transparent reporting of the system boundary is essential for the public to understand what is accounted for in HGS-LCA.

To ensure a standardized and transparent reporting of the HGS-LCA system boundary, it should include a description of:

1. Which HGS project elements (i.e. construction assemblies, materials, etc.) are included in scope. The reporting of project elements should be in a format consistent with the EIS *Project Description*[29] supporting volume.

[29] The *Project Description* supporting volume of the EIS provides a thorough description of the proposed project such that the audience understands the scope of work considered by the proponent. This volume describes the infrastructure that is to be constructed as well as all lands that are affected.

2. Which life cycle processes the HGS project elements undergo are included in scope. The reporting of processes should be in a format consistent with EN 15978 information modules.

In lieu of producing a detailed process flow diagram that describes the system boundary, two reporting template tables have been proposed and presented in Appendix 1.

CHAPTER 6: LIFE CYCLE INVENTORY (LCI)

The LCI phase links the HGS structures and processes to the inputs from nature and emissions to nature (elementary flows) that are related to the product system by upstream and downstream cause-effect chains (ISO 14040). Figure 8 is a schematic representation of a complete LCI model for the LCA of an HGS. The four stages are consistent with the scope as defined in EN 15978 (See Figure 5 in Section 2.2). For each module in the EN 15978 classification (A1-C4), data is required to model the intermediate inputs and outputs back to the boundary with nature.

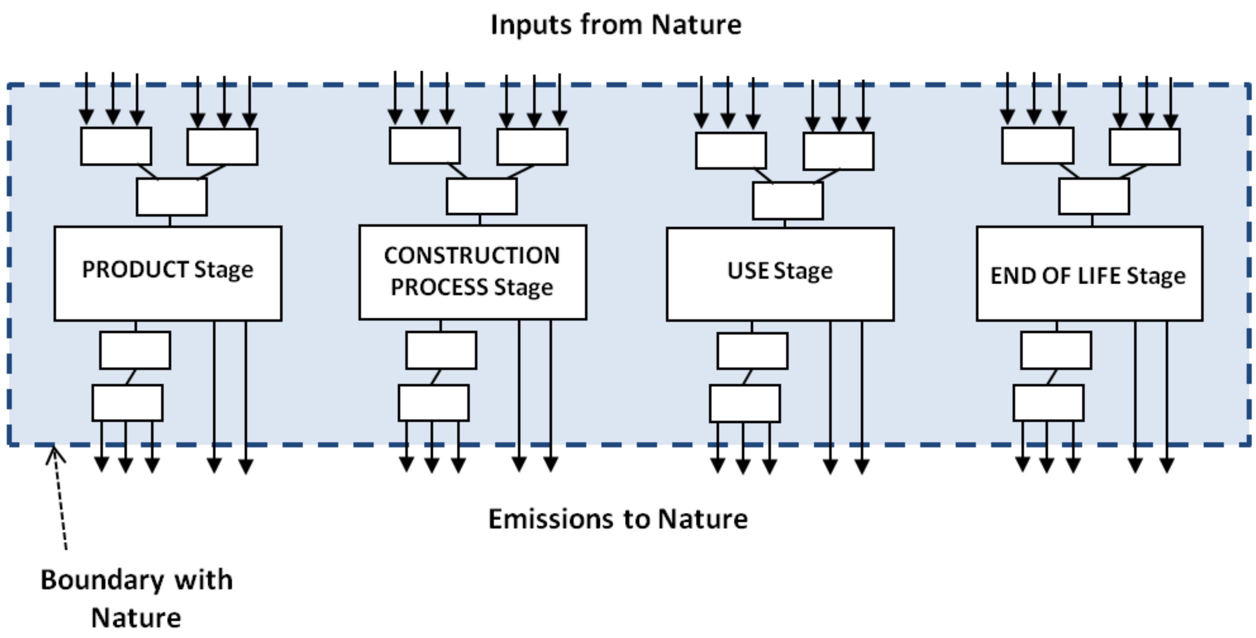

FIGURE 8: LIFE CYCLE INVENTORY SCHEMATIC FOR LIFE CYCLE ASSESSMENT OF A CONSTRUCTED WORK (BASED ON EUROPEAN STANDARD EN 15978 AND INTERNATIONAL STANDARD ISO 14040)

Three types of data are required to model the LCI of an HGS:

1. *Model Inputs* are data that comprise or otherwise define the HGS object of assessment, e.g. material takeoffs;
2. *Scenario Information* are the assumptions required to model the HGS over its life cycle, e.g. material replacement rates;

3. *LCI Process Data* is input and output flow data for unit processes within the system boundary, e.g. the LCI of cement production.

When producing an LCI, the source of data used is dependent on the phase of the project during which an LCA study occurs. For the purpose of this document, it is assumed that an HGS-LCA prepared as part of an EIS is conducted late in the design phase, prior to construction bidding.

At this point in the project it is assumed:

- The model inputs are sufficiently defined such that they can be compiled based on primary data collected from engineering and costing documents specific to the project in question;
- The project is not yet at a state where much of the scenarios information can be compiled from primary data, and therefore generally come from relevant secondary sources;
- The LCI data comes exclusively from secondary sources such as publically available ISO-compliant LCI databases.

Sections 6.1, 6.2, and 6.3 that follow provide further information and recommendations for each of the three data types.

6.1 MODEL INPUTS

Several key model inputs are required to define the object of assessment (i.e. the HGS) and to later relate the project-level flows to a product-level LCI model:

- Service life of the project: the estimated service life is required so that the cumulative use-phase impacts may be estimated.
- Electricity generation estimates: the total electricity generated by the HGS over its service life is required to estimate impacts on a per kWh basis.
- Average line losses of from the HGS to consumer: line loss estimates are needed to relate the generation of electricity to the amount that is available to consumers.
- Material takeoffs: quantities comprising the proposed infrastructure elements are required to calculate material flows throughout the life cycle of the HGS.
- Land use change information: data is required for the existing land cover and several parameters that will be used to estimate greenhouse gas emissions over the life cycle of the project.

Data collection surveys should be developed to elicit the material takeoffs from the various source documents. The data collection should be designed in collaboration with Manitoba Hydro staff that is most familiar with the structure of supporting documentation. The underlying sources may not be aligned with the HGS infrastructure components as defined in the EIS Project Description supporting volume. In this case, the materials takeoffs should be clearly mapped to the project description elements so that the completeness of the scope may be ensured and to facilitate communication of the system boundary. Maintaining the overall structure of LCI data collection in this way also enables refinement of the models as the design is completed and takeoffs are finalized.

The primary data pertaining to existing and projected land cover is required to estimate the greenhouse gas fluxes that are result from the project. Required inputs to the land use calculations include:

- Carbon stock estimates for all lands listed in the Project Description for the current year.
- Volume of wood entering manufacturing streams, for all logs and fibre to be removed from the project area.
- Volume of wood material to be cleared from the project area, and then burned.
- Land cover descriptions (plant species) for all lands affected by the project listed in the project description.
- Carbon stocks and land cover descriptions for lands affected by the project but not listed in the Project Description (e.g. quarries, blasting)

6.2 SCENARIO INFORMATION

For a typical HGS-LCA, scenario information includes, but is not limited to[31]:

- Material compositions;
- Material manufacturing locations;
- Material, energy, and worker transportation distances and modes;
- Material (i.e. temporary infrastructure and ancillary material), energy, and water use for information modules B4 and C1;
- Material, energy and water use, and activity rates for information modules B2-B5;
- Annual ancillary material, energy, and water use for information modules B6-B7;
- Construction waste rates, and waste disposal, incineration, re-use, and recycling rates;
- Pre-inundation clearing and biomass treatment

This information is required for estimating some of the life cycle intermediate flows not defined by the model inputs and/or determining some of the subsequent LCI data needs. While the source of data to be used is dependent on the scenario in question, the following is a general hierarchy that should be used, in order of preference:

1. **Primary data specific to the HGS:** whenever possible, scenario information specific to the HGS should be used. This is possible when, e.g. it is known who will be supplying a particular material. In this case the proper manufacturing location, material transportation distance and mode to site, estimated replacement rate, etc. can be used.
2. **The primary data of other MH projects:** the next best source of information provided it reasonably applies to the HGS, e.g. the concrete mix design of a past project could be assumed if it is used for the same purpose in the HGS.
3. **The primary data of non-MH projects:** if a past MH project is unavailable for a particular scenario, non-MH projects are the next best source of information provided it reasonably applies to the HGS.

[31] See EN 15978 for a comprehensive list of building scenario requirements that can be applied to a HGS LCA.

4. **Statistical data and third-party databases:** statistics and third-party scenario databases (typically based on statistical information or professional consensus) provide another basis to make some assumptions, e.g. the recycling rate of rebar.
5. **Professional judgment:** if no other source of information is available, professional judgment may be used to define a scenario. This may take the form of estimates or assumptions made by MH, or the use of secondary data found in the reports of other similar projects.

6.3 LIFE CYCLE INVENTORY PROCESS DATA

LCI process data quality should conform to the following requirements, as adapted from the International EPD System PCR *CPC 171: Electricity Generation and Distribution*:

1. As a general rule, primary LCI process data should always be used if available[32].
2. Secondary data may be used if [1] primary data is unavailable, [2] it is applicable to the HGS, and [3] it is no more than 10 years old.
   a. Secondary data should be selected from commercially and publically available LCI databases.
   b. If secondary data is available in commercially and publically available LCI databases, other secondary LCI process data may be used and documented. The environmental impact of the processes where the other secondary LCI data are used must not exceed 10% of the overall environmental impact from the product system.

The model inputs and scenario information data that is compiled will be linked to secondary LCI process data to complete the life cycle inventory such that all intermediate flows are related to upstream and downstream elementary flows (See Figure 9). The LCI should be completed in LCA-specific software such as SimaPro[33] or GaBi[34] and the entire model of flows may be maintained so various impact assessment methods may applied.

6.4 LAND USE CHANGE

The calculation of land use change emissions may be performed based on the rough estimates from the Intergovernmental Panel on Climate Change (IPCC) Guidance document, but should be refined based on the International Hydropower Association (IHA) and United Nations Educational Scientific and Cultural Organization's (UNESCO) guidelines after the project has been completed. This will allow more refined estimates for future projects.

[32] Given the defined goal of the HGS-LCA and the likely timing of the study within the project life, it is expected that the production of primary LCI process data will generally not be undertaken.
[33] http://www.pre-sustainability.com/simapro-lca-software
[34] http://www.gabi-software.com/

6.4.1 PRELIMINARY ESTIMATIONS

The Tier 1 calculations may be easily performed based on a few key parameters gathered in the primary data collection. The basic calculations are summarized in *Reservoir Greenhouse Gases Technical Memo, Manitoba Hydro File 00195-11100-0180 01* and can be summarized as follows:

Pre-flood emissions from fire

Equation 2.27 (Vol. 4 Chap. 2) may be used to estimate emission from fire.

Post-flood emissions from diffusive flux

Equation 2A.1 may be used to estimate the emissions of methane and carbon dioxide from diffusive flux. The diffusive flux does not apply to the carbon removed from the prescribed fire and thus combining the fire equation with the default IPCC flux equations will overestimate emissions.

6.4.2 ADVANCED LAND USE CHANGE MODELING

The IPCC guidance document notes that the results from Equation 2A.1 are “highly uncertain”. The International Hydropower Association (IHA) and United Nations Educational Scientific and Cultural Organization’s (UNESCO) International Hydrological Programme responded to the lack of a consensus methodology for more precise modeling and thus produced their own GHG Measurement Guidelines for Freshwater Reservoirs. This document provides a comprehensive protocol for estimating GHG emissions from reservoirs and should serve as the basis for research on this topic by Manitoba Hydro.

The IHA/UNESCO guidelines require post-inundation measurements and thus are impossible to complete at the EIS phase. The adoption of the IHA/UNEWCO guidelines does allow the development of a knowledge base from previous projects that may be used to refine the estimations for future EIS estimations.

6.5 LIFE CYCLE INVENTORY MODEL DATA REPORTING

With respect to reporting, EN 15978 states "The findings of the all results shall be traceable and transparent". Proper reporting of model inputs, scenario information, and LCI process data is central to demonstrating traceability and transparency, as they have a significant influence on study results and reflect a significant share of the modeling choices made by the assessor.

At minimum, the following information should be reported for any data used in the HGS LCI:

1. Model Inputs:
    a. Value and unit
    b. Source
2. Scenario Information:
    a. The applicable process and information module it belongs to
    b. Value and unit
    c. Source

3. LCI Process Data:
    a. Scope and information module(s) covered
    b. Data quality description
    c. Source

How this information is presented best in the report will be study-dependant, but should generally be in the form of tables, and any given type of information should be presented together (i.e. should not be spread out within the report).

6.6 LIFE CYCLE INVENTORY RESULTS REPORTING

The cumulative life cycle inventory flows must be reported as per the EIS requirements prior to the life cycle impact assessment. The total of all elementary flows (i.e. raw material inputs and emissions to air, land, and water) may be readily calculated if LCI databases are used within LCA-specific software. The LCI results will typically be in excess of several hundred or even thousands of substances and may be included as an appendix to the LCA report. Publishing the LCI results separately from the impact assessment also allows future analysts to apply new or updated impact assessment models.

CHAPTER 7: LIFE CYCLE IMPACT ASSESSMENT

Typically, Life Cycle Impact Assessment (LCIA) is completed in isolation of the LCI; that is, the LCI requests a complete mass and energy balance for each unit process or product system under consideration, and once completed, the LCI is sifted through various LCIA indicator categories to determine possible impacts.

ISO 14044 requires only that the impact assessment aligns with the goal and scope of the study. Since the goals presented in this protocol are to inform a variety of project stakeholders with differing perspectives, it is recommended that the HGS-LCA adopt a range of different environmental indicators. The impact assessment portion of the LCA is also of minimal effort since much of the calculations are automated in LCA software which means there is no reason to exclude impact categories.

7.1 INDICATORS TO BE REPORTED AND CALCULATION METHODOLOGIES

Table 7 presents the recommended EN 15978 indicators to be reported for the HGS-LCA, which includes a variety of LCIA mid-point[36] impact categories (aka "environmental indicators") and summations of various resource use, waste, and system output LCI flows. Three indicators advocated by EN 15978 (*Use of renewable secondary fuels*, *Use of non-renewable secondary fuels*, and *Radioactive waste disposed*) are not recommended to be included since [1] North American LCI databases do not support them, or support them well, at present and [2] the indicators not of particular significance to a HGS.

7.1.1 LIFE CYCLE IMPACT CATEGORIES

For six of the seven LCIA impact categories to be reported, the recommended calculation methodology is version 2.1 of the US Environmental Protection Agency's *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts*[37] (TRACI, or TRACI v2.1). The TRACI methodology was developed specifically for the United States using input parameters consistent with US locations and ISO 21930. Since there is no available North American calculation methodology for the seventh LCIA impact category (*Abiotic resource depletion potential for elements*), the European methodology *CML* 2002[38] is recommended for this indicator. A description of each LCIA impact category listed in Table 7 is provided in Appendix 2.

It is important to note that the LCIA impact categories described by an LCA are estimates of relative and potential impacts, rather than direct measurements of real impacts, with limitations as described in the ISO international standards series 14040:2006.

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[36] Mid-point impact indicators describe the potential for impacts as opposed to the eventual impacts on human health, ecological systems, and resource depletion. Midpoint indicators carry less inherent uncertainty than end-point indicators and are thus more widely accepted in LCA.

[37] See *http://www.epa.gov/nrmrl/std/traci/traci.html* for further information.

[38] *CML 2002* is a LCIA methodology developed by the *Center of Environmental Science (CML)* at Leiden University in the Netherlands.

TABLE 7: RECOMMENDED ENVIRONMENTAL INDICATORS TO BE REPORTED IN THE HYDROELECTRIC GENERATION STATION LCA

EN 15978 Environmental Indicator	Methodology	Unit
Environmental Impacts		
Global warming potential, non-biogenic	TRACI v2.1*	kg CO_2 eq.
Global warming potential, biogenic	TRACI v2.1*	kg CO_2 eq.
Depletion of the stratospheric ozone layer	TRACI v2.1*	kg CFC-11 eq.
Acidification potential of land and water	TRACI v2.1*	kg SO_2 eq.
Eutrophication potential	TRACI v2.1*	kg N eq.
Formation potential of troposheric ozone photochemical oxidants	TRACI v2.1*	kg O_3 eq.
Abiotic resource depletion potential for elements	CML 2002*	kg S_b eq.
Abiotic resource depletion potential of fossil fuels	TRACI v2.1*	MJ surplus
Resource Use		
Use of renewable primary energy excluding energy resources used as raw material	CED*	MJ
Use of renewable primary energy resources used as raw material	CED*	MJ
Use of non-renewable primary energy excluding resources used as raw material	CED*	MJ
Use of non-renewable primary energy resources used as raw material	CED*	MJ
Use of secondary material	Sum of LCI flows	kg
Use of renewable secondary fuels	*not recommended to be included*	
Use of non-renewable secondary fuels	*not recommended to be included*	
Net use of fresh water	Sum of LCI flows	m^3
Waste Categories		
Hazardous waste disposed	Sum of LCI flows	kg
Non-hazardous waste disposed	Sum of LCI flows	kg
Radioactive waste disposed	*not recommended to be included*	
Output Flows Leaving the System		
Components for re-use	Sum of LCI flows	kg
Materials for recycling	Sum of LCI flows	kg
Materials for energy recovery (not being waste incineration)	Sum of LCI flows	kg
Exported energy	Sum of LCI flows	MJ

*TRACI, CML, and CED are published impact assessment methods. Links to their corresponding documentation have been provided in the References Section.

7.1.2 LIFE CYCLE INVENTORY FLOW SUMMATIONS

Summations of various types of elementary and intermediate LCI flows are also useful to decision-makers without needing to relate them to the environmental impacts that they may cause.

While TRACI supports fossil fuel depletion on a global scale, it does not readily report primary energy use. Primary energy is the sum of elementary LCI flows of energy sources drawn directly from the earth, such as natural gas, oil, coal, biomass or hydropower energy. Higher heating value (HHV) of primary energy carriers should be used to calculate the primary energy values. The four primary energy use indicators advocated by EN 15978 (Use of renewable primary energy excluding energy resources used as raw material, Use of renewable primary energy resources used as raw material, Use of non-renewable primary energy excluding resources used as raw material, and Use of non-renewable primary energy resources used as raw material) should be tabulated and summarized from the LCI results using the Cumulative Energy Demand (CED) methodology.

Net use of fresh water is the other EN 15978 indicator based on the summation of elementary LCI flows, and is calculated as the difference between fresh water (i.e. excludes saltwater) inputs and outputs from the product system. For example, water passing through the turbines of an HGS should be excluded from the total but evaporation should be accounted for.

Biogenic global warming potential is reported separately from the global warming from fossil fuels because these land-use change impacts are subject to separate modeling and assumptions. The biogenic CO2 emissions, as they occur over a number of years after the construction of the project, are also subject to dynamic global warming estimation as described in Section 8.2.

Other EN 15978 indicators noted in Table 7 are summations of intermediate LCI flows. The two indicators dealing with waste (Hazardous waste disposed and Non-hazardous waste disposed) address (by proxy) the environmental burden imposed on disposal facilities, and should constitute summations of the mass of HGS materials that are assumed to be either landfilled or incinerated over the life cycle of the HGS. Similarly, Use of secondary material and the four indicators addressing "Output Flows Leaving the System" (i.e. Components for re-use, Materials for recycling, Materials for energy recovery, and Exported energy) address (by proxy) the environmental benefits and/or burdens of the use of secondary materials and production of useful material and energy for other product systems, respectively.

7.2 OPTIONAL IMPACT ASSESSMENT ELEMENTS

As discussed in Section 1.2.3, the indicator results may be aggregated with several optional modeling steps to facilitate decision-making, but this additional modeling must be transparent and include the underlying results and factors.

7.2.1 NORMALIZATION AND WEIGHTING

If normalization is to be performed, the recommended methodology is TRACI v2.1 as it includes factors that normalize the various impacts to 2005 Canadian per-capita emissions. Please note that the TRACI methodology does not include normalization factors for abiotic resource depletion potential for elements nor EN 15978 indicators based on LCI flow summations.

The weighting of normalized results provides further interpretation of the relative importance of the various impacts incurred. Due to the subjective nature of weighting, it is not recommended that it be reported in the HGS-LCA, since [1] the choice of weighting factors can skew the public's interpretation of the HGS project and [2] the weighting factors may not be representative of the views of the various stakeholders involved in the public-approval process.

7.2.2 ECONOMIC VALUATION

Several of the environmental impacts that will be calculated also carry economic burden that may not be built into the price structure of the life cycles that cause them. Ecological economics principles may be applied to relate the environmental impacts to economic damage that they cause. Such modeling adds significant uncertainty as no uniform databases or modeling framework is available that directly relates LCA results to economic value. Despite this, economic valuation is increasingly being used to relate LCA results to the cost-benefit analysis that underlies economic decision making.

Additional information pertaining to economic evaluation is provided in Appendix 3.

8. INTERPRETATION

The Interpretation stage of LCA seeks to provide greater insight as to the LCA results so that they may be used to inform more sustainable decision making. Recall from Section 5.1 that the primary goal of LCA in the EIS is to communicate the HGS's cumulative environmental impacts. This goal is largely met by producing the cumulative life cycle inventory (See Section 6.6) and range of impact indicators (See Section 7.1).

8.1 CONTRIBUTION ANALYSIS AND BENCHMARKING

The secondary goal of LCA for the EIS, mitigating impacts, requires interpretation of the LCA results. The first step in interpreting the LCA results for this purpose is to recognize which portions of the life cycle cause the greatest impacts and thus may be influenced to cause the greatest impact mitigation. Contribution analysis is applied by determining what percentage of impacts occurs in the various modules as defined in Section 5.4. Benchmarks should be established for these inputs first and others in decreasing priority as recognized in the contribution analysis. Benchmarks should be developed for road construction, earth moving processes, office and utility buildings, major dam elements, various grades of concrete, steel etc.

Benchmarking based on a single LCA study is limited but provides a useful starting point for discussions with suppliers and contractors. The recognition of key impact drivers allows streamlined surveying that may be included within contract bids to gain an understanding as to whether the project will be above or below the LCA estimate as it is completed. The influence on procurement decisions on the overall environmental impacts of the project may thus be weighed against other criteria. Again, the contribution analysis will indicate the priority to be given to the environmental criteria based on its potential to increase or decrease the cumulative impacts of the project.

The primary goal of benchmarking is the establishment of a knowledge base within Manitoba Hydro to influence decisions at the conceptual and early design phases in future projects where much of the overall impacts of a project are determined. This is particularly the case for land use change impacts which are, at best, only roughly estimated based on IPCC Tier 1 calculations. Monitoring existing reservoirs in Manitoba will allow future decisions regarding options for land management (i.e. whether to clear the land prior to inundation with combustion) to more accurately include global warming implications.

8.2 DYNAMIC MODELING OF GLOBAL WARMING POTENTIAL

The global warming potential of the proposed project is one area that warrants special interpretation to fully communicate the warming impacts over time. The non-linear nature of emissions per year and per kWh (e.g. large pulses of up front impacts from land-use change and construction) may be addressed in terms of a dynamic GWP metric. Typical LCA models all emissions from various processes, without consideration of the timing of the emissions, and then characterizes these flows by IPCC GWP (100-yr) factors. These GWP_{100} factors relate the relative warming potential of various greenhouse gases to the equivalent amount warming impact of an equivalent amount of CO_2 over a 100 year time frame.

The recently published IPCC 5th Assessment[40] notes that "There is no scientific argument for selecting 100 years compared with other choices …The choice of time horizon is a value judgement since it depends on the relative weight assigned to effects at different times." This is particularly relevant to methane, which varies significantly relative to carbon dioxide over different time horizons.

An improvement over this static approach (a single carbon footprint value for the product system that ignores timing of emissions and impacts) is the use of a dynamic GWP metric. Such a metric may be the running year-to-year total of greenhouse gas emissions multiplied by static GWP_{100} factors (dynamic LCI, static LCIA), the total of all emissions multiplied by the greenhouse forcing functions ($W/m^2/yr$) that underpin the GWP_{100} factors (static LCI, dynamic LCIA), or a complete estimation of the warming impacts as they occur by accounting for annual greenhouse gas emissions characterized by the forcing functions (dynamic LCI, dynamic LCIA). The complete dynamic approach (LCI and LCIA) provides the most precise estimation of warming impacts caused by a project and may easily be calculated by retaining the temporal dimension in the LCI data collection (e.g. estimating annual emissions from construction and land use change) and characterizing these emissions in a tool such as CIRAIG's DynCO2[41].

8.3 COMPARISON TO ALTERNATIVE TECHNOLOGIES

The EIS requirements include the consideration of alternative electricity options from the perspective of the customer. As discussed in Section 4.2, this is best accomplished through the completion of a literature review on previously completed LCA studies. In completing the literature review, every effort should be made to identify the inconsistencies between the studies and those that are most comparable to the proposed project. The literature review must consider how to address the results from LCAs completed in Europe (based on European LCI data and LCIA models), those that were completed more than 10 years ago, those in which portions of the product system have been excluded, and those that consider a limited set of inventory flows or impact assessment results.

In drawing comparisons based on the literature review, the conclusions are limited to the extreme scenarios of the various technologies and must be qualified based on the inconsistencies of the studies. For example, if multiple LCAs have been completed on a particular electricity generation technology, the most similar studies should be given the greatest consideration but all surveyed results should be presented unless there are explicit criteria used to disqualify them.

To avoid criticism based on confusion as to whether the literature review is actually a non-ISO compliant comparative LCA, the conclusions of the literature review should be largely qualitative and describe the relative merits of the alternative technologies.

[40] http://www.ipcc.ch/report/ar5/wg1/
[41] http://www.ciraig.org/en/dynco2.php

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APPENDIX 1: SYSTEM BOUNDARY REPORTING TEMPLATES

Tables 8 presents a recommended template for reporting the system boundary of a HGS-LCA in terms of the elements and materials. For each project element detailed in the EIS *Project Description* supporting volume, the sub-elements that are included in scope are listed. For each sub-element included in scope, any materials that are excluded from analysis are then listed in the adjacent column.

Table 9 presents a recommended template for reporting the system boundary of a HGS-LCA in terms of life cycle processes. The process type are grouped according to the EN 15978 information modules they belong to. Any particular process that is excluded from analysis is listed in the appropriate row.

TABLE 8: EXAMPLE HYDROELECTRIC GENERATION STATION LCA SYSTEM BOUNDARY REPORTING TEMPLATE, BY PROJECT ELEMENT

Project Element	EIS Project Description Reference	Sub-elements Included	Materials Excluded
Powerhouse Complex	2.3.1	Powerhouse, service bay, and control building structure and envelope	
		Parking lot	
		Trash racks and gates	
		Hoists and cranes	
		Turbines, generators, and transformers	
		Other mechanical equipment	
Spillway	2.3.2	Overflow structure	
		Vertical lift gates	
		Stop logs	
		Hoists and monorail supported by structural steel	
		Road bridge	
		Downstream side bridge	
Powerhouse and Spillway Channels	2.3.3	Powerhouse intake channel	
		Tailrace channel	
		Spillway channel	
Wing Walls	2.3.4	5 concrete gravity walls (A through E)	
...	...	...	
Waterways Public Safety	2.4.16	none	
Infrastructure of Other Projects/Facilities	2.4.17	Infrastructure developed prior to the start of the Project: provincial roadways, rail lines, fibre-optic cable, and electrical distribution lines	
		3 transmission lines and switching stations to connect with Manitoba Hydro’s Integrated Power System	

TABLE 9: EXAMPLE HYDROELECTRIC GENERATION STATION LCA SYSTEM BOUNDARY REPORTING TEMPLATE, BY INFORMATION MODULE

Information Module	Processes Type	Exclusions
A1 Raw material supply	primary raw resource extraction	
A2 Transport	materials transport up to manufacturing plant gate	
A3 Manufacturing	manufacture of raw materials into products	
A4 Transport	material transport from manufacturing plant gate to site	
	construction equipment transport to and from site	
	worker transport to and from site	
A5 Construction-installation process	on-site construction equipment energy and water use	
	all temporary infrastructure effects	
	production and construction process of ancillary materials	
	production and construction process of waste materials	
	end of life of waste materials	
	land use change effects	
B1 Installed product in use	emissions from installed products	
	reservoir inundation effects	
B2 Maintenance	production and construction process of maintenance materials	
	end of life of waste materials	
B3 Repair	production and construction process of repair materials	
	end of life of waste materials	
B4 Replacement	production and construction process of replacement materials	
	end of life of waste materials	
B5 Refurbishment	production and construction process of refurbishment materials	
	end of life of waste materials	
B6 Operational energy use	operating energy use for facilities, reserve power	
	ancillary materials effects	
B7 Operational water use	operating water and wastewater treatment for facilities	
C1 De-construction demolition	on-site decommissioning equipment energy and water use	
	temporary infrastructure effects	
	worker transport to and from site during decommissioning	
	decommissioning equipment transport to and from site	
	production and construction process of ancillary materials	
C2 Transport	material transport from site to disposal facility	
	material transport from site to locate of end-of-waste state	
C3 Waste Processing	processes required for materials to each end-of-waste state	
C4 Disposal	disposal facility equipment energy and water use	
	landfill effects	
	incineration effects	

APPENDIX 2: DESCRIPTION OF RECOMMENDED LCIA IMPACT CATEGORIES

Global warming potential - kg CO_2 eq. (TRACI v2.1)

TRACI uses global warming potentials (CF), a midpoint metric proposed by the International Panel on Climate Change (IPCC), for the calculation of the potency of greenhouse gases relative to CO2. The 100-year time horizons recommended by the IPCC and used by the United States for policy making and reporting are adopted within TRACI. Global warming potential (GWP) – the methodology and science behind the GWP calculation can be considered one of the most accepted LCIA categories. GWP_{100} should be expressed on equivalency basis relative to CO_2 – i.e., equivalent CO_2 mass basis.

Acidification potential of land and water - kg SO_2 eq. (TRACI v2.1)

As per TRACI, acidification comprises processes that increase the acidity of water and soil systems. Acidification is a more regional rather than global impact effecting fresh water and forests as well as human health when high concentrations of SO_2 are attained. The Acidification potential (CF) of an air emission is calculated on the basis of the equivalence to kg $SO_{2.}$ This unit is updated from the previous H+ moles used in TRACI 2.

Depletion of the stratospheric ozone layer - kg CFC-11 eq. (TRACI v2.1)

Stratospheric ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substances. International consensus exists on the use of Ozone Depletion Potentials (CF), a metric proposed by the World Meteorological Organization for calculating the relative importance of CFCs, hydrochlorofluorocarbons (HFCs), and halons expected to contribute significantly to the breakdown of the ozone layer. TRACI uses the ozone depletion potentials published in the Handbook for the International Treaties for the Protection of the Ozone Layer (UNEP-SETAC 2000), where chemicals are characterized relative to CFC-11.

Eutrophication potential - kg N eq. (TRACI v2.1)

In TRACI, eutrophication is defined as the fertilization of surface waters by nutrients that were previously scarce. This measure encompasses the release of mineral salts and their nutrient enrichment effects on waters – typically made up of phosphorous and nitrogen compounds and organic matter flowing into waterways. The result is expressed on an equivalent mass of nitrogen (N) basis. The characterization factors estimate the eutrophication potential of a release of chemicals containing N or P to air or water, per kilogram of chemical released, relative to 1 kg N discharged directly to surface freshwater.

Formation potential of troposheric ozone photochemical oxidants - kg O_3 eq. (TRACI v2.1)

Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). The "smog" indicator is expressed on a mass of equivalent ozone (O_3) basis.

Abiotic resource depletion potential of fossil fuels - MJ surplus (TRACI v2.1)

Fossil fuel depletion takes into account the increase in future energy requirements for extraction and production of fossil fuels, relative to current practice. The future extraction and production scenarios developed for this purpose are replacement fuels at a time when total cumulative consumption equals 5 times the present cumulative consumption. The increase in energy requirements for each fuel therefore provides an estimate of the future incremental energy input "cost" per unit of fuel consumed. The geographic representation of this indicator is worldwide.

Abiotic resource depletion potential for elements - kg Sb eq.(CML 2002)

Abiotic resource depletion potential for elements considers the environmental problem to be the decrease of the resources, and is a function of resource reserves and their extraction rates. The indicator characterisation factor is the abiotic depletion potential (ADP), calculated according to the following equation:

$$ADP_i = ER_i/(R_i)^2 * (R_{ref})^2/ER_{ref}$$

where,

ADP_i = Abiotic resource depletion potential of resource *i* (kg of antimony eq./kg)

R_i = resource reserve of resource *i* (kg);

ER_i = extraction rate of resource *i* (kg/year)

R_{ref} = resource reserve of antimony (kg);

ER_{ref} = extraction rate of antimony (kg/year)

The ADP is derived for each element extraction and is a relative measure with the depletion of the element antimony as a reference. The geographic representation of this indicator is worldwide.

APPENDIX 3: ECONOMIC EVALUATION OF ENVIRONMENTAL IMPACTS

The economic costs of the environmental impacts may be calculated based on models that are specific to the various impact indicators. This modeling relates the impacts to market prices for impact abatement and loss of productivity in the case of health effects. Several examples for valuation methods follow:

Global Warming

Global warming is one impact category that has undergone significant economic research. Carbon taxes have been implemented in Quebec, British Columbia, and Alberta and a potential Canadian national carbon tax has received significant attention. Alternatively, cap and trade mechanisms have been proposed as a market-based approach to price carbon. In addition to these approaches, a US government interagency study[43], among other similar studies, has estimated the long-term social costs of greenhouse gas emissions based on damage modeling.

Smog and Acidification

In some jurisdictions, permits must be purchased through competitive markets for the emission of NO_x (commonly associated with smog) and SO_2 (commonly associated with acidification). Such models are highly dependent on the geographic location of the emission source.

Eutrophication

The price of eutrophication may be determined based on estimates to remove nitrogen from freshwater. This modeling, similar to that for smog and acidification, is highly dependent on geographic location and the efforts to clean freshwater systems in those locations.

[43] http://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf