The Environmental Attributes of Solar PV in the Canadian Context

CanSIA

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Summary of Findings

Findings of the report are under three broad categories.

1. Energy Performance

Life cycle assessment studies of photovoltaic in Canada have generally tended to understate energy performance.

- The efficiencies of PV modules have steadily improved over the past 20 years and have increased by over 30% over the last 10 years. PV modules are now in the range of 15-17% efficient.

- The life expectancy of solar generating systems is approximately double (40 years) that of other generating systems such as wind, nuclear, or natural gas turbines. However many LCA comparative analyses assume that all generators have the same life expectancy.

- International values of embodied energy for PV modules range from 120 – 600 kW/m^2 while a recent Canadian estimate have put this figure as high as 1,500 kW/m^2. CanSIA recommends using the value of 600 kW/m^2 (high end of international studies). Further study is required here in order to determine more accurate values in the Canadian context.

- Energy Payback is the length of time that a generation asset takes to generate the amount of energy that is used to manufacture it. The Energy Payback of PV in Canada is approximately 2.75 years while a Pollution Probe report estimated wind's Energy Payback to be about 1.3 years. However Energy Payback is not a good method in comparing the energy effectiveness of different energy sources as this methodology does not account for the life cycle energy produced. The benefits of a long-lived source such as solar are marginalized using an Energy Payback analysis.

- Energy Yield is a better method of comparing different generators. For example an energy yield of 10 would mean that the generator, over its lifetime, produces 10xs the energy that is needed to manufacture it. The Energy Yield of PV in Canada is estimated in this report to be about 14, which is considerably higher than the current published values of 3-6. The Energy Yield for nuclear is 14-16, wind is 18 –35, and hydropower: 170 – 180.

- The annual energy output of a PV module in Canada ranges from 200 – 240 kWh/m^2 (1,350-1,600 kWh/kW) while the lifetime output is between 8,100 kWh/m^2 – 9,600 kWh/m^2 (54,000 – 64,000 kWh/kW.

2. Environmental Impacts

Life cycle assessments studies of photovoltaics in Canada have generally overstated its environmental impacts.

- A review of the two Canadian reports (by Pollution Probe and the Ontario Power Authority (OPA)) on the environmental impacts of renewable energy were found to have a number of errors related to PV's environmental attributes. In the case of the SENES report done for OPA it was found that there were a number of basic unit conversion errors which increased the environmental impacts of PV by a factor of 10 from the referenced data.

- Using Life Cycle Assessment (LCA) studies from other nations does not properly show PV's environmental attributes in Canada. Conditions in Canada are sufficiently different so that values used for PV in other nations often significantly overstate the environmental impacts of PV in Canada.

- The high percentage of electrical energy used to manufacture solar modules has considerable consequences when considering the production of CO_2 emissions from PV systems. PV modules are currently manufactured in regions of the world that have a high GHG content in their electricity generation mix. This results in PV having a high (compared to other renewables) GHG content. International studies place PV's GHG production at between 13-731 g CO_2/kWh (versus wind at 7-124). However if the solar cells and PV modules were manufactured in Quebec or BC, where the GHG content of the electricity is low, this report estimates that the GHG emissions could be reduced to a negligible value of 0-3 g CO_2/kWh). Ontario (once coal is phased out) and possible other provinces may also present a high opportunity.

- Air pollution values for PV are, like GHG emissions, primarily due to the electrical energy mix in the region where the PV modules are manufactured. This would drop significantly if manufactured in regions of Canada that have clean sources of electricity. No specific calculation of the potential Canadian value was calculated for this report however it is expected that it would be on the low end of international standards (0.24 – 4.90 g SO_2/kWh).

- Solid waste and water pollution during the manufacturing process is not considered an issue as manufacturing processes are generally close looped.

- The land use impacts of PV have been overstated in Canada. The majority of PV modules are installed on buildings and hence have no land use impacts. However even assuming that PV is installed as ground mounted systems then, based on information from the OPA report, solar's energy density is about the same as nuclear power plants (land use for nuclear is given as 0.0014 km^2/MW while solar PV is 0.0013 km^2/MW).

- The majority of PV installations globally are installed on buildings where the energy is used. Thus the LCAs of solar should be based on the installation of solar PV on buildings. This reduces the need for expensive ground mounting and reduces the need of transmission and distribution assets.
- The use of Building Integrated PV (BIPV) can reduce PV's environmental impacts by as much as 30%.

- There is some concern about decommissioning waste after the useful life of PV modules however due to the long-life of PV modules this is not an immediate concern. Further study is important here.

3. The Need for Further Research

This report is not designed as an authoritative, exhaustive study of the environmental attributes of PV in Canada. The report highlights the urgent need for a serious effort in undertaking further research on these matters to get the numbers "rights" given the stakes in the debate of future energy use in Canada.

- A total of 12 recommendations were made for further study – these can be found in Appendix A.

- One of the examples of where a more thorough understanding of the parameters of LCA in regards to distributed generation (versus central power) is needed is in the inclusion of transmission and distribution impacts. When doing a LCA comparison with other generation options, the LCA of the transmission and distribution assets must be included. This currently is not done in Canada. One of solar PV's primary environmental benefits is that it is a distributed generation source – generating power where it is needed – and requires no transmission and distribution.

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1 Introduction

There are many methods and techniques to convert the sun's rays into useful energy. Generally there are three main solar technologies:

- Photovoltaics (PV) or solar electricity: the direct conversion of light into electricity;
- Solar thermal (ST): the production of thermal energy from sunlight for direct heating;
- Passive solar: the transmission of energy (light and heat) directly into buildings using non-mechanical methods.

This report provides an analysis of the environmental attributes of photovoltaic (PV) systems in Canada and does an initial estimate of "made in Canada" numbers. The estimates in this report are not done rigorously but do allow for an initial understanding of issues and provide a point for developing further work. The life cycle indicators that are evaluated include air emissions, land use and water use. The overall environmental attributes of PV are also examined in the context of other renewable energy sources and conventional electricity generating sources.

PV's impact on the environment is the sum of two broad types of impacts:

- The impact it has due to the manufacturing, operating and decommissioning of PV systems – often referred to as its environmental impacts – these have a negative impact on the environment;
- The impact it has by displacing the environmental impacts of other fuel sources such as coal, oil and natural gas – this generally has a positive impact.

The environmental impacts of more commonly used energy sources, such as coal, oil, and natural gas, are well documented although the exact values are often still debated. On the other hand, while there has been some study of solar energy's environmental impacts internationally, there has been virtually no study that places solar's environmental attributes into the Canadian context. This has resulted in a number of Canadian "myths" on solar PV's effect on the environment that create major barriers to the greater acceptance of solar energy in Canada.

If solar products were manufactured in Canada then what would be their environmental impacts? This has not been studied in depth and represents an opportunity for further Canadian research. Understanding the environmental attributes of solar PV in Canada will allow policy makers to correctly identify how solar can contribute to a clean energy future for Canadians.

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2 Life Cycle Assessment

2.1 General Overview

Environmental impacts of a specific technology are often studied through a process called Life Cycle Assessment (LCA), which is a composite measure of sustainability that estimates the impacts that a product may have on the environment. It can generally be described as:

"Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials, manufacturing, transporting and distribution; use, re-use, maintenance; recycling, and final disposal."[1]

Typical life cycle assessment parameters of energy generators include:

- **Embodied Energy** – the amount of energy associated with extraction, processing, manufacturing, transportation, and assembly of the generator plus the supply of its fuel.
- **Energy Effectiveness** – the energy output versus the embodied energy.
- **Green House Gas Emissions** – emissions of carbon dioxide, which contribute to global warming.
- **Air Pollution** – emissions of sulphur dioxide, nitrous oxides, methane, particulate and volatile organic compounds.
- **Solid Waste** – the solid waste produced from the manufacturing and generation phases or at the end of the generator's life.
- **Water Pollution** – the quantity of water use associated with a material process, including the effluent deposited into water bodies.
- **Land Use** – the amount of land required for the generation and the generator's impact on land use issues.

A variation of LCA is Life Cycle Costing (LCC), which involves the financial forecasting of the cost of the product or process based on construction, operation and maintenance costs. This technique relies on the time value of money and expresses the LCC as a net present value. Thus the product is expressed as a single sum of money needed today to cover these costs over the study period selected for the LCC analysis. Virtually no work has been done in Canada on a comparative analysis of the LCC of various energy generation sources and this represents an opportunity for further Canadian research.

2.2 Drawbacks of Current LCA Methodologies for Comparing Solar with Other Energy Sources

One of the major drawbacks with life cycle assessment methods is the time and the cost associated with performing rigorous analyses. In certain cases, some of the assessment parameters are not readily available. It is also often difficult to include social impacts due to the difficulties of quantifying issues. In the case of new technologies that are rapidly evolving and changing, such as solar PV, care must also be taken to ensure that the LCA is based on current technologies rather than older technologies that may no longer be relevant.

Another difficulty is that LCA is generally used as a method to compare two alternatives to determine which is better for the environment. Difficulties arise where the technologies being evaluated have different impacts on the environment that are not comparable. For example, the radioactive waste of nuclear power is a relevant assessment parameter for nuclear as its impact on the environment can last for thousands of years. Yet, how can this then be quantified compared to other technologies such as solar whose impact is felt mainly during its manufacturing stage? Often only the easily compared attributes are used and others – which may be important – are discounted. Examples of this can be found throughout this report.

"Social" impacts of energy sources are not included in this report due to the significant absence of comparative studies in this area. In a "sustainability assessment" PV may have many benefits, such as local economic development benefits, when compared to other energy choice. This represents an opportunity for further research.

Since solar is a distributed source of energy it does not generally require transmission from a centralized power plant. In almost all cases, the LCAs of central power generation supplies (which includes wind, hydro, nuclear, and fossil fuels) do not include the environmental impacts of those transmission "assets." A recent report by the Ontario Power Authority (OPA) on the review of the various environmental attributes of energy options for Ontario stated, "transmission and distribution requirements associated with generation options were not considered."[2] This may be acceptable when comparing different central power plant options that have similar transmission and distribution issues. However one of solar's primary environmental benefits - that of no transmission and distribution impacts – are thus discounted from the very beginning. A study of the transmission LCAs of various energy sources and inclusion into the LCAs of the energy sources is crucial to understanding and valuing the potential environmental and cost benefits of solar technologies.

Another example of where current LCA methods can create a barrier to a true evaluation of solar's impact on the environment is the use of Building Integrated PV (BIPV). While all other energy sources require a stand-alone generator, solar can actually be built into the building and displace building components thus decreasing solar's "net" LCA. Integrating PV into new construction can decrease PV's environmental impacts by as much as 30%[3]. Again this has not been studied or integrated into most LCAs of solar.

3 Life Cycle Assessment of PV

A PV system consists of PV modules, mounting hardware, inverters, wires and other "balance of system" components. This variety of components adds to the complexity of doing a LCA of PV. Generally most solar LCAs have focused on the PV modules, though there are other elements that can significantly impact the final assessment.

If parameters are chosen incorrectly then the LCA may be inaccurate. As there is an unfamiliarity of PV processes in Canada this has been a problem in the past. A good example of an improperly assigned parameter for PV is discussed in this report's sections on air pollution and land use.

The composition of a PV system and the relative size of the components will depend on a number of variables including location (roof or ground) and system size. A ground-mounted PV system can increase the system's life cycle GHG production by as much as 70% over a roof-mounted system due to the increased mounting materials used.[4] Different sizes of systems (i.e. home or commercial) will change the composition of components and can impact the GHG component by almost 100%[5] - for example the physical size and composition of an inverter that provides the AC power from a grid-connected PV array does not change significantly between a 3 KW solar array that is used by a homeowner and a 50 kW solar array that is used in commercial applications.

There has not been a study of PV's environmental impacts in the Canadian context. In fact, Canadian government-sponsored studies have often excluded PV such as a recent unpublished NRCan study on the LCAs of various electrical generation technologies.[6] The two most well known Canadian reviews of international LCA studies of electrical generation that includes PV have been done by Pollution Probe, in 2004, and by the Ontario Power Authority (OPA), in 2005. The environmental ranking of generation options from these reports can be found in Appendices B and C of this report.

Both reports from Pollution Probe and OPA indicate that PV technologies have relatively high environmental impacts compared to other renewable energies (but still orders of magnitude lower than fossil fuel technologies). As the Supply Mix Advice Report[7] from the Ontario Power Authority writes on page 23, "the challenge of solar-powered generation is its environmental life-cycle impact."

As part of this report, a review of the reports noted above was carried out and it was found that the assessments of solar by Pollution Probe and OPA have generally been based on either out-of-date data and /or certain assumptions that are not relevant in the Canadian context. The review illustrates the need of a thorough study of the Canadian parameters used in Life Cycle Assessments. As PV technology is rapidly evolving, referencing processes or efficiencies of 10 years ago does not accurately reflect the current state of the technology.

3.1 The Embodied Energy of PV

There are a number of steps involved in providing a comparative environmental analysis of different energy options. Defining the embodied energy of the generator is the first step.

Embodied energy is the energy it takes to make a product and includes the extraction, processing, manufacturing, transportation, assembly, and final installation. However to compare the energy "effectiveness" of different energy options, one must also compare the life expectancy of the generating plant and its energy output.

Energy requirements for manufacturing PV modules can be broken into:

- Energy needed to extract raw materials (i.e. silicon, aluminium);
- Energy used for manufacturing.

Currently solar PV modules are primarily based on silicon and the solar cells (the basic building block of a module) are produced using one of three primary manufacturing processes: mono (or single) crystalline silicon; poly (or multi) crystalline silicon; or thin film silicon. Estimates of the energy requirements for the manufacturing of the solar cells and modules vary considerably and one complexity is that the different PV technologies have different energy requirements.

Energy required for silicon mining has generally been considered insignificant[8] and is not included in most LCA studies of solar. Much of the silicon feedstock used for PV modules is "off-grade" silicon from the electronics industry and estimates of the energy used to purify the silicon vary considerably. This is changing as the demand for PV products continues to grow resulting in the need for dedicated silicon feedstock. A difficulty also arises in that some studies have looked at the entire process (through the mining of silica) while other analyses have not "charged" for the energy that originally went into crystallizing microelectronic scrap.

A 1998 report[9] that is one of the most often quoted sources provides embodied energy values of between 120 – 600 kWh/ m^2 of module area. A recent review done for NRCan's TEAM (Technology Early Action Measures) office[10] independently calculated embodied energy values of 1,000 kWh/m^2 for multi-crystalline cells and 1,500 kWh/m^2 for single-crystalline cells. These values are considerably above those assigned in international studies.

There are also discussions on whether the frame of the module (normally aluminium) should be included in the analysis of the PV modules embodied energy. Aluminium has a high energy input (but can be recycled) and more modules are becoming available that are frameless (i.e. solar roofing tiles). Also, as the module size increases - from an average of 50 watts in the 1990s to a current average size of 80-100 watts - the percentage of aluminium used for framing is being reduced. Finally, if the PV array is displacing roofing material (which can be very energy-intensive to manufacture and install) then "net" embodied energy is significantly reduced.

Due to the high variations in quoted values of embodied energy for PV further study is recommended here. For this report a value of 600 kWh/m^2 of module area, which is the high end of international values, is used.

3.2 The Energy Effectiveness of PV

The energy effectiveness of a generating source is the relationship of its embodied energy to the energy it generates. There are a number of methods used to compare the energy effectiveness of different energy sources. These methods, and their limitations, are often not understood by policy makers and are discussed in further detail below.

There are also a number of complexities when comparing PV's energy effectiveness to other energy sources:

- PV's life expectancy is extremely long when compared to other technologies;
- The lifetime energy output of a PV module depends on solar resources at the generation site – energy output varies from site to site;
- Different PV technologies have significantly different embodied energy and energy generation efficiency values. Using the average of these values will not necessarily provide an accurate result due the unequal level of deployment amongst technologies (90% of the market is crystalline silicon).

The total energy output of a PV module is governed by three variables:

- The life of the PV module

- The efficiency of the PV module
- The solar resource at the site of generation

3.2.1 Life Expectancy

It is generally acknowledged that PV technologies have an extremely long life compared to other energy sources. Warranties of PV modules are typically in the range of 20-30 years while wind generators often offer product warranties of 3-5 years. No other energy technology (let alone few consumer products) offers guarantees of the duration of the PV warranties. The original solar cells developed by Bell Labs in the 1950s are on display at the Smithsonian – still producing power. There are many examples of PV cells that were produced in the 1950s – over 50 years ago - that are still generating electricity today.

Generally the life expectancy of solar PV modules has been improving – however little documentation can be found on projections of life expectancy of systems now in operation or being manufactured today. A brief literature review (unreferenced) placed values in the range of 18 - 51 years for PV life (varying between technologies). Further study is required here. This report assumes a life expectancy of 40 years for current technologies.

The estimated life expectancy of a generator is either to the end of its useful life or to the point where major reconditioning is required - as reconditioning may require significant new energy needs to extend the life of the generator. There has been little review of the life expectancy of electricity generating options and the impact that generator life expectancy has on a comparative LCA analysis. Table 1 provides estimates using commonly accepted generator life expectancies. It should be noted that this table is based more on a subjective assessment by the author, as there is little comparative analysis available. It is the starting point for further research.

Table 1: Estimates of Life Expectancy of Electricity Generating Sources

Nuclear	Wind Farm	Natural Gas Turbine	Solar PV
20 years	20 years	20 years	40 years

Thus, over a 40-year period, the impact of a natural gas turbine or wind generator may double while solar PV's impact would stay the same. Further, it is important to note that while most of a non-renewable energy source's impact is during the generation stage, a renewable energy source's impact is primarily felt at the manufacturing stage. These are critical points, often overlooked, when doing a LCA analysis of different energy technologies.

3.2.2 PV Efficiencies

For silicon technologies, which are the dominant PV technology, cell efficiencies have improved consistently over the last 20 years. Modules in the late 1990s had efficiencies in the range of 12-14% while most modules now have efficiencies in the range of 15-17%. As an example Sanyo's HIT 200 watt module has a 17% efficiency. Modules now in development are achieving efficiency levels greater than 20%.

The slight change in the efficiency (i.e. from 12% to 16%) may not seem significant however it represents a 33% improvement in the energy production and reduces the LCA impacts accordingly. Thus a LCA of PV can quickly become dated, as is the case of the Pollution Probe report that used data published in 1998 and which, presumably used lower efficiency data from an earlier period.

It should be noted here that improving energy performance efficiencies is only one option in increasing the energy effectiveness of PV. A less efficient PV module, which requires significantly less energy input, such as the case of thin film technologies, may have improved energy effectiveness.

In calculating the operating energy output of a PV system it is necessary to include efficiency losses due other equipment that is required when connecting to the grid, such as the DC-AC transformer (or inverter), wire line losses, etc.

However the power losses that are a result of similar factors are generally not included when evaluating the energy generation from a central power generating plant. Power losses from transformers and line losses are usually accounted for by the system rather than allocated to the generating plant. These power losses can account for as much as 5-15% of the total energy generation from a central power station.

In order to provide an equitable comparison between PV and central power generation, these "system losses" need to be accounted for. However these losses are not generally accounted for in the evaluations of the energy effectiveness of central power generation plants and as such, for this study, they are not included in the evaluation of the PV system to allow for a more equitable comparison. Ideally, in order to do a thorough and accurate comparison of PV with central power generation, the transmission and distribution power losses for central power generation and PV systems should be included. This is a recommendation for further study.

Calculations in this report use a PV module conversion efficiency of 15%.

3.2.3 The Solar Resource

Renewable energy generation is dependent on the energy resource at the site. For PV this relates to the solar radiation, which varies significantly from site to site. A small solar resource will result in poorer energy effectiveness. Many of the energy effectiveness studies have been done using the solar resource of Northern Europe, which is poorer than in many of the urban areas of Canada. Thus, it is expected that energy effectiveness will be higher in Canada than in Europe.

This adds a complexity in evaluating energy effectiveness for PV and is the main reason why energy values for PV vary so significantly amongst different reports. The variation of solar energy between locations in the following chart is almost 40%.

Table 2: The Solar Resource At Different Sites[11]

	Berlin	Tokyo	Los Angles	Moncton	Montreal	Toronto	Edmonton	Vancouver
Solar radiation (kWh/ m^2/year)*	1,200	1,350	2,000	1,400	1,450	1,450	1,600	1,350

* Radiation on an optimally tilted surface (tilt angle = latitude)

3.2.4 Energy Output

Using the data from the above sections it is now possible to estimate the life-cycle energy generation of a PV module.

- Efficiency: 15%
- Available solar power: 1,000 W/m^2 - this is a global solar constant
- Life expectancy: 40 years

The energy output of a solar array is calculated using the following equations:

Energy Output (kWh/m^2) = Global Solar Constant (W/m^2) X PV Efficiency X Solar Radiation (at site kWh/m^2)

Table 3: Energy Output of PV Modules

		Berlin	Tokyo	Los Angeles	Moncton	Montreal	Toronto	Edmonton	Vancouver
Annual Energy Output	kWh/m^2	180	203	300	210	218	218	240	203
	kWh/kW	1,206	1,357	2,010	1,407	1,457	1,457	1,608	1,357
Lifetime Energy Output	kWh/m^2	7,200	8,100	12,000	8,400	8,700	8,700	9,600	8,100
	kWh/kW	48,200	54,300	80,400	56,300	58,300	58,300	64,300	54,300

As noted in the previous section, in order to provide an equitable comparison with other generating sources, system losses have not been included in these calculations. Generally 1 watt of PV will yield 1 – 1.2 kWh annually in most of southern Canada. The energy output presented here is using a similar methodology of central generation plants – where transmission and distribution losses are not included in the assessment.

Not included in this is an evaluation of the "down time" of PV systems necessitated by maintenance and repairs. When solar power is available it has been assumed that the solar array will produce electricity.

However as the maintenance of a PV system is a relatively minor issue and since PV systems are made of modular, off-the-shelf components, it is not expected that PV systems would be inoperable for more than 1 day a year (0.3%). There is little documented study on this issue for many generating sources (and no comparative analysis) and further study is recommended here.

3.2.5 Methods of Evaluating Energy Effectiveness

There are a number of methods used in evaluating the energy effectiveness of generation sources. The two most popular methods are discussed here.

3.2.5.1 Energy Payback

Energy Payback is generally defined as the length of time that a generator takes to pay back the energy that is required to produce it.

Energy Payback (years) = Embodied Energy (kWh/unit) / Annual Energy Generation (kWh/year/unit)

One of the myths associated with PV is that it takes more energy to produce a PV module than the module will generate during its lifetime.[12]

International studies have shown a steady decrease in the energy payback of PV technologies. Reports from the early 1990s typically placed the energy payback values at 4-7 years. More recent reports place the energy payback between 1-5 years depending on the technology as shown in the table below.

Table 4: Published Reports on Solar's Energy Payback (in years)[13,14,15,16]

Single-crystal Silicon	Multi-crystal Silicon	Thin Film Silicon	Other Technologies (i.e. CdTe)
3	0.5-3.8, 2, 4, 4.9	1-2, 2.7, 3	1.9

All these reports evaluate module efficiency and embodied energy differently. The National Renewable Energy Laboratory (NREL) in the US reports that, under US conditions, the energy payback of solar PV systems is between 9 months and 4 years depending on the solar technology.

In the Canadian context, a first estimate of solar PV's energy payback is as follows:

Table 5: An Estimate of the PV Payback in Toronto

A. Embodied Energy	600 kWh/m^2
B. Solar Radiation (Toronto)	1,450 kWh/m^2
C. Module Efficiency	15%
D. Annual Energy production (D = B x C)	218 kWh/m^2 /yr
E. Energy Payback (E = A ÷ D)	2.75 years

While energy payback is one of the most common methods of comparing different energy generating technologies there are some biases built into this assessment. Energy Payback simply looks at how fast the energy investment is returned without considering the life expectancy of the system. A generator that that has a life expectancy of 4 years (such as a typical portable gasoline generator) has considerably less energy value than a generator that has a life expectancy of 20 years even if the energy paybacks of the two sources are the same.

To illustrate how the life of a generator can impact the perceptions of which source provides the "best" value, energy payback values for solar and wind from the Pollution Probe report are placed in the context of an energy yield over a set period.

Table 6: Energy Payback of Wind and Solar (Pollution Probe)

Technology	Energy Payback[17]	System Life (Years)	Years of energy invested to produce energy over 80 years
Wind	1.3 Years	20	5.2
PV	3.0 years	40	6.0

Generally comparing energy paybacks of different generators creates a disadvantage for long-life generators, as it does not properly reflect the true amount of energy that is "invested" into power generation over a set time frame of, say, 50 to 100 years.

3.2.5.2 Energy Yield Ratio

Using a ratio of the embodied energy versus lifetime energy output is generally a much more useful tool in evaluating energy effectiveness than the energy payback as it considers the total energy generated over the life of the generating plant. There is considerable mixing of terminology between various reports reviewed by the author with some reports using the term "Energy Payback Ratio" while others use "Energy Yield" or "Energy Yield Ratio." There are few published reports from independent sources on the energy yields of different technologies and it is necessary to know both the life expectancy and the embodied energy in order to calculate it. Further research is needed here.

Energy Yield = Lifetime Energy Produced / Embedded Energy

Using the data derived from previous sections it is possible to derive an estimate of the Energy Yield of PV in Canada and compare it to published material.[18]

Table 7: Energy Yield of PV and Other Energy Sources

Estimate of PV's Energy Yield in Canada	
A. Embodied Energy	600 kwh/m^2
B. Lifetime Energy Produced (Toronto)	8,700 kwh/m^2
C. Energy Yield (C = B ÷ A)	14.5
Published Data of Energy Sources	
Hydropower	170 – 280
Wind power	18 – 34
Nuclear	14-16
Solar	3-6
Natural Gas (Combined-cycle)	2.5-5

The estimate for PV done in this report is approximately 2.5 – 5 times greater than the values found in published material. The value however is in line with wind power (a value of 18-34). If a site was selected that had an even better resource than Toronto, such as Los Angeles, then using the embodied energy and life expectancy estimates from this report the Energy Yield of PV would be even greater (20 for Los Angeles). This can partially be explained by this report selecting a similar methodology of that used by central power plants (no accounting of line losses) however it is unclear why this difference is so great and further research is recommended into this topic.

3.3 Greenhouse Gas Emissions

Almost all of solar PV's CO_2 emissions are a result of the energy used to manufacture the solar modules, in particular the production of the aluminium frame and the silicon. One of the unique features of solar PV is that it uses an extremely high percentage of electrical energy in the manufacturing of the solar module compared to the percentage of electricity used in the manufacture of other electricity generating sources. The estimates of the electrical content of the embedded energy for the manufacturing of PV modules vary from 70-90% (with the remaining 10-30% coming from thermal energy).[19]

As the energy used to produce the solar cell and module is mainly electrical energy (vs. mainly thermal energy for other electrical generators), PV's GHG emissions are closely tied to the emissions of the electrical generation source. Studies of PV's GHG emissions generally use the energy mix of the country in which the study occurs, thus a high coal content in the energy mix in the country or region will result in a high CO_2 content in the PV product.

PV's CO2 emissions vary more than those of other energy sources – moving from one of the cleanest (in line with other renewables such as wind) to one of the dirtiest (in line with "clean" coal). Due to the high electrical intensity of PV manufacturing, as well as the variance of grid-related CO_2 emissions in each jurisdiction, PV's CO_2 emissions vary significantly when compared to other energy technologies. The following table illustrates this.

Table 8: Variance in Reported CO_2 Emissions of Various Electrical Energy Sources[20]

	CO_2 g/kWh	Variance (by multiples)
Hydro power	2 – 48	24
Nuclear	2 - 59	30
Wind	7 - 124	18
Biomass	15 - 101	7
Natural gas (combined cycle)	389 - 511	1
PV	13 - 731	56
Coal	790 - 1,182	1

Since the generator type used to supply the embodied electrical energy of PV manufacturing is the greatest factor in the environmental externalities of PV, using cleaner energy in the material's production and manufacturing will result in significantly lower emissions.[21] Where the source of electrical generation has low carbon content, PV's CO_2 emissions will be in the same range as other renewable energy technologies.[22] This is not reflected in the Pollution Probe or the OPA report, which indicate that PV's emissions are higher by factors of 18 and 44 times, respectively, than those of wind and are in the same order of magnitude of natural gas and coal. Both reports used sources of information from outside Canada.

The GHG production caused by the manufacture of PV modules can be reduced significantly by producing the solar products in regions that have less carbon content in the production energy. This represents a large manufacturing opportunity for certain regions in Canada.

3.3.1 Estimates of CO_2 Production from Canadian Manufactured PV Modules

This report attempts to derive a preliminary estimate of the CO_2 production for PV modules if they were manufactured in Canada.

The following equation was derived to calculate the CO_2 emissions from the manufacturing of PV modules:

$$m_{GHG} =((E_{total} \times E_{grid} \times EF_{grid}) + (E_{total} \times E_{therm} \times EF_{therm}))/ (S_{rad} \times EF_{PV} \times L_{PV})$$

Table 9: PV Values for Calculating CO2 Emissions

		Units	Value	Notes
m_{GHG}	Mass of GHG emitted	kg/m^2 CO_2		
E_{total}	Total energy used in manufacturing PV modules	KWh/m^2	600	May vary depending on the industrial processes
E_{grid}	The percentage of electrical energy used in the manufacturing of PV modules		80%	May vary depending on the industrial processes
EF_{Grid}	The average emission factor for generating grid electricity in the jurisdiction where the manufacturing plant is located	kg/kWh CO_2		Site specific – dependent on the energy mix of the grid – see table below for values used
E_{therm}	The percentage of thermal energy used in the manufacturing of PV modules		20%	May vary depending on the industrial processes
EF_{therm}	The average emission factor for producing thermal energy in the jurisdiction where the manufacturing plant is located	kg/kWh CO_2	400	Natural gas is selected for these calculations as this is the dominant source of energy for thermal uses in the industrialized world. May vary depending on the source of thermal energy.
S_{rad}	The solar radiation at the site	KWh/m^2/year		Site specific
EF_{PV}	The average efficiency of a PV module		15%	May vary depending on the industrial processes
L_{PV}	The average life of a PV module	Years	40	Uncertainty of life of current product

Table 10 below was developed by applying the GHG emissions equation to the CO_2 emissions for the electrical grid in each province and some specific international jurisdictions.

Table 10: Estimated GHG Emissions in Different Regions

Electricity source	CO_2 Emissions from the Electrical Grid[23] (g/kWh)	Estimated CO_2 Emissions from PV modules manufactured in region (g/kWh)
Grid - Canada (average)	221	16
Grid – Québec	9	0
Grid – Ontario	295	18
Grid - BC	27	3
Grid - Alberta	908	59
Grid - USA	608	34
Grid – Germany	638	53
Grid – Austria	155	12
Grid – Japan	436	32

Germany, Japan and the US are the main manufacturing locations today of PV modules. While the calculations derived in Table 10 above (0-53 g/kWh) are at the extreme low end of published international values (13-721 g/kWh) - the reduction of GHG emissions from PV manufacturing, if PV modules are produced in specific regions of Canada with clean electricity supply, is apparent.

Quebec and BC, with their low carbon content, inexpensive electricity, good supply of raw silicon, a well developed mining infrastructure, and aluminium fabrication capacity (less so in BC) have one of the greatest potentials of any region in the world to be global providers of clean solar PV modules. Ontario (once coal is phased out) also has a high potential of being a source of clean PV products. Other provinces may have similar opportunities.

3.3.2 Comparison of GHG Estimates for PV in Canada

A comparison of the various values given for PV's CO_2 internationally and from the three reports done in Canada (Pollution Probe, OPA, and CanSIA's estimates given in this report) is shown in the following table. A separate discussion of OPA's results can be found in the appendices.

Table 11: Comparison of PV's Estimated CO_2 Values for Canada

	g/kWh
International Reports (Range)	13- 731
Pollution Probe	167
OPA	531
CanSIA (estimate) – Canada	16
CanSIA (estimate) - Quebec	0

Further study of the GHG and air pollution content of PV manufacturing based in Canada is considered critical in the development of a Canadian PV industry development strategy.

3.4 Air Pollution

Air pollution, excluding Green House Gas emissions, consists of sulphur dioxide, nitrous oxides, and particulate and volatile organic compounds.

Like CO_2, PV's air pollution emissions primarily relate to the production of the solar modules and the source of electricity used in their manufacture. As discussed in the above section on CO_2, the greatest variable relates to where the PV modules are manufactured. Air pollution would be considered nominal for modules manufactured in many jurisdictions in Canada, particularly in Quebec, Ontario (once coal is phased out), Manitoba and BC and should be well below the values in regions that have a coal dominated electrical energy supply.

Values for air pollutions emission of various sources from international studies are presented in Table 12 below. PV has the greatest variance of all the renewable energy sources. As with GHG emissions, this is because of the high electrical content of its embedded energy.

Table 12: Variance in Emissions of Various Electrical Energy Sources[24]

	SO_2		Nox	
	mg/kWh	Variance	mg/kWh	Variance
Hydro power	5-60	12	3-42	14
Coal	700-32,321+	46	700-5,273+	8
Nuclear	3-50	17	2-100	50
Natural gas (combined cycle)	4-15,000+	3,750	13 – 1,500	115
Biomass	12-140	12	701-1,950	3
Wind	21-87	4	14-50	4
PV	24-490	20	16-340	21

CanSIA estimates that the pollutants associated with PV modules manufactured in Canada would be at the low end of international values and would be similar to values for wind. Pollution Probe assigned a value for wind below the values normally given in international studies, which has created the impression that PV's impact is greater. OPA's values for PV are well above those given in published reports and it is possible that they were derived incorrectly due to an incorrect conversion of units. This is discussed briefly in Appendix C.

Table 13: Values of SO_2 (g/kWh) for Solar and Wind in Canada

PV	
International values	0.24 – 4.90
Pollution Probe	0.25
OPA	360
Estimated Canadian value (CanSIA)	0.25
Wind	
International values	0.21-0.87
Pollution Probe	0.05

A review of other air pollution elements was not done for this report however is it considered likely that the results would be reflective of the trends identified in the SO_2 pollution review done here.

PV systems do not emit any pollutants during their operation, but there is the possibility of accidental emission during fires of residential PV systems. This may result in emissions of CO_2 and burning products of EVA and Tedlar foils (possibly HF and HCL). However fire simulated tests have shown that such emissions are negligible and that no hazardous wastes are released.[25]

3.5 Solid Waste & Water Pollution

Manufacturing of PV modules can involve the use of some scarce, hazardous and/or toxic substances. For crystalline silicon cell technologies, these include:[26]

- Toxic and flammable/explosive gases like silane, phosphine, arsine, and diborane
- Sulphuric and nitric acid

During the production stage of PV modules much of the potential toxic materials are now in closed systems where the chemicals (such as hydrochloric acid) are separated from impurities and then recycled. In the case of the one Canadian manufacturer, the toxic materials used in the manufacturing are carefully controlled and fully recycled. The manufacturer states that the water leaving the manufacturing plant is actually cleaner than the water that is brought in.[27]

3.5.1 Decommissioning

One of the main solid waste issues is the end of life disposal of PV modules. However, due to the long life of PV modules, there is currently little experience or knowledge on disposal issues or recycling possibilities. The recycling of the actual PV module presents a number of difficulties due to the lamination of the various layers of the module however these issues are being addressed by the international PV industry and a prototype recycling facility is currently being tested in Germany.

There is a high LCA value to the aluminium frame and recycling it would significantly reduce the energy value of the module. In most studies the assumption has been that the frame is not recycled and that the module is disposed of as solid waste.

The SENES report for OPA (page 7-42) identified that decommissioning waste for PV is a concern. "Decommissioning waste for PV is suspected to result in the largest impact in the life-cycle of PV. However there is very little data. It is anticipated that many of the components can be recycled. The (lead-acid) battery is primarily responsible for the environmental impacts of solar home systems. It is also possible that heavy metal leaching from some modules may exceed environmental limits."

The SENES report's comments highlight one of the problems faced by the Canadian solar industry – the lack of knowledge of solar technology by policy advisors and decisions makers. While batteries can increase the environmental impact of a solar system by 55%-435% over its life, [28] the use of batteries is primarily related to off-grid applications where they provide energy storage. On-grid PV systems do not use batteries as excess PV power is fed to the grid and reduces the demand for other generation. The on-grid market is now the dominant market for PV globally, accounting for 76% of annual sales. As the market for PV expands in Canada, it is assumed that the primary market will also be for on-grid applications. While the emissions from the manufacturing of batteries may be significant it is not relevant to include them in any assessment of PV's future potential in Canada.

Further study of the decommissioning issues of solar systems is required before this matter can be fully addressed.

3.6 Land Use

Land use assessment usually includes the impact on soil, wildlife habitat, landscape, visual setting, traditional land and resource use. The amount of land required for PV power generation has come under frequent discussion during LCA reviews. PV power generation is generally believed to have a relatively low energy density compared to other energy sources. It however has the unique advantage of being easily integrated into existing structures. Specifically, it can be installed on the roof or the façade of existing buildings. It is estimated that approximately 98% of all installations globally are installed on buildings and thus have no land use requirements or impacts.

However this continues to not be fully understood by policy advisors and the two Canadian studies by OPA and Pollution Probe assigned a relatively high value to PV's land use compared to actual PV installation practices.

For this report, land use values were calculated as if the PV array was displacing other land uses. However it must be kept in mind that the land impact value is effectively nil if the PV modules are installed on buildings.

Table 14: Calculations of Land Use Values for PV

A. Solar energy density	1,000 watt/m^2	The global constant
B. PV Efficiency	15%	
C. PV power density (C=AxB)	150 watts/m^2	0.00667 m^2/watt =0.00667 km^2/MW
D. Solar energy (Toronto)	1,314 kWh/year/m^2	
E. PV generation (E=DxB)	197 kWh/m^2	
	0.0051 m^2/kWh	0.0051 km^2/GWh

Table 15: Reported Values for Land Use for PV in Canada

Pollution Probe	2,000 ha/1000 GWh	20 km^2/1,000 GWh
OPA (SENES)	0.0013 km^2/MW	1 km^2/1,000 GWh
CanSIA Calculations	0.0067 km^2/MW	5.1 km^2/1,000 GWh

It is interesting to note that the energy density of PV is approximately the same as nuclear in the OPA report (0.0013 vs 0.0014 km^2/MW) and both were assigned a land use rank of 1 (0 being lowest and 10 being the highest impact). This highlights one of the problems of LCA evaluations – where two technologies have similar LCA ratings however society's impression of the impact produced by the two differs. The SENES report does not delve into the other impacts associated with land use (such as soil contamination, traditional land use, etc).

Using this report's calculations on the land use for PV, the current peak power requirements for Ontario (about 25,000 MW) could be met by an area of 170 km^2 of PV modules – an area of 13 km x 13 km.

4 Conclusions

This report attempts to provide some preliminary estimates of Canadian values on the environmental attributes of PV electrical generation. This report should only be considered a preliminary assessment of issues and highlights the need of further study. Nevertheless some key issues and opportunities have been identified.

PV's environmental impacts are generally more variable than other energy sources as PV's energy generation is dependent on local climatic conditions and the environmental impacts of PV manufacturing is highly dependent on the source of electricity used in its manufacturing.

It was found that the environmental impacts of PV in Canada, particularly if the products are manufactured in specific regions in Canada are well below international averages. This presents an opportunity for the PV industry in Canada is assisting with government objectives of reducing Canada's impact on the environment. It also represents a good opportunity for Canada to attract PV manufacturers who are looking at opportunities to provide "clean" solar power globally. Clean inexpensive electricity sources are an important consideration when reviewing the location of a new PV manufacturing.

5 Appendix A: Further Research Needs

Research on solar's environmental attributes have been carried out internationally and is available in various international reports and publications. However this information is still incomplete and this is acknowledged in most international research papers on this issue. Further, solar's environmental attributes vary due to the location of manufacturing and type of installation. The following general recommendations are derived from the preliminary work done by the author. There is much work still to be done…

1. Virtually no work has been done in Canada on a comparative analysis of the LCC of various energy generation sources and this represents an opportunity for further Canadian research.

2. A study of the LCA of the transmission of various energy sources and inclusion in the generator's LCA is crucial to understanding and valuing the potential environmental and cost benefits of solar technologies.

3. Solar technologies – because they are distributed generators - can displace building components and thus decreasing solar's "net" LCA. This has not been studied or integrated into most LCA analyses of solar.

4. Values of between 120 and 1,500 kWh/m^2 have been found for the embodied energy for PV. Due to the high variations in quoted values further study in the Canadian context is recommended here.

5. Generally the life expectancy of solar PV modules has been improving – however little documentation can be found on projections of life expectancy of systems now in the field.

6. There has been little review of the life expectancy of generator options and the impact the life has on the assessment of generator options.

7. There is little documented study on generator "down-time" due to repairs and maintenance and providing a comparative analysis for generating options.

8. There are few reliable integrated reports on the energy yields of different technologies and it is necessary to know both the life expectancy and embodied energy to calculate.

9. A study of the GHG and air pollution content of PV manufacturing based in Canada is considered critical as it could increase the potential of attracting manufacturing of PV modules to Canada.

10. An analysis of the impact of electricity rates on the cost of PV modules would support the attraction of PV manufacturing in Canada. Canada's electrical rates are generally lower than those countries that are the primary manufacturing centres for PV (US, Germany, Japan).

11. Further study of the decommissioning issues of solar systems is required before this issue can be fully addressed.

12. "Social" impacts of energy sources have not been well studies internationally and are notable absent in Canada. A "sustainability assessment" of PV may indicate some unique benefits, such as local economic development benefits, when compared to other energy choice. This represents an opportunity for further research.

6 Appendix B: Pollution Probe's Renewable Energy Environmental Impacts

In Canada, a frequently quoted resource on renewable energy environmental attributes is from Pollution Probe. A copy of their table is reproduced here.

Table 7: Life Cycle Indicators[29]

		Air Emissions			Land Use	Water Use
		CO_2 (g/kWh)	SO_2 (g/kWh)	NOx (g/kWh)	ha/1000 GWh	m^3/GWh
Traditional (incumbent) Electricity Generation	Nuclear	15	0.03	0.03	48	1.6 (consumptive) 995,000 (non-consumptive)
	Coal	955	11.80	4.30	363	3.5 (consumptive) 730,000 (non-consumptive)
	Clean Coal	741	0.72	0.54	363	N/A
	Oil	818	14.20	4.00	115	1.3 (consumptive)
	Natural Gas	430	0	0.50	115	1.1 (consumptive) 730,000 (non-consumptive
	Diesel	772	1.60	12.3	N/A	N/A
Renewable Energy Electricity Generation	Wind	9	0.05	0.04	233	0
	Solar PV	167	0.25	0.22	2,000	0.14
	Stationary Fuel Cells	N/A	N/A	N/A	N/A	N/A
	Bio-electricity	22	0.12	1.80	445 (from waste) 60,000 (from crops) 176,000 (from forests)	11.8

7 Appendix C: OPA Ranking of Generation Options

The Ontario Power Authority (OPA) contracted SENES Consultants to review various electrical generation options during Ontario's Supply Mix consultations, which occurred in Ontario through the summer and fall of 2005. The report environmentally ranked the various energy options as outlined in the following table with a ranking of between 1 – 10, with 10 having the greatest impact.

Technology	Air Ranking			Land Use	Water Use	Waste	Sustainability	Total Rank
	Conventional	Radioactivity	GHG					
Natural Gas	1 - 2	0	3 - 4	1	1.5 - 2.5	0	8	15.5 - 17.5
Coal	1 - 8	10	7 - 9	1	2.5 - 3.5	10	2	33.5 - 40.5
Biomass	2	0	1	1	2.5 - 3.5	1	1	8.5 - 17.5
Nuclear	1	5 - 6	1	1	3.0 - 4.25	1	5.33	17.3 - 19.6
Hydro electric	0	0	0 - 1	0 - 4	5.5	0	1	6.5 - 11.5
Wind	1	0	1	5	0	0	0	6.5
PV	5	0	5	1	0	0	0	11
Transmission Lines	0	0	1	4	0	0	2	7

SENES Consultants Limited; Methods to Assess the Impacts on the Natural Environment of Generation Options; OPA, September 2005

8 Appendix D: A Review of OPA's SENES Report

8.1 GHG Emissions

The results from OPA's SENES report on solar PV's high CO_2 content is puzzling. It presents PV as having a similar CO_2 value as natural gas and coal, yet PV's GHG ranking was assigned a higher (worse) value than natural gas.

OPA's CO_2 Results

	CO_2 eq. Tonnes/MWh	Ranking (0 is best – 10 worst)
PV	0.531	5
Wind	0.012	1
Nuclear	0.005 – 0.012	1
Natural Gas	0.25-0.88	3 - 4
Coal	0.59 – 1.14	7 - 9
Biomass	0.07	1
Hydro	0.003-0.033	0 - 1

OPA SENES report: Life cycle CO_2 emissions for PV were taken from a presentation by Frankl[30] (2001) at the Externalities and Energy Policy: Nuclear Energy Agency Workshop Proceedings (15-16 Nov 2001). These emissions were used to develop the relative life cycle emissions for different generation options. The values in this report were expressed in g/kWh. It is possible that the OPA report has incorrectly converted g/kWh to tonnes/MWh – as the study where this information is obtained from lists PV CO_2 value as 53 g/kWh which is a factor of 10 lower than the 0.53 tonnes/MWh presented by SENES.

8.2 Air Pollution

A similar situation appears to occur with SENES reporting air pollution values 10 times the values used in the referenced document.

LCA Conventional contaminant emissions from PV

	SO_2 (kg/MWh)	NO_x (kg/MWh)	PM10 (kg/MWh)	PM2,5 (kg/MWh)	Normalized (kg/MWh)
Construction	0.36	0.25	0.14	0.10	1.9

8.3 Solid Waste

It is illustrative to note that while the SENES report discussed the decommissioning of PV, the waste from the decommissioning of nuclear power plants was not included in its assessment. "The actual number to compare waste generated through decommissioning [of nuclear power plants] was not readily available." This illustrates one of the problems of doing a LCA of different technologies that have vastly different parameters and where there can be an arbitrary setting of what parameters should be studied for each technology.

8.4 Land Use

Despite this usage pattern, it is illustrative how OPA dealt with the land use of PV (Page 7-24): "There are three types of PV installations (1) Roof Integration; (2) Building Façade Integration; and (3) Open Field Location. Estimating land for either roof or building façade integration does not capture the intent of the land evaluation criteria because land has not been altered to create the generation option. As such, only for open field applications of PV was the land use criterion calculated." Further down in the report, "actual data on land requirements is not readily available since there are few array field power plants presently in operation as most PV applications are roof integrated"

Thus, while SENES acknowledged that PV is primarily used on buildings it continued to evaluate PV for its land use for only ground-mounted systems. This may also help account for the large discrepancy between OPA air impacts for PV and international reports as identified above as ground installations increase the requirements for racking (and increase production energy consumption). While PV's land use impact is in fact almost zero, OPA placed PV's land impact as 1 (which is similar to nuclear but greater than hydro-electric).

8.5 A Review of OPA's Assessment

Based on information presented in this report it would appear that OPA has made a number of significant errors in its assessment of PV. It would seem that appropriate figures would be as follows:

CanSIA's Recommended PV Ranking

	Ranking	Comments
Air – Pollution	1	A similar value to wind
Air – Radioactivity	0	
Air – GHG	1	A similar value to wind
Land	0	No land use – a similar value to run of river hydroelectric
Water	0	
Waste	0	
Sustainability	0	
Total	2	

With this ranking, which is comparable to wind except for the Land Use values, solar would have had the lowest LCA of any of the energy technologies evaluated and its value to the Ontario ratepayer would have been increased significantly.

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