



Environment
Canada

Environnement
Canada

Assessment of the Environmental Performance of Solar Photovoltaic Technologies

A report funded under the Clean Energy Fund

Environment Canada, in partnership with Natural Resources Canada's CanmetENERGY



Canada

Print version
Cat. No.: En84-88/2012E
ISBN 978-1-100-21268-5

PDF version
Cat. No.: En84-88/2012E-PDF
ISBN 978-1-100-21269-2

Information contained in this publication or product may be reproduced, in part or in whole, and by any means, for personal or public non-commercial purposes, without charge or further permission, unless otherwise specified.

You are asked to:

- Exercise due diligence in ensuring the accuracy of the materials reproduced;
- Indicate both the complete title of the materials reproduced, as well as the author organization; and
- Indicate that the reproduction is a copy of an official work that is published by the Government of Canada and that the reproduction has not been produced in affiliation with or with the endorsement of the Government of Canada.

Commercial reproduction and distribution is prohibited except with written permission from the Government of Canada's copyright administrator, Public Works and Government Services of Canada (PWGSC). For more information, please contact PWGSC at 613-996-6886 or at droitdauteur.copyright@tpsgc-pwgsc.gc.ca.

Front cover photo: © Photos.com 2010, Getty Images

© Her Majesty the Queen in Right of Canada, represented by the Minister of the Environment, 2012

Aussi disponible en français

| | |
|--|-----------|
| 5.5. Comparison with Other Technologies | 33 |
| 5.5.1. Greenhouse Gases..... | 33 |
| 5.5.2. Air Pollutants..... | 34 |
| 5.6. Areas for Further Work..... | 35 |
| 6. Heavy Metals and Other Chemicals..... | 36 |
| 6.1. Introduction..... | 36 |
| 6.1.1. Impact | 36 |
| 6.1.2. Trend..... | 37 |
| 6.1.3. Information Sources and Limitations | 38 |
| 6.2. Manufacturing..... | 38 |
| 6.2.1. Monocrystalline and Multicrystalline Silicon | 40 |
| 6.2.2. Thin-film Cadmium Telluride | 41 |
| 6.2.2.1. Total Cadmium Emissions | 41 |
| 6.2.2.2. Direct Cadmium Emissions..... | 42 |
| 6.2.2.3. Indirect Cadmium Emissions | 42 |
| 6.2.3. Other Thin-film Technologies | 43 |
| 6.2.3.1. Copper Indium Selenide/Copper Indium Gallium Selenide | 43 |
| 6.2.3.2. Amorphous Silicon..... | 44 |
| 6.2.4. Toxicology Studies on Photovoltaic Modules | 45 |
| 6.3. Operation and Maintenance | 45 |
| 6.4. Decommissioning | 46 |
| 6.4.1. Waste | 46 |
| 6.4.2. Recycling..... | 47 |
| 6.5. Comparison with Other Technologies | 48 |
| 6.6. Areas for Further Work..... | 49 |
| 7. Water Use and Quality | 50 |
| 7.1. Introduction..... | 50 |
| 7.1.1. Impact | 50 |
| 7.1.2. Trend..... | 50 |
| 7.2. Manufacturing..... | 50 |
| 7.2.1. Water Use | 50 |
| 7.2.2. Water Quality – Eutrophication..... | 51 |
| 7.3. Operation and Maintenance | 52 |
| 7.4. Comparison with Other Technologies | 52 |
| 7.5. Areas for Further Work..... | 53 |
| 8. Landscape and Ecology | 54 |
| 8.1. Introduction..... | 54 |
| 8.1.1. Impact | 54 |
| 8.1.2. Trend..... | 54 |
| 8.2. Manufacturing..... | 55 |
| 8.2.1. Land Use..... | 55 |
| 8.2.2. Abiotic Resource Depletion..... | 55 |

| | |
|--|-----------|
| 8.3. Operation and Maintenance | 56 |
| 8.3.1. Land Use..... | 56 |
| 8.3.2. Biodiversity | 56 |
| 8.4. Decommissioning | 57 |
| 8.4.1. Land Reclamation..... | 57 |
| 8.4.2. Abiotic Resource Depletion..... | 58 |
| 8.5 Comparison with Other Technologies | 58 |
| 8.6. Areas for Further Work..... | 60 |
| 9. Conclusions..... | 61 |
| Glossary | 62 |
| References | 71 |

Preface

The *Assessment of the Environmental Performance of Solar Photovoltaic Technologies* has been developed by Environment Canada, in partnership with Natural Resources Canada's CanmetENERGY and with input from Task 12 "Photovoltaic Environmental Health and Safety" of the International Energy Agency's Photovoltaic Power Systems Programme and several Canadian researchers and industry stakeholders.

This initiative was funded under the \$1 billion Clean Energy Fund announced by the Government of Canada in 2009. Part of Canada's Economic Action Plan, the Clean Energy Fund is investing in large-scale carbon capture and storage demonstration projects, smaller-scale demonstration projects of renewable and alternative energy technologies, and research and development projects, including related technology assessments such as the current report.

This assessment has been conducted with the recognition that renewable energy technologies have, in general, fewer negative environmental impacts than traditional fossil fuel-based electricity production. In 2009, the US National Academies of Sciences performed a comprehensive analysis of the available literature on comparative electricity generation technologies, including various renewable energy technologies. Ranges were generally provided indicating the minimum and maximum environmental releases for the technologies, as the literature findings were found to vary considerably. Nevertheless, the following conclusions were reached in terms of environmental impacts:

- Renewable electricity technologies have inherently low life-cycle carbon dioxide *emissions* compared with traditional fossil fuel-based electricity production;
- Most emissions occur during the manufacturing and deployment of the renewable energy technologies;
- Except for biopower, renewable electricity generation has low or zero direct emissions of regulated atmospheric pollutants;
- Most renewable energy technologies consume significantly less water and have much smaller impacts on water quality;
- Land use impacts tend to remain localized, and some affected land may also be used for other purposes; and
- At high deployment rates, local impacts can be important.

The assessment is designed to enhance the scientific and technical understanding of solar photovoltaic technologies in Canada and to help support development of effective public policy, regulations and federal investment decisions. Where possible, this assessment provides an understanding of the relative environmental impacts of various electrical power sources, which is essential for development of sound energy policy and allocation of funds to strategic research priorities.

Acknowledgements

This report was made possible by the financial support of the Clean Energy Fund. It was prepared by Kelly Vandelight of Environment Canada's Technology Impacts and Programs Division, with contributions from Sophie Pelland and Yves Poissant of Natural Resources Canada's CanmetENERGY Photovoltaic Research Group in Varennes, Quebec.

This assessment has benefited greatly from the knowledge and expertise of our peer reviewers: Dr. Vasilis Fthenakis, Brookhaven National Laboratory and Columbia University, 5N Plus Inc., and the Centre interuniversitaire de recherche sur le cycle de vie des produits, procédés et service.

We are also grateful for the cooperation and contribution of the International Energy Agency's Photovoltaic Power Systems Programme and the Natural Sciences and Engineering Research Council of Canada Photovoltaic Innovation Network. Our sincere thanks go out to these groups for inviting us to their meetings; the opportunities for learning that these meetings offered were vital to the preparation of the report.

Executive Summary

Background

The *Assessment of the Environmental Performance of Solar Photovoltaic Technologies* has been conducted against a backdrop of international and national interest in photovoltaic (PV) technologies as a sustainable, renewable source of energy. On the international front, cumulative installed PV capacity grew an impressive 68% (IEA, 2011b) from 2009 to 2010, with most installations taking place in a limited number of countries, including Germany, Japan, Italy, the United States, Spain and France. In Canada, the PV sector grew by more than 22% annually between 1993 and 2009 (IEA, 2009), currently employing over 5 000 people, and generating business value of more than \$1 billion per year.

The Government of Canada has committed to reduce Canada's total greenhouse gas (GHG) emissions by 17% from 2005 levels by 2020. To help deliver on this commitment, and to support research, development, and testing of renewable and alternative energy technologies, including PV technologies, the Clean Energy Fund was announced in 2009.

Objective

The assessment is intended to enhance the scientific and technical understanding of PV technologies and support effective public policy, regulations and federal investment decisions that advance PV and other clean energy technologies in Canada. Where possible, it provides an understanding of the relative environmental impacts of various electrical power sources and identifies knowledge gaps, essential information for development of sound energy policy and allocation of funds to strategic research priorities.

Method

The assessment sets out the worldwide and Canadian PV context, and then provides a short primer on solar cells, PV systems, applications (including off-grid and remote-grid applications), a brief overview of the main PV technologies currently available on the market, and a summary of the life cycle of PV systems. The body of the report is a comprehensive review of published studies, with the findings presented and discussed in chapters organized according to five environmental indicators: energy payback time, GHG emissions and air pollutant emissions, heavy metals and other chemicals, water use and quality, and landscape and ecology. Each chapter includes a comparison with other technologies, where this information is available.

Overall, the assessment provides an evaluation of the environmental performance of PV technologies across their full life cycle: material sourcing, manufacturing, product use, transmission, distribution and decommissioning. Of these, the manufacturing stage is the most important with regard to environmental consequences of PV technologies. The report focuses on two categories of PV technologies, crystalline silicon modules (70% of module production according to the International Energy Agency's [IEA] survey) and thin films (30% of module production); these two are considered the most important in the current Canadian market. Efforts were made to examine all available materials that may have relevance in the Canadian context, including studies from western Europe where the climate may be similar to Canada's.

Key Findings

The comprehensive review and evaluation of PV technologies over the entire life cycle has produced a clear picture of their performance measured against key environmental indicators. In brief:

- PV technologies have, in general, fewer negative environmental impacts than traditional fossil fuel-based electricity production. Currently, many solar companies meet or exceed national and international standards for handling and mitigating hazardous materials.
- The decommissioning of PV modules is seen as an environmental challenge for the solar industry. To address this challenge, *PV CYCLE*¹, an international PV industry program that is addressing the recycling challenge in Europe, has been established. The first large-scale dismantling facility for end-of-life modules was introduced in Europe in 2009 under PV CYCLE.
- The energy payback time (EPBT) of a PV system (the period of time required for the system to generate the same amount of energy that was used to produce it) has declined significantly in recent years, with studies now reporting EPBT of approximately one year. This can be attributed to increased module efficiency, more efficient manufacturing, and improvements in technology.
- PV systems emit no GHGs or air pollutants during normal operation. The material extraction and production stages account for almost all emissions in the PV life cycle. The largest concern is associated with fluorinated GHG emissions. Recent trends show that releases of these gases are on the decline, which may be attributed to more efficient manufacturing processes and the use of alternative substances.
- Small amounts of heavy metals such as cadmium and lead are used in the production of PV cells and can arise from waste created by the decommissioning of the solar modules at the end of their useful life. Cadmium telluride, an inorganic cadmium compound widely used in PV cells, should be differentiated from that of elemental cadmium and its other compounds, as it has less toxicological risk. Cadmium is a natural by-product of zinc mining, and studies suggest that an environmentally friendly means to sequester elemental cadmium is to use it in PV modules. Recycling PV modules at the end of their life ensures that cadmium is reclaimed and used again in new PV modules now and for the foreseeable future.
- Water use in the life cycle of PV technologies is mainly from upstream usage related to manufacturing and is considered to be minimal. No water is used during the operation of PV systems, except for when modules are cleaned. In addition, the impacts on water quality are considered to be minimal.
- Ground-mounted applications can have a significant, though localized, impacts on landscape and ecology. Rooftop applications use less land because they are mounted on existing structures. As module efficiency increases, land use will decrease. However, it has been demonstrated that when PV power plants are constructed using best management practices, they can provide a positive benefit to biodiversity. Another benefit of PV power plants is that they can be located on marginal lands and *brownfields*. They can also be used on higher-quality lands in conjunction with grazing livestock and crops.

¹ Italicized words and phrases are defined in the Glossary.

Discussion/Conclusions

In general, PV technologies have fewer negative environmental impacts than traditional fossil fuel-based electricity production, as detailed in the Key Findings section above. More specifically, comparing PV technologies with more traditional modes of energy production reveals measurable benefits; for example:

- Emissions of cadmium from the life cycle of cadmium telluride (CdTe) PV modules are 100–360 times lower than those from coal power plants with optimally functioning particulate control devices. When compared with coal-fired thermal facilities, each gigawatt-hour of electricity generated during operation from CdTe PV modules can in fact prevent 8.8 g of cadmium emissions from a coal-fired facility in Europe or about 2 g from such a facility in the United States, given a median concentration of 0.5 mg/kg of cadmium in US coal.
- Studies have reported that water consumption during the normal operation of a PV system is minimal (15 L/MW h) in comparison with other energy-generating technologies. The only technology that had lower water consumption values in these studies was offshore wind (4 L/MW h). Significantly higher values for water consumption were reported for coal (1140 L/MW h), nuclear (1500 L/MW h) and oil-gas steam (1100 L/MW h).
- Land use for renewable energy sources, such as PV, is distinct in that renewable energy sources use land statically (passively), whereas conventional fuel sources use resources extracted from the land during their operation and maintenance phase.

On the other hand, the growth of the solar power sector may have its own environmental consequences. For example, the increase in PV module manufacturing, and the eventual need for decommissioning and disposal, may create a wave of electronic waste (e-waste). Decommissioning waste for PV is the stage expected to result in the largest environmental impact when PV is evaluated on a full life cycle basis. That said, recycling of spent PV modules has now begun and has shown potential to improve the environmental profile of PV technologies.

This report also identifies areas at each stage of the PV life cycle where there is a shortage of information, as summarized below in Areas for Further Work. It also examines the state of knowledge on benefits and consequences associated with each stage of the PV life cycle. Taken as a whole, and despite caveats about environmental consequences associated with decommissioning, the assessment reveals the current benefits and potential future benefits of PV technologies at every stage of the life cycle.

Areas for Further Work

The assessment revealed knowledge gaps for all five environmental indicators: EPBT, GHGs and air pollutants, heavy metals and other chemicals, water use and quality, and landscape and ecology. Areas for further work include:

- Access to current information is vital when considering the EPBT indicator, given that parameters that affect EPBT, including conversion efficiency, wafer thickness and material utilization, are continually improving. EPBT for stand-alone systems (Kaldellis et al., 2010) in Canadian remote communities is lacking, and the potential of new storage technologies to decrease EPBT for stand-alone systems has not been investigated.

- There is a lack of information on GHG emissions associated with building-integrated vs. rooftop installations, comparisons of PV systems with other renewable energy sources, and the impact of new technologies and processes. Further investigation of GHG releases for amorphous silicon (a-Si) thin-film modules would be useful, given concerns over releases of fluorinated gases (F-gases) in manufacturing. While GHG emissions were emphasized, few authors addressed air pollutants.
- Many of the currently available studies do not evaluate emissions in terms of toxicity as an indicator. For life cycle assessments (LCAs) in general, different models can produce very different results because a standard characterization method for toxicity is not available. Despite the fact that heavy metals and other chemicals are used in small quantities in PV modules, as production and deployment increase in the coming years, it will be important to monitor the use of these substances to ensure they do not exceed set limits and pose a risk to human health and the environment. Understanding the potential environmental impacts of PV technologies would benefit from a full toxicity assessment of CdTe and specific LCA toxicity characterization factors. Studies have shown that its toxicity is significantly lower than elemental or metallic cadmium and its other compounds.
- Only limited data are available on water use in the manufacturing stage, and on whether or not this water is recycled or recirculated. The impact of the use of water in the recycling of PV modules at the end of life has not yet been explored. A standard measurement for accounting for water consumption, including water recycling, would provide a more accurate account of water use in the LCA of PV systems.
- Research continues to standardize metrics to assess land use intensity, habitat fragmentation, multiple stressors on the health of populations, and the risk of collapse of complex ecosystems (Turney and Fthenakis, 2011). Currently, many land impact categories for LCA lack well-defined metrics or lack consensus among LCA practitioners; proxy impact categories such as land use intensity are often used to evaluate land impacts in LCA, but there is no consensus on which metric best describes the effects of a variety of uses on land.

1. Worldwide and Canadian Photovoltaic Context

1.1. Worldwide Photovoltaic Context

The International Energy Agency (IEA) has said that an energy technology revolution is under way and widespread deployment of low-carbon technologies will not only help address the climate change challenge but will also enhance energy security and economic development (IEA, 2010a).

Despite strong growth over the past decades, photovoltaic (PV) systems currently contribute only 0.1% of worldwide electricity supply (IEA, 2010b). Potential deployment scenarios range widely—from “business as usual” scenarios in which PV remains marginal in worldwide electricity supply even in 2050, to median cases with PV contributing less than 10% in 2030–2050, to aggressive scenarios in which PV supplies up to 12% of worldwide electricity in 2030 and up to 33% in 2050 (EPIA, 2011; Arvizu et al., 2011). The IEA estimates that, by 2050, PV will provide approximately 11% of global electricity production and avoid 2.3 Gt of carbon dioxide emissions per year (IEA, 2010b).

In 1993, the IEA established the Photovoltaic Power Systems Programme (IEA-PVPS), a collaborative research and development agreement among 16 Organisation for Economic Co-operation and Development (OECD) countries, including Canada. The IEA-PVPS mission is to enhance international collaboration in order to accelerate development and deployment of *PV technologies* as a significant and sustainable renewable energy option. By late 2009, it had 14 individual research projects or Tasks, of which 7 are continuing. Task 12 investigates the “Environmental Health and Safety Issues of PV.”

Cumulative PV power capacity worldwide has grown from 103 MW in 1992 to 34 953 MW in 2010 (IEA, 2011a) (Figure 1).

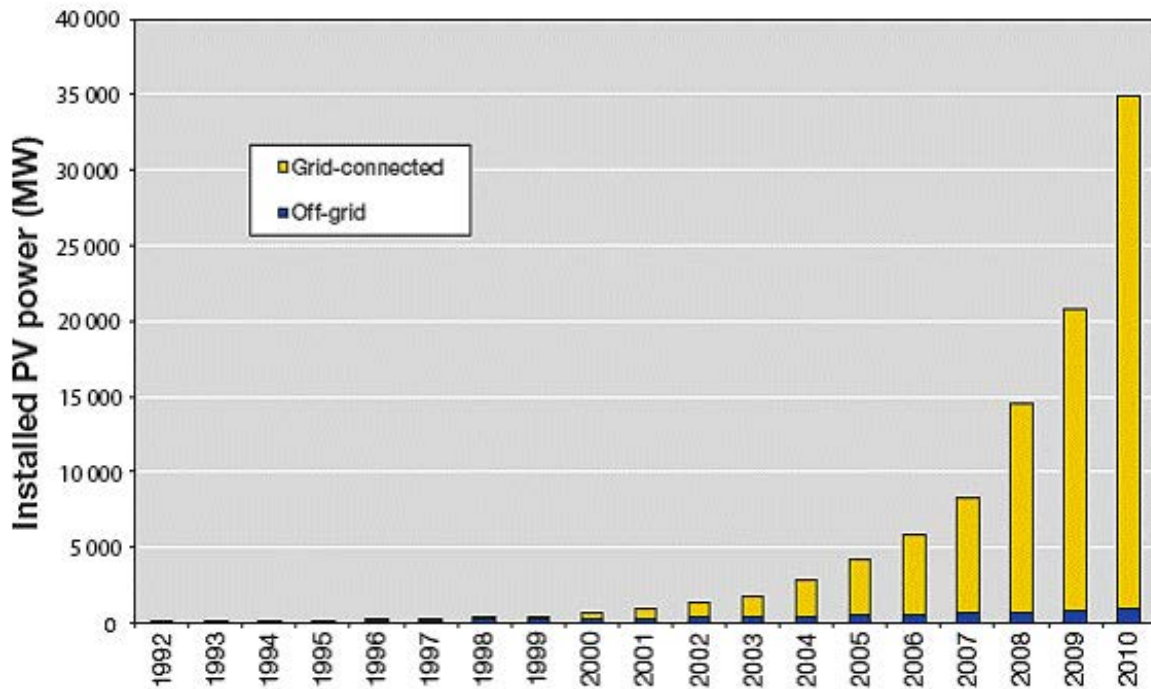


Figure 1: Evolution of cumulative installed PV capacity in OECD countries from 1992 to 2010
Source: IEA, 2011b

Figure 1 shows the evolution of the cumulative *installed PV capacity* in OECD countries from 1992 to 2010, as well as the respective contributions of *off-grid* and *grid-connected applications* (IEA, 2011b). At the end of the 1990s and early 2000s, grid-connected applications started overtaking off-grid applications as a result of subsidy programs in countries like Japan and Germany designed to speed the deployment of PV systems, drive cost reductions and stimulate the PV industry. Various types of subsidies have been used, the most popular being *feed-in tariffs* that contract with system owners to purchase PV-generated electricity at a premium price over a long-term period. At the end of 2009, feed-in tariff programs were in place in over 50 countries (Arvizu et al., 2011).

From 2009 to 2010, the cumulative installed PV capacity grew an impressive 68% (IEA, 2011b), with the bulk of installations taking place in a limited number of countries, including Germany, Japan, Italy, the United States, Spain and France. The price of PV systems and PV-generated electricity has been decreasing steadily since the commercial introduction of these systems in the 1950s. PV modules, for instance, have had a 20% median reduction in cost for every doubling of the manufactured PV module capacity (Arvizu et al., 2011). Currently, the lowest PV-generated electricity prices, which are associated with large-scale PV power plants, are in the range of 14.5 to 36.3 cents/kW h (Arvizu et al., 2011). While this remains higher than the retail price of electricity in most locations, *grid parity* is predicted in several locations by the end of the current decade (IEA, 2011b).

PV growth is spurred by both environmental and economic considerations. From an environmental perspective, PV systems generate no direct *greenhouse gas (GHG)* emissions during a normal 20–30 year operating life and can therefore play a role in mitigating climate change by displacing more GHG-intense, fossil fuel-based electricity generation. This is discussed in detail in a recent report of the Intergovernmental Panel on Climate Change (Arvizu et al., 2011). Economically speaking, the PV industry is a high-technology industry employing nearly 430 000 people in the 16 *PVPS countries* alone, with estimated total business value in 2010 that approached US\$60 billion, double the figure for the previous year (IEA, 2011b).

1.2. Canadian Photovoltaic Context

The Canadian PV sector grew in installed capacity by more than 22% annually between 1993 and 2009 (IEA, 2009). The Ontario government's Feed-In-Tariff (FIT) program is stimulating rapid deployment of grid-connected PV. Canada's total installed PV capacity reached 281 MW in 2010, up from 94 MW in 2009 (Dignard-Bailey and Ayoub, 2011). Under the Ontario FIT program, the Ontario Power Authority (OPA) offers PV system owners contracts to buy PV-generated electricity at a premium price. Tariffs range from 34.7 cents/kW h for large-scale ground-mounted PV systems to 54.9 cents/kW h for rooftop systems of less than 10 kW (OPA, 2012). As of the end of 2011, the OPA managed electricity supply contracts for 10 380 MW of renewable energy, 19.3% of which was from PV (OPA, 2012). While the largest number of applications under these programs has been for small residential systems, over 75% of the installed capacity comes from megawatt-scale PV power plants, such as the 80 MW Sarnia plant.

Canadian PV manufacturers are involved in different stages of the PV life cycle, producing *solar-grade semiconductor* materials (for example, Calisolar and 5N Plus), module and PV cells (for example, Centennial Solar, Day4 Energy, Heliene, Photowatt Canada, Celestica and Canadian Solar), and many other products all along the PV value chain. Recently, the FIT program's requirement for domestic content has attracted a large number of new companies to Ontario, resulting in a dynamic and rapidly changing industry. The PV sector in Canada currently employs over 5000 people and generates business value of over \$1 billion per year. Moreover, solar energy creates more jobs per megawatt of output and per dollar invested than any other energy source (Peters, 2010).

In December 2010, the Canadian Solar Industries Association (CanSIA), in partnership with Ernst & Young, released *Solar Vision 2025*, a roadmap document for the future of the Canadian solar energy industry (Canadian Solar Industries Association, 2010). The report envisages that “by 2025 solar energy is widely deployed throughout Canada, having already achieved market competitiveness that removes the need for government incentives, and is recognized as an established component of Canada's energy mix.”

The Government of Canada has committed to reduce Canada's total GHG emissions by 17% from 2005 levels by 2020. To help deliver on this commitment, the Government of Canada has a number of clean technology activities that help advance PV and other renewable energy technologies, including:

- Environment Canada Technology Impacts and Programs Division, a division that leads the Department's participation in a range of federal technology programs and analyzes the environmental performance of new and emerging technologies to inform policy decision makers.
- Natural Resources Canada's CanmetENERGY, the largest federal energy science and technology organization working on clean energy technologies;

- Program of Energy Research and Development (PERD), a federal program led by Natural Resources Canada that funds sustainable energy research and development; PERD is delivered by Environment Canada and 12 other departments and agencies;
- ecoEnergy Innovation Initiative (ecoEII), a new \$97 million program for comprehensive research and development and demonstration projects that support energy technology innovation to produce and use energy in a more clean and efficient way (ecoEII replaces the ecoENERGY Technology Initiative that ended in March 2011); and
- Clean Energy Fund, a fund that invests in large-scale carbon capture and storage demonstration projects and smaller-scale demonstration projects of renewable and alternative energy technologies, including this assessment.

Government of Canada PV activities and projects are directed by the interdepartmental Integrated Renewable Energy Systems (IRES) Portfolio Committee. Environment Canada is represented on IRES and helps ensure the advancement of promising clean technologies as a complementary measure to regulatory and enforcement measures.

Finally, remote communities in Canada are especially well placed to benefit from PV systems. These communities frequently lack conventional energy infrastructure (e.g., power lines) and often rely on diesel generators. PV projects are likely to improve local air quality and reduce the risk of fuel spills as they displace some or all of the diesel generation.

2. Introduction to Photovoltaics

2.1. Solar Cells

PV systems convert energy from the sun directly into electricity. Their basic component is the solar (or PV) cell, the operation of which is shown schematically in Figure 2. Solar cells are diodes: they combine two (or more) layers of semiconductor materials whose properties are manipulated in such a way as to create a permanent electric field across the junction of the two layers. When photons strike the solar cell, they excite electrons in the semiconductors. Some of these electrons get carried across the (p - n) junction by the electric field and make their way to the conducting contacts at the top of the cell. If the cell is connected to a load, as in Figure 2, these electrons will flow through the circuit and supply power to the load. The power generated is, in general, proportional to the amount of sunlight received by the solar cell.

As discussed in section 2.3, there are many different types of solar cells, corresponding to different semiconductor materials and arrangements of layers. These cell types differ in terms of their commercial maturity, their cost and their efficiency in converting solar energy into electricity. Efficiencies of commercially available cells range from about 7% to 18% (IEA, 2009), with the most expensive multi-junction cells reaching record efficiencies of over 40% (Green et al., 2011). Meanwhile, solar cells made of low-cost materials with efficiencies of only a few percent are studied in research laboratories in an attempt to drive up efficiencies and achieve breakthroughs in cost.

EXAMPLE OF THE PHOTOVOLTAIC EFFECT

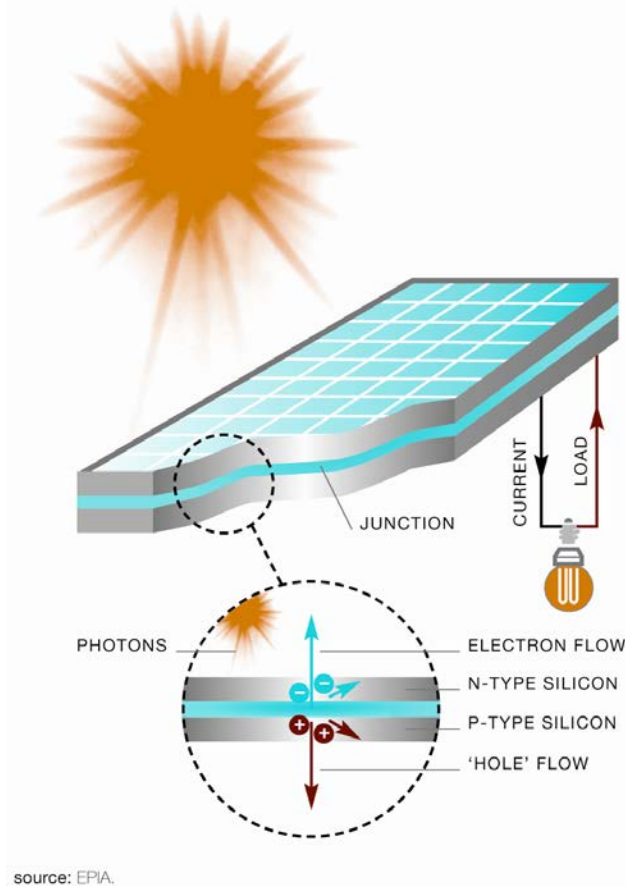


Figure 2: Generation of current in PV cells when photons excite electrons that travel across the p - n junction
Source: European Photovoltaic industry Association – Greenpeace international, “Solar Generation 6”, 2011

2.1.1. From Solar Cells to Photovoltaic Systems

Single PV cells are sometimes used to power small consumer goods such as calculators, watches and *light-emitting diodes (LEDs)*. In general, however, several cells are electrically connected, laminated with an *encapsulant* and sandwiched between protective front and back covers to form a solar module, as shown in Figure 2. Similarly, modules are wired together to form PV arrays that are mounted in racks on the ground or on building rooftops and facades. Finally, *balance of system (BOS)* components that depend on the type of application are added to the arrays to form a PV system. Since PV arrays produce direct current (DC), inverters are typically used to convert this to alternating current (AC), which is used by most electrical appliances. BOS components can also include batteries and *charge regulators* when storage is required, *sun-trackers* to enable PV arrays to follow the sun, mirrors and lenses for concentrating PV systems, and *transformers* to step up the PV-system voltage for connection to the electricity grid.

2.1.2. Photovoltaic System Applications

PV system applications can be divided into two broad categories: (1) grid-connected applications in which PV systems are connected to a centralized electricity grid; and (2) off-grid and remote-grid applications in which they are not (Figure 3).



Figure 3: Applications of PV systems: residential (left) and grid-connected power plants (right)
Left image © Yves Poissant; right image © Pixomar/FreeDigitalPhotos.net

2.1.2.1. Off-grid and Remote-grid Applications

Historically, PV technologies were initially developed for off-grid applications in niche markets, as these applications were where PV first became cost-competitive. When a location is separated by more than 1–2 km from the electricity grid or when electricity needs are modest, PV and other on-site generation technologies are often less costly than grid extension. PV also has the added advantage of requiring little maintenance, which is key for remote, unmanned sites. PV systems have been used to power a variety of remote applications, such as telecommunication stations, navigational aids, water pumps, highway signs, lighting and water treatment plants. PV systems are also being used for residential applications, to power off-grid residences as well as remote communities, in combination with other renewable energy sources and diesel generators. They are also used in developing countries, where 1.4 billion people lack access to electricity (Arvizu et al., 2011) and where electricity needs are low. In such places, they are used in village electrification, with lighting and refrigeration typically targeted.

2.1.2.2. Grid-connected Applications

Unlike many off-grid systems, grid-connected PV systems do not require storage, since electricity can be imported from the grid when needed. Costs of grid-connected systems are therefore about 50% lower than for off-grid systems. On the other hand, costs of electricity from centralized grids are much lower than for remote grids, so grid-connected PV is not yet cost-competitive except in isolated cases. For this reason, the growth of grid-connected PV has been driven by various subsidy programs, as discussed in sections 1.1 and 1.2. Grid-connected PV systems range from small residential rooftop systems of a few kilowatts to megawatt-scale PV power plants (Figure 3).

2.2. Photovoltaic Technologies and Life Cycle Overview

This section provides a quick description of the main PV technologies available on the market as well as a summary of the life cycle of PV systems. For further details on these topics, readers may consult references such as Wolden and colleagues (2011) and IEA (2011a, 2011b).

2.2.1. Current Photovoltaic Technologies and Present Status of Manufacturing

PV technologies are based on a number of semiconducting materials and are at different stages of maturity. The main PV technologies on the market today are based on *crystalline silicon* (monocrystalline, multicrystalline and ribbon silicon) and *thin films* (*cadmium telluride* [CdTe], *amorphous silicon* [a-Si] and *copper indium gallium diselenide* [CIGS]). As of 2009 (Wolden et al., 2011), crystalline silicon (c-Si) technologies represented 84% of the PV market (37% single crystalline, 2% ribbon and 45% multicrystalline), and thin films occupied the remaining 16% of market share (13% CdTe, 2% a-Si and 1% CIGS). Other novel PV technologies such as *dye-sensitized* and *organic PV cells* are at the preindustrial stage. *High-efficiency III-V multi-junction cells* based on gallium arsenide are used mainly in niche areas such as space and concentrated PV applications.

2.2.1.1. Crystalline Silicon

Silicon is the second most abundant element on Earth after oxygen and the most abundant semiconductor in the world. Crystalline silicon has benefited from decades of development within the microelectronics industry. It is well understood and has proven field stability. For these reasons, PV technologies based on crystalline silicon have dominated the PV terrestrial market for several decades and are still dominant. Efficiencies of single crystalline silicon PV modules can range between 14% and 20%. Continuous improvements in performance, yields and reliability have helped decrease the cost of this technology. Because of the lower cost of multicrystalline silicon wafers, cells based on this technology emerged in the 1980s as an alternative to single crystalline silicon although their efficiencies tend to be slightly lower. There are opportunities to further reduce costs, including using lower purity silicon feedstock, decreasing silicon use through *kerfless wafers* (ribbon silicon technology) and developing *ultrathin silicon* technologies.

The manufacture of a crystalline silicon PV module is divided into several steps, starting with wafer cutting, cell fabrication and module assembly. In the wafer stage, solar-grade multicrystalline or single-crystal silicon ingots are sliced into wafers 0.2 mm thick. During the cell stage, a *p-n junction* is formed by dopant diffusion, and electric contacts are created by applying and *sintering metallization pastes*. In the module stage, cells are connected physically and electronically and are then encapsulated by glass and plastics (*ethylene-vinyl acetate* [EVA], Tedlar, etc.).

2.2.1.2. Thin-Film Technologies

As the name implies, thin-film technologies are made of layers of semiconductors typically a few microns thick (approximately 100 times thinner than those used in conventional single and multicrystalline silicon technologies). This property is enabled by the absorption coefficient of these semiconductors being higher than that of crystalline silicon, resulting in lower material use and thus cheaper technologies. On a cost-per-watt basis, CdTe modules have achieved the lowest production cost, below \$0.85 per watt, in contrast

to an average of \$1.60 per watt for crystalline technologies in 2010. The main technical challenge for thin-film technologies is to improve module efficiencies, which range from 7% for a-Si to 14% for CIGS, with CdTe modules around 12%.

The manufacturing stage for thin-film PV technologies is relatively simple compared with crystalline silicon (resulting in an additional cost advantage). Thin-film PV manufacturing typically relies on a series of semiconductor-layer depositions on a glass or stainless steel substrate followed by module fabrication steps (e.g., encapsulation) similar to those used for crystalline silicon technologies. Other flexible substrates can sometimes be used to produce *building-integrated PV* products.

2.2.1.3. Novel and Emerging Photovoltaic Technologies (*Dye-sensitized, Organic and High-efficiency III-V Multi-junction Photovoltaic Cells*)

In addition to crystalline silicon and thin-film technologies, a number of novel PV technologies are at earlier stages of development, and other PV technologies are emerging in niche applications. While these technologies are not widely deployed, their unique characteristics make them suitable for specific applications in space, deserts, buildings and consumer products.

Dye-sensitized solar cells consist of a *photoelectrode* (nanocrystalline titanium dioxide sensitized with organometallic dye molecules), a redox electrolyte (iodine) and a counter electrode (platinum). These cells can reach 11% efficiency, but critical issues such as stability (related to device encapsulation) and production of large area modules are important to consider for this technology to compete with other PV technologies on the electricity market. At the moment, most products are geared toward the consumer market (e.g., chargeable batteries for portable electronics) and building-integrated applications, in which different colours and levels of transparency can be selected.

Organic photovoltaics, sometimes referred to as “plastic solar cells,” has made great progress in the last 10 years, with champion cells reaching 8% and commercial products approaching 4% conversion efficiencies. Carbon is an abundant element, and manufacturing costs are expected to be low. However, these cells are susceptible to chemical, physical and mechanical degradation when exposed to light and oxygen. The current manufacturing goal is to increase stability and product lifetimes from three to five years in order to enable consumer electronics applications.

High-efficiency III-V multi-junction solar cells based on gallium arsenide have been used in space for decades. The most interesting attribute of these cells is their high conversion efficiencies, which can surpass 40%. These high efficiencies are obtained, however, at the cost of complex fabrication processes and cell designs and the use of rare elements. The end result is a technology that can cost over 100 times more than conventional crystalline silicon and thin-film technologies. To get around this issue for terrestrial applications, in which cost per kilowatt-hour is the ultimate figure of merit, high-efficiency III-V PV systems make use of *concentrators* that focus the direct component of sunlight onto a small area (e.g., 1 cm²) at concentrating factors that can reach 2000 times. While the case still has to be made with regard to the performance of concentrators under Canadian climatic conditions and the ability of this technology to compete with flat-plate PV technologies such as crystalline silicon and thin films, concentrators have been deployed in dry areas such as deserts where cloudless skies ensure that a large fraction of the annual *insolation* is received as direct sunlight (rather than diffuse sunlight, which cannot be focused).

None of these novel and emerging PV technologies are addressed in this assessment because they are mainly in the development and demonstration stages and do not yet contribute to the PV market in Canada.

2.2.2. Life Cycle of Photovoltaic Systems: From Material Sourcing to Decommissioning

The environmental *life cycle assessment* (LCA) of an energy technology considers the impact analysis of all stages of production from “cradle to grave,” that is, from fuel production to decommissioning (Figure 4). In the case of PV energy, the stages shown in Figure 4 are simplified because no fuel needs to be prepared, no waste results from the conversion of sunlight into electricity, and little maintenance is required during operation. The impacts are thus associated mainly with plant construction (raw materials, PV module and BOS manufacturing, transportation, and plant manufacturing) and, to some extent, with decommissioning and recycling at the end of the PV system lifespan, typically 30 years (IEA, 2009).

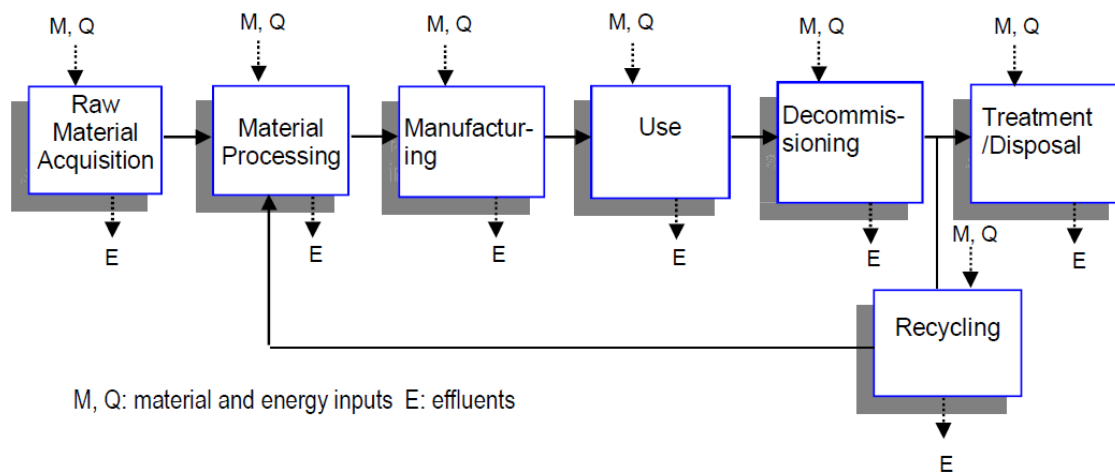


Figure 4: Life cycle diagram of PV system, including energy and material inputs and effluents

Source: Fthenakis et al., 2011b

The life cycle of PV thus starts from the extraction of raw materials and ends with the disposal or recycling and recovery of the PV components. In the case of PV module technologies based on crystalline silicon, a large amount of energy is spent on refining and purifying metallurgical-grade silicon into solar-grade silicon (>99.999999% pure). Other thin-film technologies such as CdTe, a-Si and CIGS require less energy input, as the thickness of active materials required to convert sunlight into electricity is about 100 times less than the thickness for conventional technologies based on crystalline silicon. Metal-grade cadmium and tellurium for CdTe PV modules are obtained primarily as a by-product of zinc and copper smelting, respectively, and further purification is required to obtain solar-grade purity (>99.999999%). Similarly, metals used in CIGS PV modules are recovered as by-products of zinc mining while selenium is recovered mainly from copper production. The fabrication of a-Si requires the use of silane, hydrogen, possibly germane and other *doping* gases. Finally, the raw materials also include those required for encapsulations and BOS components: for example, aluminum for module frames, silica for glass, copper ore for cables, and iron and zinc ores for mounting structures. During the PV system installation stage, support structures are erected, PV systems are mounted, and PV modules, cables, and power conditioning equipment are installed. At the end of their lifetime, PV systems are decommissioned and disposed of, with valuable parts and materials recycled.

3. Methodology

3.1. Introduction

This assessment is based on a comprehensive literature review focused on PV technology studies published up to and including February 2012. Information from the literature review has been organized according to the following environmental indicators:

- *Energy payback time*;
- Air emissions, both GHGs and air pollutants;
- Heavy metals and other chemicals;
- Water use and quality; and
- Landscape and ecology.

Each chapter also includes a comparison to other technologies, when information of this nature was available.

This assessment examines the state of knowledge on benefits and consequences associated with each stage of the PV life cycle: material sourcing, manufacturing, product use, transmission, distribution and decommissioning. While each of these stages was considered, the manufacturing stage is the most important with regard to the environmental consequences of PV technologies. In addition, for several indicators, including energy payback time, information is usually published as a total value for the full PV life cycle.

3.2. Life Cycle Assessment

Many of the studies reviewed make use of LCA. LCA is a detailed and quantitative methodology that involves an inventory of the inputs and outputs of a system, measured at the boundaries of the system, as well as an assessment of the potential impacts associated with these inputs and outputs. Each stage of a product's life cycle consumes energy and non-renewable resources, as well as generating emissions associated with certain environmental impacts, which can be global (ozone depletion, global warming, etc.), regional (*acidification, eutrophication, smog, etc.*) or local (*toxicological or ecotoxicological* impacts). General guidelines on the LCA methodology have been published by the International Organization for Standardization (ISO 14040 series of standards). LCA consists of four distinct steps:

1. Goal and scope definition: the product(s) or service(s) to be assessed are defined, a functional basis for comparison (the functional unit) is chosen and the required level of detail is defined;
2. Inventory analysis of *extractions* and emissions: the primary energy and raw materials used, and emissions to the atmosphere, water, soil and land, are quantified for each process, then combined in the process flow chart and related to the functional unit basis;
3. Impact assessment: the resources used and emissions generated are grouped and quantified into a limited number of environmental impact categories; and
4. Interpretation: the results are reported in the most informative way possible, and the need and opportunities to improve the environmental profile or reduce the impact of the product(s) or service(s) on the environment are systematically evaluated.

3.3. System Boundaries

This report considers two categories of PV technologies currently on the market:

- Crystalline silicon modules (70% of module production according to the IEA (2010c); and
- Thin films (30% of module production), focusing on the most promising technologies such as CdTe as well as other technologies for which information was available.

While other PV technologies may be available, and many emerging or novel PV technologies are in the development and demonstration stages, these two types of technologies were identified as the most important in the current Canadian PV market.

With regard to the PV power system, this assessment focuses on PV module technologies (framed and unframed PV modules); however, it also includes available results on other BOS components.

Because of their complexity and data limitations, there are few results related to material sourcing and recycling stages of the life cycle. Although material sourcing is an important stage of the PV life cycle, the environmental benefits and consequences of the PV supply chain have not been studied. Consequently, information is included for materials only once they entered PV manufacturing facilities. Similarly, many experts identified a gap in knowledge of recycling of PV modules. Until the recent introduction of module recycling, broken modules have likely been disposed of in landfills. The long lifespan of solar modules (20 to 30 years) means that full-scale end-of-life recycling will likely be needed in the next 10 to 15 years for systems installed in the 1990s. Data on the environmental benefits and consequences from facilities that recycle PV modules, while limited, are reported when available.

3.4. Data Sources and Limitations

This assessment is based on a review of the available literature. It presents the current state of knowledge for PV technologies, and all available data were taken into consideration. However, it does not compare different studies through harmonization, since the purpose of this assessment is to discuss implications of the environmental attributes of PV for Canada only. Given that there is limited information on the Canadian situation, an effort was made to include all reports that pertain to Canada specifically, and contextualize this information by summarizing the state of the knowledge globally on the environmental benefits and consequences of PV technologies.

In order to present a Canadian perspective, the most recent and most relevant studies available have been included (e.g., studies from Western Europe where climate may be similar to Canada's). Various sources were consulted, including peer reviewed journal articles, published reports, conference white papers and proceedings, graduate theses, draft IEA reports, and recognized experts in the field.

4. Energy Payback Time

4.1. Introduction

Energy payback time (EPBT) is defined as the period required for a renewable energy system to generate the same amount of energy (total primary energy equivalent) that was used to produce the system itself (Fthenakis et al., 2011a). One of the advantages of EPBT is that it is easy to understand and universally applicable to various energy technologies. Different studies calculate it using a standard input–output approach (Laleman, Albrecht and Dewulf, 2011).

Formula for calculating EPBT (Fthenakis et al. 2011a)

$$\text{EPBT} = (E_{\text{mat}} + E_{\text{manuf}} + E_{\text{trans}} + E_{\text{inst}} + E_{\text{EOL}}) / (E_{\text{agen}}/n_{\text{G}} - E_{\text{aoper}})$$

where:

| | |
|----------------------|---|
| E_{mat} = | Primary energy demand to produce constituent materials for the PV system |
| E_{manuf} = | Primary energy demand to manufacture PV system |
| E_{trans} = | Primary energy demand to transport materials used during the life cycle |
| E_{inst} = | Primary energy demand to install the system |
| E_{EOL} = | Primary energy demand for end-of-life management |
| E_{agen} = | Annual electricity generation |
| n_{G} = | <i>Grid efficiency</i> , the average primary energy-to-electricity conversion efficiency at the demand side |
| E_{aoper} = | Annual energy demand for operation and maintenance in primary energy terms |

EPBT for PV depends on various factors (Sherwani et al., 2010; Niewlaar and Alsema, 1997), including:

- Electricity mix used to manufacture PV system components;
- PV system lifetime yield (which depends on irradiation in the plane of the PV array and on PV system performance);
- *Performance ratio* of the PV system (indicator of overall system losses);
- System application type (off-grid vs. grid-connected; building-integrated vs. rack-mounted on roof vs. ground-mounted);
- Solar cell type and efficiency; and
- Other factors (e.g., manufacturing process, type of encapsulation used).

4.2. Reported Energy Payback Times for Silicon and Thin-film Photovoltaic Systems

Table 1: Summary of Reported EPBT for PV Technologies in Canada, Europe and the United States

| Reference | Technology Type | Installation Type | EPBT (years) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|--|------------------|---|--------------|----------------|---|-------------------|
| Silicon-based PV | | | | | | |
| Alsema (2000) | Multicrystalline | Rooftop | 2.50 | 13 | 1700 (southern Europe) | 0.75 |
| | Monocrystalline | Rooftop | 3.10 | 14 | 1700 (southern Europe) | 0.75 |
| Alsema and de Wild-Scholten (2005); Fthenakis and Alsema (2006) | Multicrystalline | Rooftop | 2.20 | 13.2 | 1700 (southern Europe) | 0.75 |
| | Monocrystalline | Rooftop | 2.70 | 14 | 1700 (southern Europe) | 0.75 |
| Meijer et al. (2003) | Multicrystalline | Not reported | 3.50 | 14.5 | 1000 (Netherlands) | Not reported |
| Jungbluth (2005) | Multicrystalline | Various (facade, slant-roof, flat roof) | 3.0–6.0 | 14.8 | 1100 (Switzerland) | 0.75 |
| de Wild-Scholten (2009) | Multicrystalline | Rooftop | 1.80 | 13.2 | 1700 (southern Europe) | 0.75 |
| | Monocrystalline | Rooftop | 1.80 | 14.0 | 1700 (southern Europe) | 0.75 |
| Fthenakis et al. (2011b); Fthenakis et al. (2009); de Wild-Scholten (2009) | Multicrystalline | Rooftop | 1.70 | 13.2 | 1700 (southern Europe) | 0.75 |
| | Monocrystalline | Rooftop | 1.70 | 14 | 1700 (southern Europe) | 0.75 |

Table 1: Summary of Reported EPBT for PV Technologies in Canada, Europe and the United States

| Reference | Technology Type | Installation Type | EPBT (years) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|---|------------------|-------------------|--------------|----------------|---|-------------------|
| Silicon-based PV | | | | | | |
| International Energy Agency, 2006) | Multicrystalline | Rooftop | 2.13 | Not reported | 1377 (Ottawa, Canada) | 0.75 |
| | Multicrystalline | Facade | 3.06 | Not reported | 1377 (Ottawa, Canada) | 0.75 |
| | Multicrystalline | Rooftop | 2.32 | Not reported | 1273 (Vancouver, Canada) | 0.75 |
| | Multicrystalline | Facade | 3.44 | Not reported | 1273 (Vancouver, Canada) | 0.75 |
| Pacca et al. (2007) | Multicrystalline | Rooftop | 7.50 | 12.92 | 1359 (Ann Arbor, Michigan) | 0.75 |
| Myrans (2009) | Monocrystalline | Rooftop | 2.40 | 17.4 | 1303 (Toronto, Canada) | Not reported |
| Thin-film PV | | | | | | |
| Fthenakis and Alsema (2006) | CdTe | Ground-mounted | 0.80 | 9 | 1700 (southern Europe) | 0.8 |
| Raugei et al. (2007) | CdTe | Rooftop | 1.50 | 9 | 1700 (southern Europe) | 0.75 |
| Jungbluth et al. (2008) | CdTe | Rooftop | 2.70 | 7.1 | 1117 (Switzerland) | 0.75 |
| Raugei and Frankl (2009); de Wild Scholten (2009) | CdTe | Rooftop | ~1.00 | 10 | 1700 (southern Europe) | 0.75 |

Table 1: Summary of Reported EPBT for PV Technologies in Canada, Europe and the United States

| Reference | Technology Type | Installation Type | EPBT (years) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|--|-----------------|-------------------|--------------|----------------|---|-------------------|
| Thin-film PV | | | | | | |
| Fthenakis et al. (2009) | CdTe | Ground-mounted | 0.87 | 10.9 | 1700 (southern Europe) | 0.8 |
| Fthenakis et al. (2011b); Fthenakis et al. (2009); de Wild-Scholten (2009) | CdTe | Rooftop | 0.80 | 10.9 | 1700 (southern Europe) | 0.75 |
| | CdTe | Ground-mounted | 2.20 | 10 | 1200 (Frankfurt, Germany) | Not reported |
| | | | 1.60 | | 1700 (Rome, Italy) | Not reported |
| | | | 1.20 | | 2200 (Solar Belt) | Not reported |
| Sustainable Evaluation of Solar Energy Systems (2008) | CIGS | Ground-mounted | 2.10 | 11.5 | 1200 (Frankfurt, Germany) | Not reported |
| | | | 1.50 | | 1700 (Rome, Italy) | Not reported |
| | | | 1.20 | | 2200 (Solar Belt) | Not reported |
| | a-Si | Ground-mounted | 2.60 | 5.5 | 1200 (Frankfurt, Germany) | Not reported |
| | | | 1.90 | | 1700 (Rome, Italy) | Not reported |
| | | | 1.50 | | 2200 (Solar Belt) | Not reported |

Table 1: Summary of Reported EPBT for PV Technologies in Canada, Europe and the United States

| Reference | Technology Type | Installation Type | EPBT (years) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|----------------------|-----------------|-------------------|--------------|----------------|---|-------------------|
| Thin-film PV | | | | | | |
| Pacca et al. (2007) | a-Si | Rooftop | 3.20 | 6.3 | 1359 (Ann Arbor, Michigan) | 0.75 |
| Raugei et al. (2007) | CIS | Rooftop | 2.80 | 11 | 1700 (southern Europe) | 0.75 |

Note: Assumed lifespan of a PV module is 20–30 years. Solar belt is the region that is located within 35° of the equator.

As shown above, estimates of EPBT differ among several PV LCA studies. Such divergence reflects differing assumptions about key parameters such as product design, solar irradiation, performance ratio and lifetime. The estimates also deviate because of the different types of installation used, such as ground mounts, rooftops and facades. Also, assessments often are made on the basis of outdated information in the literature. To resolve these inconsistencies, the IEA-PVPS Task 12 has published Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity that reflect a consensus among LCA experts in the United States, Europe and Asia for conducting balanced, transparent and accurate LCAs (Fthenakis et al., 2011a).

4.3. Photovoltaic Energy Payback Time and Solar Irradiation

Jungbluth et al. (2008 and 2012) noted the importance of irradiation in determining EPBT. They calculated EPBT across Europe for multicrystalline silicon based on total per annum global irradiation. Figure 5, below, shows that EPBT decreases significantly as annual irradiation increases, and vice versa. Similarly, the studies in Table 1 that consider different irradiation levels (International Energy Agency, 2006; Sustainable Evaluation of Solar Energy Systems, 2008) consistently show decreasing EPBT as irradiation increases. This is to be expected from the formula for EPBT given in section 4.1: all other things being equal (and neglecting energy use for operation and maintenance), EPBT is to a first approximation inversely proportional to the annual insolation received in the plane of a PV array.

The annual irradiation values for the studies shown in Table 1 can be compared to annual irradiation for different Canadian locations using, for instance, the maps of *PV potential* and insolation for Canada that have been developed by Natural Resources Canada and Environment Canada in Figure 6. Mean daily global insolation for a horizontal surface can be multiplied by the number of days in a year to yield the annual global horizontal irradiation value for a given location; this can then be compared to the irradiation values in Table 1.

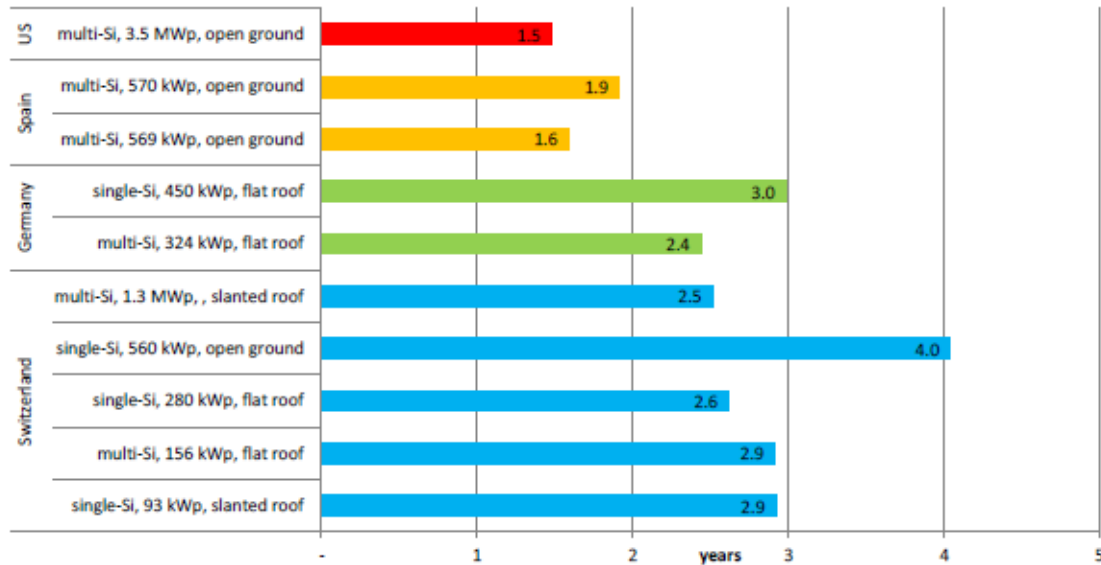


Figure 5: EPBT of 3 kWp multicrystalline modules operated in the United States, Spain, Germany and Switzerland
Source: Jungbluth et al., 2012

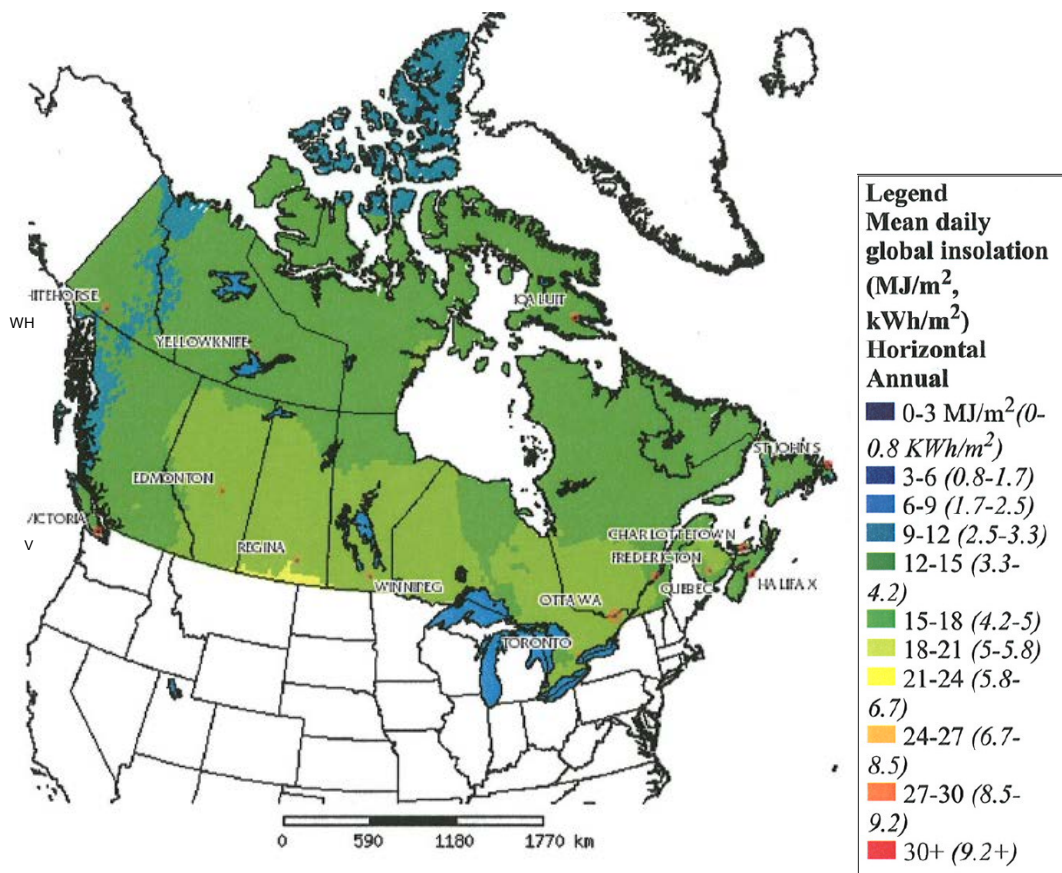


Figure 6: Mean daily solar insolation (kWh/m²) for Canada
Source: Natural Resources Canada, 2011

4.3.1. Photovoltaic Energy Payback Time and Technology Change

Over the PV life cycle, the early stages of silicon production consume the most energy and lengthen EPBT relative to non-silicon modules (EPIA and Greenpeace International, 2011). In the case of multicrystalline silicon modules, production of the silicon consumes 45% of total primary energy used in a module's life cycle (Fthenakis, Kim and Alsema, 2008). For this reason, non-silicon thin-film technologies tend to have a lower EPBT.

Older studies, such as the one by Kato and colleagues (1997), reported EPBT values of 11 to 15.5 years for crystalline silicon systems. This larger range is largely due to the different assumptions and allocation rules for modelling the purification and crystallization stages of silicon production (Alsema, 2000; Fthenakis et al., 2011b). Also, until the early 2000s, rejected electronic-grade silicon from the semiconductor industry was collected and used for PV wafer manufacturing, using a more energy-intensive process than today. The process used at the time was the *Siemens process*, which produces the purity of over nine 9's (99.9999999% pure silicon). A dedicated solar-grade silicon purification process, the modified Siemens process, has replaced the former use of off-grade silicon from the semiconductor industry (Fthenakis et al., 2011b). The modified Siemens process produces solar grade silicon with a purity of six to eight 9's and requires far less energy, so EPBT values have improved.

For CdTe modules, thin-film deposition is the most energy-intensive phase of the life cycle, requiring 54% of primary energy (Fthenakis, Kim and Alsema, 2008). Fthenakis and Kim (2011b), in their study of PV LCA, discuss the EPBT of CdTe PV modules. They note the importance of changing technologies to EPBT. They highlight recent improvements in recycling *sawing slurry*, a fluid used in wafer cutting. Fthenakis and Kim show that recovering silicon carbide and polyethylene glycol from slurry decreases the EPBT of silicon PV technologies by 10%. They also point out that thin-film technologies such as copper indium selenide (CIS) are still in the demonstration stage and that environmental impacts are likely to decrease when production of these modules is scaled up and processes can be optimized.

4.3.2. Energy Payback Time Differs According to Photovoltaic Application Type

In general, building-integrated PV (BIPV) had lower EPBT than *solar parks* or stand-alone systems, according to the 2008 Sustainability Evaluation of Solar Energy Systems (SENSE) project. This study reported EPBT for three types of technologies based on life cycle *primary energy demand*. The EPBT found in Table 1 are for ground-mounted applications. The SENSE report also estimated the EPBT for BIPV applications for CIGS, a-Si and CdTe. For Frankfurt, Germany (irradiation 1 200 kW h/m² per year), EPBTs were 1.9, 1.8 and 1.9, respectively, for BIPV systems, compared to 2.1, 2.6 and 2.2 for ground-mounted systems. Differences between BIPV and ground-mounted EPBTs followed the same pattern for other locations considered, and were of the order of 20% to 40% for a given PV module type (Alsema, 2000; SENSE, 2008).

In considering the difference in EPBT between grid-connected and stand-alone systems, an IEA PVPS Task 1 Workshop report from 1997 noted that stand-alone/battery systems would have significantly higher EPBT. A 2010 study using measurements from Greece found EPBTs for stand-alone systems of 3.5–6 years (Kaldellis et al., 2010). Stand-alone systems have higher EPBT than grid-connected PV systems because they typically include high storage capacity, in the form of lead-acid (PbA) batteries, for example, and because surplus energy generated during periods of high irradiation can exceed storage capacity, leading to wasted energy. That said, the authors still conclude that stand-alone systems are a financially viable and sustainable source of energy for people living in remote areas.

4.3.3. Photovoltaic Energy Payback Time and Module Efficiency

As PV manufacturing processes improve and the amount of material used is reduced and recycled at the end-of-life, one would expect PV EPBTs to decrease accordingly (Held and Ilg, 2011). As well, any increase in the electric-conversion efficiencies of PV modules results in a proportional improvement in EPBT (Fthenakis et al., 2011b). Higher module efficiency means that fewer modules would be needed for an installation, resulting in less racking and decreased EPBT (Laleman et al., 2011).

Since 2005, the EPBT of thin-film CdTe has dropped 15–35% and of silicon PV modules 24–40% as a result of increased efficiency, decreased electricity requirement of CdTe modules, and the thinner wafers used for silicon PV modules (Fthenakis et al., 2009). In a presentation made in 2006 at a SENSE workshop in Dresden, Germany, Alsema expressed optimism about future developments for PV technologies in general, indicating that improvements of 50% in EPBT may be expected, taking into account changes in the technology.

Considering the case of CdTe systems, decreasing EPBT values have been reported as module efficiency has increased. An EPBT of 1.6 was reported by the SENSE study (2008), while an EPBT of less than 1 year was reported by Fthenakis and colleagues (2009) and by deWild-Scholten (2009). The EPBT value of 2.7, reported by Jungbluth et al. (2008), is linked to lower insolation (as can be seen in Table 1). Over this time frame, CdTe module efficiency has increased: efficiencies attaining 7.1% were noted by Jungbluth et al. (2008), while efficiencies of 10.9 % were reported in later publications (Raugei and Frankl, 2009; de Wild-Scholten, 2009; EPIA/Greenpeace, 2011; Fthenakis et al., 2011a). A recent publication from the IEA reports module efficiency for CdTe at 11.7% (Fthenakis et al., 2011b).

4.4. Areas for Further Work

There is a substantial amount of literature on the EPBT of PV technologies. Some authors, most notably Laleman, Albrecht and Dewulf (2011), distinguish between high-irradiation and low-irradiation countries. These authors drew conclusions about Canadian EPBT based onecoinvent data for countries with high irradiation. However, it is unclear to what extent EPBT from one region and PV system type can be applied to another region and PV system.

There is a clear trend in the decrease in EPBT in PV technologies, and timely updates of the EPBT indicator is warranted (Fthenakis et al., 2011b). The parameters that affect EPBT include conversion efficiency, wafer thickness and material utilization. These parameters are continually improving and, as shown in the latest publications by Fthenakis and colleagues (2011b), even the latest EPBT estimates do not represent the most current data available. For example, module efficiency for CdTe is now reported to be 11.7%, whereas current information on EPBT uses a figure of 10.9% module efficiency (Fthenakis et al., 2009; de Wild-Scholten, 2009). As well, Fthenakis and colleagues (2011b) note that wafer thickness has also been reduced in current technologies to around 200 μm for multicrystalline and monocrystalline silicon wafers.

In addition to CdTe, information on EPBT for other thin-film technologies such as CIS and CIGS is limited. Meijer and colleagues (2003) also identify knowledge gaps for their study of Indium Gallium Phosphide technology. The authors emphasize that, since this technology is in the demonstration stage, it is unclear how scaling up processes would affect its environmental performance. The authors also noted the lack of information concerning certain materials and energy consumption in manufacturing processes (e.g., no data on the production of trimethyl compounds, arsine and phosphine). Manufacturers were unwilling to provide certain types of information, and this difficulty in obtaining data posed a barrier to the study.

With regard to various PV applications, a few studies reported EPBT values for Canadian rooftop and facade PV systems in 2006 but did not differentiate between different types of PV technologies (IEA, 2006). Another study reported similar values for Canadian EPBT for a monocrystalline silicon PV system installed on a rooftop in Toronto (Myrans, 2009). The potential of new storage technologies to decrease EPBT for stand-alone systems (Kaldellis et al., 2010) may be important for applications in remote Canadian communities.

As various experts have emphasized, there is very little data on the decommissioning stage of the PV life cycle (Raugei et al., 2007; Meijer et al., 2003). Some studies, such as the SENSE project, identified possible recycling strategies for thin-film PV modules (CIGS, CdTe and a-Si) (SENSE 2008). However, there is a shortage of information on the effectiveness of these recycling strategies.

5. Greenhouse Gases and Air Pollutants

5.1. Introduction

PV systems emit no GHGs or *air pollutants* during normal operation (EPIA/Greenpeace International, 2011; Kaygusuz, 2009). Consequently, the material extraction and production stages account for almost all emissions in the PV life cycle. There is no published data on GHG and air pollutant emissions in the recycling and decommissioning stages of the PV life cycle.

This chapter discusses reported GHG and air pollutant emission values for crystalline silicon and thin-film PV technologies, summarized in Tables 2 and 3. A range of studies was used to populate these tables. These studies were somewhat inconsistent in the scope of substances considered and the manner in which substances were categorized.

5.2. Greenhouse Gas Life Cycle Emissions

In the literature, GHG emissions during operation of PV systems did not emerge as an issue. Although there is no published data on recycling and decommissioning, authors typically assume that proper recycling measures are in place for the purpose of determining GHG emissions.

GHGs are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit the sun's radiation (the greenhouse effect). Owing primarily to human activities, global atmospheric concentrations of GHGs have increased markedly since 1750, and warming of the climate system is unequivocal (IPCC, 2007). The GHGs examined in this chapter include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and fluorinated gases (F-gases) (EC, 2010). Air pollutants contribute to smog and acid rain, and have impacts on human health and the environment. Air pollutants considered here include particulate matter (PM), *ground-level ozone* (O₃), *sulphur oxides* (SO_x), *nitrogen oxides* (NO_x), volatile organic compounds (VOCs), and carbon monoxide (CO).

Table 2: Reported Life Cycle GHG Emissions for Silicon and Thin-film PV Technologies

| Reference | Technology Type | Electricity Mix | Life Cycle GHG Emissions (CO ₂ eq, g/kW h) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|-------------------------|-------------------|-------------------|---|----------------|---|-------------------|
| Silicon-based PV | | | | | | |
| Alsema (2000) | Multicrystal line | UCTE ^a | 46 | 13 | 1700 (southern Europe) | 0.75 |
| | Monocrystal line | UCTE | 63 | 14 | 1700 (southern Europe) | 0.75 |

Table 2: Reported Life Cycle GHG Emissions for Silicon and Thin-film PV Technologies

| Reference | Technology Type | Electricity Mix | Life Cycle GHG Emissions (CO ₂ eq, g/kW h) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|--|-------------------|-----------------|---|----------------|---|-------------------|
| Silicon-based PV | | | | | | |
| Alsema and de Wild-Scholten (2005); Fthenakis and Alsema (2006) | Multicrystal line | UCTE and US | 37 | 13.2 | 1700 (southern Europe) | 0.75 |
| | Monocrystal line | UCTE and US | 45 | 14 | 1700 (southern Europe) | 0.75 |
| Jungbluth (2005) | Multicrystal line | UCTE | 39–110 | 14.8 | 1100 (Switzerland) | 0.75 |
| de Wild-Scholten (2009) | Multicrystal line | US and UCTE | 30 | 13.2 | 1700 (southern Europe) | 0.75 |
| | Monocrystal line | US and UCTE | 30 | 14.0 | 1700 (southern Europe) | 0.75 |
| Fthenakis et al. (2011b); Fthenakis et al. (2009); de Wild-Scholten (2009) | Multicrystal line | UCTE and US | 28 | 13.2 | 1700 (southern Europe) | 0.75 |
| | Monocrystal line | UCTE and US | 29 | 14 | 1700 (southern Europe) | 0.75 |
| Pacca et al. (2007) | Multicrystal line | UCTE and US | 72.4 | 12.9 | 1359 (Ann Arbor, Michigan) | 0.75 |
| Thin-film PV | | | | | | |
| Fthenakis and Alsema (2006) | CdTe | US | 19 | 9 | 1700 (southern Europe) | 0.8 |
| Raugei et al. (2007) | CdTe | UCTE | 48 | 9 | 1700 (southern Europe) | 0.75 |

Table 2: Reported Life Cycle GHG Emissions for Silicon and Thin-film PV Technologies

| Reference | Technology Type | Electricity Mix | Life Cycle GHG Emissions (CO ₂ eq, g/kW h) | Efficiency (%) | Global Horizontal Insolation (kW h/m ² per year) | Performance Ratio |
|--|-----------------|-----------------|---|----------------|---|-------------------|
| Silicon-based PV | | | | | | |
| Raugei and Frankl (2009); de Wild-Scholten (2009) | CdTe | UCTE and US | ~20 | 10 | 1700 (southern Europe) | 0.75 |
| Fthenakis et al. (2009) | CdTe | UCTE and US | 18 | 10.9 | 1700 (southern Europe) | 0.8 |
| Fthenakis et al. (2011b); Fthenakis et al. (2009); de Wild-Scholten (2009) | CdTe | UCTE and US | 18 | 10.9 | 1700 (southern Europe) | 0.75 |
| Pacca et al. (2007) | a-Si | US and UCTE | 34.3 | 6.3 | 1359 (Ann Arbor, Michigan) | 0.75 |

^a UCTE = Union for the Coordination of the Transmission of Electricity, organization responsible for the operation and development of the transmission grid in continental Europe.

Note: Assumed lifespan of a PV module is 20–30 years. Conversion efficiency for US grid mix is 0.29; UCTE, 0.31.

As shown in Table 2, total life cycle emissions of GHGs (in *carbon dioxide equivalence*, CO₂ eq) have been reported to be 28 to 72.4 g/kW h for crystalline silicon (with one study reporting high ranges of 110 g/kW h), and 18 to 20 g/kW h for CdTe (with one study reporting high range of 48g/kW h). Information on other thin-film technologies was limited, and the wide-ranging estimates make it difficult to identify trends in GHG emissions. Estimates were based on European and US data.

As similar PV environmental assessments conducted in Europe indicate, CdTe is clearly superior to other PV technologies in terms of GHG emissions.

Older figures from Alsema, as part of the SENSE study, indicate a trend towards declining GHG emissions for three types of silicon technologies (monocrystalline, ribbon and multicrystalline) (Alsema, 2006). Researchers predicted that life-cycle carbon dioxide emissions could drop to 17 g/kW h for ribbon and 20 g/kW h for multicrystalline silicon technologies.

5.2.1. Fluorinated Greenhouse Gas Emissions During the Manufacturing Stage of Photovoltaics

Several authors have focused on the manufacturing stage of PV to examine releases of *fluorinated gases* (*F-gases*). F-gases have a high *global warming potential* and may also pose a health risk. Overall, F-gas releases associated with silicon PV manufacturing, both crystalline silicon and thin-film, are estimated to contribute roughly 5 g /kW h (CO₂ eq) to GHG emissions (Alsema, 2006). A 2007 study based on industry data concluded that emissions of F-gases are fairly low for most processes, except for the dry surface texturing steps, which contribute approximately 8 g/kW h (CO₂ eq; de Wild-Scholten et al., 2007). Nitrogen trifluoride (NF₃), one of the most potent F-gases, is used to clean equipment when manufacturing amorphous-silicon and nanocrystalline-silicon thin-film PV modules and adds 2 and 7 g/kW h (CO₂ eq), respectively, to the processes for these materials. An analysis of production data and atmospheric measurements of NF₃ identified a declining trend in releases of this gas, which may be attributed to more efficient processing (Fthenakis et al., 2010).

However, the main concern over the use of F-gases stems from manufacture of the modules for crystalline silicon PV solar energy, in which *plasma edge isolation* using F-gases is still common in the industry (SVTC, 2009; de Wild-Scholten et al., 2007). In 2012, it will be mandatory for solar manufacturers that emit 25 000 or more metric tons of CO₂ eq to also report F-gas emissions to the United States Environmental Protection Agency (EPA) (As You Sow, 2012).

5.3. Air Pollutant Life Cycle Emissions

Table 3: Reported Air Pollutant Emissions and Thin-film PV Technologies

| Technology | NO _x (mg/kW h) | SO _x (mg/kW h) | Electricity Mix | Insolation (kW h/m ² per year) | Performance Ratio | Application Type |
|------------------|------------------------------|------------------------------|--------------------|---|----------------------|---------------------|
| Multicrystalline | 75–85 | 125–150 | UCTE ^a | 1700 | 0.8 | Ground-mounted |
| Monocrystalline | 80–85 | 140–160 | UCTE | 1700 | 0.8 | Ground-mounted |
| CdTe | 35–45 | 50–90 | UCTE | 1700 | 0.8 | Ground-mounted |
| Multicrystalline | 175–185 | 350–375 | US | 1700 | 0.8 | Ground-mounted |
| Monocrystalline | 180–200 | 360–390 | US | 1700 | 0.8 | Ground-mounted |
| CdTe | 75–85 | 150–175 | US | 1700 | 0.8 | Ground-mounted |

^a UCTE = Union for the Coordination of the Transmission of Electricity, organization responsible for the operation and development of the transmission grid in continental Europe.

Note: Values for air pollutants are estimates from graphs (Fthenakis et al., 2008), based on all PV and BOS components and a lifespan of 30 years.

The emissions of air pollutants during the life cycle of a PV system are proportional to the amount of fuel burned during its material processing and manufacturing stages (Fthenakis and Kim, 2011). Therefore, as with GHG emissions, air pollutant emissions are largely influenced by the regional electricity grid mixture.

There were few studies that reported on air pollutant emissions and none that reported on *particulate matter* specifically.

5.4. Factors Affecting Greenhouse Gas and Air Pollutant Emissions

5.4.1. Electricity Grid Mix – Implications for Canadian Assessment

As shown in Tables 2 and 3, GHG and air pollutant emissions for PV systems are significantly influenced by upstream electricity-generating methods (Fthenakis and Kim, 2011; Jungbluth et al., 2008; García-Valverde et al., 2009). For instance, the GHG emission factor of the US electricity grid is higher on average than that of the Western European (UCTE) electricity grid on average (Table 4). The effect of grid mix results in higher GHG emission estimates for US-produced modules than for European-produced modules (Fthenakis and Alsema, 2006; Dones et al., 2003; Franklin, 1998). Based on Environment Canada's GHG Inventory Database, the overall GHG intensity for the Canadian electricity industry (utility, non-utility and industrial generators) in 2008 was 200 g/kW h (CO₂ eq; Environment Canada, 2010b).

Fthenakis, Kim and Alsema (2008) reported emissions for air pollutants (NO_x and SO_x) during PV life cycles, as well as providing GHG totals, for both the US and Western European electricity mixes (Table 4). This study, based on 2004–2006 PV production data, presented the life-cycle GHG and air pollutant emissions from major commercial PV systems: multicrystalline and monocrystalline silicon as well as thin-film CdTe systems. Among crystalline silicon modules, the study found that emissions from monocrystalline silicon PV are high relative to the others because of the energy required for the *Czochralski process*, the method of crystal growth used to obtain single crystals of silicon.

Table 4: Estimated GHG and Air Pollutant Emissions by Regional Electricity Grid Mix

| Region and Fuel Mix | GHG Emissions Associated with Fuel Mix (CO ₂ eq, g/kW h) | Technology | GHG Emissions (CO ₂ eq, g/kW h) | NO _x (mg/kW h) | SO _x (mg/kW h) |
|---------------------|---|------------------|--|---------------------------|---------------------------|
| Western Europe | 484 | Multicrystalline | 40–50 | 75–85 | 125–150 |
| | | Monocrystalline | 40–50 | 80–85 | 140–160 |
| | | CdTe | 15–25 | 35–45 | 50–90 |
| United States | 678 | Multicrystalline | 50–60 | 175–185 | 350–375 |
| | | Monocrystalline | 50–60 | 180–200 | 360–390 |
| | | CdTe | 20–30 | 75–85 | 150–175 |

Note: Data from Fthenakis et al. (2008), based on all PV and BOS components and a lifespan of 30 years.

A 2006 study by CanSIA, sponsored by Environment Canada, identified a shortage of information in Canada on environmental impacts of PV because of Canada's unique geography and climate (irradiation, snow, etc.) and unique electricity mix (McMonagle, 2006). Canada's electricity mix comes from primarily low-GHG-emitting sources with approximately 63% from hydroelectricity, 17.4% from conventional steam (including coal), 14.8% from nuclear sources and 4.5% from other sources (Statistics Canada, 2010).

Table 4 shows emissions of GHGs (NO_x and SO_x) for the European and US electricity mixes. The GHG emission factor of the average US electricity grid is higher than that of the average Western Europe (UCTE) grid (Fthenakis and Kim, 2011). Canada's average GHG grid intensity compares favourably to that of other regions, being even lower than the average UCTE intensity at 200 g/kW h (CO₂ eq, based on 2008 data from Environment Canada's GHG Inventory).

5.4.2. Photovoltaic Life Cycle Stages

The chapter has not examined each stage in the PV life cycle, for two reasons. The first is that most authors report total GHG emissions over the entire PV life cycle rather than by stage (Table 1). Second, almost all emissions in the PV life cycle are from the material sourcing and the manufacturing stages (Fthenakis and Kim, 2011).

5.5. Comparison with Other Technologies

PV systems emit no emissions of any kind during normal operation (European Photovoltaic Industry Association, 2011; Kaygusuz, 2009). By comparison, coal and natural gas power plants emit dramatically more GHGs and significantly more air pollutants than PV (Jazayeri et al., 2008).

5.5.1. Greenhouse Gases

Comparative estimates for GHG emission intensities were compiled by the Canadian Energy Research Institute in 2008 (Jazayeri et al., 2008; Table 5) for the province of Ontario. These estimates show that coal and natural gas emit significantly more GHGs than PV energy systems. The study included fuel preparation, fuel transportation and electricity generation operations. It did not include construction, decommissioning, heavy water manufacturing and waste management. Data for PV include all life stages including manufacturing, construction and decommissioning, as PV systems emit no GHG emissions during normal operation (EPIA/Greenpeace International, 2011; Kaygusuz, 2009).

Table 5: Life Cycle Environmental Releases from Power Generation in Ontario

| Pollutants | CO ₂ eq, t/TW h | | | |
|---------------|----------------------------|--------------|-------------|---------------|
| | Nuclear | Coal | Natural Gas | PV* |
| GHG emissions | 1 836.74 | 1 051 215.33 | 540 391.16 | 18 000–28 000 |

Source: Jazayeri et al., 2008

* Data from Fthenakis et al., 2011b, assumed lifespan of a PV module is 20–30 years. Conversion efficiency for US grid mix is 0.29; UCTE, 0.31.

In 2010, Environment Canada submitted Canada's National Inventory Report for 1990–2008 on Greenhouse Gas Sources and Sinks (EC, 2010c) to the United Nations Framework Convention on Climate Change, detailing GHG emissions (CO₂ eq) for the electricity sector. In 2008, hydroelectric generation is essentially free of direct GHG emissions except for the CH₄ emissions that result from the flooding of lands to build reservoirs and produced 340 000 GW h. Nuclear power was reported as the second-largest source of direct GHG emission-free electricity, producing 96 600 GW h. This report does not consider the emissions related to uranium mining (i.e., processing or disposal of waste fuel for nuclear energy). In 2008, coal-based electricity generation in Canada was responsible for 83 Mt of GHG emissions, and the production of 97 300 GW h. Total GHG emissions from natural gas in 2008 were 12.3 Mt, and it produced 26 700 GW h of electricity (EC, 2010c). The report did not provide GHG emissions from PV operation; however, as discussed above, PV systems emit no GHG emissions during normal operation.

In 2003, Hydro-Québec published fact sheets for the comparison of power generating options, in which they evaluated the life-cycle assessment of GHG emissions intensities for different energy generating options, including PV (Gagnon, 2003). When comparing GHG emissions across a full life cycle for energy generating technologies, there are considerable benefits to PV technologies in comparison to fossil fuel-based electricity production.

5.5.2. Air Pollutants

The best comparative estimates for air pollutant emissions are again shown in the 2008 study by the Canadian Energy Research Institute (Jazayeri et al., 2008; Table 6). These estimates show that coal and natural gas emit significantly more air pollutants than PV energy systems.

Table 6: Life Cycle Environmental Releases from Power Generation in Ontario

| Pollutants | t/TW h | | | |
|-----------------------------------|---------|---------|-------------|----------|
| | Nuclear | Coal | Natural Gas | CdTe PV* |
| Total air pollutants | 12.42 | 6712.78 | 1452.63 | NA |
| Nitrogen oxides | 2.45 | 1676.58 | 720.12 | 75–85 |
| Sulphur dioxide | 8.54 | 3907.36 | 363.32 | 150–175 |
| Carbon monoxide | 0.00 | 418.11 | 274.47 | NA |
| Total particulates | 0.61 | 685.68 | 20.91 | NA |
| <i>Volatile organic compounds</i> | 0.81 | 25.05 | 73.81 | NA |

Source: Jazayeri et al., 2008

* Data from Fthenakis et al. (2008), based on all PV and BOS components and a lifespan of 30 years.

5.6. Areas for Further Work

There is very little data on the decommissioning stage (McMonagle, 2006), building-integrated vs. rooftop installations (McMonagle, 2006), the impact of new technologies and processes on GHG emissions and comparisons of PV systems with other renewable energy sources in regard to GHG emissions. In addition, while GHG emissions were emphasized, few authors addressed air pollutants. Finally, little information is available on emissions from emerging PV technologies, such as releases of F-gases in the manufacturing of a-Si thin-film modules.

An LCA stage not included in published LCAs is the potential impact of site clearing required during installation of large ground-mounted *solar farms*. In cases where a lot of trees are removed, the GHG emissions of the PV life cycle can increase significantly, owing to the loss of offsetting carbon sinks from trees (Turney and Fthenakis, 2011).

A 2006 CanSIA study (McMonagle, 2006) also mentions other areas for further work or opportunities for data collection, including:

- Inclusion of transmission and distribution benefits and consequences in PV LCA;
- Documentation on life expectancy of PV modules and impact on LCA; and
- Further research on decommissioning issues.

6. Heavy Metals and Other Chemicals

6.1. Introduction

6.1.1. Impact

Many of the findings in the recent literature suggest that while some substances used in manufacturing PV solar cells are considered toxic, they do not pose a risk because they are used in small quantities. PV energy is often viewed as having very minimal waste because there is none produced during operation. With the increase in manufacturing of PV systems, the potential risks and consequences of the use of heavy metals and other chemicals in PV cell production are garnering attention. In addition, the waste created by the decommissioning of the solar modules at the end of their useful lives cannot be ignored.

Currently, many solar companies meet or exceed national and international standards for handling and mitigating hazardous materials (As You Sow, 2012). Companies are engaged in research and development to use less hazardous materials with the aim of further reducing the environmental impact of manufacturing. For example, companies are modifying processes to eliminate the use of hazardous gases or lessen their concentrations and switch to more environmentally friendly alternatives. Lead was initially used as a solder to connect crystalline silicon cells into modules; however, advances in manufacturing have now led to lead-free solder to connect its cells (As You Sow, 2012).

The decommissioning of PV modules is seen as an environmental challenge for the solar industry. To address this challenge, PV CYCLE, an international PV industry program that is addressing the recycling challenge in Europe, has been established. The first large-scale dismantling facility for end-of-life modules was introduced in Europe in 2009 under PV CYCLE. The PV CYCLE target is to collect at least 65% of modules at the end-of-life, with 85% of the module content to be recycled (Raugei et al., 2012).

Currently, the most widely used PV modules contain heavy metals such as lead and cadmium (both of which are considered toxic under the *Canadian Environmental Protection Act, 1999* [CEPA 1999]) as well as tellurium and selenium, which are considered hazardous. It is important to note that these substances are used in small quantities in manufacturing PV modules.

CdTe is an inorganic cadmium compound, which was added to the CEPA 1999 Toxic Substances List on March 31, 2000. Cadmium compounds are currently regulated in many countries because of their toxicity in fish and wildlife and because they can pass to humans through the food chain (McDonald and Pearce, 2010). Cadmium can also accumulate in the natural environment from PV cells in landfills by leaching into ground water and surface water and can enter the atmosphere through incinerator emissions. Incinerators make use of pollution control equipment that traps cadmium, but the resulting incinerator ash then contains cadmium that can still escape into the environment through ashfill leachate (McDonald and Pearce, 2010).

Under the *Canadian Environmental Protection Act, 1999*, a substance is considered toxic if it enters or may enter the environment in amounts that may have an immediate or long-term harmful effect on the environment or its biological diversity; may constitute a danger to the environment on which life depends; or may constitute a danger in Canada to human life or health.

While inorganic cadmium compounds are of concern, the understanding of the potential environmental impacts of PV technologies would benefit from a full toxicity assessment of CdTe. CdTe toxicity has been differentiated from that of elemental cadmium and other cadmium compounds (Zayed and Philippe, 2009; Kaczmar, 2011). Studies have reported that CdTe:

- Has aqueous solubility and bioavailability properties approximately two orders of magnitude lower than the 100% solubility and bioavailability of cadmium chloride (CdCl_2);
- Does not readily release the reactive ionic form of $\text{Cd}(\text{Cd}^{2+})$ upon contact with water or biological fluids; and
- Has low acute inhalation, oral and aquatic toxicity, and is negative in the Ames mutagenicity test, a biological assay to assess the mutagenic potential of chemical compounds.

Cadmium is a natural by-product of zinc mining (Wolden et al., 2011). Researchers often argue that CdTe PV manufacturing is the best means to sequester elemental cadmium in an environmentally beneficial manner. Research on CdTe modules has shown that, once incorporated into the PV module, cadmium exposure is minimal (Wolden et al., 2011).

6.1.2. Trend

Many of the heavy metals and other chemicals currently used in the PV sector, including cadmium and lead, are being phased out of e-products in the European Union under a directive restricting the use of certain hazardous substances in electrical and electronic equipment (Restriction of Hazardous Substances Directive 2002/95/EC). In the last recast (or review) of the directive, PV modules were exempt if installed by professionals for permanent use at a defined location to produce energy. On January 18, 2012, the European Union Parliament officially voted that 85% of all end-of-life PV modules in Europe must be collected and that 80% must be recycled under the Waste Electronic and Electrical Equipment Directive (Directive 2008/34/EC). Many of these substances are still used in electrical and electronic equipment products in the United States and other countries, including Canada.

The increase in PV module manufacturing, and their eventual decommissioning and disposal, may create a new wave of e-waste. The lifetime of a PV module is estimated at 20 to 30 years (Fthenakis et al., 2011a; SVTC, 2009). The rapid expansion of the PV industry will therefore likely lead to challenges regarding waste disposal in the next 25 to 30 years (McDonald and Pearce, 2010). However, First Solar is currently recycling spent PV modules, and such material recycling has shown the potential to improve the environmental profile of PV technologies (Held and Ilg, 2011).

Canada's National Pollutant Release Inventory (NPRI) database reports that total cadmium emissions to air for 2010 were 15 881.3 kg. The largest sources of emissions were from the non-ferrous smelting and refining industry (primary and secondary nickel, copper, zinc and lead) at 12 747.3 kg of air emissions in 2010. Another 1 074.3 kg of air emissions were from non-industrial sources such as electricity generation and fuel combustion. PV manufacturing is a new activity in Canada and, as such, no reporting to the NPRI database to date on cadmium emissions from this sector has, as yet, occurred.

The US Department of the Interior's Bureau of Mines (Liewellyn, 1994) reported that before cadmium production started in the United States, approximately 85% of the cadmium from zinc concentrates was lost to the environment. Zinc mines in the United States also produce germanium, indium, thorium, gallium,

gold and silver. The PV industry uses these substances in manufacturing its product and, through this, is contributing to the controlled use of these by-products, which would otherwise be discarded in landfills where they can leach out into the environment.

LCA of cadmium use in PV modules suggests that the growth of the PV sector has the potential to reduce overall global cadmium-related environmental pollution from mining (Raugei and Fthenakis, 2010). The use of CdTe in thin-film PV technologies provides a benefit if a sufficient life cycle management approach, such as the adoption of an end-of-life take-back and recycling program, is used by industry and prevents further cadmium emissions (Sinha et al., 2008; Raugei and Fthenakis, 2010).

The use of cadmium in CdTe PV effectively sequesters a non-negligible amount of cadmium, diverting it from stockpiles where potential leaching and contamination can occur (Raugei and Fthenakis, 2010). These stockpiles would otherwise be disposed of as hazardous waste (Sinha et al., 2008). To add to the benefit of PV systems, CdTe PV technology has the potential to decrease cadmium emissions to air when it replaces coal-based power generation, which routinely emits 100 to 360 times more cadmium into the air than does the whole life cycle of CdTe PV (Raugei and Fthenakis, 2010).

6.1.3. Information Sources and Limitations

With the exception of cadmium, direct emissions of heavy metals and other chemicals from material processing have not been studied in detail in LCA of PV systems for the reasons cited below:

- Emissions during processing are dependent on the selection of the system's boundary and the allocation method that an LCA study adopts;
- The amount of unabated emissions may significantly decrease with technological progress and stricter regulatory standards; and
- The amount of impurities mixed with matrix metal often determines heavy metal emission factors.

For these reasons, estimating emissions of heavy metals and other chemicals directly from material processing (i.e., mining, smelting and purification) entails large uncertainties (Fthenakis et al., 2008). Based on data from the ecoinvent database, a high proportion of direct lead emissions (80%) from material processing is related to glass manufacturing for PV modules. However, this assumes construction-grade glass is used for PV modules, whereas the glass used in PV modules typically contains far less lead because it is not added to the glass used in their production. Therefore, lead emissions can be assumed to be lower than reported in ecoinvent (de Wild-Sholten et al., 2005).

6.2. Manufacturing

Many of the findings in the recent literature suggest that while some substances used in manufacturing of the semiconductor materials for PV solar cells are considered toxic, they do not pose a risk because they are used in small quantities (EPRI, 2003). There are a range of environmental impacts from the manufacturing of PV systems depending on the type: multicrystalline and monocrystalline, or thin-film (e.g., CdTe, a-Si, CIS/CIGS). Many substances have been used in manufacturing PV modules, some of which are hazardous and/or toxic (Table 7).

Table 7: Substances Commonly Used in Manufacturing PV Cells

| Type of Cell; Substances Used | | | | |
|-------------------------------|--------------------------|--|-------------------|--|
| Monocrystalline Silicon | Multicrystalline Silicon | Amorphous Silicon | Cadmium Telluride | CIS/CIGS Cells |
| Aluminum | Aluminum | Acetone | Cadmium | Cadmium |
| Ammonia | Ammonia | Aluminum | Cadmium chloride | Copper |
| Ammonium fluoride | Arsine | Chlorosilanes | Nickel | Hydride gas |
| Hydrochloric acid | Boron trichloride | Diborane | Sulphur | Hydrogen gas |
| Hydrofluoric acid | Copper catalyst | Germane | Tellurium | Hydrogen sulphide |
| Hydrogen fluoride | Diborane | Germanium tetrafluoride (used in some) | Tellurium dioxide | Hydrogen selenide |
| Isopropyl alcohol | Ethyl acetate | Hydrochloric acid | Tin | Indium |
| Nitric acid | Ethyl vinyl acetate | Hydrofluoric acid | Cadmium sulphate | Molybdenum |
| Nitrogen | Hydrochloric acid | Hydrogen | Cadmium sulphide | Selenium |
| Oxygen | Hydrogen | Isopropanol | | Zinc |
| Phosphorus | Hydrogen fluoride | Nitrogen | | Selenium hydroxide |
| Phosphorus oxychloride | Hydrogen peroxide | Phosphine | | Gallium |
| Silane | Ion amine catalyst | Phosphoric acid | | Cadmium sulphide (alternatives are zinc sulphide or indium sulphate) |
| Silicon | Isopropyl alcohol | Silane | | |
| Silver | Nitric acid | Silicon tetrafluoride | | |
| Sodium hydroxide | Nitrogen | Silicon | | |
| Sulphuric acid | Phosphine | Sodium hydroxide | | |
| Tin | Phosphorus trichloride | Tin | | |
| | Silicon | Arsine | | |
| | Silicon dioxide | Methane | | |
| | Silane | | | |

Table 7: Substances Commonly Used in Manufacturing PV Cells

| Type of Cell; Substances Used | | | | |
|-------------------------------|--------------------------|-------------------|-------------------|----------------|
| Monocrystalline Silicon | Multicrystalline Silicon | Amorphous Silicon | Cadmium Telluride | CIS/CIGS Cells |
| | Silicon trioxide | | | |
| | Silicon tetrachloride | | | |
| | Silver | | | |
| | Sodium hydroxide | | | |
| | Stannic chloride | | | |
| | Sulphuric acid | | | |
| | Tantalum pentoxide | | | |
| | Titanium | | | |
| | Titanium dioxide | | | |
| | Trichlorosilane | | | |
| | Sulphur hexafluoride | | | |
| | Nitrogen trifluoride | | | |

6.2.1. Monocrystalline and Multicrystalline Silicon

Monocrystalline and multicrystalline silicon are produced in large quantities for the computer industry. Electronic-grade silicon is processed using the energy-intensive Siemens process, as discussed in Chapter 4: Energy Payback Time. The production of solar-grade silicon, which uses a modified Siemens process, retains a higher level of metals such as iron and aluminum (Wolden et al., 2011). Active research is being carried out to establish the purity level that can be tolerated by solar cells, as well as devising processing strategies to mitigate these defects. Improvements are expected to reduce the ecotoxicity associated with silicon production (Wolden et al., 2011).

Manufacturing multicrystalline and monocrystalline silicon cells generates substances of concern (both toxic and hazardous) at various stages, although the amounts are small and, with the implementation of best practices, their release to the environment is less and less likely (Wolden et al., 2011; Fthenakis, 2003). Stages include wafer slicing, cleaning, etching, processing and assembly of the solar cells (Fthenakis, 2003). Wafers are sliced using a wire-saw technology, resulting in over 50% of the silicon being lost as silicon sawdust or kerf (Wolden et al., 2011). This material can be recycled, providing some environmental benefit by diverting it from the manufacturing waste stream. Techniques for the direct production of wafers, which would eliminate wire-saw cutting and kerf, would increase the environmental benefits of crystalline silicon cells.

The PV industry in Europe has adopted a program for waste minimization, take-back and recovery, called PV CYCLE. This initiative also continues to examine environmentally friendly alternatives to solder, slurries and solvents. Efforts have been made to reduce caustic waste generated by etching and to find in-house methods of neutralization of acid and alkali solutions, while recycling efforts have included recycling stainless-steel cutting wires and recovering silicon carbide and polyglycol from the slurry (Fthenakis, 2003).

6.2.2. Thin-film Cadmium Telluride

Before cadmium can be used to make CdTe thin-film PV cells, the cadmium sponge (a precipitate from the mining and smelting of zinc and other metals), must be purified to 99.999% cadmium (Raugei and Fthenakis, 2010). Tellurium is a rare metalloid that is used in the manufacturing of photosensitive materials and catalysts (Fthenakis, 2004).

Current CdTe production begins with a glass substrate followed by the successive deposition of a *transparent conducting oxide (TCO)*, an *n*-type window layer (cadmium sulphide, CdS), a *p*-type CdTe absorber and a back contact (of zinc telluride, copper or carbon) (Wolden et al., 2011).

| Table 8: Substances of Concern in the Manufacturing of CdTe PV Cells | | |
|---|-----------------------------------|--|
| Substance | Use | Concern |
| Cadmium sulphate | Thin-film semiconductor layer | Cadmium (parent compound): adverse effects on human health and the environment; persistent and <i>bioaccumulative</i> |
| CdTe | Thin-film semiconductor | Persistent because it is a metal but has not been found to be bioaccumulative; recent studies have shown that CdTe has a low acute inhalation, oral and aquatic toxicity |
| Tellurium dioxide | Produces the CdTe thin-film layer | Persistent to the environment |
| Source: SVTC, 2009; EPRI, 2003; Kaczmar, 2011; Fthenakis and Kim, 2011; Canada, 2012 | | |

6.2.2.1. Total Cadmium Emissions

Cadmium emissions can be direct or indirect. Direct cadmium emissions are those associated with the mining, smelting and purification of elemental cadmium. Indirect cadmium emissions are due to fuel and electricity use for the production and manufacture of a PV system. Some processes, for example, manufacturing CdTe PV emit cadmium both directly and indirectly, whereas the stages in manufacturing crystalline silicon PV emit cadmium only indirectly.

Total direct and indirect cadmium emissions from all manufacturing and recycling operations (storage, deposition, lasers, *annealing*, *edge deletion*, acid etch, recycling glass shredder and recycling hammer mill) are approximately 0.5 g cadmium per ton (1016 kg) cadmium input. Total life cycle indirect cadmium

emissions from fossil fuels used in the electricity mix in the life cycle of a CdTe module are more than 10 times (0.23 g/GW h) those from direct cadmium emissions (0.02 g/GW h) (Fthenakis, 2009).

6.2.2.2. Direct Cadmium Emissions

Direct cadmium emissions were calculated based on a 30-year module lifetime, 9% efficiency and the average US solar insolation of 1800 kW h/m² per year. The total direct emissions of cadmium during the mining, smelting and purification of the element and the synthesis of CdTe are 0.015 g/GW h. The total emissions of cadmium during module manufacturing are 0.004 g/GW h (Fthenakis et al., 2008).

| Table 9: Atmospheric Cadmium Emissions from the Life Cycle of CdTe PV Modules | | |
|--|-------------------|------------------|
| Life Cycle Stage | Emissions | |
| | (g/ton Cd) | (mg/GW h) |
| Mining of zinc ore | 2.70 | 0.02 |
| Zinc smelting/refining | 40.00 | 0.30 |
| Cadmium purification | 6.00 | 7.79 |
| CdTe production | 6.00 | 7.79 |
| CdTe PV manufacturing | 0.40 | 0.52 |
| CdTe PV operation | 0.05 | 0.06 |
| CdTe PV recycling | 0.10 | 0.13 |
| Total emissions | 55.25 | 16.61 |
| Source: Fthenakis, 2009; Fthenakis, 2004; Raugei and Fthenakis, 2010 | | |

6.2.2.3. Indirect Cadmium Emissions

Electricity generation, using fossil fuels such as coal, emits heavy metal emissions into the atmosphere during combustion. Based on the electricity demand for PV modules and BOS components (circuitry, batteries, inverters, etc.), indirect cadmium emissions from sources such as natural gas, heavy oil and coal to provide heat and mechanical energy during material processing, climate control for the plant, and transportation of the materials and products were estimated. The largest share of the emissions of cadmium to the atmosphere is unrelated to the specific type of PV technology being manufactured and deployed; rather, it is related to the production of *tempered glass*, EVA and TCO used in making modules (Raugei and Fthenakis, 2010). The largest sources of indirect cadmium emissions were the use of coal during steel-making processes and the use of natural gas during glass-making processes. Cadmium emissions from natural gas are not from burning the gas itself but mainly from manufacturing the boiler systems (Fthenakis et al., 2008). The BOS also contribute approximately an additional 25% of the atmospheric cadmium emissions, mainly owing to the steel for the support structure and the fuel used for construction (Raugei and Fthenakis, 2010). The complete life cycle cadmium emissions are shown in Table 9.

Water discharges from the manufacture of CdTe cells are cleaned to the point that remaining amounts of substances are below permissible limits. In Ohio and Germany, where CdTe cells are produced, these

levels are below 0.3 mg/L (Ohio) and 0.07 mg/L (Germany), and there are no discharges to soil in the current PV manufacturing plants (Raugei and Fthenakis, 2010). In Canada, by-laws for the discharge of cadmium to wastewater range from 0.5 to 4.0 mg/L (Marbek Resource Consultants Inc., 2009), and cadmium in liquid effluents of existing CdTe PV manufacturing facilities are well below these limits. The total cadmium in liquid effluents is about 300 g/100 MW production or 0.3 mg/m² (Raugei and Fthenakis, 2010). The ecoinvent database allocates an additional 0.8 mg/m² as releases to fresh water through the production of the TCO and tempered glass. The balance of system components add another 2.0 mg/m² (60% of the total), owing to steel construction. This totals just over 3 mg/m² of cadmium discharges to water, which would fall within the range of Canadian municipal by-laws. These values pertain specifically to the manufacturing of the modules rather than to the operation of the PV system. Figure 7 shows total reported cadmium releases to water in Canada from 1999 to 2010 (Environment Canada, 2011b)

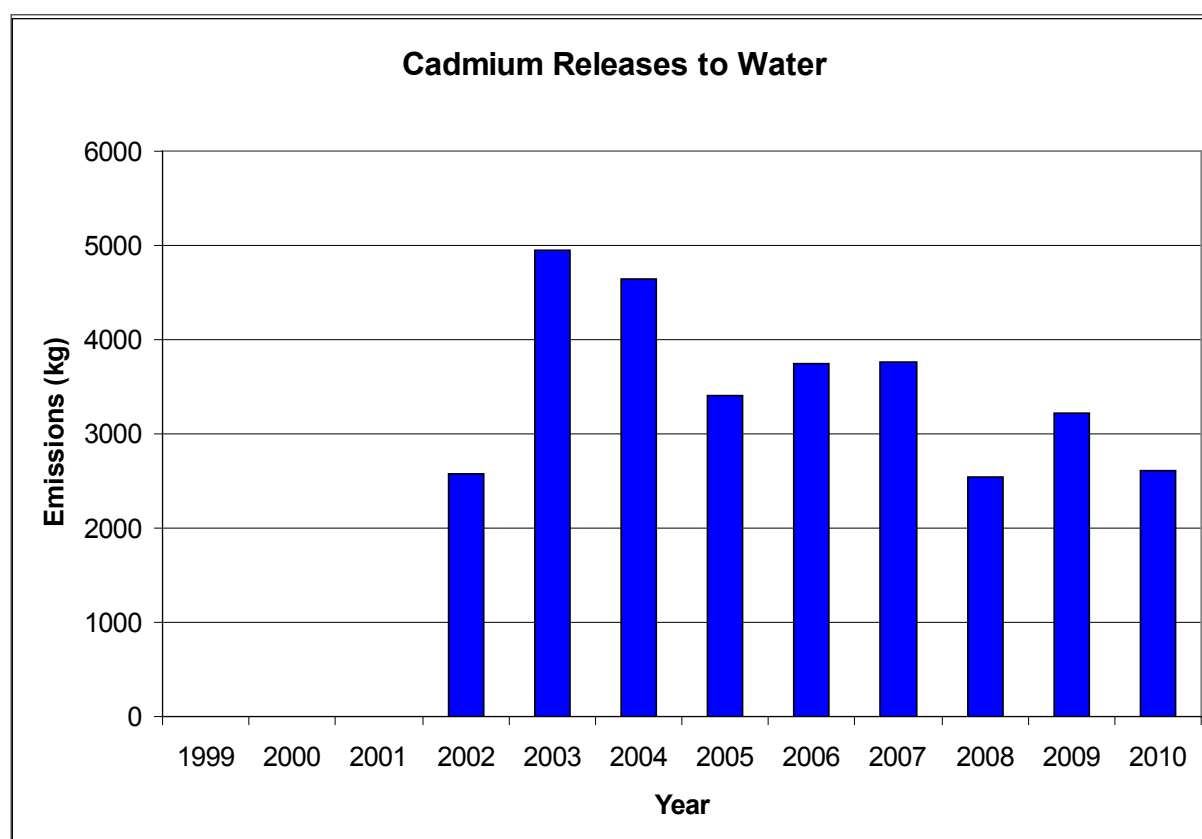


Figure 7: Total reported cadmium releases to water from 1999 to 2010 from all industries in Canada

Source: Environment Canada (2011b)

6.2.3. Other Thin-film Technologies

6.2.3.1. Copper Indium Selenide/Copper Indium Gallium Selenide

CIS and CIGS are technologies that are processed by the deposition of a molybdenum back contact, followed by a *p*-type CIGS absorber and a thin buffer layer, with doped Zinc Oxide serving as the transparent front

contact (Wolden et al., 2011). Many companies are working to commercialize this technology, and the approach to the fabrication of the CIS/CIGS absorber involves one of the following:

- *Coevaporation*: a process that alternates between copper-rich and copper-poor conditions to produce the large grains and graded indium and gallium material;
- *Selenization/sulphurization* of metal films: a two-step process in which metals (copper, indium, gallium and sulphur) are sputtered onto the substrate and converted to CIGS through annealing in a *chalcogen*-containing environment (either elemental vapours or hydride gases); and
- *Non-vacuum techniques*: a two-step process that involves application of a coating followed by high-temperature annealing or sintering of the metals (Wolden et al., 2011).

Gallium, copper and indium are associated with a low toxicity (Fthenakis, 2003). As discussed above, there is little information on the toxicity of CIS and CIGS technologies. Animal studies have shown that CIS has a mild to moderate respiratory tract toxicity. In comparing CIS, CGS and CdTe (as discussed in section 6.2.1.1), CIS was found to be less toxic than CdTe (Fthenakis, 2003).

Numerous chemicals have been used in the production of CIS and CIGS modules (Table 7). Selenium is a regulated substance that bioaccumulates in the food chain and forms compounds such as hydrogen selenide (SVTC, 2009). It is used as the primary source of selenium in the deposition of the CIS and CIGS layer. It is consumed in the selenization step in which hydrogen selenide is introduced into the atmosphere of a reactor to provide the excess selenium needed to react with the other metals (SVTC, 2009).

Used at high temperatures, as in the production of CIS and CIGS crystals, selenium has the potential to form selenium dioxide. This can be vented into a water solution, where it forms elemental selenium, which is then recovered. The recovery rate of selenium is high, but not 100%, and fugitive emissions do occur (SVTC, 2009). Environmental issues are also related to the disposal of manufacturing waste and to the end of the life of the module (see section 6.4).

A buffer layer of CdS is also used in the semiconductors for CIS/CIGS cells (SVTC, 2009). The use of CdS would inherently have the same toxicity issues associated with CdTe discussed above. The CdS layer can be replaced with an alternative buffer layer of zinc sulphide or indium sulphate; however, CdS is more efficient (SVTC, 2009).

6.2.3.2. Amorphous Silicon

Amorphous silicon (a-Si) is manufactured by depositing silicon layers through a plasma-enhanced *chemical vapour deposition* process using mixtures of hydrogen dioxide and silane (Wolden et al., 2011).

Doping gases used such as arsine, phosphine and germane (see Table 7) are toxic, but are used in quantities too small to pose any significant threat to public health and the environment (Fthenakis, 2003). Arsine is considered toxic under CEPA 1999 in Canada. Leakage of these gases can cause significant occupational risks.

Methane is often mixed with the waste streams from the deposition process to burn off additional hydrogen (SVTC, 2009). Methane is flammable and a potent GHG (see Chapter 5: Greenhouse Gases and Air Pollutants).

Similar to the manufacturing of monocrystalline and multicrystalline cells, there are many substances used in the manufacturing of a-Si cells that pose a risk to human health and the environment.

6.2.4. Toxicology Studies on Photovoltaic Modules

While studies on the toxicology of CdTe PV modules are limited, the US National Institute of Environmental Health Studies and Brookhaven National Laboratories examined the toxicological impacts on laboratory rats from exposure to CdTe, CIS and copper gallium diselenide (CGS). The study focused on systemic, reproductive and pulmonary impacts (Fthenakis et al., 1999).

The results of the study showed that CdTe was the most toxic of the substances in PV modules examined, followed by CIS and then CGS. Exposure of laboratory rats to CdTe led to significant decrease in weight gain, and the highest and second-highest respiratory tract toxicity led to deaths (EPRI, 2003; Sinha et al., 2008; Fthenakis et al., 1999). Morgan et al. (1997) also examined the toxicological effects of CdTe, and the results documented the inhibition of weight gain, possible kidney effects, lung inflammation, pulmonary fibrosis and mortality in exposed laboratory rats.

As these studies were based on exposure through direct ingestion or inhalation of the compounds, it is assumed that the results were an overestimate of the exposure of *biotic* organisms at or near a PV manufacturing facility (Sinha et al., 2008). The exposure route of direct ingestion or inhalation is an unlikely pathway, as actual exposure would involve the inhalation of ambient air containing the chemicals found in the PV modules (EPRI, 2003).

From these studies, Fthenakis et al. (1999) developed a *toxicological reference dose (RfD)* for CdTe using the US EPA protocols and methodology. They derived an RfD of 0.0006 mg/kg/d for CdTe. This RfD is similar to the EPA's RfD for cadmium exposure via drinking water of 0.0005 mg/kg/d. Health Canada also uses an RfD derived from that of the EPA. The low water solubility in comparison with other cadmium compounds is expected to reduce the toxicity of CdTe (EPRI, 2003; Sinha et al., 2008).

6.3. Operation and Maintenance

There are no emissions associated with the operational or use phase of PV modules. The modules are enclosed and sealed within two glass modules, and therefore there are no expected emissions while the modules are in use (Raugei and Fthenakis, 2010; Fthenakis, 2003; Fthenakis 2004; Sinha et al., 2008).

The cadmium found in a CdTe PV module poses no threat during the normal use of the PV module since cadmium is present as CdTe and CdS, which are chemically stable compounds (Raugei and Fthenakis, 2010; Fthenakis, 2004). The vapour pressure and water solubility of CdTe is essentially zero (Sinha et al., 2008), and therefore there is essentially no potential for human exposure to CdTe during the normal use and lifetime of a CdTe solar module.

There is a possibility that a CdTe PV module could break during operation and maintenance, exposing CdTe to the environment. In the case of such a limited release, CdTe would be dispersed in ambient air at concentrations well below acute exposure guidelines and subsequently diluted (Sinha et al., 2008; Beckmann and Mennenga, 2011). This scenario is unlikely because of the laminate bonding with the semiconductor material. In addition to limited atmospheric releases, potential exposure to Cd from rainwater leaching of broken modules is highly unlikely to pose a potential health risk (Sinha et al., 2011). Studies have shown that limited cadmium releases (0.04% under American Society for Testing and Materials/Underwriters Laboratories protocols) could occur during fire (Fthenakis et al., 2005).

6.4. Decommissioning

6.4.1. Waste

End-of-life disposal can be an environmental issue with PV modules; however, because of their long lifespan (25 to 30 years), most PV modules have not reached the disposal stage. As a result, there is very little experience with or knowledge of the disposal or recycling of PV modules. Recycling presents a number of challenges because of the lamination of the layers of the module (McMonagle, 2006). As with other laminated, layered and mixed-material items, it can be difficult to separate the various components safely and efficiently.

McMonagle (2006) concluded that decommissioning waste for PV is the stage expected to result in the largest environmental impact when PV is evaluated on a full life-cycle basis. The BOS components (circuitry, inverters, etc.) make up a large proportion of the environmental impact of PV systems, as well as the large amount of glass used in the modules (EPIA/Greenpeace International, 2006). Heavy metals and organic substances found in the capsule material may leach from modules and may exceed environmental limits (McMonagle, 2006; EPIA/Greenpeace International, 2006). Rare and valuable materials (including rare *metalloids* such as tellurium, indium and gallium) are also waste material from the life cycle of a PV module (Sander, 2007). Failing to reclaim these materials through recycling contributes to resource depletion (see Chapter 8: Landscape and Ecology).

The circuitry and inverters (BOS) associated with PV systems can contain hazardous materials such as lead, *brominated flame retardants* and *hexavalent chromium* (SVTC, 2009; Fthenakis, 2003). For crystalline silicon modules, the toxic materials contained in the actual semiconductor material are below levels regulated by the EPA (SVTC, 2009).

Amorphous silicon PV modules contain no EPA-regulated toxic material, aside from the BOS as noted above (SVTC, 2009). However, arsine has been reported as being used in the manufacturing of amorphous silicon modules (Table 8). Inorganic arsenic and its compounds are found on the CEPA 1999 Toxic Substance List. Amorphous silicon modules are found in consumer products such as solar lights and calculators. As with other small electronic devices, they are typically disposed of in household waste streams and contribute to the overall e-waste load in landfills.

CdTe, CIS and CIGS PV modules all contain cadmium compounds, which are considered toxic to the environment and human health. CIS and CIGS PV modules also contain selenium, a regulated substance that bioaccumulates in food chains and forms hydrogen selenide, which is highly toxic and carcinogenic (SVTC, 2009). In addition to BOS components, these PV cells also pose an environmental concern because of the presence of heavy metals and other chemicals in the encapsulated materials.

Should these modules inadvertently end up in municipal waste incinerators, the heavy metals would gasify and a fraction would be released into the atmosphere (Fthenakis, 2003). Electrostatic precipitators can reduce this release to less than 0.5%. The remaining heavy metals would end up in the incinerator ash, which would be disposed of in a controlled landfill (Fthenakis, 2003).

Modules that are disposed of in municipal landfills pose the risk of heavy metals leaching out into the surrounding soil. The leachability of metals in landfill is characterized by two elution tests: (1) the US EPA Toxicity Characterization Leachate Profile (TCLP) and (2) the German DEV S4. Should the metal

concentration exceed the limit of these two tests, the modules would then be required to be recycled or disposed of as hazardous waste. Early CdTe modules failed the TCLP and DEV S4 tests (Fthenakis, 2003). Current studies have found that broken module scraps pass the TCLP test (Raugei et al., 2012).

Exploratory tests with a small number of multicrystalline silicon modules resulted in some modules failing the TCLP test and exceeding the limit for lead by approximately 30% (Fthenakis, 2003). CIS modules passed the TCLP test for selenium. Amorphous silicon passed the TCLP test, as it contains very little hazardous material (Fthenakis, 2003).

The TCLP requires that the modules be broken into small pieces, whereas the PV layer is often sandwiched between two layers of glass and isolated from the environment when disposed of in landfill. Recycling of these modules would allow for the recovery of valuable metals and reduce the risk of contamination to the environment.

6.4.2. Recycling

In recent years, PV module recycling and LCA have been receiving worldwide attention. The Second International Conference on Photovoltaic Module Recycling was held in 2011, and the IEA-PVPS Task 12 deals specifically with PV Environmental Health and Safety.

Since its introduction onto the PV market, CdTe has been the subject of concern related to the potential impacts on the environment and human health caused by the use of cadmium and end-of-life decommissioning (Raugei et al., 2012). Recycling has been the most advisable approach to the end-of-life management of CdTe modules. To ensure that the modules are recycled, a leading manufacturer, First Solar, has implemented a take-back policy whereby sufficient funds are set aside to meet the cost of collection and recycling of modules, and other manufacturers are also following this example (Raugei et al., 2012).

In Canada, many of the megawatt-scale PV systems installed in Ontario have First Solar modules. First Solar offers unconditional recycling of its modules, and about 90% of the module materials are being recovered.

CdTe PV solar cell recycling has been a large focus of the PV industry, and recycling facilities are operating in all First Solar's manufacturing plants (Germany; Perrysburg, Ohio; and Kulim, Malaysia). The recycling of spent CdTe PV modules involves cutting and crushing the spent module into pea-sized fragments, which are then leached in a dilute solution of sulphuric acid and hydrogen peroxide (Raugei and Fthenakis, 2010). Cadmium, tellurium and copper are precipitated from the solution and are sent for reprocessing into high-purity metals. Recycling processes employ highly efficient (99.97% efficiency) HEPA filters so that cadmium emissions to air from the crushing are captured. Residue emissions have been calculated and are 0.4 mg/kg of cadmium processed (Raugei and Fthenakis, 2010).

PV CYCLE, an international PV industry program that is addressing the recycling challenge in Europe, has also been established. The first large-scale dismantling facility for end-of-life modules was introduced in Europe in 2009 under PV CYCLE. The PV CYCLE target is to collect at least 65% of modules at the end-of-life, with 85% of the module content to be recycled (Raugei et al., 2012).

For CIS and CIGS PV modules, no recycling process to recover the materials for reuse has been developed beyond pilot scale (SVTC, 2009). Indium is extremely rare, and the high value of this metal will make recycling an important initiative.

Amorphous silicon products could be recycled through standard glass recovery and recycling processes (SVTC, 2009). The greater challenge with a-Si cell recycling is that they are often embedded in products and end up being disposed of in the household waste stream. Thus, the challenge with recycling this specific PV technology is changing consumer habits. Figure 8 illustrates the trend in recycling of cadmium in Canada in 1999–2010 (Environment Canada, 2011b).

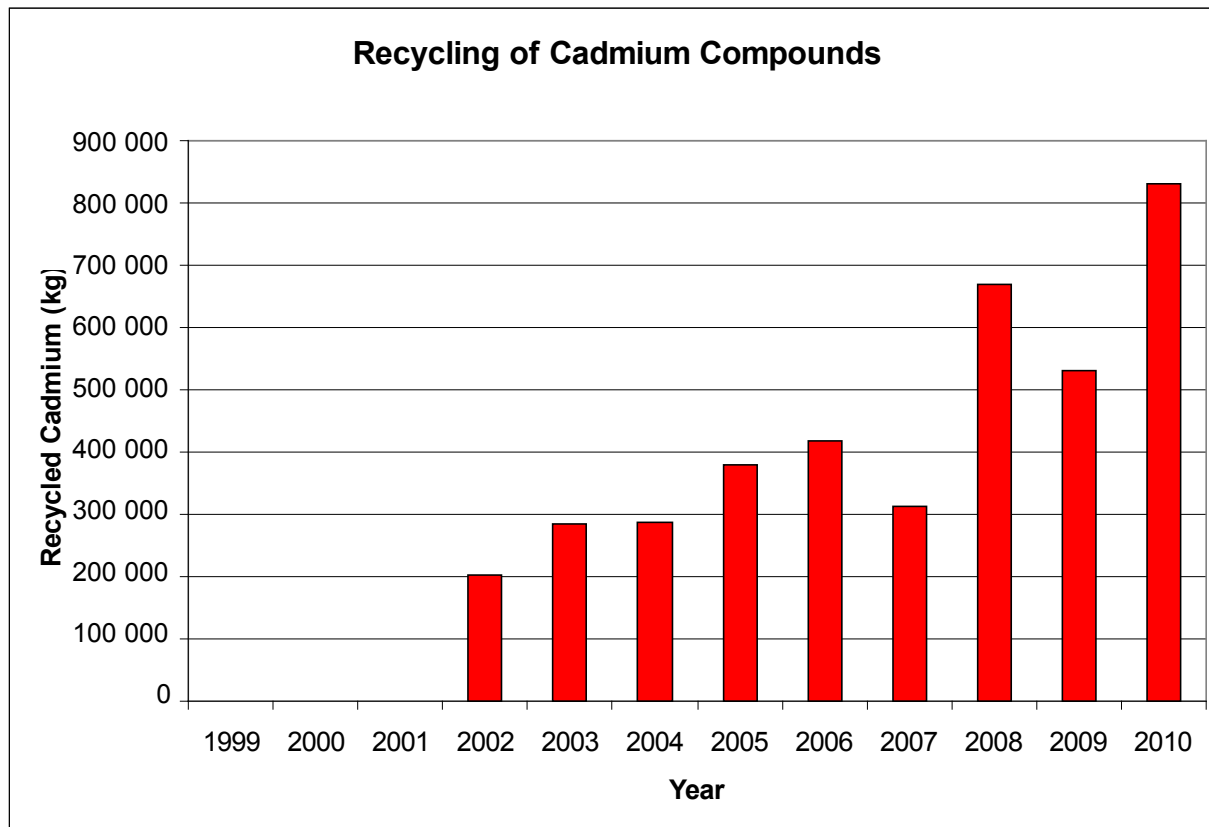


Figure 8: Trend in recycling of cadmium compounds in Canada 1999–2010 from all industries

Source: Environment Canada, 2011b

6.5. Comparison with Other Technologies

Although cadmium is a concern in the manufacturing and disposal of PV modules, cadmium from the life cycle of CdTe is 100–360 times lower than from coal power plants with optimally functioning particulate control devices. When compared with coal-fired thermal facilities, each gigawatt-hour of electricity generated during operation from CdTe PV modules may prevent 8.8 g of cadmium emissions from a coal-fired facility in Europe or about 2 g from such a facility in the United States, given a median concentration of 0.5 mg/kg of cadmium in US coal (Fthenakis and Kim, 2006).

Sinha et al. (2008) reported that replacing grid electricity with central PV systems presents significant environmental benefits, which for CdTe PV modules amounts to 89–98% reductions in GHG emissions, air pollutants, heavy metals and radioactive waste. The emissions of heavy metals are greatly reduced even for types of PV that make direct use of related compounds.

To put the releases of cadmium from CdTe PV modules into perspective, it is worth comparing cadmium flows in CdTe PV modules with those in nickel-cadmium (Ni-Cd) batteries. Ni-Cd batteries are widely considered to be the least dissipative of the current major uses of cadmium, and are by far the largest consumer of raw cadmium in the world, absorbing about 80% of the primary cadmium supply (Raugei et al., 2012; Fthenakis, 2004). The cadmium in Ni-Cd batteries is in the form of cadmium and cadmium hydroxide materials, which are less stable and more soluble than CdTe (Fthenakis, 2004). The amount of cadmium in Ni-Cd batteries ranges from 3.2 to 21 g depending on size, and an average AA or C size Ni-Cd battery can be recharged approximately 700 to 1200 times over its life (Fthenakis, 2004). Based on data from the Ni-Cd battery industry, a battery would produce an average of 0.046 kW h/g of its weight, which corresponds to 0.306 KW h/g of cadmium contained in the battery. This corresponds to a considerably lower efficiency in using cadmium for Ni-Cd batteries than in a CdTe PV module (Fthenakis, 2004).

6.6. Areas for Further Work

There is little published information on the life cycle environmental impacts of cadmium use and management. In the mining and smelting industry, cadmium stocks are not reported, nor are they classified as actual emissions from the mining of zinc ores (Raugei and Fthenakis, 2010). The lack of information on their management raises uncertainties about their environmental effects. In order to understand fully the benefit or impact of using cadmium in products such as PV cells, cadmium management and stockpiling in mining and smelting would need to be examined.

It is important to distinguish the uses of cadmium in terms of its dissipation (i.e., the degree of inevitable spread into the environment), and cadmium-bearing waste streams in terms of their physical and chemical forms as they affect mobility and toxicity (Fthenakis, 2004).

Many of the currently available studies investigate the life cycle emissions on a quantitative level for GHGs and EPBT but do not evaluate emissions in terms of toxicity as an indicator. Different models can produce very different results because a standard characterization method for toxicity in LCA is not available. As PV technologies advance, it is also important to collect information on substances used across the life cycle and regularly update data to ensure representativeness of LCA results.

Many of the findings in the recent literature suggest that while some substances used in manufacturing PV solar cells are considered toxic, they do not pose a risk because they are used in small quantities. As PV solar cell production and deployment increase in the coming years, it will be important to monitor the use of these substances to ensure that they do not exceed limits and pose a risk to human health and the environment.

Understanding the potential environmental impacts of PV technologies would benefit from a full toxicity assessment of CdTe and specific LCA toxicity characterization factors.

7. Water Use and Quality

7.1. Introduction

7.1.1. Impact

Water withdrawal is measured in terms of the quantity of intake, discharge and consumption. Water intake is the amount of water withdrawn from a source for a particular activity over a specific period of time. The water that is taken out and subsequently returned at or near the source is termed water discharge. Water consumption is the difference between water intake and water discharge (Environment Canada, 2010c).

Water use in PV systems is mostly upstream usage related to manufacturing. This includes direct water use for cleaning and cooling silicon wafers, glass, cells and modules, and for preparing chemical solutions. Production of semiconductor materials and the purification of silicon also use water indirectly, in the form of large amounts of thermoelectric power, which relies on water-cooling systems (Fthenakis and Kim, 2010). No water is used during the operation of PV systems, except when modules are cleaned to remove dust or dirt (EPIA, 2012b). Water use in the end-of-life phase (e.g., decommissioning and recycling) is not known.

Regarding water quality, this chapter includes a discussion of eutrophication (nutrient enrichment). Toxic substances in water are discussed in Chapter 6: Heavy Metals and Other Chemicals.

7.1.2. Trend

Water use and impacts on water quality associated with PV are considered minimal. That being said, the Canadian PV sector is growing rapidly—it grew by more than 22% annually between 1993 and 2009 (IEA, 2009)—and this rate of growth will mean increased water use and impacts on water quality associated with manufacturing as well as the eventual decommissioning and recycling of PV systems, although the impact of these latter activities on water use is still unknown. This impact will grow in significance as the demand for water continues to increase and supplies of fresh water become increasingly limited (Fthenakis and Kim, 2010; Environment Canada, 2010c).

For context, in 2005, 63% (32 137 500 000 m³) of Canada's gross water use was from thermal power generation, which includes conventional power generation (e.g., coal- and natural-gas-fired power plants as well as hydroelectricity) and nuclear energy (Statistics Canada, 2007; Environment Canada, 2010c). This is followed by manufacturing (18.5%), municipal (9.5%) and agricultural (9.4%) gross water use.

7.2. Manufacturing

7.2.1. Water Use

Water use during PV manufacturing is considered to be minimal and, as such, there have been few studies on it. Table 10 summarizes the water withdrawals for the manufacturing of PV systems and construction of PV power plants. On-site water withdrawals are used for cleaning and cooling wafers, cells and modules.

While overall water use is low, the manufacturing of silicon-based PV requires more water than that of thin-film CdTe (Fthenakis and Kim, 2010). For silicon-based PV, water consumed throughout the manufacturing of a system is approximately 200 L/MW h (Fthenakis and Kim, 2010). Most of this water is used in the production of high-purity silicon. For multicrystalline and monocrystalline silicon PV, 66% and 68%, respectively, of the upstream water use is accounted for in silicon production (Kammen et al., 2011). Water is used for cooling in the fabrication of the cells, including contact forming and edge isolation (Fthenakis and Kim, 2010). Indirect water withdrawals for silicon-based PV systems are related to producing cast-silicon and growing single crystals (Fthenakis and Kim, 2010).

For thin-film CdTe PV, there is a lower PV material requirement in manufacturing. Combined with a less energy-intensive process, as described in Chapter 4: Energy Payback Time and shown in Table 10, water consumption is lower than for silicon PV, at approximately 0.8 L/MW h (Fthenakis and Kim, 2010).

Table 10: Water Withdrawals for PV Technologies During Manufacturing and Power Plant Construction

| Type of PV | Module Efficiency (%) | On-site (L/MW h) | Upstream (L/MW h) |
|--|-----------------------|------------------|-------------------|
| Multicrystalline silicon | 13.2 | 200 | 1470 |
| Monocrystalline silicon | 14.0 | 190 | 1530 |
| CdTe | 10.9 | 0.8 | 575 |
| Frame (based on multicrystalline silicon PV) | NA | NA | 64 |
| BOS (ground-mounted PV) | NA | 1.5 | 210 |

Note: Calculations based on insolation = 1800 kW h/m² per year; lifetime = 30 years; performance ratio = 0.8.

Source: Fthenakis and Kim, 2010

7.2.2. Water Quality – Eutrophication

Water quality will be discussed here with respect to eutrophication (nutrient enrichment in a given location) only. Toxic substances in water are discussed in Chapter 6: Heavy Metals and Other Chemicals. Enriched nutrients in water accelerate algae growth, which blocks sunlight from reaching the lower depths. Decreased photosynthesis and less oxygen production eventually lead to the death of fish and to anaerobic decomposition, including production of hydrogen sulphide and methane, which in turn damage the ecosystem (De Keulenaer, 2006). *Eutrophication potential* (EP) is calculated in phosphate equivalents (PO₄ eq).

Table 11 provides an overview of the associated EP for various PV systems. For CIGS, the most significant contributions to EP come from the generation of electricity for the manufacturing process, which includes absorber simultaneous deposition and production of the BOS components (SENSE, 2008). For a-Si, EP,

as well as *acidification potential*, is mainly caused by BOS component production and the plasma-enhanced chemical vapour deposition stage (SENSE, 2008). For CdTe production, the main contributors to EP are the sourcing of raw materials, the production of glass sheets and BOS components (not including frames and inverters), and the generation of the electricity used in production (SENSE, 2008).

Table 11: Eutrophication Potential per kWp for PV Technologies

| PV Technology ^a | Eutrophication Potential (kg PO ₄ eq) per kWp ^b |
|----------------------------|---|
| CIGS | 0.475 |
| a-Si | 0.45 |
| CdTe | 0.55 |

^a Includes all BOS components.

^b kWp (kilowatt peak) is the rated output of a PV system at standard conditions.

Source: SENSE (2008)

7.3. Operation and Maintenance

During the operation and maintenance of PV systems, water is in some cases used to wash dust and dirt off modules, as cell efficiency is reduced when the modules are dirty (Kammen et al., 2011). It has been estimated that water use during PV operations in the United States is 15 L/MW h for cleaning (Fthenakis and Kim, 2010; Leitner, Platts and NREL, 2002).

PV systems operations also have little to no impact on water quality; water used for cleaning, as described above, would have a similar impact on water quality as regular window washing. As discussed previously in Chapter 6, there is also a potential risk associated with accidental chemical discharge (Grossmann et al., 2010), should the PV modules be broken open or destroyed by fire.

7.4. Comparison with Other Technologies

For PV systems the production of electricity is not dependent on water requirements. This independence provides PV technologies with the added advantage of installation in places where water is scarce without placing a strain on local water resources (EPIA, 2012b). Water use during the PV manufacturing stage is considered to be minimal. By comparison, reported water use rates are very high for thermoelectric energy-generating technologies, such as fossil fuel, nuclear, geothermal, hydroelectric and solar thermal systems. For these technologies, water consumption withdrawals can be several thousand litres per MW h, and water consumption can be several hundreds or thousands of litres per MW h. Water withdrawals and water consumption are both important, since access to a large water body is generally required. There is a wide range of values, specific to sites, found in the literature (National Academy of Science, National Academy of Engineering, and National Research Council, 2009).

Studies have reported that water consumption during the normal operation of a PV system is minimal (15 L/MW h) in comparison with other energy-generating technologies (Fthenakis and Kim, 2010b; Kammen

et al., 2011). The only technology that had lower water consumption values in these studies was offshore wind (4 L/MW h). Significantly higher values for water consumption were reported for coal (1140 L/MW h), nuclear (1500 L/MW h) and oil-gas steam (1100 L/MW h) (Fthenakis and Kim 2010b; Kammen et al., 2011).

Table 12 reflects the comparative estimates of water pollutants for the Province of Ontario. The release of chemical substances from the life cycle of PV technologies was discussed in detail in Chapter 6: Heavy Metals and Other Chemicals.

Table 12: Life Cycle Environmental Releases from Power Generation in Ontario

| Water Pollutants | Nuclear | Coal | Natural Gas | PV |
|-----------------------------|---------|------|-------------|----|
| Lead compounds (kg/TW h) | 0.00 | 0.47 | 0.00 | NA |
| Mercury compounds (kg/TW h) | 0.00 | 0.13 | 0.00 | NA |
| Arsenic compounds (kg/TW h) | 0.19 | 1.56 | 0.00 | NA |
| Radionuclides (TBq/TW h) | 21.04 | 0.00 | 0.10 | NA |

Source: Jazayeri et al. (2008)

7.5. Areas for Further Work

The impact of the use of water in the recycling of PV modules at the end of life has not yet been explored. PV module recycling is still in its infancy, as few modules have reached the end-of-life stage. Accounting for the use of water in the recycling stage of the PV system will provide a more accurate account of water use in the LCA of PV systems.

There are limited data available on water use in the PV manufacturing stage, nor on whether this water is recycled or recirculated. As noted by Kammen and colleagues (2011), methodologies for accounting for water use in the LCA process are still in their infancy; there is no standard measurement for accounting for water consumption, including water recycling, in the LCA process.

Another gap identified in the review of literature is the lack of information on acidification and EP for PV systems in comparison with other electricity-generating systems.

8. Landscape and Ecology

8.1. Introduction

8.1.1. Impact

Critics of PV technologies often claim that PV farms or stations require large amounts of land compared with conventional energy-generating technologies, such as coal and natural gas. Similar criticisms are also levelled at wind farms. PV farms or stations have also come under scrutiny with regard to their impacts on local flora and fauna. A CNBC media report in 2009 highlighted the controversy over a solar power farm in the Mojave Desert in the United States, because of concern that it was disturbing fragile desert tortoise habitat (Associated Press, 2009). The LCA of direct land use commonly uses metrics that include land transformation (area of land altered from a reference state, measured in m^2) and land occupation (area of land occupied and the duration of the occupation, measured in $\text{m}^2 \times \text{years}$). Review of direct land use suggests that the current information available on this indicator is too incomplete to accurately describe the potential for ecosystem damage (Fthenakis and Kim, 2009). As PV development increases, the debate over its direct impact on landscape and ecology will only increase. However, evidence has been published that large-scale PV plants in areas of high solar irradiation use less land than some traditional energy sources, such as coal, when land used for mining is taken into consideration (Fthenakis and Kim, 2009).

Like manufacturing of other electronic devices (e.g., cellphones and computers) and other renewable energy technologies (e.g., wind turbines and electric vehicles), manufacturing of PV modules has indirect impacts on landscape and ecology. PV modules contain metalloids (tellurium, gallium and indium). The mining of such rare earth metals has high environmental risks (Schuler et al., 2011). Currently, China provides approximately 95% of the world's supply of rare earth metals. The main risks associated with metal mining are the tailings or wastewater produced in the metal separation and concentration process, which contain acid solvents, radioactive by-products (thorium and uranium), heavy metals and fluorides. These tailing ponds contribute to a large landscape impact. Furthermore, there is a potential risk that these tailing ponds can fail (i.e., leak) and lead to site-specific air and water emissions (of radioactive materials, heavy metal and fluorides), soil contamination and ecological damage (Schüler et al., 2011).

8.1.2. Trend

When mining, transportation and disposal of non-renewable energy are taken into account, the land utilization of ground-mounted PV is comparable to that for non-renewable fuels, while that for rooftop PV systems is lower by an order of magnitude (Kammen et al., 2011). Table 13 shows reported land use values for ground-mounted PV systems in Canada.

Table 13: Land Use Values for PV in Canadian Studies

| Study | Land Use |
|-------------------------------------|--------------------------------|
| Pollution Probe | 20 km ² /1000 GW h |
| Ontario Power Authority | 1 km ² /1000 GW h |
| Canadian Solar Industry Association | 5.1 km ² /1000 GW h |
| Source: McMonagle (2006) | |

8.2. Manufacturing

8.2.1. Land Use

Indirect land use is linked to materials and energy use during PV manufacturing. Fthenakis and Kim (2009) assessed the life cycle inventories of PV modules, power plants and their components, and determined that indirect land use was insignificant compared with direct land use. This study found indirect land use was 18.4 m²/GW h for multicrystalline silicon, 18 m²/GW h for monocrystalline silicon and 15 m²/GW h for ribbon silicon. Additional land use for BOS manufacturing was determined to be 7.5 m²/GW h. The study was based on an insolation of 1 800 kW h/m² per year and a 30-year power-plant lifespan; land use under average Canadian insolation would be higher.

8.2.2. Abiotic Resource Depletion

Abiotic resource depletion is the decreasing availability of natural, non-living, non-renewable resources. Examples include iron ore or crude oil and, in the case of PV, materials such as selenium and tellurium. Resource availability is a concern for the thin-film PV industry. Shortages in these resources can mean they become limiting components of PV manufacturing. Tellurium is considered the limiting component for CdTe (Zweibel, 2010), indium and selenium are the limiting components for CIGS, and germanium is the limiting component for thin-film silicon (Grossmann et al., 2010). A few years ago, a significant shift occurred in silicon feedstock production, as the PV industry surpassed the integrated circuit industry as the largest consumer of refined silicon. This transition caught silicon suppliers by surprise and caused a short-term shortage and price increase (Wolden et al., 2011). Despite this, there is no bottleneck foreseeable for silicon used in wafer or thin-film technologies. Silicon is the second most abundant mineral in the upper crust of the earth (Grossmann et al, 2010).

For the present CdTe technology, generating 1 GW of PV modules requires 91 000 kg of tellurium. If all the installed capacity of PV globally in 2009 (7 GW) were from CdTe PV technology, about 640 000 kg of tellurium would have been required (Zweibel, 2010). This is comparable to the average annual production of tellurium worldwide. However, the production of tellurium is increasing with the increase in the production of copper and enhanced recovery from copper production circuits.

8.3. Operation and Maintenance

8.3.1. Land Use

A typical ground-mounted PV configuration occupies more land than just the PV module area. Enough land is needed for access and maintenance as well as to avoid shading.

Many solar project developers flatten the landscape and erect fences around major solar plants. During the environmental impact studies and planning, it is best practice for developers to move endangered or threatened species off a disturbed land. Developers may also set aside pristine parcels of land to compensate for the loss of the habitat (Kammen et al., 2010). Security options that avoid fencing, such as security cameras or establishing wildlife corridors throughout a farm, can allow wildlife to move freely. These options help reduce the impacts of security options to the surrounding ecosystem (Kammen et al., 2010).

Soil erosion rates for PV solar farms (ground-mounted) depend largely on the type of ground cover. PV projects that are sustainably developed and that use soil conservation techniques, such as elevated PV modules with grass cover underfoot, can reduce soil erosion to negligible rates (Graebig et al., 2010; German Renewable Energy Agency, 2010). For example, Graebig et al. (2010) reported that grass cover fields, which are not tilled, can reduce soil losses to 0.08 t/ha per year.

Land use for renewable energy sources, such as PV, is distinct in that renewable energy sources use land statically (passively), whereas conventional fuel sources use resources extracted from the land during their operation and maintenance phase. Another benefit of PV power plants is that they can be located on marginal lands and *brownfields*. They can also be used on higher-quality lands in conjunction with grazing livestock and crops (Fthenakis and Kim, 2009).

Rooftop PV installations use the least land of any of the PV technologies, as they are situated on land already disturbed by the building on which they are installed (Kammen et al., 2011).

Sustainable land use by solar farms has important benefits in decreasing effects on local plant and wildlife habitat, as discussed below.

8.3.2. Biodiversity

PV power plants have the potential to provide positive benefits for wildlife (EPIA, 2012a). They can eliminate invasive or overpopulating species, provide suitable habitat for endemic species and exclude disturbances from off-road recreation vehicles (Turney and Fthenakis, 2011).

In December 2010, the German Renewable Energy Agency completed a project exploring the impact of solar parks on biodiversity. The results of this study show that solar parks can increase the number of species in a given area (German Renewable Energy Agency, 2010). When solar parks are managed responsibly, they can create new habitats for endangered animals and plants and make positive use of marginal and remediated lands. In 2005, the Nature Conservation Association of Germany (NABU) and the German Solar Association developed the NABU Criteria, a guideline that defines environmental protection requirements that solar parks should follow. The NABU Criteria (German Renewable Energy Agency, 2010) include the following:

- Dedicated buffer areas for endangered species;

- Consideration of the local environment and compensatory measures;
- Involvement of local experts on ecological planning;
- Avoidance of *soil sealing* (no more than 1% of the surface);
- Proper crop selection to ensure the preservation of local genetic diversity;
- Avoidance of negative effects from fencing; and
- Development of a proper monitoring program.

Other recommended best practices in the NABU Criteria include avoidance of pesticides and fertilizers, use of sheep for grazing to reduce site maintenance activities, and risk assessments in accordance with the EU Directive on the Conservation of Wild Birds (Directive 2009/147/EC) (German Renewable Energy Agency, 2010). Germany has led the way in best practices for the development of solar parks.

The impacts on wildlife and habitat due to land occupation by PV power plants are not well understood, however, which may pose a hurdle to approvals for construction of PV power plants (Turney and Fthenakis, 2011). The lack of knowledge is mainly due to the fact that the technology is relatively new. As discussed above, there is concern about potential effects on wildlife. Power plants are typically fenced, limiting the movement of animals. This can affect their habitat significantly by altering hiding spots, prey strategy and food availability (Turney and Fthenakis, 2011). To address this, some fences have openings to allow for small animals to enter and leave the PV power plant area. As mentioned earlier, wildlife corridors and alternatives to fences are other solutions. In animal sciences, the concept of connectivity captures how easily wildlife can move across tracts of land and interact. This concept will be beneficial in gauging disturbances to habitat from regional patterns in land use, including the introduction of large-scale PV power plants (Turney and Fthenakis, 2011).

While there are no recent quantitative studies of the impacts on wildlife from PV power plants, McCrary and colleagues (1984) conducted a quantitative analysis of the impact on wildlife from a concentrating solar power tower in California. The study concluded that six birds per year died and hundreds of insects per hour were incinerated in the intense light. This impact was concluded to be low compared with other anthropogenic sources of bird mortality (Turney and Fthenakis, 2011).

8.4. Decommissioning

8.4.1. Land Reclamation

When PV farms are developed responsibly (as discussed in Section 8.3.2: Biodiversity), they use land with minimal disruption.

Many energy sources are associated with soil acidification through the deposition of hydrogen, sulphates and nitrates from sulphuric acid, nitric acid and acid rain (Pollution Issues, 2011). Acid deposition from energy sources is chiefly associated with the combustion of fossil fuels. Restoring land damaged by acid deposition can take years to decades and, for some soils, even centuries (US EPA, 2010). In comparison with conventional fossil fuel production, soil acidification from PV is negligible.

However, when compared with manufacturing of other renewable energy technologies, soil acidification from PV manufacturing is considered to be mid-range. Pehnt (2005) reported an acidification (sulphur dioxide equivalence, SO₂ eq) of 528 mg/kW h for PV (multicrystalline silicon). This value is relatively higher than wind energy and hydroelectricity, but much lower than *biogas* and other renewable heat systems (e.g., waste wood steam turbine) (Pehnt, 2005). Furthermore, increased efficiency and lifespan of PV modules will minimize the acidification impact of PV solar technologies (Pehnt, 2005).

Another concern is the recovery of soil and ecosystem following a disturbance. Similar to recovery from acidification, recovery following a disturbance can require many years or decades, depending on the use of the land. Coal strip mining disturbs the land to such a degree that recovery can take 50 to 100 years (Turney and Fithenakis, 2011). This is because soil takes several decades to regenerate.

The disturbance caused by decommissioning a PV system is expected to be minimal because only a small amount of soil is removed (Turney and Fthenakis, 2011). No major structure or machines such as generators, reactors or cooling systems need to be decommissioned for economic or safety reasons at the end of life of a PV power plant except the modules and BOS components (Fthenakis and Kim, 2009).

8.4.2. Abiotic Resource Depletion

Recycling of decommissioned PV thin-film modules can help alleviate abiotic resource depletion by providing another supply of the metalloids, such as tellurium, used in semiconductor materials. For example, First Solar Inc., a leading CdTe module manufacturer, has published results that indicate that up to 95% of its semiconductor material is recycled (Krueger, 2011).

8.5 Comparison with Other Technologies

Landscape issues, including wildlife considerations, can be problematic for PV, especially as more and larger PV installations are considered in many places. Nevertheless, landscape impacts tend to remain localized, while some of the affected land can simultaneously be used for other purposes (e.g., grazing livestock). Additional analysis of affected land is minimal; however, a recent study by Turney and Fthenakis (2011) demonstrated that large-scale, ground-mounted PV power plants are largely beneficial with regard to wildlife and habitat environmental indicators compared with fossil fuel-based power generation.

One way of measuring the landscape impact of energy-generating technologies is the generating efficiency of the technology per unit area (m²/MW h per year). Published studies provided the comparisons in Figure 9 and Table 14.

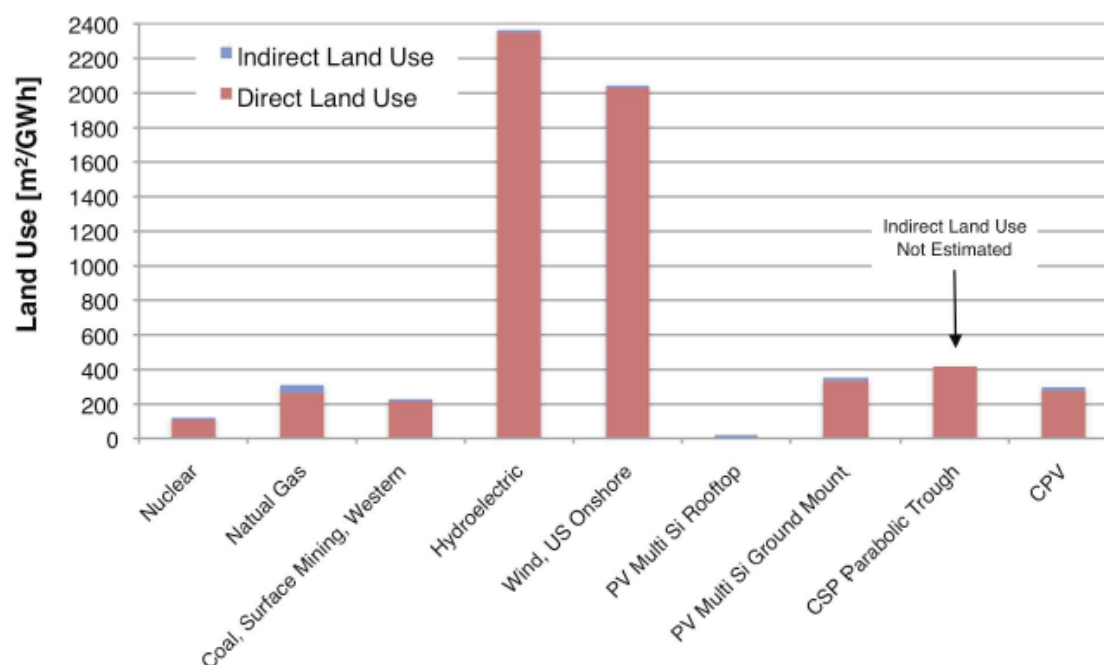


Figure 9: Land use (m²/GW h) by energy-generating technologies

Note: Land use values include direct and indirect land use and represent median cases for each technology, including concentrating solar power (CSP or solar thermal) and concentrator photovoltaics (CPV).

Source: Fthenakis and Kim, 2009; Kammen et al., 2011

Table 14: Comparison of Landscape Impact of Renewable Electricity

| Energy Source | Land-Use Values (m ² /MW h year) |
|--------------------------------|---|
| Natural gas ^a | 0.45 |
| Coal ^a | 4.4–5.80 |
| Nuclear ^a | 6.50 |
| Solar | 9.0–14.30 |
| Wind ^b | 69–94 |
| Hydroelectricity (large-scale) | 122 |
| Biomass ^c | 360–488 |

^a Excludes resource extraction.

^b Allows multiple use (i.e., grazing).

^c Based on cropping with no waste.

Source: National Academy of Sciences, National Academy of Engineering, and National Research Council (2010)

8.6. Areas for Further Work

Many land impact categories for LCA lack well-defined metrics or lack consensus among LCA practitioners (Turney and Fthenakis, 2011). Proxy impact categories such as land use intensity are often used to evaluate land impacts in LCA, and there is no consensus on which metric best describes the effects of a variety of uses on land. Research continues on the measurement methods for land use intensity, habitat fragmentation, multiple stressors on the health of populations, and the risk of collapse of complex ecosystems (Turney and Fthenakis, 2011).

The understanding of the potential environmental impacts of PV technologies would benefit from the standardization of metrics to assess land use intensity, habitat and ecosystem impacts, as well as the continual monitoring of impacts on land and ecosystems. It is also important to follow emerging concepts in restoration ecology, such as connectivity. The rate of soil and ecosystem recovery following the decommissioning of PV power plants is not yet known because it may take decades. (Turney and Fthenakis, 2011).

9. Conclusions

This assessment finds that PV technologies have, in general, fewer negative environmental impacts than traditional fossil fuel-based electricity production. The EPBT of a PV system has declined significantly in recent years, with studies now reporting EPBT of approximately one year. PV systems emit no GHGs or air pollutants during normal operation. Small amounts of heavy metals and other chemicals such as cadmium and lead are used in the production of PV cells, and can arise from waste created by decommissioning, but PV modules can be an environmentally friendly means to sequester elemental cadmium, and it can be reclaimed and used again when PV modules are recycled. Water use and impacts on water quality in the life cycle of PV technologies are considered to be minimal. Although PV technologies can require a considerable amount of land (more for ground-mounted applications, less for rooftop), they can be located on marginal lands and *brownfields* or can be installed on higher-quality lands in conjunction with grazing livestock and crops. As module efficiency increases, land use will decrease, and when PV power plants are constructed using best management practices, they can provide a positive benefit to biodiversity. The increase in PV module manufacturing, and the eventual need for decommissioning and disposal, may create a new wave of e-waste, but recycling of spent PV modules has now begun and has shown potential to improve the environmental profile of PV technologies.

Comparing PV technologies with more traditional modes of electricity production reveals measurable benefits. Emissions of cadmium from the life cycle of CdTe are 100–360 times lower than those from coal power plants with optimally functioning particulate control devices. Each gigawatt-hour of electricity generated during operation from CdTe PV modules can prevent 8.8 g of cadmium emissions from a coal-fired facility in Europe or about 2 g from such a facility in the US, given a median concentration of 0.5 mg/kg of cadmium in US coal. Water consumption during the normal operation of a PV system is minimal (15 L/MW h) in comparison with other energy-generating technologies. The only technology that had lower water consumption values in these studies was offshore wind (4 L/MW h). Significantly higher values for water consumption were reported for coal (1140 L/MW h), nuclear (1500 L/MW h) and oil-gas steam (1100 L/MW h). Land use for renewable energy sources, such as PV, is static (passive), whereas conventional fuel sources use land actively when extracting resources (e.g., coal).

This report also identifies areas for further work, including: the potential of new storage technologies to decrease EPBT for stand-alone systems, which may be important for applications in remote Canadian communities; GHG emissions associated with building-integrated vs. rooftop installations; comparisons of PV systems with other renewable energy sources; the toxicity of CdTe; water use in PV manufacturing and recycling stages; and which metric or metrics best describe the effects of a variety of PV applications on land.

Taken as a whole, and despite caveats about environmental consequences associated with decommissioning, the assessment reveals the current benefits and potential future benefits of PV technologies at every stage of the life cycle.

Glossary

| | |
|---|--|
| Abiotic | Referring to non-living natural substances such as minerals. “Abiotic resource depletion” is the exhaustion of abiotic resources such as metalloids used in fabrication of photovoltaic systems. |
| Acidification | Process of becoming acidic (alkalinity less than 0). In environmental sciences, the main concern is atmospheric deposition of pollutants such as sulphur dioxide and nitrogen oxides that cause surface waters and soils to acidify, harming ecological balances. |
| Acidification potential | The potential of emissions to release H^+ ions, thereby acidifying the environment, measured in sulphur dioxide equivalent units. |
| Air pollutants | In Canada, substances that typically contribute to smog, poor air quality and acid rain, including <i>particulate matter</i> less than or equal to $10\ \mu m$ (PM_{10}), particulate matter less than or equal to $2.5\ \mu m$ ($PM_{2.5}$), <i>sulphur oxides</i> (SO_x), <i>nitrogen oxides</i> (NO_x), <i>volatile organic compounds</i> (VOCs), carbon monoxide (CO) and ammonia (NH_3). |
| Amorphous silicon (a-Si) | Form of silicon in which the atoms form a continuous random network, in contrast to crystalline silicon in which the atoms form a crystal lattice. Amorphous silicon is used in thin films. Because of the lack of long-range order to the atoms, dangling bonds can cause anomalous electrical behaviour. To use amorphous silicon in devices, the dangling bond density is often reduced through hydrogenation, producing “hydrogenated amorphous silicon” (a-Si:H). |
| Annealing | Heat treatment to alter the conditions of a metal, such as strength and hardness. Metals are typically heated and then cooled before stamping, shaping or forming. |
| Balance of system (BOS) components | Parts of a PV system other than the PV array, including switches, controls, meters, power conditioning equipment, PV array support structure and electricity storage components, if any. |
| Bioaccumulative | Referring to the accumulation of substances, often toxins, in an organism. Some toxins accumulate in organisms at a greater rate than they are eliminated, resulting in increasing toxicity. |
| Biogas | Gas produced by the biological breakdown of organic matter in the absence of oxygen (anaerobic digestion or fermentation), containing primarily methane and carbon dioxide. |

| | |
|---|---|
| Biomass | Biological material from living, or recently living, organisms; for example, forest residues or animal matter or municipal solid waste. Often used to produce biofuels. |
| Biotic | Referring to living components of a community; organisms such as plants and animals. |
| Brominated fire retardants | A wide range of organobromine chemical compounds added to materials to inhibit their ignition and slow their rate of combustion. |
| Brownfields | Former industrial lands that are now vacant or underused but could be redeveloped for new uses. Brownfields may be contaminated due to past or present activities. |
| Building-integrated photovoltaics (BIPV) | Photovoltaics as an integral part of a building; PV modules may serve as the exterior weather skin or be incorporated into the building envelope, such as the roof or facade. |
| Cadmium telluride (CT or CdTe) | Crystalline compound of cadmium and tellurium. It is used as a thin-film photovoltaic material. |
| Carbon dioxide equivalence | Each greenhouse gas has a unique average atmospheric lifetime and heat-trapping potential. For comparison purposes, greenhouse gas emissions are reported in units of carbon dioxide equivalence (CO ₂ eq)—how much carbon dioxide would be required to produce a similar warming effect. The carbon dioxide equivalent value is calculated by multiplying the amount of the gas by its associated <i>global warming potential</i> . |
| Chalcogen | The chemical elements found in group 16 of the period table. This group is known as the oxygen family and consists of the elements oxygen, sulfur, selenium, tellurium, the radioactive element polonium and the synthetic element ununhexium. |
| Charge regulator | Device that limits the rate at which electric current is added to or drawn from a battery. Also known as a charge controller or battery regulator. |
| Chemical vapour deposition (CVD) | A chemical process used to produce high-purity, high-performance solid materials. In a typical CVD process, the substrate (wafer) is exposed to one or more volatile precursors that react and/or decompose on the substrate surface to produce the desired deposit. |
| Coevaporation | Coevaporation, or codeposition, is the most prevalent CIGS fabrication technique in the laboratory and an important method in industry. The coevaporation process deposits bilayers of CIGS with different stoichiometries onto a heated substrate and allows them to intermix. |

| | |
|---|--|
| Concentrators | Optical lenses and mirrors that concentrate sunlight onto smaller area solar cells. |
| Copper indium gallium selenide (CIGS) | Semiconductor material composed of copper, indium, gallium and selenium. Also referred to as copper indium gallium diselenide. It is commonly used as a thin-film photovoltaic material. |
| Crystalline silicon (c-Si) | Silicon atoms connected to one another to form a crystal lattice. This lattice constitutes the semiconductor material used in many types of PV cells. There are several forms of crystalline silicon. In single crystalline (or monocrystalline) silicon, the material used for integrated circuits in the electronics industry, the crystal lattice of the entire solid is continuous and unbroken, with no grain boundaries. In polycrystalline (or multicrystalline) silicon, multiple small silicon crystals create a visible grain or “metal flake effect.” Ribbon (or string ribbon) silicon is a method of producing polycrystalline silicon strips for solar cells. |
| Czochralski process | Method of crystal growth used to obtain single crystals of semiconductor materials, metals, salts and synthetic gemstones. Named for its discoverer, Polish chemist Jan Czochralski. |
| Doping | Process used to create semiconductor materials, in which an atom of another element is introduced into silicon crystal to alter its electrical properties. The introduced element (dopant) is most commonly either phosphorus (for <i>n</i> -type silicon) or boron (for <i>p</i> -type silicon). The most common method of doping is to coat a layer of silicon material with phosphorus and then heat the surface. Other methods of introducing phosphorus into silicon include gaseous diffusion, a liquid spray-on process, and a technique in which phosphorus ions are precisely driven into the surface of the silicon. Boron is introduced when the silicon is purified for use in PV devices. |
| Dye-sensitized photovoltaic cell (DSC, DYSC or DSSC) | Thin-film solar cell based on a photoelectrochemical process, in which the semiconductor consists of a <i>photoelectrode</i> (nanocrystalline titanium dioxide sensitized with organometallic dye molecules), a redox electrolyte (iodine) and a counter electrode (platinum). A well-known DSC developed by Michael Grätzel and Brian O'Regan in 1991 is known as the Grätzel cell. |
| Ecotoxicological | Related to the nature, effects and detection of substances deleterious to biological communities, their encompassing ecosystems and processes. |

| | |
|---------------------------------------|---|
| Edge deletion | Glass covers for thin-film PV modules are typically bought in bulk, with a conductive stannous oxide film covering the entire sheet of glass. The film must be removed from the edges of the glass by mechanical, chemical or laser methods; this process is called edge deletion. |
| Emissions | Discharges of substances into the environment, most commonly gases discharged into the atmosphere or effluent discharged into bodies of water. |
| Encapsulant | Substance used to laminate or encase solar cells, to provide physical protection, electrical isolation and thermal conduction. |
| Energy payback time (EPBT) | The length of time (in years) for an operating PV system to produce as much energy as it required over its life cycle. |
| Eutrophication | Overfertilization of a water body by nutrients, producing more organic matter than the self-purification reactions of the water body can overcome. Also known as “nutrient enrichment.” |
| Eutrophication potential | The potential of emissions to result in nutrient enrichment of the environment, measured in phosphate equivalent units. |
| Ethylene-vinyl acetate (EVA) | Substance used as an <i>encapsulant</i> for PV cells. |
| Extractions | Procurement of raw materials from their natural origin, through mining, drilling, logging, etc. |
| Feed-in tariffs | A form of subsidy or incentive for renewable-source electricity in which utilities establish long-term contracts with system owners to purchase renewably generated electricity at a premium price, typically reflecting the cost of generation. |
| Fluorinated gases (F-gases) | Various gases containing fluorine, widely used in appliances and devices as a replacement for ozone-depleting gases such as chlorofluorocarbons, hydrochlorofluorocarbons and halons. The F-gases, such as hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride, are not ozone-depleting but are considered greenhouse gases and contribute to climate change. |
| Global horizontal irradiation | Total amount of sunlight received by a horizontal surface. |
| Global warming potential (GWP) | The ability of each greenhouse gas to trap heat in the atmosphere relative to carbon dioxide (CO ₂) over a specified time horizon, based on a number of factors, including the heat-absorbing ability (“radiative efficiency”) of each gas, as well as the amount of each gas removed from the atmosphere over a given number of years (“decay rate”), relative to those of carbon dioxide. For example, the GWP for methane is 21, so each tonne of methane emitted is considered to have a cumulative warming effect over the next 100 years equivalent to 21 tonnes of carbon dioxide. |

| | |
|--|---|
| Greenhouse gas (GHG) | Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H ₂ O), carbon dioxide (CO ₂), nitrous oxide (N ₂ O), methane (CH ₄) and ozone (O ₃) are the primary greenhouse gases in the earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as sulphur hexafluoride (SF ₆), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). |
| Grid-connected applications | Energy systems contributing to the network that delivers electricity from suppliers to consumers. |
| Grid efficiency | The average efficiency, at the demand side, of conversion of primary energy to electricity. |
| Grid parity | The economic situation in which the price of electricity generated by a renewable source is equal to the retail price of electricity generated from traditional sources. |
| Ground-level ozone | Ozone (O ₃), the main component of smog, is created at ground level by the chemical reaction between nitrogen oxides (NO _x) and volatile organic compounds (VOCs) in the presence of sunlight. |
| Hexavalent chromium | Chemical compounds containing chromium in the +6 oxidative state. |
| High-efficiency III-V multi-junction cell | Multi-junction solar cells, commonly used in space applications, use a combination of semiconductor materials to efficiently capture photons of a large range of energies. A series of single-junction cells are layered to convert photons of different energies. Manufactured from alloys of groups III and V of the periodic table. |
| Insolation | Energy of incoming solar radiation incident on a given surface area over a defined time period. |
| Installed photovoltaic capacity | The rated power under standard testing conditions of all active PV systems in a given area (region, country or group of countries). |
| Kerfless wafers | Silicon wafers produced by an implantation and cleaving method, without "kerf" (sawing or cutting) associated with traditional methods. Also known as "kerf-free" wafers. Wafers are sliced from monocrystalline silicon boules to thicknesses of 50 µm or less, avoiding the use of slurry and production of waste. |

| | |
|---|---|
| Life cycle assessment | A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy as well as the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. |
| Light-emitting diode (LED) | A light source based on semiconductor materials. Used in a growing variety of commercial applications, LEDs can provide light across the infrared, ultraviolet and visible spectra. Light so produced is very bright, while consuming less energy than traditional lighting technologies. |
| Metallization paste | Metal in paste format, applied to PV cells as electric contacts for thin-film connections. |
| Metalloids | Chemical elements with properties between or a mixture of those of metals and those of non-metals. |
| Net energy ratio (NER) | The ratio of (1) useful energy output to the grid to (2) the fossil fuel energy consumed during the lifetime of the technology. For PV, the NER can be calculated by dividing the lifespan of a PV system by the energy payback time. |
| Nitrogen oxides (NO_x) | Term encompassing nitric oxide (NO) and nitrogen dioxide (NO ₂), produced by the reaction of nitrogen and oxygen gases during combustion and constituting a major contributor to smog. |
| Off-grid applications | Energy systems that are not connected to a central transmission and distribution electricity network. |
| Organic photovoltaic (OPV) cell | Recently developed type of PV cell based on conductive organic polymers or small organic molecules that absorb light and conduct current. Also known as “polymer” or “plastic” solar cells. |
| Particulate matter (PM) | Complex mixture of extremely small particles and liquid droplets. It is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. |
| Performance ratio | Ratio of the actual to the theoretically possible energy outputs. Performance ratio is largely independent of the orientation and the incident solar irradiation on a PV plant. For this reason, it can be used to compare PV plants at different locations around the world. |
| Photoelectrode | A material that absorbs light to produce current in a circuit. |

Photovoltaic (PV) technologies

Technologies that convert sunlight into electricity, used primarily for grid-connected electricity to operate residential appliances, commercial equipment, lighting and air conditioning for all types of buildings. Through stand-alone systems and the use of batteries, it is also well-suited for remote regions where there is no electricity source. PV modules can be ground mounted, installed on building rooftops or designed into building materials during manufacturing.

Plasma edge isolation

In PV cell manufacturing, edge isolation removes the phosphorous diffusion around the edge of the cell so that the front emitter is electrically isolated from the cell rear. A common way to achieve this is to plasma etch cells using F-gases that contribute to climate change.

***p-n* junction**

In a *semiconductor diode*, the interface between two different types of materials, *p*-type and *n*-type semiconductors. These materials are formed by adding impurities to pure high-purity silicon. Semiconductors of *p*-type contain “holes” that simulate positively charged particles, whereas *n*-type semiconductors contain free electrons. Electric current flows more easily across such a junction in one direction than in the other.

Primary energy demand

Direct use at the source, or supply to users, of energy that has not undergone any conversion or transformation. It refers to raw fuels, both renewable and non-renewable, received as inputs into a system.

PV CYCLE

PV CYCLE is a non-profit, independent association managing a collection and recycling scheme for end-of-life PV modules throughout Europe. It works on behalf of PV module manufacturers and importers in all European markets.

PVPS countries

Countries participating in the Photovoltaic Power Systems Programme of the International Energy Agency. The long-term participating countries are Australia, Austria, Canada, Denmark, France, Germany, Israel, Italy, Japan, Korea, Mexico, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom and the United States of America. The European Commission and the European Photovoltaic Industry Association are also members. Malaysia, Turkey, the Solar Electric Power Association and China are recent participants.

Sawing slurry

Fluid used in cutting silicon wafers.

Selenization

In CIGS/CIS thin-film production, Se is supplied in the gas phase (for example as H₂Se or elemental Se) at high temperatures, and is incorporated into the film via absorption and subsequent diffusion.

| | |
|--|--|
| Semiconductor | Solid-state materials are classified as insulators, semiconductors or conductors, depending on their electrical conductivity and resistivity. Semiconductor materials can conduct electricity under some conditions, but not others, and are therefore often used to control current. Several semiconductor materials are used commercially, with silicon, used in integrated circuits, being the most important. |
| Siemens process | Process for purifying silicon for the electronics industry, producing silicon that is 99.99999999% pure. A modified Siemens process specifically to produce <i>solar-grade silicon</i> uses less energy and produces silicon that is slightly less pure (99.999999% to 99.99999999%). |
| Sintering | Process used to shape materials. Based on atomic diffusion, sintering involves heating powdered material in a mould to a high temperature, but below the material's melting point. It is therefore useful for shaping materials with a high melting point. |
| Soil sealing | The covering of the soil surface with impervious materials for urban development and infrastructure construction. Also used to describe a change in the nature of the soil, leading to impermeability (e.g., compaction by agricultural machinery). Sealed areas are lost to agriculture or forestry while the ecological soil functions (as a buffer and filter system or as a carbon sink) are severely impaired or even lost. Surrounding soils may be influenced by change in water flow patterns or fragmentation of habitat. |
| Solar farms | Same as <i>solar parks</i> ; the term “solar farm” tends to be used for sites in agricultural areas. |
| Solar-grade | Semiconductor material (polycrystalline silicon) sufficiently pure to be useful for PV cells. Solar-grade silicon is not as pure as silicon for electronic purposes. |
| Solar parks | Large-scale PV sites generating electricity for addition to the electrical grid. See also <i>solar farms</i> . |
| Sulphur oxides (SO_x) | Term encompassing many compounds containing sulphur and oxygen; the most common of the sulphur oxides is sulphur dioxide, which is a major contributor to smog and <i>acidification</i> . While sulphur dioxide occurs naturally in volcanoes and hot springs, human-made sources include sour gas processing, oil sands production, coal combustion, ore refining, chemical manufacturing and other fossil fuel processing and burning. |

| | |
|---|--|
| Sun-tracker | Also known as a “solar tracker,” a device that orients a PV module toward the sun, minimizing the angle of incidence of the incoming light in order to maximize the energy produced. |
| Tempered glass | Glass manufactured through extreme heating and rapid cooling in order to withstand heat and to shatter without dangerous sharp edges. Also known as safety glass. Tempered glass is widely used in door windows, oven windows, carafes in automatic coffee makers, shower doors, etc. |
| Thin film | Layer of material ranging in thickness from less than a nanometer to several micrometers. Thin films are commonly used in electronic semiconductors and optical coatings. In PV cells, one or more thin films are deposited on a substrate. Thin-film PV cells are categorized according to the PV material used, mainly <i>amorphous silicon</i> (a-Si), cadmium telluride (CT or CdTe) or copper indium gallium selenide (CIS or CIGS). |
| Toxicological | Related to the adverse effects of chemical, physical or biological agents on living organisms and the ecosystem. |
| Toxicological reference dose (RfD) | An estimate of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. RfDs are based on non-carcinogenic effects. |
| Transformer | Device to transfer electrical energy from one circuit to another; transformers enable the voltage of alternating current to be changed (“stepped up” or “stepped down”). |
| Transparent conductive oxide (TCO) | A <i>doped</i> metal oxide thin film predominantly used in optoelectronic devices such as flat module displays and photovoltaics (including inorganic and organic as well as dye-sensitized solar cells). Most TCOs are manufactured with polycrystalline or amorphous silicon microstructures. They use electrode materials with higher than 80% transmittance of incident light as well as conductivities of more than 10 ³ S/cm for efficient carrier transport. |
| Ultrathin silicon | Silicon wafers less than 100 µm thick, being developed as a high-conversion-efficiency and lower-cost alternative. |
| Volatile organic compounds (VOCs) | Organic compounds containing one or more carbon atoms that evaporate readily to the atmosphere. VOCs do not include photochemically non-reactive compounds such as methane, ethane and the chlorofluorocarbons (CFCs). VOCs are primary precursors to the formation of ground-level ozone and particulate matter, the main constituents of smog. |

References

- Alsema, E.A. (2000). Energy Pay-back time and CO₂ emissions of PV systems. *Prog. Photovolt.: Res. Appl.* 8, 17–25.
- Alsema, E.A. (2006). Life cycle assessment of PV technology: current status and further needs, paper presented at SENSE Workshop, Dresden, Germany.
- Alsema, E.A., and de Wild-Scholten, M.J. (2005). Environmental Impacts of Crystalline Silicon Photovoltaic Module Production. Presented at the Materials Research Society Fall Meeting, November 2005, Boston, USA.
- Arvizu, D., Balaya, P., Cabeza, L., Hollands, T., Jäger-Waldau, A., Kondo, M., Konseibo, C., Meleshko, V., Stein, W., Tamaura, Y., et al. (2011). Direct solar energy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, et al., eds. (Cambridge, UK, and New York, NY: Cambridge University Press), <http://srren.ipcc-wg3.de/report> (accessed September 6, 2011).
- As You Sow. (2012). *Clean & Green: Best Practices in Photovoltaics* (San Francisco, CA). www.asyousow.org/health_safety/solar_report.shtml
- Associated Press. (2009). Mojave desert a battleground over solar power, March 24, www.msnbc.msn.com/id/29837101 (accessed February 16, 2011).
- Beckmann, J., Mennenga, A. (2011). Berechnung von Immissionen beim Brand einer Photovoltaik-Anlage aus Cadmiumtellurid-Modulen. (Augsberg, Germany: Bayerisches Landesamt für Umwelt). Available at: www.lfu.bayern.de/luft/doc/pvbraende.pdf.
- Bradshaw, K. (2009). Earth friendly elements, mined destructively. *The New York Times*, December 25, www.nytimes.com/2009/12/26/business/global/26rare.html?pagewanted=all (accessed October 12, 2011).
- Canada. (2012). Chemical Substance Website, www.chemicalsubstanceschimiques.gc.ca/index-eng.php (accessed March 26, 2012)
- Canadian Solar Industries Association. (2010). *Solar Vision 2025: Beyond Market Competitiveness* (Ottawa: Canadian Solar Industries Association).
- Cha, A.E. (2008). Solar energy firms leave waste behind in China. *The Washington Post*, March 9.
- De Keulenaer, H. (2006). Eutrophication potential (EP), Leonardo ENERGY, www.leonardo-energy.org/eutrophication-potential-ep (accessed September 20, 2011).
- de Wild-Scholten, M. (2009). Sustainability: keeping the thin film industry green, paper presented at the 2nd International Thin Film Conference, Munich, Germany.
- de Wild-Scholten, M.J., Alsema, E.A., Fthenakis, V.M., Agostinelli, G., Dekkers, H., Roth, K., and Kinsig V. (2007). Fluorinated greenhouse gases in photovoltaic module manufacturing: potential emissions and abatement strategies, paper presented at 22nd European Photovoltaic Solar Energy Conference, Milan, Italy.
- de Wild-Scholten, M.J., Wamback, K., Alsema, E., and Jäger-Waldau, A. (2005). Implications of European environmental legislation for photovoltaic systems, paper presented at the 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain.

- Dignard-Bailey, L., and Ayoub, J. (2011). Canada Photovoltaic Technology Status and Prospects: Canadian Annual Report 2010, CETC Number 2011-046 (Ottawa: CanmetENERGY, Natural Resources Canada). Full text available at:
http://198.103.48.154/eng/renewables/standalone_pv/publications/2011046.html
- Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N. and Röder A. (2007) Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final report ecoinvent data v2.0, No. 6. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
- Electric Power Research Institute (EPRI). (2003). Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells (Palo Alto, CA: EPRI).
- Environment Canada. (2010a). Canada's GHG emissions,
www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=EAF0E96A-1#section1 (accessed January 24, 2012).
- Environment Canada. (2010b). Canada's GHG inventory,
www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=B710AE51-1#section7 (accessed January 23, 2012).
- Environment Canada. (2010c). National Inventory Report 1990–2008: Greenhouse Gas Sources and Sinks in Canada. Submitted to the United Nations Framework Convention on Climate Change on April 15, 2010.
- Environment Canada. (2010d). Water use,
www.ec.gc.ca/eau-water/default.asp?lang=En&n=96F2B222-1 (accessed September 19, 2011).
- Environment Canada. (2011a). Criteria air pollutants and related pollutants,
www.ec.gc.ca/air/default.asp?lang=En&n=7C43740B-1 (accessed January 23, 2012).
- Environment Canada. (2011b). National Pollution Release Inventory [database],
http://ec.gc.ca/pdb/websol/emissions/ap/ap_result_e.cfm?year=2010&substance=cd&location=CA§or=&submit=Search (accessed March 2012).
- European Photovoltaic Industry Association (EPIA). (2012a) Sustainability of Photovoltaic Systems: Land Use and Biodiversity [fact sheet] (Brussels, Belgium: EPIA Sustainability Working Group).
- European Photovoltaic Industry Association (EPIA). (2012b) Sustainability of Photovoltaic Systems: The Water Footprint [fact sheet] (Brussels, Belgium: EPIA Sustainability Working Group).
- European Photovoltaic Industry Association (EPIA) and Greenpeace International. (2011). Solar Generation: Solar Photovoltaic Electricity Empowering the World, 6th edition (Brussels, Belgium: EPIA and Greenpeace International).
www.epia.org/publications/epia-publications/solar-generation-6.html (accessed September 6, 2011).
- Franklin Associates. (1998). USA LCI Database Documentation. Prairie Village, Kansas.
- Fthenakis, V.M. (2003). Overview of potential hazards. In Practical Handbook of Photovoltaics: Fundamentals and Applications, T. Markvart and L. Castafier, eds. (Amsterdam, the Netherlands: Elsevier Science), pp. 858–867.
- Fthenakis, V. (2004). Life cycle impact analysis of cadmium in CdTe PV production. *Renew. Sustain. Energy Rev.* 8, 303–334.
- Fthenakis, V. (2009). Review of CdTe PV EH&S Aspects, presentation to the French Ministry of Ecology, Energy, Sustainable Development and Land Management CdTe PV Review Meeting, Frankfurt-Oder, Germany.

- Fthenakis, V., Clark, D.O., Moalem, M., Chandler, P., Ridgeway, R.G., Hulbert, F.E., Cooper, D.B., and Maroulis, P.J. (2010). Life-cycle nitrogen trifluoride emissions from photovoltaics. *Environ. Sci. Technol.* 44(22), 8750–8757. doi:10.1021/es100401y.
- Fthenakis, V., and Alsema, E. (2006). Photovoltaic energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status. *Prog. Photovolt: Res. Appl.* 44, 275–280. doi: 10.1002/pip.706
- Fthenakis, V., Frischknecht, R., Raugei, M., Kim, H.C., Alsema, E., Held, M., and de Wild-Scholten, M. (2011a). Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 2nd Edition, PVPS Task 12, Report T12-03. (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program).
- Fthenakis, V.M., Fuhrmann, M., Heiser, J., Lanzirrotti, A., Fitts, J., and Wang, W. (2005). Emissions and encapsulation of cadmium in CdTe PV modules during fires. *Prog. Photovolt. Res. Appl.* 13, 713–723.
- Fthenakis, V.M., and Kim, H.C. (2006). CdTe Photovoltaics: Life Cycle Environmental Profile and Comparisons, paper presented at the European Materials Research Society Meeting, Symposium O, Nice, France.
- Fthenakis, V., and Kim, H.C. (2009). Land use and electricity generation: a life-cycle analysis. *Renew. Sustain. Energy Rev* 13, 1465–1474.
- Fthenakis, V., and Kim, H.C. (2010). Life-cycle uses of water in U.S. electricity generation. *Renew. Sustain. Energy Rev.* 14, 2039–2048.
- Fthenakis, V.M., and Kim, H.C. (2011). Photovoltaics: life-cycle analyses. *Solar Energy* 85(8), 1609–1628.
- Fthenakis, V.M., Kim, H.C., and Alsema, E. (2008). Emissions from photovoltaic life cycles. *Environ. Sci. Technol.* 42(6), 2168–2174. doi:10.1021/es071763q.
- Fthenakis, V., Kim, H.C., Frishknecht, R., Raugei, M., Sinha, P., and Stucki, M. (2011b). Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, PVPS Task 12, Report T12-02. (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program). www.iea-pvps.org (accessed February 22, 2012).
- Fthenakis, V., Kim, H.C., Raugei, M., and Krones, J. (2009). Update of PV Energy Payback Times and Life-Cycle Greenhouse Gas Emissions, paper presented at the 24th European Photovoltaic Solar Energy Conference, Hamburg, Germany.
- Fthenakis, V.M., Morris, S.C., Moskowitz, P.D., and Morgan, D. (1999). Toxicity of CdTe, CIS, and CGS. *Prog. Photovolt.* 7, 489–497.
- Gagnon, L. (2003). Comparing Power Generating Options: Greenhouse Gas Emissions [2002G130-1A] (Montreal: Hydro-Quebec).
- Garcia-Valverde, R., Miguel, C., Martinez-Bejar, R., Urbina, A. (2009). Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. *Solar Energy*, 83(9), 1434-1445
- German Renewable Energy Agency. (2010). Solar Parks – Opportunities for Biodiversity, [English summary of the report about biodiversity in and around solar parks]. *Renews Spezial* 45, www.unendlich-viel-energie.de/en/details/article/523/solar-parks-opportunities-for-biodiversity-1.html (accessed February 22, 2012).
- Graebig, M., Bringezu, S., and Fenner, R. (2010). Comparative analysis of environment impacts of maize-biogas and photovoltaics on a land use basis. *Solar Energy*, 84, 1255–1263.

- Green, M.A., Emery, K., Hishikawa, Y., and Warta, W. (2011). Solar cell efficiency tables (version 37). *Prog. Photovolt.: Res. Appl.* 19(1), 84–92. doi:10.1002/pip.1088.
- Grossmann, W.D., Grossmann, I., and Steininger, K. (2010). Indicators to determine winning renewable energy technologies with an application to photovoltaics. *Environ. Sci. Technol.* 44(13), 4849–4855.
- Held, M., and Ilg, R. (2011). Update of environmental indicators and energy payback time of CdTe PV systems in Europe. *Prog. Photovolt.: Res. Appl.* 19, 614–626.
- International Energy Agency (IEA). (2006). Compared Assessment of Selected Environmental Indicators of Photovoltaic Electricity, Report of IEA PVPS Task 10 (St-Ursen Switzerland: International Energy Agency Photovoltaic Power System Program) <http://iea-pvps.org/index.php?id=9> (accessed October 3, 2012).
- International Energy Agency (IEA). (2009). Photovoltaic Power Systems Program (PVPS) Annual Report 2009 (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program) <http://iea-pvps.org/index.php?id=6> (accessed January 10, 2012).
- International Energy Agency (IEA). (2010a). Energy Technology Perspectives (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program).
- International Energy Agency (IEA). (2010b). Technology Roadmap: Solar Photovoltaic Energy (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program) www.iea.org/papers/2010/pv_roadmap.pdf (accessed September 6, 2011).
- International Energy Agency (IEA). (2010c). Trends in Photovoltaic Applications – Survey Report of Selected IEA Countries between 1992 and 2009, Report IEA-PVPS T1-19:2010 (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program) www.iea-pvps.org/index.php?id=32 (accessed February 22, 2012).
- International Energy Agency (IEA). (2011a). Trends in Photovoltaic Applications — Survey Report of Selected IEA Countries between 1992 and 2009: Preliminary Statistical Data, Report IEA-PVPS T1-20:2011 (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program) www.iea-pvps.org/index.php?id=32 (accessed September 6, 2011).
- International Energy Agency (IEA). (2011b). Trends in Photovoltaic Applications — Survey Report of Selected IEA Countries between 2002 and 2010, Report IEA-PVPS T1-2011 (St-Ursen, Switzerland: International Energy Agency Photovoltaic Power Systems Program).
- Intergovernmental Panel on Climate Change (IPCC). (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
- Jazayeri, S., Kralovic, P., Honarvar, A., Abbas, N., Rozhon, J., Shabaneh, R., and Walden, T. (2008). Comparative Life Cycle Assessment (LCA) of Base Load Electricity Generation in Ontario (Calgary, AB: Canadian Energy Research Institute). P. 226.
- Jungbluth, N., Stucki, M., Flury, F., Frischknecht, R., Busser, S. (2012). Life Cycle Inventories of Photovoltaics. Available at: www.esu-services.ch/projects/pv
- Jungbluth, N., Tuchschnid M., and de Wild-Scholten, M. (2008). Life Cycle Assessment of Photovoltaics: Update of ecoinvent Data v 2.0. Available at: www.esu-services.ch/projects/pv

- Jungbluth, N. (2005). Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database. *Prog. Photovolt.: Res. Appl.* 13(5), 429–446.
- Kaczmar, S. (2011). Evaluating the read-across approach on CdTe toxicity for CdTe photovoltaics, paper presented at the Society of Environmental Toxicology and Chemistry North America 32nd Annual Meeting, Boston, MA.
- Kaldellis, J.K., Zafirakis, D., and Kondili, E. (2010). Energy pay-back period analysis of stand-alone photovoltaic systems. *Renew. Energy* 35, 1444–1454.
- Kammen, D., Nelson, J., Mileva A., and Johnston, J. (2011). An Assessment of the Environmental Impacts of Concentrator Photovoltaics and Modeling of Concentrator Photovoltaic Deployment Using the SWITCH Model (Berkeley, CA: Renewable and Appropriate Energy Laboratory, Energy and Resources Group, University of California at Berkeley). www.cpvconsortium.org/Portals/0/Berkeley_CPV_Environmental%20Report (accessed March 28, 2012).
- Kato, K., Murata, A., and Sakuta, K. (1997). An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon. *Solar Energy Mat. Solar Cells* 47, 95–100.
- Kaygusuz, K. (2009). Environmental impacts of the solar energy systems. *Energy Sources Part A: Recovery Util. Environ. Eff.* 31(15), 1376–1386.
- Krueger, L. (2011). Overview of First Solar’s Module Collection and Recycling Program, paper presented at the 2nd International Conference on PV Module Recycling, Madrid, Spain.
- Laleman, R., Albrecht, J., and Dewulf, J. (2011). Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. *Renew. Sustain. Energy Rev.* 15(1), 267–281.
- Leitner, A., Platts Research and Consulting, National Renewable Energy Laboratory (NREL). (2002). *Fuel from the Sky: Solar Power’s Potential for Western Energy Supply*, NREL/SR-550-32160 (Lakewood, CO: National Renewable Energy Laboratory).
- Liewellyn, T.O. (1994). Cadmium (Material flow), Bureau of Mines, Information Circular 9380.
- Marbek Resource Consultants Inc. (2009). *Model Sewer Use By Law Development Report* (Ottawa: Canadian Council of the Ministers of the Environment) www.ccme.ca/assets/pdf/pn_1424_mwwe_md1_bylaw_dvlpmt_rpt.pdf (accessed February 23, 2012).
- McCrary, M.D., McKernan, P.A.F., and Wagner, W.D. (1984). *Wildlife interactions at Solar One: final report* (Rosemead, CA: Southern California Edison).
- McDonald, N.C., and Pearce, J.M. (2010). Producer responsibility and recycling solar photovoltaic modules. *Energy Policy* 38, 741–747.
- McMonagle, R. (2006). *The Environmental Attributes of Solar PV in the Canadian Context* (Ottawa: Canadian Solar Industries Association).
- Meijer, A., Huijbregts, M.A.J., Schermer, J.J., and Reijnders, L. (2003). Life-cycle assessment of photovoltaic modules: comparison of mc-Si, InGaP and InGaP/mc-Si solar modules. *Prog. Photovolt.: Res. Appl.* 11(4), 275–287.

- Morgan, L.M., Shines, C.J., Jeter, S.P., Blazka, M.E., Elwell, P.E., Wilson, R.E., Ward, S.M., Price, H.C., and Moskowitz, P.D. (1997). Comparative pulmonary absorption, distribution, and toxicity of copper gallium diselenide, copper indium diselenide, and cadmium telluride in Sprague-Dawley rats. *Toxicol. Appl. Pharmacol.* 147, 399–410.
- Myrans, K. (2009). Comparative Energy and Carbon Assessment of Three Green Technologies for a Toronto Roof [MSc thesis] (Toronto: Graduate Department of Geography and Centre for Environment, University of Toronto).
- Natural Resources Canada. (2011). PV Potential and Insolation, <http://pv.nrcan.gc.ca/index.php> (accessed February 22, 2012).
- Niewlaar, E. and Alsema, E. (1997). Environmental Aspects of PV Power Systems, paper presented at the International Energy Association Photovoltaic Power Systems Program Task 1 Workshop, Utrecht, the Netherlands.
- Ontario Power Authority. (2011a). Feed-in tariff program, <http://fit.powerauthority.on.ca> (accessed September 6, 2011).
- Ontario Power Authority. (2011b). A Progress Report on Electricity Supply, Second Quarter 2011 (Toronto, ON: Ontario Power Authority).
- Ontario Power Authority (2012). Ontario's Feed-in Tariff Program: Two-Year Review Report, Appendix 4, www.energy.gov.on.ca/en/fit-and-microfit-program/2-year-fit-review/appendix-4 (accessed May 15, 2012).
- Pacca, S., Sivaraman, D., Keoleian, G.A. (2007). Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy* 35, 3316–3326.
- Pehnt, M. (2005). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renew. Energy* 31, 55–71.
- Peters, N. (2010). Promoting Solar Jobs (Princeton, NJ: Princeton University).
- Pollution Issues. (2011). Acid rain. www.pollutionissues.com/A-Bo/Acid-Rain.html (accessed October 12, 2011).
- Raugei, M., and Frankl, P. (2009). Life cycle impact and costs of photovoltaic systems: current state of the art and future outlooks. *Energy* 34, 392–399.
- Raugei, M., and Fthenakis, V. (2010). Cadmium flows and emissions from CdTe PV: future expectations. *Energy Policy* 38, 5223–5228.
- Raugei, M., Bargigli, S., and Ulgiati, S. (2007). Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. *Energy* 32(8), 1310–1318.
- Raugei, M., Isasa, M., and Fullana Palmer, P. (2012). Potential Cd Emissions from end-of-life CdTe. *Int. J. Life Cycle Assess.* 17, 192–198.
- Sander, K., Schilling, S., Reinschmidt, J., Wambach, K., Schlenker, S., Muller, A., Springer, J., Fouquet, D., Jelitte, A., Stryi-Hipp, G., Chrometzka, T. (2007). Study on the Development of a Takeback and Recovery System for Photovoltaic Products (Brussels, Belgium: PV Cycles).
- Schüler, D., Buchert, M., Liu, R., Dittrich, S., and Merz, C. (2011). Study on Rare Earths and Their Recycling (Freiburg, Germany: Oeko-Institute for Applied Ecology; The Greens/European Free Alliance in the European Parliament) www.oeko.de/oekodoc/1112/2011-003-en.pdf (accessed February 22, 2012).

- Sherwani, A.F., Usmani, J.A., and Varun. (2010). Life cycle assessment of solar based electricity generation systems: a review. *Renew. Sustain. Energy Rev.* 14, 540–544.
- Silicon Valley Toxics Coalition. (2009). Towards a Just and Sustainable Solar Energy Industry [white paper] (San Jose, CA: Silicon Valley Toxics Coalition)
http://svtc.org/wp-content/uploads/Silicon_Valley_Toxics_Coalition_-_Toward_a_Just_and_Sust.pdf (accessed February 22, 2012).
- Sinha, P., Balas, R., and Krueger, L. (2011). Fate and Transport Evaluation of Potential Leaching and Fire Risks from CdTe PV, paper presented at 37th IEEE Photovoltaic Specialist Conference, Seattle, WA.
- Sinha, P., Kriegner, C.J., Schew, W.A., Kaczmar, S.W., Traister, M., and Wilson, D.J. (2008). Regulatory policy governing cadmium telluride photovoltaics: a case study contrasting life cycle management with the precautionary principle. *Energy Policy* 36, 381–387.
- Statistics Canada. (2007). Industrial water Survey 2005.
<http://www23.statcan.gc.ca:81/imdb/p2SV.pl?Function=getSurvey&SurvId=29599&SurvVer=1&InstaId=29600&InstaVer=1&SDDS=5120&lang=en&db=imdb&adm=8&dis=2#b9> (accessed March 30, 2012)
- Statistics Canada. (2010). Monthly electricity, survey 2151.
www.statcan.gc.ca/cgi-bin/imdb/p2SV.pl?Function=getSurvey&SDDS=2151&lang=en&db=imdb&adm=8&dis=2 (accessed February 22, 2012).
- Sustainable Evaluation of Solar Energy Systems (SENSE). (2008). LCA Analysis, Revised Version 06 (Stuttgart, Germany: SENSE).
www.sense-eu.net/fileadmin/user_upload/intern/documents/Results_and_Downloads/SENSE_LCA_results.pdf (accessed February 22, 2012).
- Thevenard, D., and Pelland, S. (2011). Estimating the uncertainty in long-term photovoltaic yield predictions. *Solar Energy*.
<http://dx.doi.org/10.1016/j.solener.2011.05.006>
- Turney, D., and Fthenakis, V. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. *Renew. Sustain. Energy Rev.* 15, 3261–3270.
- US Environmental Protection Agency. (2010). Acid rain.
www.epa.gov/acidrain/reducing/index.html (accessed October 12, 2011).
- Wolden C., Kurtin J., Baxter J., Repins I., Shaheen S., Torvik J., Rockett A., Fthenakis V., and Aydil E. (2011). Photovoltaic manufacturing: present status, future prospects, and research needs. *J. Vacuum Sci. Technol. A* 29(3), 030801.
- Zayed, J., and Philippe, S. (2009). Acute oral and inhalation toxicities in rats with cadmium telluride. *Int. J. Toxicol.* 29(4), 259–265.
- Zweibel, K. (2010). The impact of tellurium supply on cadmium telluride photovoltaics. *Science* 328, 699–701.