IRRIGATION RETURN FLOW OR DISCRETE DISCHARGE? WHY WATER POLLUTION FROM CRANBERRY BOGS SHOULD FALL WITHIN THE CLEAN WATER ACT'S NPDES PROGRAM

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Despite license plates proclaiming it as the "dairy state," Wisconsin is the top cranberry producing state in the nation. Cranberry operations are unique in that they are agricultural operations that require vast quantities of water. Water discharged to lakes, wetlands, and rivers through ditches and canals during the production process can contain the phosphorus fertilizers and residues of pesticides that were applied during the growing season, which can cause serious water quality problems. Although the cranberry industry has not historically been subject to the Clean Water Act, cranberry bog discharges appear to fit squarely within the purview of the National Pollutant Discharge Elimination System (NPDES) program under that statute. In 2004, the Wisconsin attorney general filed a public nuisance lawsuit against a cranberry grower, alleging that the grower discharged bog water laced with phosphorus to the lake. However, provided that cranberry bog discharges do not fall within the "irrigation return flow" exemption from the Clean Water Act, the NPDES permit program may be a more cost-effective approach to addressing the water quality problems that can be caused by cranberry bog discharges.

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I. INTRODUCTION

Imagine a temporary detention pond that stores water laced with phosphorus fertilizers and pesticides. Now, imagine that pond discharging its polluted contents through a series of ditches, dikes, and channels to the nearest lake. Environmental practitioners might quickly assume that the Federal Water Pollution Control Act Amendments of 1972, (Clean Water Act or Act)[1] regulates that discharge. Indeed, in most instances the Clean Water Act would—unless the discharger is a "cranberry bog," part of a small industry that has historically not been subject to the extensive reach of the Act.

Despite license plates proclaiming it as the "dairy state," Wisconsin is not the leading milk producer in the United States. It is, however, the top cranberry producing state in the nation. Wisconsin—the "cranberry state"—more than doubles the cranberry production of the second largest producer, Massachusetts. In 2003, Wisconsin planned to produce more than 3 million barrels, or 300 million pounds, of the fruit,[2] more than one half of the almost 600 million pounds of cranberries consumed each year.[3] The remaining top

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[1] Federal Water Pollution Control Act, 33 U.S.C. §§ 1251–1387 (2000).

[2] AGRIC. STATISTICS BD., U.S. DEP'T OF AGRIC., CRANBERRIES (Aug. 19, 2003), *available at* http://usda.mannlib.cornell.edu/usda/nass/Cran//2000s/2003/Cran-08-19-2003.pdf.

[3] Wis. State Cranberry Growers Ass'n, http://www.wiscran.org (last visited Apr. 15, 2007).

cranberry-producing states like New Jersey, Oregon, and Washington, combined, would not surpass Wisconsin's production.[4] Today, there are 150 cranberry marshes in eighteen counties in Wisconsin covering 110,000 acres.[5]

Cranberry operations are unique in that they are agricultural operations that require vast quantities of water.[6] In fact, water is the single most important resource for growing cranberries.[7] With over 84,000 miles of streams, 1.2 million acres of lakes, and 5 million acres of remaining wetlands,[8] Wisconsin seems ideal for cranberry production.

Given the need for a large water supply, cranberry "bogs" are typically located on or near wetlands that are directly adjacent to lakes and rivers.[9] Production involves pumping water from adjacent wetlands or lakes, irrigating and flooding the below-grade cranberry beds for harvest and frost protection, and then discharging the water back to the lake or river from which it came through a series of ditches, dikes, and dams.[10] The discharged water contains the phosphorus fertilizers and residues of pesticides that were applied during the growing season.[11] The end result is relatively clean water coming into the bog, and relatively polluted water pouring out.[12]

The cranberry industry has not historically been subject to the reach of the Clean Water Act despite the fact that cranberry bog discharges appear to fit squarely within the purview of the National Pollutant Discharge Elimination System (NPDES) program under the Act.[13] Recently, the Wisconsin attorney general has attempted to abate polluted cranberry bog discharges through public nuisance litigation.[14] However, rather than apply the complicated common law of public nuisance, this Article explores how the Clean Water Act can, and should, apply to control pollutant discharges from cranberry bogs.

Part II of this Article describes the nature of cranberry production and the pollutants typically discharged in cranberry bog water to streams, wetlands, and lakes. Part III of this Article summarizes the recent public nuisance litigation in *State v. Zawistowski*,[15] where the Wisconsin attorney general joined with private landowners to abate pollutant discharges to a lake by a cranberry operation. Part IV summarizes the jurisdictional elements of the Clean Water Act's NPDES permit program. Part V of this Article analyzes

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[4] *Id.*

[5] Wis. State Cranberry Growers Ass'n, A History of Cranberry Growing, http://www.wiscran.org/history.htm (last visited Apr. 15, 2007).

[6] *See infra* Part II.

[7] CAPE COD CRANBERRY GROWERS' ASS'N, CRANBERRY WATER USE: AN INFORMATION FACT SHEET (2001), *available at* http://www.cranberries.org/pdf/wateruse.pdf.

[8] WATER DIV., WIS. DEP'T OF NATURAL RES., WIS. WATER QUALITY ASSESSMENT REPORT TO CONGRESS 2004, at 9 (2004), *available at* http://www.dnr.state.wi.us/org/water/wm/watersummary/305b_2004/download/wqreport_2004_part_I_II.pdf.

[9] CAPE COD CRANBERRY GROWERS' ASS'N, *supra* note 7.

[10] *See infra* Part II.

[11] *Id.*

[12] *Id.*

[13] 33 U.S.C. §§ 1311(a), 1342(a) (2000).

[14] *See infra* Part III.

[15] State v. Zawistowski, No. 04-CV-75 (Wis. Cir. Ct., Sawyer County, Wis. Apr. 5, 2006).

whether cranberry bog discharges fall within the purview of the Clean Water Act's mandatory NPDES permit program, despite the "irrigation return flow" exemption from that program in the Act. Part VI of this Article suggests that not only should the Clean Water Act regulate pollutant discharges from cranberry bogs, but that doing so is a more efficient allocation of scarce public resources than filing public nuisance cases. The Article concludes that the Clean Water Act's NPDES permit program was designed to address the types of discharges from cranberry bogs, and should be applied by the U.S. Environmental Protection Agency (EPA) and state environmental agencies to ensure that navigable waters are protected from this unique and potent source of water pollution.

II. POLLUTANT DISCHARGES FROM COMMERCIAL CRANBERRY PRODUCTION

A native species to North America, cranberries grow on vines naturally in bogs and marshes.[16] However, commercial cranberry production involves dramatic landscape alterations for the cultivation of artificial bogs or "cranberry beds." The land is cleared of vegetation, scalped, and leveled approximately two feet below the existing grade of the soil.[17] A layer of sand is laid to create an acidic surface optimum for vine growth, and sand is periodically added to maintain the beds.[18] The vines take root in the sand, forming a monoculture that takes three to five years to produce commercial quantities of fruit.[19] Water is added to irrigate, to flood the beds for frost protection, and for harvest.[20]

To the casual observer, cranberry production might seem environmentally benign. In fact, proponents of the cranberry industry frequently claim that cranberry bogs serve as valuable wetlands that provide

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[16] Frank L. Caruso et al., *Cranberries: The Most Intriguing American Fruit*, APSNET, Nov. 2000, *available at* http://www.apsnet.org/online/feature/cranberry/.

[17] N.S. DEP'T OF AGRIC. & FISHERIES, GROWING NOVA SCOTIA 22, *available at* http://www.gov.ns.ca/nsaf/agaware/teacher/06_cranb.pdf; Wis. State Cranberry Growers Ass'n, Cranberry Production in Wisconsin, http://www.wiscran.org/production.htm (last visited Apr. 14, 2007).

[18] Wis. State Cranberry Growers Ass'n, *supra* note 17.

[19] *Id.*; N.S. DEP'T OF AGRIC. & FISHERIES, *supra* note 17.

[20] KEN SCHREIBER, WIS. DEP'T OF NATURAL RES., THE IMPACTS OF COMMERCIAL CRANBERRY PRODUCTION ON WATER RESOURCES 5 (Mar. 1988) (on file with authors); *see also* Wis. State Cranberry Growers Ass'n, *supra* note 17 (explaining that water is used for irrigation, frost protection, and harvest); Oregon Cranberry Network, Growing Cranberries, http://www.oregoncranberry.net/growing_cranberry.htm (last visited Apr. 15, 2007) (explaining that sprinkling is used to protect against frost and that ample water is necessary for irrigation and harvesting); The Cranberry Institute, Frequently Asked Questions, http://www.cranberryinstitute.org/cranfacts/faq.htm (last visited Apr. 15, 2007) (explaining that cranberries do not grow in water, but that water is used to make harvesting easier and to protect from freezing); Decas Cranberry Products Inc., Frequently Asked Questions, http://www.decascranberry.com/faqs.htm (last visited Apr. 15, 2007) (explaining that cranberries are usually grown in bogs surrounded by water to aid in irrigation, flooding, and harvesting); N.S. DEP'T OF AGRIC. & FISHERIES, *supra* note 17 (explaining that water is used for irrigation and flooding).

ecological functions for habitat and wildlife.[21] Cranberry production involves creation of artificial wetlands[22] during a time when wetlands are disappearing rapidly across the United States.[23] But the intensive application of pesticides, herbicides, fungicides, and fertilizers attendant to industrial cranberry production tells a different story.

Fertilizer application plays a critical role in cranberry production.[24] The acidic soils in which cranberry vines take hold are naturally low in phosphorus, so cranberry growers must add phosphorus to increase crop productivity.[25] Cranberries typically require no more than twenty pounds of actual phosphorus per acre,[26] yet one study indicated that Wisconsin cranberry growers may be over applying phosphorus on their cranberry beds.[27] Over application of this plant nutrient can result in more soluble phosphorus being discharged to the nearest surface water during the seasonal discharges from the bogs, associated with either the spring planting or fall harvest, after the phosphorus fertilizer has been applied to the bog.[28]

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[21] *See* Wis. State Cranberry Growers Ass'n, Wetlands & Cranberry Growing: Environmental Partners, http://www.wiscran.org/crangrow.htm (last visited Apr. 15, 2007) (asserting that cranberry wetlands provide important wetlands for plants and wildlife and mentioning a study finding that "there is a high probability that these commercial cranberry wetlands systems can also perform many of the functions commonly attributed to wetlands"); *see also* Wis. State Cranberry Growers Ass'n, Cranberry Wetlands, http://www.wiscran.org/wetlands.htm (last visited Apr. 15, 2007) (asserting that cranberry wetlands provide stable environments that support "almost every species of wildlife in the state [of Wisconsin]" and stating that many cranberry growers recognize the importance of wildlife and encourage wildlife habitation). However, the U.S. Army Corps of Engineers has determined that although cranberry bogs can be similar to wetlands, "[m]ost of the functions/values of natural wetlands are lost or substantially reduced by conversion to cranberry beds." ST. PAUL DISTRICT, U.S. ARMY CORPS OF ENG'RS, ST. PAUL DISTRICT ANALYSIS REGARDING SECTION 404 REVIEW OF COMMERCIAL CRANBERRY OPERATIONS 29 (Sept. 1995) [hereinafter ST. PAUL DISTRICT ANALYSIS] (on file with authors).

[22] Wis. State Cranberry Growers Ass'n, Wetlands and Cranberry Growing: Environmental Partners, http://www.wiscran.org/crangrow.htm (last visited Apr. 15, 2007).

[23] *See* Press Release, Ass'n of State Wetland Managers, Ponds Proliferate, but Wetland Losses Continue (Mar. 30, 2006), *available at* http://www.aswm.org/fwp/pressrelease2006.htm (reporting that, while the rate of wetland loss declined somewhat between 1998 and 2004, the quality and type of the new wetlands created in the United States has been inadequate to provide the needed natural wetland functions for habitat and wildlife). *But see* T.E. DAHL, U.S. FISH & WILDLIFE SERV., STATUS AND TRENDS OF WETLANDS IN THE CONTERMINOUS UNITED STATES 1998 TO 2004, at 15 (2006), *available at* http://wetlandsfws.er.usgs.gov/status_trends/National_ Reports /trends_2005_report.pdf (indicating that wetland loss had declined between 1998 and 2004, with an overall net gain of almost 200,000 wetland acres during that time period).

[24] TERYL ROPER ET AL., PHOSPHORUS FOR BEARING CRANBERRIES IN NORTH AMERICA 2 (2004), *available at* http://www.hort.wisc.edu/cran/mgt_articles/articles_nutr_mgt/Phoshorus%20 Publication%20.pdf.

[25] *Id.* at 5.

[26] *Id.* at 8.

[27] *See* TERYL R. ROPER, HOW MUCH PHOSPHORUS IS REALLY NEEDED? (2005), *available at* http://www.hort.wisc.edu/cran/pubs_archive/proceedings/2005/HowMuchP.pdf (suggesting that Wisconsin cranberry growers may be applying more phosphorus than what is needed to maintain crop fertility).

[28] ROPER ET AL., *supra* note 24, at 7; FAITH A. FITZPATRICK ET AL., U.S. GEOLOGICAL SURVEY, REPORT 02-4225, NUTRIENT, TRACE-ELEMENT, AND ECOLOGICAL HISTORY OF MUSKY BAY, LAC COURTE OREILLES, WISCONSIN AS INFERRED FROM SEDIMENT CORES, WATER-RESOURCES

Several studies of northern Wisconsin lakes located downstream from areas of intense cranberry production showed increased levels of nutrients, particularly phosphorus, which contribute to harmful aquatic plant growth such as algae and weeds.[29] One study showed that phosphorus releases from a cranberry bog exceeded that of a nearby residential housing development.[30] Another found that phosphorus loading from cranberry bog water returned to a surface water comprised more than seventy-five percent of the total phosphorus load to the lakes, based on computer modeling.[31]

Pesticide discharges from cranberry bogs—or bog-water laced with pesticides—also pose a well-documented water pollution problem. There are approximately twenty-two pesticides commonly used on cranberries, including napropromide, norflurazon, dichlovenil, 2, 4-D, carbaryl, diazinon, chlorpyrifos, and azinphos-methyl.[32] One study in Wisconsin found that pesticide concentrations in surface water downstream from cranberry marsh discharges were sufficient to cause total mortality of two species of test organisms.[33] Another study in Washington, also a leading cranberry producer, detected three toxic organophosphorus insecticides, one of which includes the dangerous chemical diazinon, at lethal concentrations for aquatic invertebrates, exceeding that state's water quality criteria for aquatic life.[34] Yet another study in northern Wisconsin found elevated concentrations of lead, arsenic, cadmium, selenium, and other toxic metals in cranberry bog discharges.[35]

INVESTIGATIONS 9 (2003) (citing Brian L. Howes & John M. Teal, *Nutrient Balance of a Massachusetts Cranberry Bog and Relationships to Coastal Eutrophication*, 29 ENVTL. SCI. & TECH. 960, 960–74 (1995)) (noting that a Massachusetts cranberry bog's releases of nitrogen and phosphorus coincided with flooding of the bog for harvest and frost protection) (on file with authors); SCHREIBER, *supra* note 20, at 11.

[29] MARJORIE WINKLER & PATRICIA SANFORD, FINAL REPORT: ENVIRONMENTAL CHANGES IN THE LAST CENTURY IN LITTLE TROUT LAKE, INKSPOT BAY, GREAT CORN AND LITTLE CORN LAKES, LAC DU FLAMBEAU TRIBAL LANDS, WISCONSIN 10 (2000) (on file with authors); FITZPATRICK ET AL., *supra* note 28, at 9; JIM SENTZ ET AL., U.S. ARMY CORP. OF ENG'RS, GREAT CORN AND LITTLE CORN LAKES, SECTION 22—WATER QUALITY STUDY 1 (2000); ROPER ET AL., *supra* note 24, at 7.

[30] FITZPATRICK ET AL., *supra* note 28, at 9.

[31] SENTZ ET AL., *supra* note 29, at 1; *see also* ST. PAUL DISTRICT ANALYSIS, *supra* note 21, at 15 (noting a Lac du Flambeau Tribal Natural Resources Department study finding that "[i]n some cases, cranberry marsh discharges were found to contain total phosphorus concentrations ten times higher than that of ambient lake concentrations").

[32] FITZPATRICK ET AL., *supra* note 28, at 9.

[33] KEN SCHREIBER, WIS. DEP'T OF NATURAL RES, BIOMONITORING BELOW TWO COMMERCIAL CRANBERRY MARSHES IN JACKSON COUNTY, WISCONSIN 7 (Dec. 1993) (on file with authors). *But see* ST. PAUL DISTRICT ANALYSIS, *supra* note 21, at 15 (noting the limited sampling of the 1993 Schreiber study).

[34] DALE DAVIS ET AL., WASH. DEP'T OF ECOLOGY, ASSESSMENT OF CRANBERRY BOG DRAINAGE PESTICIDE CONTAMINATION: RESULTS FROM CHEMICAL ANALYSES OF SURFACE WATER, TISSUE, AND SEDIMENT SAMPLES COLLECTED IN 1996, at iii, 1 (July 1997), *available at* http://www.ecy.wa.gov/pubs/97329.pdf; *see also* PAUL ANDERSON & DALE DAVIS, WASH. DEP'T OF ECOLOGY, EVALUATION OF EFFORTS TO REDUCE PESTICIDE CONTAMINATION IN CRANBERRY BOG DRAINAGE (Sept. 2000), a*vailable at* http://www.ecy.wa.gov/pubs/0003041.pdf (finding no reduction in chlorpyrifos, diazinon, or azinphos-methyl in cranberry bog discharges even after application of best management practices).

[35] WINKLER & SANFORD, *supra* note 29, at 3–4, 9. The elevated lead and arsenic

In short, the point source discharge of phosphorus and pesticides from cranberry bogs is well-documented, as is the water quality impact of those discharges. Due to their heavy use of water for production and the use of pesticides and fertilizers, the residue of those pesticides and fertilizers can be washed away through the canals and bulkheads by successive flooding and drainage of the cranberry bogs.[36] In this way, pollutant discharges from cranberry bogs are more direct and discrete than typical agricultural runoff.[37]

III. *STATE V. ZAWISTOWSKI* AND THE ATTEMPT TO USE PUBLIC NUISANCE AUTHORITY TO CONTROL POLLUTANT DISCHARGES FROM CRANBERRY BOGS

Concerned with alleged discharges of phosphorus pollution from a cranberry bog in northern Wisconsin, in 2004, the Wisconsin attorney general joined with a group of private property owners on Musky Bay of Lac Courtes Oreilles Lake[38] to file a lawsuit against a cranberry grower named William Zawistowski.[39] Zawistowski owns cranberry marshes that withdraw water and discharge cranberry bog effluent into Musky Bay.[40] The attorney general and the property owners alleged that Mr. Zawistowski created a public and private nuisance by applying phosphorus-containing fertilizers and pesticides to his cranberry beds and then discharging the phosphorus-containing residues back to Musky Bay.[41] They alleged that phosphorus discharges over the decades had "fed the growth of dense, choking aquatic plants and a thick, slimy, smelly green algal mat" on Musky Bay during the summer months, and that the floating mat of algae was a public nuisance under Wisconsin common law that interfered with public rights in navigable waters.[42] The State of Wisconsin and the private property owners on Musky Bay asked that Mr. Zawistowski be required to stop his discharges of phosphorus into Musky Bay, and significantly, be ordered to dredge the phosphorus-laden sediment out of the bay, and pay damages and costs.[43]

Since at least 1939, the Zawistowski cranberry operation has included two bogs, known as the "east" and "west" marshes, located on the southern shore of Musky Bay.[44] These marshes have independent pumping systems and man-made ditches that extract water from Musky Bay to flood the

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concentrations are likely from the application of lead-arsenate as a pesticide on cranberry beds.

[36] SCHREIBER, *supra* note 20, at 5, 7; SCHREIBER, *supra* note 33, at 1.

[37] SCHREIBER, *supra* note 20, at 5.

[38] Lac Courtes Lake is the eighth largest lake in Wisconsin, and the largest lake in Sawyer County, Wisconsin. *See* State v. Zawistowski, No. 04-CV-75, at 3 (Wis. Cir. Ct., Sawyer County, Wis. Apr. 5, 2006).

[39] Complaint at 2, State v. Zawistowski, No. 04-CV-75 (Wis. Cir. Ct., Sawyer County, Wis. June 8, 2004).

[40] *Zawistowski*, No. 04-CV-75, at 3.

[41] Complaint at 4, *Zawistowski*, No. 04-CV-75 (Wis. Cir. Ct., Sawyer County, Wis. June 8, 2004),

[42] *Id.*

[43] *Id.* at 5.

[44] *Zawistowski*, No. 04-CV-75, at 3.

cranberry beds and that drain the marsh and return the water to Musky Bay from each cranberry marsh.[45] Each ditch is connected to Musky Bay to service the water needs of the cranberry operation, making the marshes "open" systems that depend upon Musky Bay for water.[46] Zawistowski applies various fertilizers containing phosphorus to the bog.[47]

The trial court in *State v. Zawistowski* found that "a direct result of the method Zawistowski uses to retrieve and discharge water to and from Musky Bay causes substantial amounts of nutrients, including phosphorus, to be discharged directly into Musky Bay" and this is "the primary source of phosphorus entering Musky Bay."[48] The court further found that the discharge occurs through the man-made canal and ditch system[49] and contributes about 40–50% of the phosphorus entering Musky Bay.[50] Moreover, the court found that Zawistowski knew, or at least he should have known, that he was discharging phosphorus into the bay.[51]

The trial record in *Zawistowski* indicates that Musky Bay has been suffering from the effects of frequent phosphorus-laden bog discharges from Zawistowski's cranberry operation.[52] Musky Bay is becoming more "eutrophic" over time, meaning that nutrients like phosphorus-containing fertilizers are causing Musky Bay to experience severe algae blooms that cover the surface of the bay.[53] By 2005, fish populations in Musky Bay had dropped as a result, in part, of an increase in aquatic weeds and vegetation that are depleting the dissolved oxygen levels near the lake bed where fish spawn, thereby increasing fish mortality.[54]

Significantly, the trial court found that Zawistowski's discharge of phosphorus-containing bog water was contributing to the growth of algal plants and weeds in Musky Bay, and that algal mats on the surface prevented the public from swimming or using water craft like motorboats, canoes, and kayaks in certain areas of Musky Bay during the summer months.[55] However, the court found that Zawistowski's activities were not causing Musky Bay to be entirely unusable, particularly not during the spring, fall, and winter.[56] While Zawistowski's discharge was causing some interference with the public's use and enjoyment of Musky Bay, it could not determine after trial how many days out of the year the public was prevented from using Musky Bay or what portions of Musky Bay were rendered completely

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[45] *Id.*

[46] *Id.* at 3–4.

[47] *Id.* at 4. Some of the fertilizer was periodically applied by airplanes, but that practice has been discontinued. According to the court's findings of fact after trial, Zawistowski uses less phosphorus fertilizers than recommended by experts in cranberry farming. *Id.*

[48] *Id.* at 10–11.

[49] *Id.*

[50] *Id.* at 12–13.

[51] *Id.* at 14.

[52] *Id.* at 9–11.

[53] *Id.*

[54] *Id.* at 6.

[55] *Id.* at 14–16.

[56] *Id.* at 15–16.

unusable to the public.[57] The court concluded that it could not find that Zawistowski's discharges of phosphorus-containing bog water to Musky Bay constituted a public nuisance.[58] The Wisconsin attorney general has appealed the trial court's decision.[59]

The trial court stated that it was not aware of, nor had it been shown "any water quality standard established by the Wisconsin legislature, or any rulemaking body within this state, which regulates the discharge of water" from cranberry operations.[60] Apparently, neither the U.S. EPA, nor Wisconsin Department of Natural Resources, has proposed applying the Clean Water Act's core pollution program for point source discharges—the NPDES program[61]—to the discrete discharges of pollutants from cranberry bogs. However, the NPDES program appears to be perfect for controlling documented pollutant discharges that can occur from cranberry bogs.

IV. OVERVIEW OF THE CLEAN WATER ACT

The Clean Water Act created a comprehensive scheme to restore and maintain the quality of the nation's waters, relying primarily on a system that prohibits the discharge of pollutants to waters of the United States except in compliance with an NPDES permit issued by EPA or a state.[62] Section 301 of the Clean Water Act prohibits any person from discharging any pollutant without a permit issued by the state or EPA under Section 402 of the Act.[63] The Act defines "discharge of a pollutant" to mean "any addition of any pollutant to navigable waters from any point source."[64] The Act further defines "point source" to include "any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, [or] discrete fissure . . . from which pollutants are or may be discharged."[65]

Significantly, the Clean Water Act excludes from the definition of point source "agricultural stormwater discharges and return flows from irrigated agriculture."[66] The latter exclusion is known as the "irrigation return flow exemption" and its legislative and regulatory history is both tortured and limited.[67] Perhaps because of its lack of clarity, the irrigation return flow

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[57] *Id.*

[58] *Id.* at 25–26.

[59] Notice of Appeal, State v. Zawistowski, App. No. 2006AP001439 (Wis. Ct. App. June 22, 2006).

[60] *Zawistowski*, No. 04-CV-75, at 4.

[61] 33 U.S.C. § 1342(a) (2000).

[62] *Id.* §§ 1251(a), 1342(a); Theodore L. Garrett, *Overview of the Clean Water Act*, *in* THE CLEAN WATER ACT HANDBOOK 1, 1 (Mark A. Ryan ed., 2d ed. 2003).

[63] 33 U.S.C. §§ 1311(a), 1342(a) (2000).

[64] *Id.* § 1362(12).

[65] *Id.* § 1362(14).

[66] *Id.* § 1342(l) (exempting agricultural stormwater and irrigation return flows from the purview of the NPDES permit program).

[67] *Id.* In addition, and somewhat unhelpfully, the Clean Water Act defines "navigable waters" as "waters of the United States" and offers nothing else in the way of statutory guidance. 33 U.S.C. § 1362(7) (2000). However, the U.S. EPA and Army Corps of Engineers have

exemption has stood as a formidable obstacle to controlling point sources of pollution on agricultural lands.

V. CRANBERRY BOGS, THE NPDES PERMIT PROGRAM, AND THE IRRIGATION RETURN FLOW EXEMPTION

Despite the direct discharges from many cranberry beds, neither EPA nor the five largest cranberry producing states has required the bogs to obtain NPDES permits. The Wisconsin Department of Natural Resources (DNR) has raised the possibility of regulating cranberry bogs through discharge permits in Wisconsin, but only for documented water pollutant discharges that are creating a demonstrably negative water quality impact.[68] To date, DNR has never followed through with this proposal, and no cranberry bogs in Wisconsin have been required to obtain a NPDES permit.[69]

The first question when determining whether Clean Water Act jurisdiction over cranberry bog discharges should attach is whether those bogs discharge pollutants from a point source.[70] There are several features of the cranberry production that appear to involve point sources. For example, the ditches and bulkheads surrounding the bogs are identifiable point sources, as are the pesticide and fertilizer application equipment.[71] The next question is whether Congress and EPA excluded cranberry bogs from the NPDES permit program through the "irrigation return flow" exemption.[72] If cranberry bog discharges either 1) do not fit within the broad "point source" definition, or 2) are excluded as irrigation return flow, they are not covered by the Act.[73]

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stepped in to fill the void, defining navigable waters to include "all waters which are currently used . . . in interstate . . . commerce," "tributaries of [covered] waters," and "wetlands adjacent to [covered] waters [including tributaries]," among others. 33 C.F.R. § 328.3(a)(1), (5), (7) (2006). Only those intermittent and ephemeral waters that share a "significant nexus" to interstate waters fall within the definition of "navigable waters" and, therefore, the jurisdiction of the Clean Water Act. Rapanos v. United States, 126 S.Ct. 2208, 2236 (2006) (Kennedy, J., concurring).

[68] SCHREIBER, *supra* note 20, at 21. These permits are known as WPDES permits in Wisconsin. *See* WIS. STAT. ch. 283 (2006).

[69] For a list of the 412 industrial dischargers operating under individual WPDES permits in Wisconsin, see Wis. Dep't of Natural Res., Current WPDES Wastewater Permit Holders, http://dnr.wi.gov/org/water/wm/ww/indus.xls (last visited Apr. 14, 2007).

[70] 33 U.S.C. § 1362(6) (2000).

[71] *See infra* Part V.A.

[72] *See infra* Part V.B.

[73] The Ninth Circuit in League of Wilderness Defenders v. Forsgren, 309 F.3d 1181 (9th Cir. 2002), reaffirmed that although EPA has reasonable discretion to interpret the term "point source," it does not have the discretion to exempt classes of activities where those activities meet the parameters of the statutory definition. *Id.* at 1190; *see also* Natural Resources Defense Council v. Costle, 568 F.2d 1369, 1377 (D.C. Cir. 1977) (same). As a result, it is doubtful that EPA or states have the authority to specifically exclude cranberry operations, categorically, from the definition of point source.

A. Ditches and Bulkheads As Point Sources

There can be little doubt that many features of a typical cranberry bed, including the bulkhead, dams, and ditches through which pollutants are discharged at the end of the harvest season (and seasonally throughout the year), could at least theoretically fall within the definition of "point source." In fact, the plain language definition of "point source" specifically includes "ditches," and "discrete conveyances"[74] that are common at cranberry bogs. And, precedent has established that gullies, rills, check dams, sediment traps, and other natural or manmade conveyances or systems designed to catch runoff can also be point sources under the Clean Water Act.[75] After all, it is well established that Congress intended the "broadest possible definition" of the term point source.[76]

However, relatively few cases, if any, have characterized agricultural operations as point sources subject to the NPDES permit program.[77] Courts have been more inclined to find that discharges of pollutants from agricultural operations fall within the nonpoint source category, specifically, the irrigation return flow exemption from the NPDES permit program.[78]

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[74] 33 U.S.C. § 1362(14) (2000).

[75] *See, e.g.*, N.C. Shellfish Growers' Ass'n v. Holly Ridge Assocs., 278 F. Supp. 2d 654, 679–80 (E.D.N.C. 2003) (check dams, sediment traps, gullies and rills as part of a home development site on a wetland are point sources); Froebel v. Meyer, 217 F.3d 928, 938–39 (7th Cir. 2000) (recognizing that a partially destroyed dam can be a point source); Comm. to Save Mokelumne River v. E. Bay Mun. Util. Dist., 13 F.3d 305, 308 & n.1 (9th Cir. 1993) (dam that discharged mine tailings in pond-water to clean water downstream was a point source); Catskill Mountains Chapter of Trout Unlimited v. City of N.Y., 273 F.3d 481, 493 (2d Cir. 2001) (tunnel was a point source that transferred water from one basin to another); Sierra Club v. Abston Constr. Co., 620 F.2d 41, 45 (5th Cir. 1980) (manmade sediment basin was a point source); United States v. Earth Scis, Inc., 599 F.2d 368, 374 (10th Cir. 1979) (mining operation's sump pit was a point source).

[76] *See, e.g.*, *Earth Sciences*, 599 F.2d at 373 (concluding that the broadest possible definition of point source must be adopted in order to further the congressional intent to regulate pollution emitting sources to the fullest extent possible); United States v. W. Indies Transp. Inc., 127 F.3d 299, 309 (3d Cir. 1993); Dague v. City of Burlington, 935 F.2d 1343, 1354–55 (2d Cir. 1991).

[77] This assertion excludes concentrated animal feeding operations, which are specifically included within the definition of point source. 33 U.S.C. § 1362(14) (2000); *see also* 40 C.F.R. § 122.23 (2006).

[78] Fishermen Against the Destruction of the Env't v. Closter Farms, Inc., 300 F.3d 1294, 1297 (11th Cir. 2002) (sugarcane farm that discharged pollutants through irrigation ditches constituted irrigation return flow); Hiebenthal v. Meduri Farms, 242 F. Supp. 2d 885, 888 (D. Or. 2002) (commercial fruit operator that over-applied wastewater to fields, causing runoff, exempt from the NPDES permit program because runoff fell within irrigation return flow exemption). Courts appear to have used the irrigation return flow exemption and the agricultural stormwater exemption interchangeably, despite their different definitions. In fact, agricultural stormwater is specifically limited to discharges comprised entirely of stormwater, and does not include other pollutants not typically included in the stormwater runoff. 40 C.F.R. § 122.23(e) (2006). Despite this, for purposes of this Article, we treat as relevant to the irrigation return flow exemption all cases that address both of the exemptions, as the rationale and policy of exempting those types of nonpoint sources from the NPDES program are the same.

At least one court has identified a non-concentrated animal feeding operations (CAFOs) agricultural operation as a point source. In *United States v. Oxford Royal Mushroom*, 487 F. Supp. 852 (E.D. Pa. 1980), the defendant mushroom farm discharged wastewater onto fields via

Other than showing a proclivity to find the irrigation return flow exemption applies in a given a case, these decisions fail to offer a discernible rule for defining the extent of the exemption.

B. The "Irrigation Return Flow" Exemption from the Definition of Point Source

The irrigation return flow exemption[79] is a largely undefined area of law, but one for which clarification should be demanded by both water quality advocates and agribusiness. As it stands, operators and regulators have little guidance for defining whether and when the Clean Water Act's NPDES permit program applies to cranberry operations. Although cranberry beds are not specifically defined as point sources, they are not specifically excluded from the Clean Water Act as point sources either, indicating that their coverage under the Clean Water Act is an open question.[80] However, a review of the legislative and regulatory history of, as well as case law on, the irrigation return flow exemption indicates that cranberry bogs fall within the definition of point source, and are not exempt from the NPDES permit program.

1. Legislative and Regulatory History of the Irrigation Return Flow Exemption

The irrigation return flow exemption was first included in the Federal Water Pollution Control Act Amendments of 1977.[81] Before that time, in

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a spray irrigation system that was designed to spray only enough water to be absorbed into the fields as irrigation. *Id.* at 854. The defendant argued that the agricultural runoff was not a point source. *Id.* The court held simply that the discharge of pollutants from the over-application of waste to land application areas could fall within the definition of point source. *Id.* Although not addressing the irrigation return flow exemption, *Oxford Royal Mushroom*'s holding indicates that the irrigation return flow exemption (and later, the agricultural stormwater exemption created in the 1987 Clean Water Act Amendments) does not apply to wastewater applied and discharged from land application areas where the irrigation water greatly exceeds the absorption capacity of the soil.

The same court later indicated that for the agricultural stormwater exemption or the irrigation return flow exemption to apply, the discharger must actually be engaged in agriculture. For example, in *Reynolds v. Rick's Mushroom Serv., Inc.*, 246 F. Supp. 2d 449, 456–57 (E.D. Pa. 2003), the Eastern District of Pennsylvania held that the waste pits, spray irrigation equipment, and landspreading fields as part of mushroom composting operation could all be characterized as a point source. *Id.* However, the court refused to apply the irrigation return flow exemption or the agricultural stormwater exemption to the mushroom composting operation because it was not engaged in the actual growing of mushrooms, only their composting. *Id.* at 257 n.4. The court asserted that this was more akin to a manufacturing process than an agricultural operation. *Id.*

[79] 33 U.S.C. § 1342 (l)(1) (2000) ("The Administrator shall not require a permit under this section for discharges composed entirely of return flows from irrigated agriculture, nor shall the Administrator directly or indirectly, require any State to require such a permit.").

[80] *See Reynolds*, 246 F. Supp. 2d at 457 (discussing other examples of sources that have not specifically been classified as point sources, but which *could* be, namely waste pits, spray irrigation equipment, and landspreading fields).

[81] 123 CONG. REC. 21, 26,778 (1977).

1975, EPA issued regulations that exempted irrigation return flows from the NPDES permit program. Those regulations were struck down by the District Court for the District of Columbia in *Natural Resources Defense Council, Inc. v. Train*[82] on the basis that EPA lacked the statutory authority to create an exemption from the definition of point source where none existed in the Clean Water Act.[83] After finding the exemption invalid, the court ordered EPA to promulgate regulations applying the NPDES permit program to point source discharges from agriculture by June 10, 1976.[84] Despite its pending appeal of the court's decision, EPA complied with the court's order.[85]

On July 12, 1976, EPA amended the permit exemption for irrigation return flows and required a permit for "agricultural point sources."[86] EPA defined an "agricultural point source" as "any discernible, confined and discrete conveyance from which any irrigation return flow is discharged into navigable waters."[87] "Irrigation return flow" was defined as "surface water, other than navigable waters, containing pollutants which result from the controlled application of water by any person to land used primarily for crops, forage growth, or nursery operations."[88] Most significantly, the definition of "irrigation return flow" included the following note: "Comment: This term includes water used for *cranberry harvesting*, rice crops, and other such controlled application of water to land for purposes of farm management."[89] In short, EPA attempted to apply the NPDES permit requirement to point sources that had irrigation return flows, including heavily water dependent or "wet" crops such as rice and cranberry production.

However, shortly after its promulgation, Congress obliterated EPA's rule promulgation by creating the irrigation return flow exemption in sections 502(14) and 402(l) of the 1977 Clean Water Act Amendments.[90] Significantly, Congress never defined an "irrigation return flow" and the congressional record is devoid of any references to EPA's "cranberry comment" in its 1976 rulemaking. Instead, a Senate Report on the 1977 Clean Water Act Amendments creating the irrigation return flow exemption reflects a tangential affirmation of EPA's definition of irrigation

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[82] 396 F. Supp. 1393 (D.D.C. 1975), *aff'd sub nom.* Natural Res. Def. Council v. Costle, 568 F.2d 1369 (D.C. Cir. 1977).

[83] *Id.* at 1398.

[84] *See* Agricultural Activities, National Pollutant Discharge Elimination System, 41 Fed. Reg. 7963, 7963 (Feb. 23, 1976) ("Although EPA is proceeding with the appeal of this decision, the Agency is still required to comply with the court order. Thus under the terms of the order . . . regulations applying the NPDES permit program to point source discharges in the agriculture and silviculture categories are required to be proposed by February 10, 1976 and promulgated by June 10, 1976.").

[85] *Id.*

[86] 40 C.F.R. § 125.4(i)(3) (2006); *see* 41 Fed. Reg. 28,493–28,496 (July 12, 1976).

[87] 40 C.F.R. § 125.53(a)(1) (2006).

[88] *Id.* § 125.53(a)(2).

[89] *Id.* (emphasis added).

[90] Federal Water Pollution Control Act, Pub. L. No. 95-217, 91 Stat. 1566, 1577 (1977) (codified at 33 U.S.C. §§ 1362(14), 1342(*l*)(1) (2000)).

return flows as "conveyances carrying surface irrigation return as a result of the *controlled* application of water by any person to land used primarily for crops."[91]

The Senate Report's definition is an obvious paraphrasing of EPA's definition of "irrigation return flow" exemption promulgated by EPA in 1976. But, the report noticeably omits the "cranberry comment." Based on this omission alone, one could easily argue that if Congress intended to exempt irrigation return flows, and EPA at one point considered cranberry harvesting to be an example of an irrigation return flow, then Congress's silence could be inferred to exempt cranberry bog discharges from the NPDES permit program.

However, if Congress intended to include cranberry bogs in the definition of irrigation return flow, Congress could have easily said as much in the statute or the legislative history. It did not. Instead, Congress's rationale for exempting irrigation return flows from the definition of point source instead had several other premises. The most significant of those was the need to protect western farmers on arid lands from unfair and burdensome regulation. Specifically, farmers claimed that requiring NPDES permits discriminated against western farmers on arid lands who relied much more heavily on irrigation ditches and drain tiles for storage and return of irrigated water.[92] Irrigation is the only means of sustaining those western farmers.[93] By classifying irrigation return flows as point sources and non-irrigated agricultural runoff as a nonpoint source, the farmers said, the 1972 Clean Water Act unfairly discriminated against western farmers who, by nature of the land and their farming operations, had to irrigate their lands and were predisposed to discharge pollutants when returning irrigated water to drainage ditches and points downstream.[94] Moreover, the water was needed for other downstream farmers.[95] Application of the NPDES permit requirement imposed an incentive for a farmer to prevent the water discharge and consequently withhold the water from those other downstream farmers who needed it.[96] Also, for good measure, western farmers invoked federalism policies and argued that water pollution

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[91] S. REP. NO. 95-370, at 35 (1977), *as reprinted in* 1977 U.S.C.C.A.N. 4326, 4360 (emphasis added).

[92] 123 CONG. REC. S21, 26,702, 26,762 (Aug. 4, 1977).

[93] *Federal Water Pollution Control Act Amendments of 1977: Field Hearing Before the Subcomm. on Envtl. Pollution of the Comm. on Env't and Public Works*, 95th Cong. 83 (1977) (statement of Jack D. Palma, III, Asst. Attorney General of Wyoming).

[94] *Id.*; *see also* Memorandum from EPA General Counsel Robert E. Fabricant, EPA Assistant Administrator for Water G. Tracy Mehan, III, and EPA Assistant Administrator for Prevention, Pesticides, and Toxic Substances to Regional Administrators, Interpretative Statement and Regional Guidance on the Clean Water Act's Exemption for Return Flows from Irrigated Agriculture 3 n.2 (Mar. 29, 2002), *available at* http://www.epa.gov/npdes/pubs/talentfinal.pdf ("In 1977, Congress thought that 'Farmers in areas of the country which were blessed with adequate rainfall were not subject to permit requirements on their rainwater run-off, which in effect had been used for the same purpose and contained the same pollutants [as water used by western farmers].'" (quoting 3 LEGISLATIVE HISTORY OF THE CLEAN WATER ACT 527 (1978)).

[95] *Federal Water Pollution Control Act Amendments of 1977*, *supra* note 93.

[96] *Id.*

abatement programs need to be based on local conditions, rather than a national program for point sources.[97]

Based mainly on these concerns, Congress amended the Clean Water Act in 1977 to exempt "irrigated agriculture, [originally] defined under the act as a point source, from the 402 permit program."[98] Recognizing that irrigation return flows nonetheless represented a significant water pollution problem, Congress hoped that the locally-based wastewater treatment management planning program in section 208 of the Clean Water Act would be used to address pollution from irrigation return flows and other agriculturally related nonpoint source pollution.[99] As a result, section 208(f) of the Clean Water Act was specifically written to include consideration of irrigation return flows as a nonpoint source of water pollution.[100]

In summary, the legislative history of the irrigation return exemption reflects that Congress created the exemption to accommodate the geography and uniquely arid climate of the western United States, not heavily water-dependent crops like cranberry bogs.[101] In fact, the legislative

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[97] 123 CONG. REC. S21, 26,702, 26,762, & 26,774 (daily ed. Aug. 4, 1977); *see also* S. REP. NO. 95-370, at 35, *as reprinted in* 1977 U.S.C.C.A.N. 4326, 4360 (indicating that the purpose of the irrigation return flow exemption was to "exempt irrigation return flows from all permit requirements under section 402 of the [Clean Water Act], and assure that areawide waste treatment management plans under section 208 include consideration of irrigated agriculture").

[98] 123 CONG. REC. S21, 26,697 (daily ed. Aug. 4, 1977) (statement of Sen. Muskie (D-Me.)). Amending the Clean Water Act to create the exemption was intended to reverse the effects of the court decisions in *Natural Resources Defense Council v. Costle*, 568 F.2d 1369 (D.C. Cir. 1977), which vacated a similar exemption created by EPA regulations. Natural Res. Def. Council v. Train, 396 F.Supp. 1393, 1396 (D.D.C. 1975), *aff'd sub nom. Costle*, 568 F.2d at 1382; *see also* Memorandum from EPA General Counsel, *supra* note 94, at 2 n.1 (indicating that after the D.C. Circuit upheld the district court's decision requiring EPA to issue NPDES permits for irrigation return flows, Congress simply responded by amending the definition of point source to exclude irrigation return flows).

[99] 123 CONG. REC. S21, 26,697 (daily ed. Aug. 4, 1977) (statement of Sen. Muskie (D-Me.)). Specifically, Senator Muskie stated that the section 402 NPDES permit program was an inefficient means of addressing irrigation return flows:

> Agriculture was demonstrated to be a major source of pollution. The current strategy in the act to divide agriculture into point and non-point sources is effective with regard to feedlots, but ineffective with regard to irrigation return flows. . . . Section 208 offers the potential for abatement programs to control both irrigation return flows and nonpoint source agricultural runoff, and the committee considered several proposals to pursue this proposal.
>
> For these reasons, the committee adopted several amendments which generally concern section 208 and specifically relate to agriculture.

Id.; *see also* Memorandum from EPA General Counsel, *supra* note 94, at 3 (noting that Congress "intended to ensure a level playing field between irrigated and non-irrigated agriculture" (citing 3 LEGISLATIVE HISTORY OF THE CLEAN WATER ACT, 1978, at 527 (1978); 4 LEGISLATIVE HISTORY OF THE CLEAN WATER ACT, 1978, at 882 (1978)).

[100] 33 U.S.C. § 1288(b)(2)(F) (2000).

[101] 123 CONG. REC. S21, 26,702 (daily ed. Aug. 4, 1977) (statement of Sen. Stafford (R-Vt.)). Moreover, Senator Stafford's introductory remarks at the public hearing in Fort Collins, Colorado in 1977 indicate that the irrigation return flow exemption was intended for western farmers on arid land who irrigate crops and then return the irrigation flow to drainage ditches. Specifically, Senator Stafford (R-Vt.) stated:

history on irrigation return flows is devoid of any actual evidence that suggests an intent to exempt other types of agricultural point sources from the NPDES permit program, such as "wet" crops like cranberry production or rice harvesting. As a result, it would be a mistake to simply assume that these wet crops automatically enjoy the benefit of the irrigation flow exemption, particularly in light of Congress's and EPA's silence on the issue.

2. Judicial Application of the Irrigation Return Exemption

The courts, on the other hand, have not been silent on the scope of the irrigation return flow exemption. Granted, relatively few cases have interpreted or addressed the irrigation return flow exemption. Of the few courts that have, some have fumbled with the exemption and others have sought to avoid its application. The widely divergent holdings, and the absence of clear legislative or regulatory guidance, leave the Clean Water Act jurisdictional status of bulkheads and ditches at cranberry bogs in question.

In *Hiebenthal v. Meduri Farms*,[102] the plaintiffs asserted that a commercial fruit dehydrator in the dry, arid climate of eastern Oregon was required to obtain a NPDES permit before discharging excess irrigation water from land application areas into waters of the United States.[103] The plaintiffs claimed that because the defendant applied irrigation wastewater in excess of the fertilizer needs of the crops, the discharge of that excess wastewater could not be classified as irrigation return flow.[104] The U.S. District Court for the District of Oregon rejected this argument, but with relatively little reasoning to support it. The court simply stated that all discharges from agriculture are exempt from the NPDES permit program unless they are from concentrated animal feeding operations (CAFOs).[105] Pointing to the Clean Water Act's regulation of CAFOs as point sources notwithstanding the agriculture stormwater exemption, the court in *Hiebenthal* essentially held that if all CAFOs are point sources despite the

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> Thanks to the combined efforts of Senator Wallop and Senator Hart, who conducted a field hearing in Fort Collins, Colo., on July 13 on agriculture's concerns about the Water Pollution Control Act, the committee adopted an amendment which, in effect, exempts irrigated agriculture from all permit requirements under section 402 of the act, and instead insures that areawide waste treatment management plans under Section 208 [for voluntarily addressing nonpoint sources of pollution] include consideration of irrigated agriculture. This amendment promotes equity of treatment among farmers who depend on rainfall to irrigate their crops and those who depend on surface irrigation which is returned to a stream in discreet conveyances. While this amendment may appear to be a minor matter to those of us from the East, to the farmers in the semiarid and arid West this amendment is a critical feature of the bill.

Id.

[102] 242 F. Supp. 2d 885 (D. Or. 2002).

[103] *Id.* at 886.

[104] *Id.* at 886, 888.

[105] *Id.* at 887–88 (citing Cmty. Ass'n for Restoration of the Env't v. Henry Bosma Dairy, 305 F.3d 943, 955 (9th Cir. 2002)).

agricultural stormwater exemption, then all non-CAFOs must be nonpoint sources because of the agricultural stormwater exemption.[106]

Recent regulations promulgated by EPA for wastewater and manure discharges from CAFOs suggest the *Hiebenthal* view of the agricultural stormwater exemption is now out of step with EPA's view of the exemption. EPA's regulations provide that if a CAFO applies manure in excess of that called for under a nutrient management plan, any additional runoff of manure or nutrients from a land application area will constitute a "point source" discharge of pollutants.[107] Granted, the primary basis for holding that CAFO manure discharges resulting from over-application of manure on crop fields are point sources is grounded in the fact that CAFOs are regulated as point sources of water pollution under the Clean Water Act.[108] But the logic of regulating (and not exempting) those land application discharges applies just as easily to cranberry bogs and other operations like the commercial fruit dehydrator in *Hiebenthal*. The excess wastewater discharged from the land application area in that case should have been considered a point source discharge of pollutants, not nonpoint source pollution, if the application was, in fact, in excess of the fertilizer needs of the field.

In another application of the irrigation return flow exemption, the court in *Fishermen Against the Destruction of the Environment v. Closter Farms, Inc.*[109] found that excess irrigation and rainwater that accumulated in sugarcane fields and was discharged to a nearby surface water was an exemption as irrigation return flow.[110] In that case, a group of anglers claimed that a sugarcane farm was required to obtain a NPDES permit to regulate its discharges of pollutant-laden irrigation water from cane fields.[111] The sugarcane fields were irrigated by drawing water into irrigation canals until the water overflowed onto the fields.[112] Excess irrigation water was discharged into the lake through a culvert and originated from three sources: rainwater, groundwater drawn into the irrigation canals from areas that required drainage, and seepage from the lake.[113] The court characterized the discharged rain as "agricultural stormwater discharge" and the discharged groundwater and seepage as "return flow from irrigated agriculture."[114] The Eleventh Circuit exempted the discharged groundwater and seepage as irrigation return flow because all of that water had actually been used in the

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[106] *See Hiebenthal*, 242 F. Supp. 2d., at 888 (holding that regulation of irrigation return flows is exempted from the Clean Water Act, but acknowledging that CAFOs are not subject to the exemption because they are expressly designated in the Clean Water Act as a point source).

[107] 40 C.F.R. § 122.23(e) (2006); *see also* Waterkeeper Alliance, Inc. v. Envtl. Prot. Agency, 399 F.3d 486, 509 (2d Cir. 2005) (sustaining EPA's application of the agricultural stormwater exemption to CAFOs).

[108] 33 U.S.C. § 1362(14) (2000).

[109] 300 F.3d 1294 (11th Cir. 2002).

[110] *Id.* at 1296.

[111] *Id.*

[112] *Id.* at 1297.

[113] *Id.*

[114] *Id.*

irrigation process.[115] Therefore, unlike cases of over-application of wastes (and pollutants), the Eleventh Circuit's decision is premised on the fact that all of the water at issue was actually used for irrigation.

The Eleventh Circuit's decision in *Closter Farms* may be of limited use in determining whether cranberry bogs may be included within the irrigation return flow exemption. Although the sugarcane fields in *Closter Farms* and the typical cranberry bog both use irrigation ditches to flood growing areas as a source of water for plant growth, cranberry bogs use water for more than just irrigation. They use it for frost protection and harvest, particularly after the application of pesticides and fertilizers over the course of the growing season.[116] In short, cranberry bogs do not simply collect and discharge rainwater, like the sugarcane fields in *Closter Farms*, and the water in cranberry bogs for frost protection and harvest is not "excess water." In fact, it is typically just the right amount necessary to help the cranberries freeze during winter and float to the surface during harvest. Perhaps most importantly, unlike other agricultural crops, cranberry beds are actually built to hold water one to two feet deep similar to a natural wetland, suggesting that the purpose is to *hold* water for frost protection and harvest, not drain it.[117] In short, the broader role water plays in cranberry production compared to sugarcane production means that *Closter Farms* will be of limited value in determining whether cranberry bogs enjoy the benefit of the irrigation return flow exemption.

In sum, even a broad irrigation return flow exemption does not help with determining when the cranberry bogs should be covered under the Clean Water Act's definition of point source. And, if anything, the exemption has likely been given too much breadth by the courts, EPA, and state regulatory agencies when making that determination. Moreover, the legislative history indicates that Congress did not necessarily intend for the exemption to apply to cranberry bogs. On the contrary, cranberry bog discharges appear to fit neatly within the statutory definition of point source under the Clean Water Act.

VI. HOW *STATE V. ZAWISTOWSKI* COULD HAVE BEEN AVOIDED

Despite the relatively well-documented and discrete pollutant discharges from cranberry bogs, neither EPA nor Wisconsin Department of Natural Resources have proposed to apply the Clean Water Act's core pollution program for point source discharges: the NPDES permit program. In fact, none of the parties or the state circuit court in *Zawistowski* appear to have considered the possibility that the Clean Water Act may apply to limit Zawistowski's discharge of phosphorus to Musky Bay.[118] Instead, legislators

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[115] *Id.*

[116] SCHREIBER, *supra* note 20; Wis. State Cranberry Growers Ass'n, *supra* note 17.

[117] *See supra* notes 16–20 and accompanying text.

[118] State v. Zawistowski, No. 04-CV-75, at 4 (Wis. Cir. Ct., Sawyer County, Wis. Apr. 5, 2006) ("This court has not been shown and is unaware of any water quality standard established by the Wisconsin legislature, or any rule-making body within this state, which regulates the

and regulators alike have avoided the question and neglected the problem of polluted cranberry discharges, and the *Zawistowski* case shows the impact of that neglect.[119]

A. The NPDES Permit Program of the Clean Water Act Is a More Efficient Tool for Preventing and Abating Water Pollutant Discharges from Cranberry Bogs

The common law of public nuisance is an essential cause of action to fill the gaps in statutory environmental law,[120] but it does have its limits. Proving a public nuisance requires a showing that the offending conduct, whether intentional or negligent, substantially interferes with a right common to the public and that the conduct be unreasonable.[121] In that sense, how much "interference" is too much, and the reasonableness of the conduct, both become analyses dependent on facts in an isolated case rather than on a widespread environmental problem. In contrast, the NPDES program embodied in the Clean Water Act was intended to address the common law's inadequacies with respect to establishing liability, as well as those of previous statutory schemes, in addressing water pollution on a broad scale.[122] For the reasons below, the NPDES program, unlike the common law, is relatively uniform and, as a result, lends itself to easily resolving liability questions.

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discharge of water from cranberry farms.").

[119] The Wisconsin attorney general's lawsuit became a hot political issue during the campaign for that office in Wisconsin, with opponents attacking the attorney general for using her authority under state law to file the public nuisance against the cranberry grower. *See, e.g.*, Jason Stein, *Ugly Race, Qualified Candidates*, MADISON DAILY J., Sept. 3, 2006, at A1, *available at* http://www.madison.com/archives/read.php?ref=/wsj/2006/09/03/0609020663.php; Press Release, Dairy Bus. Ass'n, Attorney General Threatens Wisconsin's Right to Farm Law (June 23, 2006), *available at* http://www.widba.com/Files_pdf/AttorneyGeneralThreatensWisconsin.pdf. In addition, partly as a result of the Attorney General's lawsuit, legislation was introduced in Wisconsin that would have severely restricted the attorney general's authority to file public nuisance cases. *See* S.B. 425, 2005 Sess. (Wis. 2005).

[120] *See generally* Andrew C. Hanson, *Concentrated Animal Feeding Operations and the Common Law*, *in* COMMON LAW REMEDIES FOR PROTECTING THE ENVIRONMENT: A GUIDE TO HEROIC LITIGATION (Denise Antolini & Cliff Rechtschaffen eds., 2006).

[121] RESTATEMENT (SECOND) OF TORTS §§ 821B, 822 (1979). The defendant's conduct can be intentional and unreasonable, negligent, or based on strict liability. *See* Milwaukee Metro. Sewerage Dist. v. Milwaukee (*MMSD*), 691 N.W.2d 658, 670, 675–76 (Wis. 2005) (noting that public and private nuisance essentially have the same elements, except that a public nuisance arises from interference with a right common to the public).

[122] ROBERT PERCIVAL ET AL., ENVIRONMENTAL REGULATION: LAW, SCIENCE AND POLICY 85 (4th ed. 2003) ("Even in cases of public nuisance, the common law has proved to be a crude mechanism at best for controlling the onslaught of modern-day pollution."); M. Stuart Madden, *The Vital Common Law: Its Role in a Statutory Age*, 18 U. ARK. LITTLE ROCK L. REV. 555, 560–61 (1996).

1. NPDES Protects Water Quality Through Numeric Pollutant Limits and Best Management Practices

First, NPDES permits employ enforceable numeric limits and best management practices as effluent limitations.[123] Compliance with the numeric limits and best management practices means compliance with the NPDES permit, and in turn, the Clean Water Act.[124] Assuming the permit limits and practices were established to protect water quality standards, compliance also means protection of water quality.

In contrast, the trial court in *Zawistowski* found that discharges of phosphorus were having an adverse impact on Musky Bay, but found that the adverse impacts did not amount to a public nuisance, without comparing the water pollution to any applicable narrative or numeric water quality standards.[125] In other words, the nuisance standard, alone, cannot be consistently relied upon to protect water quality because it does not hinge on a legislative determination of how much water pollution is "too much." A promulgation of water quality standards under the Clean Water Act by the state legislature would help solve that problem.

2. NPDES Civil Liability Is "Strict"

Second, NPDES permit liability is strict,[126] which renders irrelevant the reasonableness, intentionality, or negligence of the conduct critical to a nuisance analysis.[127] In terms of defining civil liability, it does not matter how reasonable a grower's actions might have been in violating the conditions of his NPDES permit, whether he intended to discharge the phosphorus-laden bog water into Musky Bay without such a permit, or how much damage to the lake might have occurred as a result.

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[123] 33 U.S.C. § 1365(f) (2000) (defining "effluent limitation"); Waterkeeper Alliance v. Envtl. Prot. Agency, 399 F.3d 486, 502–03 (2d Cir. 2005) (holding that best management practices fall within the definition of effluent limits under the Clean Water Act).

[124] 33 U.S.C. § 1342(k) (2000).

[125] State v. Zawistowski, No. 04-CV-75, at 13, 25–26 (Wis. Cir. Ct., Sawyer County, Wis. Apr. 5, 2006).

[126] 33 U.S.C. § 1311(a) (2000) (discharge of a pollutant to navigable waters prohibited except in compliance with a NPDES permit); United States v. Pozsgai, 999 F.2d 719, 725 (3d Cir. 1993); United States v. Amoco Oil Co., 580 F. Supp. 1042, 1050 (W.D. Mo. 1984); Stoddard v. W. Carolina Reg'l Sewer Auth., 784 F.2d 1200, 1208 (4th Cir. 1986).

[127] *See* RESTATEMENT (SECOND) OF TORTS § 821D (1979) (defining private nuisance); *id.* § 822 cmt. a (describing the types of conduct that create nuisance liability). As for private nuisance, it is important to distinguish between the first two types of conduct that can give rise to a private nuisance, that is, "intentional and unreasonable" conduct and "negligent" conduct. *MMSD*, 691 N.W.2d at 671 (citing RESTATEMENT (SECOND) OF TORTS § 822). The difference is important because each requires different elements of proof. An interference with a person's use and enjoyment of land is "intentional" if the actor "(a) acts for the purpose of causing it, or (b) knows that it is resulting or is substantially certain to result from his conduct." *MMSD*, 691 N.W.2d at 672 (citing RESTATEMENT (SECOND) OF TORTS § 825). In other words, the defendant may not intend to cause harm to others, but because of the nature of the defendant's lawful business activities, he knows that he is doing harm to others. *MMSD*, 691 N.W.2d at 672 (citations omitted).

For example, in *Zawistowski*, the trial court explained in detail how the evidence at trial showed that Zawistowski intended to discharge the bog water and knew what effect it was having on Musky Bay.[128] On the other hand, the court noted that Zawistowski was not applying more phosphorus than what other growers typically apply, which relates to the "reasonableness" of Zawistowski's actions.[129] Ultimately, the court concluded that the interference with the use and enjoyment of Musky Bay was not so substantial as to amount to a nuisance.[130] All of this discussion becomes superfluous when the NPDES permit program is employed. What matters is whether the NPDES effluent limits have been violated and the best management practices have not been implemented. If that is the case, liability is clear. And, if relevant at all, the damage to the lake relates to appropriate injunctive relief and civil penalties, not liability.[131]

3. NPDES Permits Prevent Pollution, Rather Than Solely Abate it After it Happens

Third, the relative ease of implementation and enforcement of the Clean Water Act's NPDES permit scheme should operate to save the public money spent on cleaning up waterways after they are already degraded. Effluent limits and best management practices for cranberry bogs can be categorically applied through NPDES permits to all cranberry bogs, rather than only to the operations that are causing the most severe water quality impacts. NPDES permits should obviate the need for public nuisance litigation that, where the state prevails, results in only site-specific environmental protection.

For example, in *Zawistowski*, the trial court noted that there was no governing standard for the appropriate amount of phosphorus to be discharged into Musky Bay.[132] And, even if the attorney general obtained the injunctive relief that it sought and Musky Bay were cleaned up, one is left to wonder what should be done on other lakes polluted by surface water discharges from cranberry bogs in cranberry producing states like Wisconsin, Massachusetts, and Washington. The general deterrent effect of nuisance litigation is doubtful where the litigation outcome depends largely on site-specific circumstances that other cranberry growers may not think apply to them. Application of the NPDES permit program would create a standard of care through mandatory implementation of effluent limits and best management practices that would apply throughout the industry, not just at specific facilities. Furthermore, the NPDES permit program would provide cranberry growers with clear standards, taking away the uncertain liability created by the threat of common law nuisance actions.

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[128] *Zawistowski*, No. 04-CV-75 at 13.

[129] *Id.* at 4.

[130] *Id.* at 25–26.

[131] 33 U.S.C. § 1319(d) (2000) (establishing "seriousness of the violation" as a factor to be considered by courts in imposing civil penalties on persons liable for violating the Clean Water Act).

[132] *Zawistowski*, No. 04-CV-75 at 14.

4. Public Nuisance Actions Mimic the Failed Pre-NPDES Statutory Scheme

In fact, using public nuisance law to address water pollution from cranberry bogs is akin to relying on the failed statutory scheme that preceded the 1972 Clean Water Act Amendments.[133] The previous water pollution control scheme in the United States relied exclusively on measuring compliance with water quality standards from point source dischargers in determining whether water pollution existed and whether it needed to be abated.[134] In short, the government had to prove not that any effluent limits in a permit were being violated, because there were none, but instead that water quality standards in the receiving water were being violated.[135] This was costly, time consuming, and generally difficult to do.[136] This failed "water quality based" approach led to enactment of the modern version of the NPDES permit program today. Significantly, the NPDES permit program does not depend exclusively on demonstrated harm to the environment before jurisdiction attaches; if the permit requirement is triggered, then a permit must be obtained that incorporates effluent limits, including those more stringent limits needed to meet water quality standards.[137] Further, the NPDES program was designed to make it unnecessary to trace pollution back from an over-polluted waterbody, and then decide which sources needed to be abated.[138]

However, a common law action similar to *Zawistowski* includes all of the problems with the pre-Clean Water Act scheme. Specifically, the attorney general was required to show "unreasonable" harm to Musky Bay before any abatement measures could be ordered by a court. Relying on the common law as a means of regulating phosphorus and pesticide discharges from cranberry bogs is an inefficient step backwards in controlling pollutant discharges and protecting water quality.

5. NPDES Permit Liability Is Not Necessarily Limited by Right to Farm Laws

Nuisance liability can be precluded by application of state Right to Farm laws. NPDES permit implementation and enforcement obviates the need to address liability questions presented by those laws. Right to Farm laws typically insulate agricultural uses from common liability when the agricultural practices employed are consistent with what is used in the

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[133] Cal. *ex rel.* State Water Res. Bd. v. Envtl. Prot. Agency, 426 U.S. 200, 202–05 (1976).

[134] *Id.*

[135] *See* 118 CONG. REC. 37,056 (1972) (statement of Rep. Robert E. Jones) ("Other than [the Refuse Act], we had the 1965 Water Pollution Control Act, the enforcement provisions of which are so cumbersome they have proven to be ineffective—as even the administration itself has stated."); H.R. REP. NO. 92-911, at 394 (1972) (additional views of Bella S. Abzug & Charles B. Rangel) ("Even the water quality standards program enacted in 1965 has proven to be of little value. More than half of the States unilaterally extended time-tables for achieving the standards.").

[136] *State Water Res. Bd.*, 426 U.S. at 204–05.

[137] *Id.* at 204.

[138] *Id.*

industry, or where the practices do not present a substantial threat to public health and safety.[139] Almost every state in the country has a Right to Farm law,[140] including Wisconsin.[141]

Wisconsin's Right to Farm law was raised as a defense in *Zawistowski*, and both the landowners and the State sought to limit application of that law.[142] However, Right to Farm laws are typically only a defense to common law actions, not statutory actions.[143] And, state Right to Farm liability shields do not negate federal liability under the Clean Water Act. In short, Right to Farm laws become a non-issue with respect to establishing Clean Water Act liability for point source discharges from cranberry bogs.

B. The Clean Water Act Can Resolve Questions of Appropriate Technology and Injunctive Relief

It is worth noting that NPDES permit liability is only as clear as the permit that imposes it. For toxic or nonconventional pollutants, such as phosphorus or pesticides, the NPDES permit must impose effluent limits based on the best available technology economically achievable (BAT) and effluent limitation guidelines achievable by BAT.[144] Even if EPA does not

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[139] Alexander A. Reinert, Note, *The Right to Farm: Hog-Tied and Nuisance-Bound*, 73 N.Y.U. L. REV. 1694, 1695 (1998); Andrew C. Hanson, *Brewing Land Use Conflicts: Wisconsin's Right to Farm Law*, 75 WIS. LAW 10, 12 (Dec. 2002), *available at* http://www.wisbar.org/AM/Template.cfm?Section=Search_Archive1&template=/CM/HTMLDisplay.cfm&ContentID=53190.

[140] Hanson, *supra* note 139, at 11.

[141] WIS. STAT. § 823.08 (2006).

[142] For example, the State of Wisconsin argued that the Right to Farm law must be read consistently with Wisconsin's Public Trust Doctrine, requiring that the state hold navigable waters in trust for the public. WIS. CONST. art. IX, § 1. Specifically, Wisconsin's Public Trust Doctrine states:

> The state shall have concurrent jurisdiction on all rivers and lakes bordering on this state so far as such rivers or lakes shall form a common boundary to the state and any other state or territory now or hereafter to be formed, and bounded by the same; and the river Mississippi and the navigable waters leading into the Mississippi and St. Lawrence, and the carrying places between the same, shall be common highways and forever free, as well to the inhabitants of the state as to the citizens of the United States, without any tax, impost or duty therefore.

Id.; *see also* Hilton v. Wis. Dep't of Natural Res., 717 N.W.2d 166, 173 (discussing Wisconsin's Public Trust Doctrine and noting that the Wisconsin Department of Natural Resources is charged with administering the public trust for the protection of public rights in navigable waters).

[143] *See* Reinert, *supra* note 139, at 1695.

[144] 33 U.S.C. § 1311(b)(2)(A) (2000). Specifically, EPA must establish BAT for classes or categories of point sources:

> In order to carry out the objective of this Act there shall be achieved . . . for pollutants identified in subparagraphs (C), (D), and (F) of this paragraph, effluent limitations for categories and classes of point sources, other than publicly owned treatment works, which (i) shall require application of the best available technology economically achievable for such category or class, which will result in reasonable further progress toward the national goal of eliminating the discharge of all pollutants, as determined in accordance with regulations issued by the Administrator pursuant to section 1314(b)(2)

establish BAT and effluent limitation guidelines for cranberry discharges, effluent limits must be set to ensure compliance with water quality standards,[145] including designated uses, numeric and narrative water quality criteria,[146] and an antidegradation policy.[147] The question then becomes what the appropriate technology standard for cranberry bog effluent should be.

The Clean Water Act can resolve questions about appropriate technology to be applied to abate pollutant discharges and also the appropriate injunctive relief where violations of a permit have been documented. Approximately ninety percent of Wisconsin's cranberry operations use a "flow-through" system for water used in irrigation and flooding for frost protection and harvest.[148] A flow-through system is one in which water is pumped from the source, such as a lake, used directly on the cranberry beds, and then discharged back to the lake, sometimes carrying with it toxic pesticide residues and phosphorus fertilizers.[149] However, some cranberry operations in Wisconsin are beginning to use what are called "tailwater recovery" systems.[150] A tailwater recovery system consists of a

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> of this title, which such effluent limitations shall require the elimination of discharges of all pollutants if the Administrator finds, on the basis of information available to him (including information developed pursuant to section 1325 of this title), that such elimination is technologically and economically achievable for a category or class of point sources as determined in accordance with regulations issued by the Administrator pursuant to section 1314(b)(2) of this title, or (ii) in the case of the introduction of a pollutant into a publicly owned treatment works which meets the requirements of subparagraph (B) of this paragraph, shall require compliance with any applicable pretreatment requirements and any other requirement under section 1317 of this title . . . .

Id.; *see also id.* § 1314(b)(2)(B) (identifying the factors to be taken into account by EPA in setting BAT, including "the age of equipment and facilities involved, the process employed, the engineering aspects of the application of various types of control techniques, process changes, the cost of achieving such effluent reduction, non-water quality environmental impact (including energy requirements), and such other factors as the Administrator deems appropriate"); *id.* § 1314(b)(3) (requiring EPA to take cost of achieving the reductions into consideration in setting effluent limitation guidelines).

[145] 40 C.F.R. § 122.44(d) (2006) (requiring that NPDES permits ensure compliance with water quality standards).

[146] *Id.* § 131.3(b) (defining water quality criteria to include narrative and numeric water quality criteria); *id.* § 122.44(d)(1)(i) (requiring a state or EPA to determine whether a discharge of pollutants may cause or contribute to a violation of water quality standards, including narrative water quality criteria).

[147] 33 U.S.C. § 1313(d)(4)(B) (2000); 40 C.F.R. § 131.12 (2006) (setting forth the antidegradation policy under the Clean Water Act); PUD No. 1 v. Wash. Dep't of Ecology, 511 U.S. 700, 718–19 (1994).

[148] Transcript of Record at 199–200, State v. Zawistowski, No. 04-CV-75 (Wis. Cir. Ct., Sawyer County, Wis. Apr. 5, 2006).

[149] *Id.* at 192–93 (referring to Zawistowski's cranberry operation as a flow-through system, and defining it as one that is not designed to trap or redirect the irrigation, harvest or flood water); *see also* UNIV. OF MASS. CRANBERRY EXPERIMENT STATION, BEST MANAGEMENT PRACTICES GUIDE FOR MASSACHUSETTS CRANBERRY PRODUCTION 2 (2000), *available at* http://www.umass.edu/cranberry/downloads/bmp/introduction.pdf (recommending the isolation of ditch water from external water bodies for flow-through systems and prevention of surface water contamination); *supra* notes 24–37 and accompanying text (discussing pollutant discharges from cranberry bogs).

[150] Transcript of Record at 200, *Zawistowski*, No. 04-CV-75.

settling pond at the cranberry operation that is used to collect the water used for irrigation and flood protection.[151] After settling, the water is pumped to a reservoir for later use, fulfilling both water quality and water quantity goals for a cranberry operation.[152]

Tailwater recovery systems are evolving as the "best available technology" used to control pollutant discharges from cranberry operations, and already approximately ten percent of Wisconsin's cranberry growers employ those systems.[153] Moreover, the Wisconsin Cranberry Growers' Association has adopted a policy that cranberry operations should be converted to closed systems to use as little fresh water as possible and to prevent pesticides and nutrients from being discharged into surface waters.[154] Likewise, the Massachusetts Cranberry Experiment Station has included tailwater recovery systems on its list of recommended best management practices.[155]

Once a tailwater recovery system is employed on a cranberry operation, the next goal will be to identify appropriate pollutant levels, through effluent limits, that may ultimately be discharged to the surface water, if at all.[156] And, if a cranberry bog is violating an effluent limit or a condition of a permit, then the most obvious solution is to stop violating the permit. In *Zawistowski*, the State of Wisconsin and private landowners sought to require Zawistowski to dredge the phosphorus-laden sediment from Musky Bay, having resulted from decades of phosphorus discharges to Musky

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[151] *Id.* at 199–200.

[152] *Id.* at 186, 200; *see also* Natural Res. Conservation Serv., Conservation Practice Standard No. 447, Irrigation System, Tailwater Recovery (2004), *available at* ftp://ftp-fc.sc.egov.usda.gov/NHQ/practice-standards/standards/447.pdf (citing dual purposes of conservation of irrigation water supplies and improvement of offsite water quality).

[153] Transcript of Record at 200, *Zawistowski*, No. 04-CV-75.

[154] *Id.* at 186–87. The Natural Resources Conservation Service and Wisconsin State Cranberry Growers' Association has established a sample "conservation plan" for cranberry growers that recommends use of tailwater recovery systems to improve the recovery and reuse of surface water. U.S. DEP'T OF AGRIC., NATURAL RES. CONSERVATION SERV., WHOLE FARM CONSERVATION PLAN, XYZ CRANBERRY COMPANY, LLC, LINCOLN TOWNSHIP, CRANBERRY COUNTY 17–18, *available at* http://www.wiscran.org/WFPlanning/SamplePlan.pdf; *see also* U.S. DEP'T OF AGRIC., NATURAL RES. CONSERVATION SERV., ENVIRONMENTAL QUALITY INCENTIVES PROGRAM: LIST OF ELIGIBLE PRACTICES AND PAYMENT SCHEDULE (WISCONSIN) 4–56, *available at* ftp://ftp-fc.sc.egov.usda.gov/WI/eqip/2007/cookbook07.pdf ("[Tailwater recovery systems] may be applied as part of a conservation management system to support the conservation of irrigation water supplies or to improve offsite water quality.").

[155] UNIV. OF MASS. CRANBERRY EXPERIMENT STATION, BEST MANAGEMENT PRACTICES GUIDE FOR MASSACHUSETTS CRANBERRY PRODUCTION 1 (2000), *available at* http://www.umass.edu/cranberry/downloads/bmp/water_resource_protection.pdf.

[156] For example, the State of Wisconsin imposes a 1 milligram per liter (mg/l) effluent limit on all point source discharges of more than 60 pounds of phosphorus per month. WIS. ADMIN. CODE NR § 217.04(1)(a) (2006). Even in states where there may be no categorical effluent limit on phosphorus discharges, or where 1 mg/l may not be sufficient to meet water quality standards, those states must determine whether the cranberry bog has the reasonable potential to cause or contribute to a violation of water quality standards, including narrative water quality criteria, and then impose water quality based effluent limits to prevent those violations. 40 C.F.R. § 122.44(d)(1) (2006).

Bay.[157] Of course, this would presumably be expensive and onerous. If, however, Zawistowski had a NPDES permit that limited the extent of his phosphorus discharges to the bay, and if Zawistowski had violated that permit, the appropriate injunctive relief would have been to comply with the permit and to undertake measures at the cranberry operation to ensure that compliance, whether through implementation of a tailwater recovery system or, where a system is already implemented, compliance, with effluent limits and practices designed to properly maintain that system.

VII. CONCLUSION

Discharges from cranberry bogs can cause serious water pollution. Unlike other agricultural sources, cranberry bog discharges are not diffuse sources of runoff, nor do the discharges merely consist of "irrigation return flow" as Congress apparently meant when it used that phrase. Water is pumped from surface waters to flood cranberry beds that are below-grade and designed to hold water for extended periods of time. During the growing season, pesticides and fertilizers are applied. When the bogs are flooded and drained, in flow-through systems like Mr. Zawistowski's, those pesticides and fertilizers are discharged through discrete point sources back into the navigable waters, damaging aquatic life and water quality in the process. In short, the lack of clarity of the irrigation return flow exemption poses a serious obstacle to application of the NPDES permit program to cranberry bogs, but not an insurmountable one. Designed primarily for western farmers on arid lands, the exemption has likely been given too much breadth in light of its legislative and regulatory history.

The Clean Water Act's NPDES permit program is ideal for addressing the problems associated with cranberry bog discharges. The pollutant discharges are discrete, identifiable, well-documented, and arguably, not subject to the irrigation return flow exemption. And, the technology and management practices exist to reduce and eliminate those discharges through tailwater recovery systems and nutrient management practices. Further, applying the NPDES permit program reduces the need for expensive public nuisance litigation that may have only isolated environmental benefits that fail to address a more common and widespread problem in cranberry producing states. As a result, those states and EPA should broadly apply the NPDES permit program, and narrowly apply the irrigation return flow exemption, to cranberry growing operations to reduce and eliminate polluted cranberry bog discharges where they occur.

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[157] Complaint at 1–2, State v. Zawistowski, No. 04-CV-75 (Wis. Cir. Ct., Sawyer County, Wis. Jun. 8, 2004).

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PERSPECTIVES AND NOTES | Open Access

Evaluating potential effects of solar power facilities on wildlife from an animal behavior perspective

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Abstract

Solar power is a renewable energy source with great potential to help meet increasing global energy demands and reduce our reliance on fossil fuels. However, research is scarce on how solar facilities affect wildlife. With input from professionals in ecology, conservation, and energy, we conducted a research-prioritization process and identified key questions needed to better understand impacts of solar facilities on wildlife. We focused on animal behavior, which can be used to identify population responses before mortality or other fitness consequences are documented. Behavioral studies can also offer approaches to understand the mechanisms leading to negative interactions (e.g., collision, singeing, avoidance) and provide insight into mitigating effects. Here, we review how behavioral responses to solar facilities, including perception, movement, habitat use, and interspecific interactions are priority research areas. Addressing these themes will lead to a more comprehensive understanding of the effects of solar power on wildlife and guide future mitigation.

1 INTRODUCTION

As the global human population continues to grow, energy demand increases (IEA, 2019; Pazheri, Othman, & Malik, 2014). Although fossil fuels still dominate energy production, renewable energy sources are a rapidly expanding sector of the global energy market (Islam, Huda, Abdullah, & Saidur, 2018; USEIA, 2019). Renewable resources can help combat climate change, and with falling production costs, serve as an economical alternative to fossil fuels (IRENA, 2019). Most U.S. states now have Renewable Portfolio Standards and other policies that further incentivize production of renewable energy (NCCETC, 2020; NREL, 2019).

The number and size of utility-scale (e.g., >20 MW) solar energy facilities (hereafter solar facilities) have dramatically increased during the past 20 years (Figure 1; Hernandez et al., 2014); for example, the average utility-scale photovoltaic (PV) system installation size increased over 80% from 2010 to 2019 in the United States (NREL, 2020). Solar energy technologies typically fall into two main categories: (a) PV cells that convert sunlight into electrical current (Figures 1a and 2) concentrating solar power (CSP) which uses mirrors to focus sunlight to heat fluids that power steam turbines or generators (Figure 1b,c).

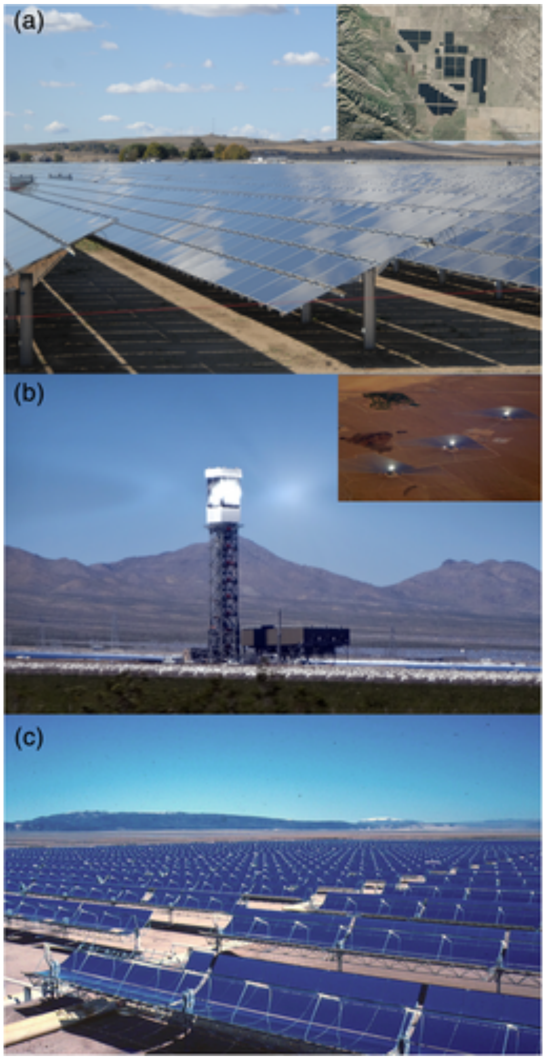

FIGURE 1

Open in figure viewer | PowerPoint

(a) An example of photovoltaic (PV) solar panels at topaz solar (550 MW; 4,700 acres). Photo by Pacific Southwest Region from Sacramento, U.S.—Solar Panels at topaz solar 1, Public Domain, https://commons.wikimedia.org/w/index.php?curid=36895794. Inset: aerial photo by Earth Observatory image by Jesse Allen, using EO-1 ALI data provided courtesy of the NASA EO-1 team. Public Domain, https://commons.wikimedia.org/w/index.php?curid=38864327. (b) An example of a concentrating solar power (CSP) tower at Ivanpah Solar Electric Generating System (377 MW; 3,500 acres). Photo by Craig Dietrich—Flickr: Ivanpah Solar Power Facility, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=28676343. Inset: aerial photo by Jllm06—Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=42975801. (c) An example of a CSP parabolic trough at Solar Energy Generating Systems (SEGS; 354 MW; 1,600 acres). Photo by USA.Gov—BLM—Public domain

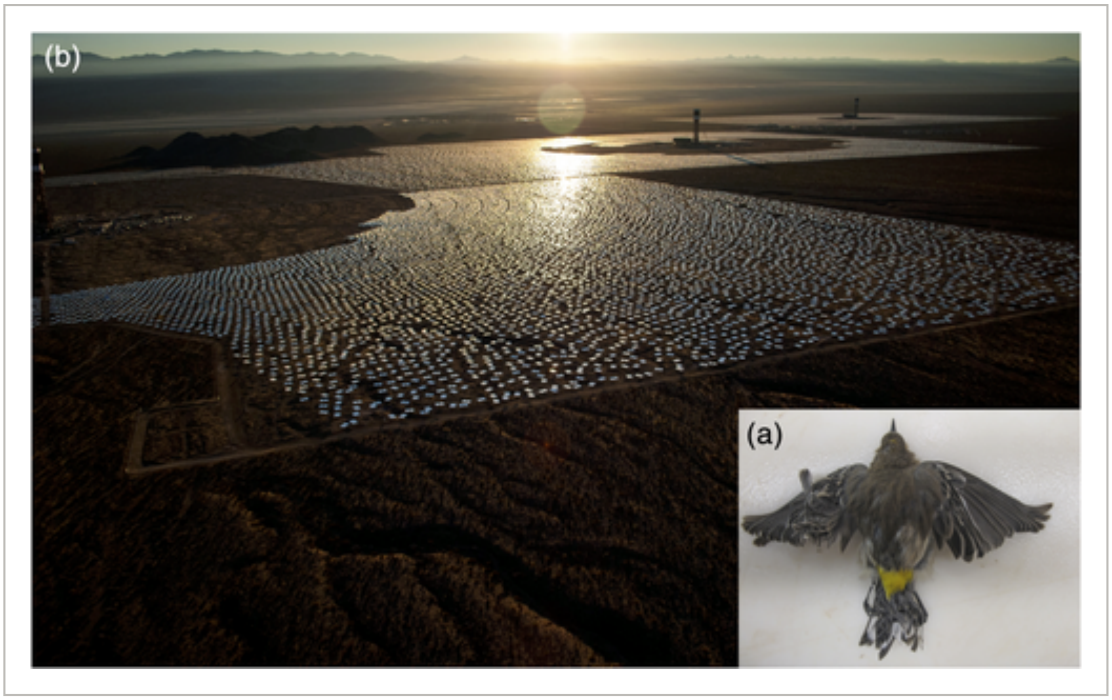

FIGURE 2

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(a) Concentrating solar power (CSP) facilities can cause direct mortality to aerial species that fly into solar flare, such as this yellow-rumped warbler burned mid-air at Ivanpah (photograph by U.S. Fish and Wildlife Service, 2013, public domain). (b) CSP or PV facilities can create a "lake effect" (photograph by Kerry Holcomb, used with permission, Ivanpah Solar Electric Generating System, CA); water birds that mistakenly land on the hard surfaces can die on impact, become injured, or are unable to take off from terrestrial surfaces and ultimately die of exposure

Our current understanding of the impacts of solar facilities on wildlife is limited, despite the pace and scale of its development. Environmental effects, such as soil erosion, changes in water use, and increases in local temperature, are well documented (Barron-Gafford et al., 2016; Hernandez et al., 2014; Moore-O'Leary et al., 2017). A few studies suggest that solar facilities could affect wildlife through exclusionary fencing, habitat destruction or alteration, and direct mortality (Table 1; Northrup & Wittemyer, 2013; Walston, Rollins, LaGory, Smith, & Meyers, 2016), but their relative scarcity highlights the need for additional research (see also Agha, Lovich, Ennen, & Todd, 2020). In particular, studies of wildlife behavioral response to solar facilities have been called for, including by working groups focused on bird interactions with solar facilities (ASCWG, 2020; ASWG, 2020); but such studies are largely still lacking from the literature (Lovich & Ennen, 2011; Northrup & Wittemyer, 2013).

TABLE 1. Examples of direct injury and mortality effects, as well as secondary mortality effects, on wildlife species that use the airspace and land covers at solar energy facilities. Noted effects are based on a select number of government and peer-reviewed literature sources, but not a complete survey or synthesis of the current literature

Effect		Taxa affected	Source[1]
Direct injury/mortality	Solar flux	Birds, insects	2, 3, 4, 6, 7, 8, 9, 10
	Undefined trauma	Birds	8
	Impact trauma	Birds, bats	1, 2, 3, 5, 6, 8, 11
	Electrocution	Birds	6, 8, 11
	Entrapment/drowning in water in-take structures and evaporation ponds	Birds, mammals, insects	4, 6, 7
	Entrapment in soil ruts from vehicle passage	Amphibians, reptiles	10
Secondary mortality	Predation trauma	Amphibians, birds, reptiles	10, 8
	Light pollution	Amphibians, birds, bats, other mammals, insects, reptiles	4, 5, 10
	Electromagnetic field effects	Amphibians, bats, insects, reptiles	4, 10
	Other anthropogenic effects	Amphibians, birds, bats, other mammals, insects, reptiles	5, 7, 8, 10

Note: 1. Costantini, Gustin, Ferrarini, and Dell'Omo (2016); 2. Diehl, Valdez, Preston, Wellik, and Cryan (2016); 3. Ho (2016); 4. Horváth et al. (2010); 5. Huso, Dietsch, and Nicolai (2016); 6. Jeal, Perold, Ralston-Paton, and Ryan (2019); 7. Jeal, Perold, Seymour, Ralston-Paton, and Ryan (2019); 8. Kagan, Viner, Trail, and Espinoza (2014); 9. Loss, Dorning, and Diffendorfer (2019); 10. Lovich and Ennen (2011); 11. McCrary, McKernan, Schreiber, Wagner, and Sciarrotta (1986).

Behavioral responses are often the most visible signs of detrimental effects, as behavioral shifts are usually an animal's first response to environmental change (Dimitri & Longland, 2018; Northrup & Wittemyer, 2013). Although direct mortality is the most obvious sign of negative impacts, large energy facilities may also impact individual fitness, as measured by survival and reproduction (hereafter "fitness"), resulting in population-level impacts that are harder to quantify without long-term demographic studies or using behavioral observations. For example, individuals could decrease mating behavior in response to increased disturbance (Holloran, Kaiser, & Hubert, 2010), stress levels (Lovich & Ennen, 2011), and pollution (Peterson et al., 2017). In addition, behavioral studies can offer approaches to understand the mechanisms leading to negative effects and to provide mitigative strategies. Animal behavior has been successfully utilized by wildlife and natural resource managers to mitigate problems and improve management strategies (Berger-Tal et al., 2011; Dimitri & Longland, 2018). For example, animal behavior has been used to understand and develop approaches to mitigate avian collisions at airports (Blackwell & Fernández-Juricic, 2013). It is imperative for the solar industry to incorporate behavioral research now, in a relatively early stage of the solar boom, to ensure solar power is sustainable for local wildlife populations and to avoid similar developmental and legal pitfalls that plagued the wind industry in its early boom (Brown & Escobar, 2007).

Using a multiphase research-prioritization process (see Supporting Information 1 for detailed methods) we implemented an online survey to ask professionals in the fields of ecology, conservation and energy to identify key behavioral research questions related to potential wildlife conservation issues at solar facilities (see Supporting Information 2 for full survey). We reduced and prioritized these questions at a 2019 workshop held by the Animal Behavior Society Conservation Committee (Supporting Information 1), and summarize here the emerging themes that resulted from this process (Table 2).

TABLE 2. Key themes in animal behavior research that could improve our understanding of impacts of solar facilities on wildlife and potential solutions. These themes emerged from a multiphase research prioritization process (see Supporting Information 1) and the final list of priority research questions (Table S4)

Theme	Research areas	Research priority questions	Examples from the literature related to or applicable to solar power facilities
Perception		Do solar facilities	Blackwell, Fernández-Juricic,

Theme	Research areas	Research priority questions	Examples from the literature related to or applicable to solar power facilities
attraction or deterrence?	2. Quantify key sensory mechanisms of species with high mortality at facilities 3. Use information in perception models to quantify conspicuousness of facility elements 4. Modify facility elements to enhance or reduce conspicuousness and measure	mechanisms involved in creating attraction or deterrence to solar facilities? What characteristics of solar facilities are attracting and/or deterring certain species? What are the fitness consequences? How can solar facilities be designed to reduce attraction and reduce negative fitness consequences?	Hein, Schirmacher, Huso, and Szewczak (2013), Kagan et al. (2014), Smith and Dwyer (2016), Fernández-Juricic (2016), Száz et al. (2016)

2 WILDLIFE PERCEPTION OF SOLAR FACILITIES

Solar facilities have the potential to deter, attract, or be imperceptible to individuals, all of which can lead to negative consequences for a variety of species (Kagan et al., 2014; Smith & Dwyer, 2016). Avoidance of solar facilities may lead to use of lower quality habitat or population fragmentation (Hernandez et al., 2014; Saunders, Hobbs, & Margules, 1991) and species attracted to solar facilities might be victims of ecological traps (Robertson & Hutto, 2006). When species attracted to facilities experience low survival or reproduction onsite, regional population dynamics could follow a source-sink pattern, affecting populations beyond site boundaries (Delibes, Gaona, & Ferreras, 2001). Alternatively, solar facilities may attract and provide high quality habitat for non-native or urban adapted species (Hufbauer et al., 2011; Tuomainen & Candolin, 2011). High population density of a few species could have cascading effects, potentially reducing food web integrity (Jessop, Smissen, Scheelings, & Dempster, 2012) or altering species' interactions (see below). Species unable to detect or avoid structures (e.g., power lines, glass windows) are at risk of collision and direct mortality (Bevanger, 1994).

At the core of the problem, we do not fully understand the mechanisms involved in wildlife perception of solar facilities or all the factors that influence avoidance or attraction (but see work by Horváth et al. (2010) and others on aquatic insect attraction to polarized light and solar panels). Individuals deterred by noise pollution might avoid facilities during construction and operation (Halfwerk & Slabbekoorn, 2015) and could also be affected by road noise from traffic associated with them. Individuals might be attracted to these sites because of microclimatic conditions, cover, water availability (e.g., evaporative cooling ponds; Walston et al., 2016), enhanced prey density, lighting, confusion of visual cues, or other potential factors (Dominoni et al., 2020). We also need to know if there is variation in perception and response to solar facilities within and between species and at different temporal scales, both seasonal and daily.

We can identify key behavioral responses by studying how species perceive solar facility structures (Kagan et al., 2014) relative to surrounding landscape elements. Ultimately, this process can allow for manipulation of stimuli and associated behavior to reduce mortality (sensu Blackwell et al., 2009 and citations therein). Birds, for example, can experience risk of mortality due to collision (i.e., direct contact with the solar facility), solar-flux (i.e., birds are either burned or singed by exposure to the solar facility; Figure 2a), or become stranded (i.e., water birds that cannot take off due to lack of water; ANL & NREL, 2015). It is therefore important to understand how birds and other wildlife perceive solar facilities and why they are attracted, deterred, or fail to detect them. In addition to individual responses to cues generated by solar facilities, vulnerability will vary according to species' ecology and behavior. We discuss below how animal movement, breeding, foraging behavior, and interspecific interactions may influence population level responses to solar facilities.

3 MOVEMENT AND HABITAT USE IN AND AROUND SOLAR FACILITIES

Many animals, particularly those living in arid environments where solar facilities are more common, are living at their physiological limits; any added movement may thus be costly (Vale & Brito, 2015). Whether and how movements are influenced by a solar facility will be determined by: (a) the trade-off of associated benefits and costs, (b) whether species are attracted or deterred by solar facilities, (c) whether a species is residential or migratory, and (d) the fitness impact of the responses.

3.1 Resident species

Solar facility construction and operation directly and indirectly alter habitat use via functional habitat fragmentation, dispersal limitations, population isolation, and altered habitat quality (as previously reviewed in Lovich and Ennen (2011)). For example, vegetation at road edges appears to attract Agassiz's desert tortoises (*Gopherus agassizii*) to build burrows there, despite the apparent noise pollution and risk of vehicle collision (Lovich & Daniels, 2000; von Seckendorff Hoff & Marlow, 2002). CSP facilities can include evaporation ponds with chemically treated waters; these polluted waters can kill via drowning, poisoning, egg mortality, or biomagnification (Jeal, Perold, Ralston-Paton, & Ryan, 2019). Electromagnetic fields created by buried and aerial cables transporting energy can affect orientation of some organisms, impairing habitat use and likely causing additional physiological harm (Lovich & Ennen, 2011; Shepherd et al., 2019; Wyszkowska, Shepherd, Sharkh, Jackson, & Newland, 2016). Also, changes in albedo from vegetation removal could cause local increases in temperature and evapotranspiration, which may influence movement patterns, reproductive success, and survival (Barron-Gafford et al., 2016). Although certain habitat modifications could benefit species, such as birds that can exploit solar facility structures for foraging, roosting or nesting (Jeal, Perold, Ralston-Paton, & Ryan, 2019) or prey species that experience reduced predation (Cypher et al., 2019), in most cases, modifications are likely to have negative impacts.

3.2 Migratory species

Migratory animals are under escalating threat due to growth in human activity (Hardesty-Moore et al., 2018; Wilcove & Wikelski, 2008). Compared to other groups of species, migratory birds appear to suffer disproportionately higher mortality from solar facilities, particularly those located on migration routes and/or near breeding and wintering grounds (Walston et al., 2016). The greater abundance of insect prey attracted by the high structures and light (Diehl et al., 2016) likely attracts aerial insectivores, resulting in a higher risk to burning via solar flux from concentrated solar power (Figure 2a; McCrary et al., 1986; Kagan et al., 2014). Migratory water bird species are also susceptible because solar facilities may be perceived as waterbodies (a hypothesized “lake effect”), attracting them to land and injuring, killing, or stranding them in the process (Figure 2b; Kagan et al., 2014).

3.3 Facility siting

The effects of solar facilities on wildlife may be exacerbated or mitigated through decisions about where to build them. Models have been developed at regional scales to identify areas that have both high potential for solar energy development and suitability for species of special concern (Phillips & Cypher, 2019), or high species richness (Thomas et al., 2018), representing potential conflict areas that should be avoided. These and other studies also identify priority areas for facility siting that minimizes the loss of high quality habitat (DRECP, 2020; Stoms, Dashiell, & Davis, 2013). While these models provide greatest benefit to resident species, research on migratory routes for aerial and terrestrial wildlife is critical to improve siting recommendations (e.g., Ruegg et al., 2014). The infrastructure necessary to operate solar facilities often extends far into the habitat, and effects of these structures on migratory wildlife have been documented in other energy sectors. For instance, mule deer (*Odocoileus hemionus*) abandoned former migration corridors as a result of oil and gas exploration and moved into suboptimal habitat, resulting in migration bottlenecks with no observed acclimation over several years (Sawyer et al., 2009). Reindeer (*Rangifer tarandus*) actively avoid power lines (Reimers et al., 2007; Vistnes et al., 2004), a behavioral response that could similarly alter migration routes for other ungulates. Gene flow in populations of desert bighorn sheep (*Ovis canadensis nelsoni*) is impeded by the presence of barriers, including roadways and large mining operations, resulting in rapid declines in genetic diversity (Epps et al., 2005). Minimizing these off-site impacts by siting facilities closer to existing infrastructure is important for mitigating effects on wildlife (Stoms et al., 2013).

4 OTHER FITNESS ASSOCIATED BEHAVIORS: FORAGING AND SPECIES INTERACTIONS

4.1 Foraging

Foraging involves a complex suite of behaviors, including detection of food sources, perceiving temporal and spatial cues about food availability, and food searching, choice, retrieval, and processing. Solar facilities might alter cues and predation risk assessment or disrupt normal search patterns via habitat change or construction of novel obstacles. Therefore, we must understand a species' trophic level (Fauvelle, Diepstraten, & Jessen, 2017; Moore-O'Leary et al., 2017) and the mechanisms underpinning its foraging decisions (e.g., olfactory cues; Schmitt, Shuttleworth, Ward, & Shrader, 2018) to estimate the impact of landscape alteration caused by solar facilities.

Spatial knowledge, which is critical in foraging behavior, increases individual fitness (Spencer, 2012), and changes in spatial distribution of resources may impact species depending on their capacity to update such information. Assessments on the plasticity of cognitive mapping and role of memory in animal foraging decisions would contribute to our understanding about the impact of solar facilities. For example, bison (*Bison bison*) remembered and used information about location and quality of meadows to make movement decisions, building individual cognitive maps of their environment (Merkle, Fortin, & Morales, 2014). Studies of species affected by solar facilities measuring the effect of changes in the distribution and availability of resources on animal behavior can help predict impacts of development at a population level.

4.2 Predation, antipredator behavior, and competition

Habitat modification can affect predator–prey dynamics (Dorresteijn et al., 2015; Hawlena, Saltz, Abramsky, & Bouskila, 2010) and competitive interactions between species (Berger-Tal & Saltz, 2019). At solar facilities, reflective surfaces of buildings and PV panels create polarized light pollution that attracts polarotactic organisms, including many insects (Horváth, Kriska, Malik, & Robertson, 2009). Insectivorous species might benefit from the increased availability of prey but trade off potential danger from collisions with reflective surfaces and increased competition for food. In the Mojave Desert, the population of urban-associated common ravens (*Corvus corax*) has increased with development, and they exert high predation pressure on threatened desert tortoise (Kristan & Boarman, 2003), which also face other impacts due to solar development (Lovich & Ennen, 2011).

Alternatively, PV panels or mirrors could serve as shelter for some animals against predators, especially aerial ones, and solar facility buildings and fences can also provide shelter and escape routes for smaller prey by excluding larger terrestrial predators (Cypher et al., 2019). Increased vegetation near structures due to runoff (BLM & DOE, 2012) may be perceived as protective cover from predators (Jacob, 2008), but the vegetation may also make it more difficult to detect predators. Peripheral visibility has been shown to be valued by both mammals (Bednekoff & Blumstein, 2009) and birds (Bednekoff & Lima, 1998); in areas with reduced peripheral visibility, animals perceive a greater risk of predation and may modify their behavior in potentially maladaptive ways, such as increasing time allocated to vigilance over foraging.

5 FUTURE RESEARCH AND DESIGNING SOLUTIONS

As evidenced by our research and those of others (Agha et al., 2020; Conkling, Loss, Diffendorfer, Duerr, & Katzner, 2020), more studies about the potential impacts of solar facilities on wildlife are needed to develop solutions. Documented efforts to deter wildlife from solar power facilities and other human-made structures include acoustic (Arnett et al., 2013; May, Reitan, Bevanger, Lorentsen, & Nygård, 2015; Swaddle, Moseley, Hinders, & Smith, 2016), visual (Martin, 2011; Goller, Blackwell, DeVault, Baumhardt, & Fernández-

Juricic, 2018; Hausberger, Boigné, Lesimple, Belin, & Henry, 2018), and tactile deterrents (Ho, 2016; Seamans, Martin, & Belant, 2013). Evaluation of the effectiveness of such deterrents, however, is often limited or inconclusive (e.g., Dorey, Dickey, & Walker, 2019), and may not address why individuals are attracted to the facilities or collide with facility structures in the first place. A more effective approach may be to understand wildlife perception of solar facilities and minimize features that attract them (e.g., Horváth et al., 2010), or modify features so that wildlife detect them and avoid collisions, burning and singeing. For instance, we can better understand how wildlife visually or otherwise perceive solar facilities by: (a) quantifying key properties of the sensory systems of species that experience high mortality, (b) use this information to quantify the degree of conspicuousness of solar panels and other structures from the species' sensory perspective, then (c) modify the properties of the solar panels to enhance or reduce their conspicuousness, and (d) measure behavioral responses to these modifications (Blackwell & Fernández-Juricic, 2013; Fernández-Juricic, 2016). For example, Horváth et al. (2010) tested the attraction of several aquatic insect species to PV solar panels with various modified features and found that white-framed and white-gridded panels were less attractive than black panels.

Our survey identified several research priorities for designing solutions focusing on where and how solar facilities can be built to minimize influences on behavior and fitness (Table 2 and Supporting Information 1). Another overarching question identified, while not specific to behavior, was whether facility designs should be exclusionary or permeable to wildlife. Some solar facilities are currently evaluating how to co-manage wildlife and PV panels by making them more permeable (e.g., Cypher et al., 2019; Wilkening & Rautenstrauch, 2019). Nevertheless, the answer to this question is likely complex and specific to geography and species (see also Moore-O'Leary et al., 2017).

With regard to assessing and minimizing impacts of solar facilities on wildlife, our workshop identified the need for more purposeful study designs to begin addressing these priority questions (Table 2). Ideally, a before-after control-impact design is desirable; whereby, key behaviors are studied before and after the solar facility is developed, both at the facility location and at control sites (Conkling et al., 2020; Lovich & Ennen, 2011). While this rarely happens (see Agha et al., 2020), such design is the most powerful way to isolate the effects of a solar facility on behavior while controlling for other spatial and temporal variation. Experimental studies assessing impacts of different design features (such as panel height and spacing, corridor placement and size, and vegetation treatment), in addition to studying behavior at different distances from solar facilities, are also necessary to minimize detrimental effects on wildlife.

6 CONCLUSIONS

Development of utility-scale solar facilities is expected to continue at a rapid pace (USEIA, 2019). There is an urgent need to address how to better locate, design, and operate solar facilities to mitigate potential negative effects on wildlife populations. We have highlighted major research themes addressing how approaches using animal behavior can be utilized to study wildlife-solar facilities interactions and how they could lead to solutions to reduce negative effects. Similar to how those in the wind energy industry have worked with animal behaviorists to reduce wildlife fatalities (e.g., Cryan et al., 2014), finding such solutions will need collaboration across industry, research, and management agencies. This can be achieved by forming working groups that can bring together entities from solar power facilities, wildlife agencies, and academia to determine shared research goals and to facilitate access to solar facilities, research permitting, and research funding opportunities (e.g., Bats and Wind Energy Cooperative, 2020).

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR' CONTRIBUTIONS

Rachel Y. Chock, **Barbara Clucas,** and **Elizabeth K. Peterson**: Organized the workshop that resulted in this study and coordinated the manuscript. All authors participated in the workshop and extensively contributed to the writing and revision of the manuscript.

ETHICS STATEMENT

The survey was approved by the Humboldt State University Institutional Review Board (IRB# 18-161).

Open Research

DATA AVAILABILITY STATEMENT

Survey questionnaire and results from the workshop are freely available and included as Supporting Information.

Supporting Information

Filename	Description
csp2319-sup-0001-SupinfoS1.docx Word 2007 document , 38 KB	**Appendix S1:** Supporting information
csp2319-sup-0002-SupinfoS2.pdf PDF document, 98.2 KB	**Appendix S2:** Supporting information

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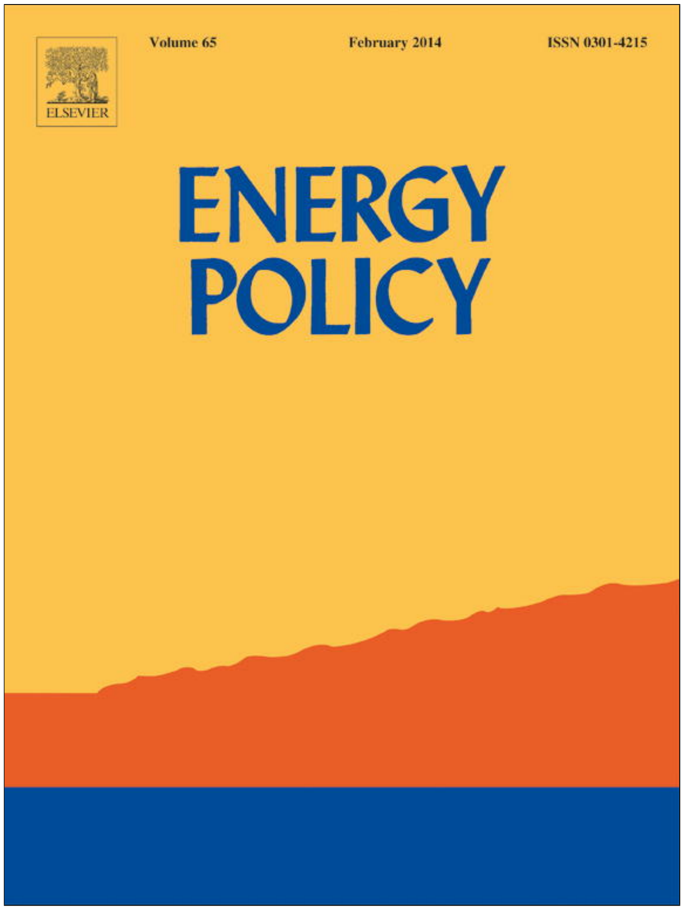

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Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey

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HIGHLIGHTS

- This article screens 153 lifecycle studies of wind and solar energy.
- Wind energy emits 0.4 g CO_2-eq/kWh to 364.8 g and a mean of 34.11 g.
- Solar PV emits 1 g CO_2-eq/kWh to 218 g and a mean of 49.91 g.

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ABSTRACT

This paper critically screens 153 lifecycle studies covering a broad range of wind and solar photovoltaic (PV) electricity generation technologies to identify 41 of the most relevant, recent, rigorous, original, and complete assessments so that the dynamics of their greenhouse gas (GHG) emissions profiles can be determined. When viewed in a holistic manner, including initial materials extraction, manufacturing, use and disposal/decommissioning, these 41 studies show that both wind and solar systems are directly tied to and responsible for GHG emissions. They are thus not actually emissions free technologies. Moreover, by spotlighting the lifecycle stages and physical characteristics of these technologies that are most responsible for emissions, improvements can be made to lower their carbon footprint. As such, through in-depth examination of the results of these studies and the variations therein, this article uncovers best practices in wind and solar design and deployment that can better inform climate change mitigation efforts in the electricity sector.

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1. Introduction

Herman Scheer, a former German Parliamentarian and influential renewable energy advocate, once stated that “[o]ur dependence on fossil fuels amounts to global pyromania… [a]nd the only fire extinguisher we have at our disposal is renewable energy” (Connolly, 2008). Scheer is famous for his work in creating Germany's renewable energy feed-in-tariff scheme and the ensuing adoption of solar photovoltaic and wind energy projects across the country. Although there are a number of options to reduce global dependence on fossil fuels that Scheer could have referred to, renewable sources of energy such as wind turbines and solar panels were his solution. This leaves at least one primary question to be resolved: how can we most effectively use the fire extinguisher?

To provide some answers, this study considers one of the most important aspects of our fossil fuel pyromania, the climate change implications of electricity generation. It assesses how two prominent renewable energy resources, solar photovoltaics (PV) and wind turbines, emit greenhouse gases (GHG), and it also offers suggestions for how such technologies can best be utilized or improved to mitigate climate change. By critically evaluating the current literature regarding lifecycle GHG emissions stemming from the full range of PV and wind electricity generation technologies, this study seeks to determine what the average lifecycle emissions are, where the emissions falls in terms of lifecycle stages, and what factors cause overall GHG variation in the literature, and can therefore be used to create the most effective climate change mitigation options.

Our assessment reveals the following. Within the “best” sample of 41 articles evaluated, the average lifecycle greenhouse gas emissions for wind energy were 34.1 g CO_2-eq/kWh, whereas solar PV averaged 49.9 g CO_2-eq/kWh. Essentially, these measures represent the amount of GHGs released in grams for each kWh of electricity that the technology provides, illustrated in Fig. 1.

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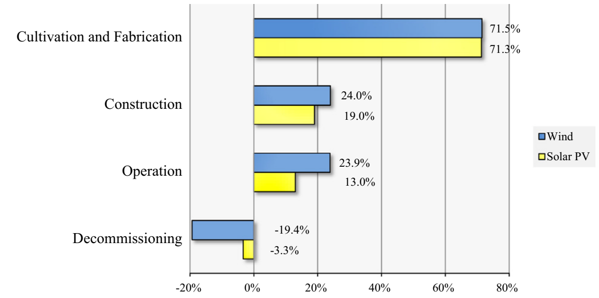

Fig. 1. Breakdown of lifecycle greenhouse gas emissions for wind energy and solar PV (% of total).

As that figure reveals, cultivation and fabrication are responsible for the largest share of emissions for both technologies, followed by construction and operation. Decommissioning practices often recycle materials from both systems back into future production processes, thus most studies argue that this constitutes an emissions "sink" that lowers the greenhouse gas profile for both types of systems.

To make its case, the article proceeds as follows. It starts by introducing readers to the specific lifecycle stages of both onshore and offshore wind turbines and solar photovoltaic panels. It then explains the research methods utilized by the authors to distill from 153 studies 41 of the most relevant, recent, peer-reviewed, original, and complete assessments. The next part of the article presents the findings from this selection process before explaining the factors behind the disparity in estimates for both wind and solar energy systems, and offering salient conclusions for technological entrepreneurs and energy policy analysts.

2. Explaining lifecycle stages

Generally, a lifecycle analysis determines a particular facet (functional unit) of an object, process, or product over the entire course of that subject's existence (Dale, 2013). For this particular study, that subject is both wind and solar photovoltaic electricity generators, and the functional unit by which both are examined is the GHG intensity in terms of grams of CO_2-equivalent emissions per kilowatt-hour (CO_2-eq/kWh) produced. Assessing the emissions of both PV and wind leads to a particularly broad categorization of what constitutes a lifecycle stage. Nonetheless, the literature suggests that four of those stages are salient: material cultivation and fabrication, construction, operation, and decommissioning. This section discusses each in turn.

2.1. Material cultivation and fabrication

In general, the material cultivation and fabrication stage represents the broadest group as it incorporates the full range of resource extraction, processing of materials, and the amalgamation of final products. Although details vary based upon the type of PV module, for instance (thin film, mono, poly, or multi-crystalline, dye-sensitized, quantum dot, and so on), material cultivation encompasses mining, refining and purification all of the silicon and/or other required metals and minerals for the cells, glass, frame, inverters, and other required electronics. Petroleum extraction for plastics, natural gas extraction used for heating, and effectively any other material extraction and processing needed to create the PV module and finished electronics are also included. Finally, the wiring, encapsulation and any other processes by which the modules and electronics are fabricated and finished (up until the point of transportation to the site of operation) are all included in this part of the stage for PV. Applying essentially the same concept to wind energy means metal and petroleum extraction for steel, plastics, internal wiring, etc., are included. Furthermore, composition and production of the blades, gears (although there are also gearless turbines), rotors, nacelle, turbine, and tower are all part of this stage.

2.2. Construction

A second stage involves the on-site construction of the generator and transportation of materials to the site. For PV, encompasses transporting the panels, and installing them along with the balance-of-system (BOS), including mounting structures, cabling and interconnection components, and inverter (although the exact BOS assumptions vary by study). GHG emissions for this stage thus include the processing of BOS materials and fossil fuels burned in transporting and assembling the system. For wind power, transportation and BOS includes a significant amount of cement and iron rebar to support structures, as well as cabling and construction of substations, when necessary.

2.3. Operation and maintenance

Operation is the third stage, and perhaps the most straightforward. Operation of solar PV includes maintenance, perhaps some minor replacements when necessary, cleaning of the modules, and any other processes that occur while the panels are in use. Essentially the same applies for wind, including regular maintenance and cleaning, possible replacement parts such as blades and gear components, and required material inputs such as hydraulic oil and oil filters used to lubricate turbines.

2.4. Decommissioning

Decommissioning is the final stage that essentially involves the deconstruction processes, disposal, recycling and (possibly) land reclamation. Because recycling is effectively a means of mitigating future GHG production, many of the studies we reference below consider this stage to decrease the total GHGs produced over the lifecycle of the generator. For instance, reclamation is not a standard practice for wind energy (the pads are often left or reused), and a majority of the steel towers, plastics, and fiberglass blades are recyclable. Accordingly, the process carries with it some significant offsetting of future emissions.

3. Research methods and selection criteria

To ensure that only the "best" peer-reviewed scientific literature was selected, as many on-topic studies as possible were collected by searching eight academic databases—Jstor, ScienceDirect, EbscoHost, Energy Citations Database, Web of Science, Water Resources Abstracts, Science Abstracts, and ProQuest abstracts (including Sustainability Science Abstracts and Engineering Abstracts)—between January 2013 and April 2013. The following terms were searched within the title, abstract, or keywords of a study: "lifecycle," "life-cycle," "life," "cycle," "analysis," "LCA (lifecycle analysis)," "GHG," "greenhouse gas," "green-house gas," "green house gas," "carbon dioxide," "CO2," "solar," "PV," "wind," "energy," "electricity," "renewable," and "resources." Generally some variation of the terms lifecycle, greenhouse gas, and solar and/or wind constituted the most effective searches.

These searches resulted in 153 lifecycle studies. To narrow within this broad base to a more robust sample, we filtered the literature to ensure that only the most relevant, modern, accurate and original findings were incorporated into this study. Fig. 2

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Fig. 2. Selection process for determining the best lifecycle studies for wind and solar energy. *Note*: Articles excluded for "relevance" refer to those articles that failed to provide any lifecycle GHG intensity estimates. Those excluded by "date" signifies an article published prior to 2003. Those excluded for "peer-review" could not be shown to have undergone any type of review prior to publication. Those excluded for "originality" refer to articles which provided no original GHG intensity analysis and merely relied on estimations contained in prior studies. Articles excluded for "completeness" only considered CO_2 lifecycle emissions, not the full range of GHGs in terms of CO_2-eq.

Table 1
Lifecycle studies excluded for relevance.

Source	Technology
Akyuz et al. (2011)	Wind, solar PV
Amor et al. (2010)	Wind, solar PV
Appleyard (2009)	Solar PV
Ardente et al. (2005)	Solar PV
Barrientos Sacari (2007)	Solar PV
Belfkira et al. (2008)	Wind, solar PV
Blanc et al. (2012)	Wind
Branker et al. (2011)	Manufacturing
Browne (2010)	Wind
Burger and Gochfeld (2012)	Wind, solar PV
Chel et al. (2009)	Solar PV
Crawford (2009)	Wind
Delucchi and Jacobson (2011)	Wind, solar PV
Espinosa et al. (2011b)	Solar PV
Espinosa et al. (2012)	Solar PV
Fthenakis (2004)	Solar PV
Fthenakis et al. (2009a)	Solar PV
Granovskii et al. (2007)	Wind, solar PV
Gustitus (2012)	Wind
Himri et al. (2008)	Wind
Huang et al. (2012)	Solar PV
Jacobson and Delucchi (2011)	Wind, solar PV
Kaldellis et al. (2012)	Wind, solar PV
Kammen (2011)	Solar PV
Katzenstein and Apt (2009)	Wind, solar PV
Kreiger et al. (2013)	Solar PV
Kubiszewski et al. (2010)	Wind
Limmeechokchai and Suksuntornsiri (2007)	Wind, solar PV
Lindstad et al. (2011)	Shipping
Lundahl (1995)	Wind, solar PV
Marimuthu and Kirubakaran (2013)	Wind, solar PV
Martinez et al. (2009b)	Wind
Martinez et al. (2010)	Wind
Martinez et al. (2012)	Wind, solar PV
Mason et al. (2006)	Solar PV
Matsuhashi and Ishitani (2000)	Solar PV
McCubbin and Sovacool (2013)	Wind
Mendes et al. (2011)	Solar PV
Mohr et al. (2009)	Solar PV
Muller et al. (2011)	Wind, solar PV
Nandi and Ghosh (2010a)	Wind
Nandi and Ghosh (2010b)	Wind
Oke et al. (2008)	Solar PV
Ou et al. (2011)	Wind, solar PV
Pearce (2002)	Solar PV
Pieragostini et al. (2012)	Lifecycle Methodology
Rashedi et al. (2012)	Wind
Raugei and Frankl (2009)	Solar PV
Rubio Rodriguez et al. (2011)	Wind
Silva (2010)	Wind, solar PV
Sioshansi (2009)	Energy technology
Tokimatsu et al. (2006)	Nuclear
Tripanagnostopoulos et al. (2005)	Solar PV
Vadirajacharya and Katti (2012)	Wind, solar PV
Velychko and Gordiyenko (2009)	GHG inventories
Vuc et al. (2011)	Wind, solar PV
Whittington (2002)	Wind, solar PV
Zhai et al. (2011)	Wind, solar PV

Table 2
Lifecycle studies excluded for recentness.

Source	Technology	g CO_2/kWh
Huber and Kolb (1995)	Solar PV	–
Kato et al. (2001)	Solar PV	14–9
Kemmoku et al. (2002)	Wind, solar PV	–
Kreith et al. (1990)	Solar PV	–
Lenzen and Munksgaard (2002)	Wind	–
Norton et al. (1998)	Solar PV	–
Schleisner (2000)	Wind	9.7–16.5
Sorensen (1994)	Wind, solar PV	–
Van de Vate (1997)	Wind, solar PV	–
Voorspools et al. (2000)	Wind, solar PV	–

shows that, through this process, the application of five selection criteria whittled our sample down to only 41 of the "best" studies. The following subsections detail this selection process.

3.1. Relevance

The first exclusionary step entailed removing a total of 58 articles based upon relevance. These studies, shown to the left in Table 1, did not specifically address lifecycle GHG emissions of either wind or solar, or else did not provide necessary information, such as total emissions and total electricity produced, that could be used to easily find that value. While there were many comprehensive and competent studies among those excluded for this reason, they primarily focused on other measures such as the efficiency or effectiveness of PV and wind, oftentimes considering total costs and rates of return, total energy input and energy-payback times, and even other environmental measures such as toxicity, carcinogen output, and water consumption, but *not* greenhouse gas emissions.

3.2. Recentness

The second exclusionary condition was that of recentness, which was responsible for the omission of the 10 articles shown in Table 2. Due to the rapid technological progress that has occurred in the efficiency, sizing, and implementation of PV and wind systems over the last decade, a 10 year publication window extending to 2003 was constructed, effectively blocking out all material published beforehand. However, as evidenced in Tables 5 and 8, the earliest retained piece of literature was published in 2004 (the only 2004 inclusion), with only three 2005 studies, and only 12 of the total 41 predating 2008. Although unintentional, more than 70% of the studies are actually within a five year window.

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3.3. Peer review

Our third step involved excluding studies that were not formally peer-reviewed. Peer review was thought critical to ensuring the integrity of the analysis. The only literature examined beyond peer reviewed journals came from conference proceedings, which were then checked for peer review by a scientific committee in order to pass this standard. In all, only one conference report – Noori et al. (2012) – was unable to be verified and was removed from the sample for not meeting this condition.

3.4. Originality

The fourth restriction was to exclude 28 studies shown in Table 3 that were not a primary source. Effectively, all articles that did not provide new and original CO_2-eq/kWh information were eliminated to avoid reliance on sources more than once (so as to not skew the analysis), and also to ensure that the other exclusionary criteria were not subverted (e.g., the secondary source could be based on primary information that was not peer reviewed). Other articles were excluded if they included a GHG intensity estimate as a part of a different type of analysis and thus relied on other sources for the numbers, or amalgamated other lifecycle studies and gave a range or average, not significantly unlike this study. A few very detailed studies done in conjunction with the National Renewable Energy Laboratory's (NREL) "Life Cycle Harmonization Project" were included despite this literature compilation approach. Examples include Hsu et al. (2012), Kim et al. (2012) and Dolan and Heath (2012), not to be confused with the NREL factsheets excluded for originality in Table 3. These included studies did much more than simply find a range or average g CO_2-eq/kWh estimate, and instead recalculated estimates from other studies by harmonizing the conditions that the studies assumed, for example by inputting consistent life expectancies, wind speeds or solar irradiance.

Table 3
Lifecycle studies excluded for lack of originality.

Source	Technology	g CO_2/kWh
Arvesen and Hertwich (2012)	Wind	6–34
Bensebaa (2011)	Solar PV	30
Chaurey and Kandpal (2009)	Solar PV	–
Dones et al. (2004)	Wind	10–20
	Solar PV	39–73
Dotzauer (2010)	Wind	9–10
	Solar PV	32
Dufo-Lopez et al. (2011)	Wind, solar PV	–
Evans et al. (2009)	Wind	25
	Solar PV	90
Fthenakis et al. (2008)	Solar PV	24, 30–45, 39–110
Fthenakis and Kim (2011)	Solar PV	38
Georgakellos (2012)	Wind	8.20
	Solar PV	104
Goralczyk (2003)	Wind, solar PV	–
Graebig et al. (2010)	Solar PV	–
Hardisty et al. (2012)	Wind, solar PV	–
Kannan et al. (2007)	Solar PV	217
Kenny et al. (2010)	Solar	21–59
NREL (National Renewable Energy Laboratory) (2012)	Solar PV	40
NREL (National Renewable Energy Laboratory) (2013)	All electricity generation	–
Pacca et al. (2007)	Solar PV	34.3–50
Padey et al. (2012)	Wind	4.5–76.7
Peng et al. (2013)	Solar PV	10.5–50
Raadal et al. (2011)	Wind	17.5
Sherwani et al. (2010)	Solar PV	15.6–280
Tyagi et al. (2013)	Solar PV	9.4–2820
Van der Meulen and Alsema (2011)	Solar PV	–
Varun et al. (2009a)	Wind	9.7–123.7
	Solar PV	53.4–250
Varun et al. (2009b)	Wind	16.5–123.7
	Solar PV	9.4–300
Weisser (2007)	Wind	18
	Solar PV	56
Yang et al. (2011)	Wind	.56

Table 4
Lifecycle studies excluded for failure to consider all GHGs.

Source	Technology	g CO_2/kWh
Garcia-Valverde et al. (2009)	Solar PV	131
Ito et al. (2008)	Solar PV	9–16
Ito et al. (2009)	Solar PV	51.5–71
Ito et al. (2010)	Solar PV	43–54
Kleijn et al. (2011)	Wind	15
	Solar PV	60
Krauter and Ruther (2004)	Solar PV	11–75
Lee and Tzeng (2008)	Wind	3.6
Lenzen and Wachsmann (2004)	Wind	2–81
Li et al. (2012)	Wind	69.9
McMonagle (2006)	Solar PV	0–59
Pehnt et al. (2008)	Wind	22
Sherwani et al. (2011)	Solar PV	55.7
Sumper et al. (2011)	Solar PV	–
Wang and Sun (2012)	Wind	4.97–8.21
Zhai and Williams (2010)	Solar PV	21

3.5. Completeness

A final factor used to screen the literature was for failure to consider the entire range of GHGs, which then led to the removal of 15 articles shown in Table 4. Although these articles generally met the previous requirements, they only attempted to quantify the CO_2 lifecycle emissions attributed to wind and/or solar PV. In the interests of focusing this study on the entirety of GHGs (in order to assess the totality of the global warming potential of wind and solar PV), these articles were excluded.

4. Assessing the greenhouse gas intensity of wind energy

After removing a total of 112 studies based upon our five selection criteria, 41 studies remained which are relevant, published in the past 10 years, peer-reviewed, provided original estimates of total GHG intensity, and incorporated all greenhouse gases. These studies were then disaggregated into those looking at wind and solar PV, with Table 5 presenting those related to wind energy. These studies were "weighed" equally; that is, they were not adjusted for their methodology, time of release within the past ten years, or how rigorously they were peer reviewed or cited in the literature. Additionally, the estimates were not harmonized for divergent variables or assumptions inherent in their analysis. The studies in Table 5 are quite global in nature, spanning at least five continents specifically, and including several studies that were global.

Statistical analysis of these 22 studies and 39 estimates reveals a range of greenhouse gas emissions over the course of wind's lifecycle at the extremely low end of 0.4 g CO_2-eq/kWh and the extremely high end of 364.8 g CO_2-eq/kWh. Accounting for the average values of emissions associated with each part of wind energy's lifecycle, the mean value reported is 34.1 g CO_2-eq/kWh—numbers reflected in Fig. 3 and Tables 6 and 7. As Fig. 1 already depicted in the introduction, cultivation and fabrication are

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Table 5
Total lifecycle GHG emissions and factors for 22 qualified wind energy studies.

Source	Location	Life (years)	Onshore/ offshore	System/turbine capacity	Hub height (m)	Rotor diameter (m)	Other assumptions	Total estimate (g CO_2-eq/kWh)
Ardente et al. (2008)	Italy	20	Onshore	11 × 660 kW turbines	55	50		**14.8**
Chen et al. (2011)	Guangxi, China	20	Onshore	24 × 1.25 MW turbines	55	31	7 m/s avg. wind speed	**0.56**
Dolan and Heath (2012)	Global	20	Both		–	–	.25 capacity factor	**11**
Fleck and Huot (2009)	–	20	Onshore	5 × 400 W turbines	30	1.17	Off-grid, with battery bank, .17 capacity factor	**364.83**
Guezuraga et al. (2012)	Global (German, Chinese, Denmark manufacturing)	20	Onshore	1.8 MW gearless turbine	–	–		**8.82**
				2 MW geared turbine	105	90	7.4 m/s avg. wind speed	**9.73**
Hondo (2005)	Japan	30	Onshore	300 kW turbines	–	–	.2 capacity factor	**29.5**
Kabir et al. (2012)	Alberta, Canada	25	Onshore	20 × 5 kW turbines	36.6	5.5	.23 capacity factor	**42.7**
				5 × 20 kW turbines	36.7	9.45	.22 capacity factor	**25.1**
				100 kW turbine	37	21	.24 capacity factor	**17.8**
Khan et al. (2005)	Newfoundland, Canada	20	Onshore	500 kW system	–	–	Turbine, no fuel cell storage	**16.86**
							Turbine with fuel cell storage	**59.31**
Mallia and Lewis (2013)	Ontario, Canada	20	Onshore		–	–	Avg. Canadian electricity mix (210 g CO_2-eq/kWh)	**10.69**
Manish et al. (2006)	India	-	Onshore	18 × 500 kW turbines	–	–	2003 global electricity mix, .1–.3 capacity factor	**12–40**
Martinez et al. (2009a)	Munilla, Spain	20	Onshore	2 MW turbine	70	80		**6.58**
Mithraratne (2009)	Production UK, Installation New Zealand	20	Onshore	1.5 kW turbines	10	2	Roof mounted, .04 – .064 capacity factor, New Zealand electricity mix (224 g CO_2-eq/kWh), 5.5–6.3 m/s avg. wind speed	**138–220**
Oebels and Pacca (2013)	North Eastern Brazil	20	Onshore	14 × 1.5 MW turbines	80	–	Brazilian electricity mix (64 g CO_2-eq/kWh), .3425 capacity factor, 7.8 m/s avg. wind speed	**7.1**
Padey et al. (2013)	Europe	-	Onshore		–	–	–	**12.9**
Pehnt (2006)	Germany	-	Onshore	1.5 MW turbine	–	–	566 g CO_2-eq/kWh electricity mix	**11**
			Offshore	2.5 MW turbine	–	–	566 g CO_2-eq/kWh electricity mix	**9**
Querini et al. (2012)	Global	20	Onshore	2 MW turbine	–	–		**12**
Songlin et al. (2011)	Fuzhou, China	–	–	2 MW turbine	–	–		**0.43**
Tremeac and Meunier (2009)	Southern France	20	Onshore	4.5 MW turbines	124	113		**15.8**
	Production Finland, Installation France	20	Onshore	250 W wind turbines	–	–	Finnish electricity mix	**46.4**
Wagner et al. (2011)	German North Sea	20	Offshore		–	–		**32**
Weinzettel et al. (2009)	–	20	Floating Offshore	40 floating 5 MW turbines	100 (above sea level)	116		**0.89**
Wiedmann et al. (2011)	UK	30	Offshore	2 MW farm	–	–	Process lifecycle analysis, .3 capacity factor	**13.4**
							Integrated hybrid lifecycle analysis, .3 capacity factor	**28.7**
							IO-based hybrid lifecycle analysis, .3 capacity factor	**29.7**
Zimmermann and Gößling-Reisemanna (2012)	Germany	20	Onshore	2.3 MW system	98	80		**7.9**
					84	80	7.5 m/s avg. wind speed	**12.5**
					98	80	7.72 m/s avg. wind speed	**12**
					108	80	7.9 m/s avg. wind speed	**11.2**
					98	80	7.9 m/s avg. wind speed	**10.8**
					108	80	8.15 m/s avg. wind speed	**10.1**
					98	80	8.14 m/s avg. wind speed	**9.8**
					108	80	8.57 avg. wind speed	**8.3**

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responsible for about 71% of wind's emissions, followed by construction (24%), operation (slightly less than 24%), and decommissioning, which offset 19.1 percent of wind's emissions.

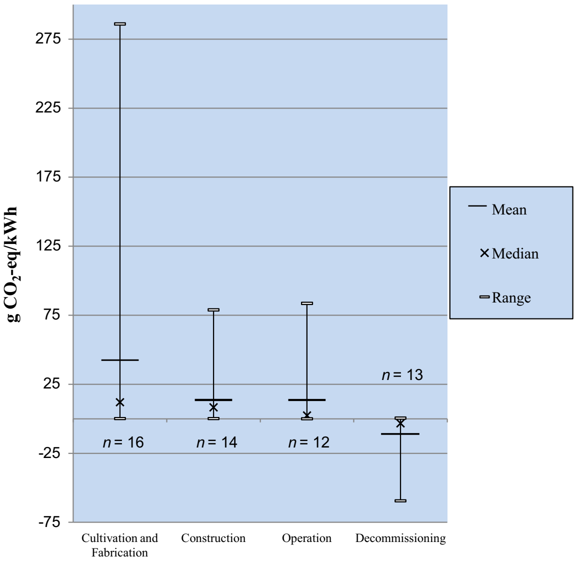

Fig. 3. Lifecycle greenhouse gas emissions for wind energy by lifecycle stage.

5. Assessing the greenhouse gas intensity of solar PV

Sticking with the same selection process, Table 7 presents the 23 most relevant, recent, peer-reviewed, original, and complete studies for solar PV. These studies, similar to those for wind energy, were weighted equally. Estimates were also not harmonized for different assumptions or variables. The studies in Table 8 are also quite global in nature, spanning three continents and/or the globe.

Statistical analysis of these 23 studies and 57 estimates reveals a range of greenhouse gas emissions over the course of solar PV's lifecycle at the extremely low end of 1 g CO_2-eq/kWh and the high end of 218 g CO_2-eq/kWh. Accounting for the average values of emissions associated with each part of solar PV's lifecycle, the mean value reported is 49.9 g CO_2-eq/kWh – numbers reflected in Fig. 4 and Tables 9 and 10 – though the number of selected studies providing estimates for operation and maintenance (2) and decommissioning (5) is low. As Fig. 1 also depicted in the introduction, cultivation and fabrication are responsible for about 71% of solar PV's emissions, followed by construction (19%), operation (13%), and decommissioning, which offset 3.3% of emissions.

6. What causes the disparity in wind and solar estimates?

Though the tables and figures above do a satisfactory job documenting the lifecycle emissions associated with wind energy

Table 6
Summary statistics of qualified studies reporting projected greenhouse gas intensity for wind energy.

	Cultivation and fabrication (**n**=16)	Construction (**n**=14)	Operation (**n**=12)	Decommissioning (**n**=13)	Total (**n**=39)
Mean	42.98	14.43	14.36	–11.64	34.1
Median	11.99	8.26	2.37	–3.27	12
Mode	–	9	–	–	12
Std. Dev.	76.95	21.17	26.3	18.76	67.23
High	286.02	78.85	83.6	0.5	364.8
Low	0.15	0.15	0.02	–59.4	0.4
Percentage of Total (%)	71.48	24.00	23.88	–19.36	100

Note that the “total” column equals the mean for all lifecycle studies that made it past our screen, not necessarily those that broke emissions down by specific lifecycle stages. “*n*” also refers to number of estimates, not necessarily number of studies.

Table 7
Detailed statistics of qualified studies reporting lifecycle equivalent greenhouse gas intensity for wind energy.

Source	Cultivation and fabrication	Construction	Operation	Decommissioning	Total
Chen et al. (2011)	0.15	0.42	0.02	–	0.56
Fleck and Huot (2009)	286.02	78.85	–	–	364.83
Guezuraga et al. (2012)	7.89	–	–	–	8.82
	7.59	–	–	–	9.73
Hondo (2005)	13.7	7.4	8.3	–	29.5
Kabir et al. (2012)	30.74	9.11	14.8	–11.96	42.7
	12.01	12.55	3.82	–3.27	25.1
	11.97	10.13	0.92	–5.22	17.8
Mallia and Lewis (2013)	–	–	0.74	0.27	10.69
Martinez et al. (2009a)	6.96	2.01	0.35	–2.75	6.58
Mithraratne (2009)	98	24.1	52.4	–37.2	138
	156.2	37.4	83.6	–59.4	220
Oebels and Pacca (2013)	5.31	1.75	0.04	–	7.1
Songlin et al. (2011)	0.27	0.15	–	–	0.43
Tremeac and Meunier (2009)	–	–	0.8	–3.6	15.8
	–	–	–	–29.5	46.4
Wagner et al. (2011)	–	–	6.5	0.4	32
Wiedmann et al. (2011)	9.5	3	–	0.43	13.4
	22.5	4.8	–	0.5	28.7
	18.8	10.3	–	0.01	29.7

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Table 8
Total lifecycle GHG emissions and factors for 23 qualified solar PV studies.

Source	Location	Life (years)	Irradiance (kWh/m^2)	Tech	Mounting	Assumptions	Estimate (g CO_2-eq/kWh)
Alsema and de Wild-Scholten (2004)	Southern Europe	–	–	Ribbon-Si	–		**28**
	Netherlands/Germany	–	–	Ribbon-Si	–		**48**
	Southern Europe	–	–	Multi-Si	Roof mount		**73**
	Netherlands/Germany	–	–	Multi-Si	Roof mount		**124**
Alsema et al. (2006)	Production US, Installation Southern Europe	30 (15 inverter)	1700	CdTe	Ground mount	9% efficiency	**25**
	Southern Europe	30 (15 inverter)	1700	Ribbon-Si	Roof mount	11.5% efficiency	**29.5**
				Mono-Si	Roof mount	14% efficiency	**35**
				Multi-Si	Roof mount	13.2% efficiency	**32**
Beylot et al. (2014)	-	30	1700	Multi-Si	30° tilt, fixed aluminum mount	5 MWp, 14% module efficiency	**53.5**
					30° tilt, fixed wood mount	5 MWp, 14% module efficiency	**38**
					30° tilt, single axis tracking	5 MWp, 14% module efficiency	**37.5**
					30° tilt, dual axis tracking	5 MWp, 14% module efficiency	**42.8**
Bravi et al. (2011)	Europe	20	1700	Micromorph	22° roof mount	125 Wp module, 8.74% efficiency, 513 g CO2/kWh European electricity mix	**20.9**
Desideri et al. (2013)	Sicily, Italy	30	1600–1800	Mono-Si	30° tilt, ground mounted single-axis tracking	13.85% module efficiency, 2 MWp	**47.9**
de Wild-Scholten et al. (2006)	Southern Europe	30 (15 inverter)	1700	Multi-Si	on-roof Phonix mounting structure	11.4 kWp, 13.2% module efficiency	**38**
					on-roof Schletter roof hooks	11.4 kWp, 13.2% module efficiency	**35.5**
					in-roof Schletter mounting structure	11.4 kWp, 13.2% module efficiency	**32**
					in-roof Schweizer mounting structure	11.4 kWp, 13.2% module efficiency	**32.5**
					ground Phonix mount	11.4 kWp, 13.2% module efficiency	**41**
					ground Springerville mount	11.4 kWp, 13.2% module efficiency	**37**
Espinosa et al. (2011a)	Manufacturing Denmark, Installation Southern Europe	15	1700	Transparent organic polymer, indium-tin-oxide (ITO)	-	2% module efficiency, 2008 Denmark energy mix (420.88 g CO_2-eq/kwh)	**37.77**
						3% module efficiency, 2008 Denmark energy mix (420.88 g CO_2-eq/kwh)	**56.65**
Fthenakis and Alsema (2006)	Europe	30	1700	Multi-si	On-roof mount	european electricity mix 13.2% efficiency	**37**
				CdTe	On-roof mount	european electricity mix, 8% efficiency	**21**
				Ribbon-Si	On-roof mount		**30**
				mono-Si	on-roof mount		**45**
	Production US, Installation Europe	30	1700	CdTe	ground mount	US electricity mix, 9% efficiency	**25**
Fthenakis and Kim. (2006)	United States	30	1800	CdTe	Ground mount	25 MWp, 9% efficiency	**24**
Fthenakis et al. (2009b)	Ohio, USA	–	1700	CdTe	–	10.9% efficiency, US electricity mix (750 g CO_2-eq/kWh)	**12.75**
Garcia-Valverde et al. (2010)	Southern Europe	15	1700	Organic/plastic	–	5% module efficiency	**109.84**
Glockner et al. (2008)	Europe	30	1700	Multi-Si	On-roof mount Schletter mounting	Siemens Si processing, 13.2% module efficiency	**30**
						Elkem Solar Si processing, 13.2% module efficiency	**23**
Hondo (2005)	Japan	30	–	Poly-Si	On-roof mount	3 kWp, 0.15 capacity factor, 10% efficiency	**53.4**
Hsu et al. (2012)	Global	30	1700	c-Si	–		**45**
				mono-Si	–	14% module efficiency	**40**
				Multi-Si	–	13.2% module efficiency	**47**
				c-Si	Ground mount		**48**
				c-Si	Roof mount		**44**
Jungbluth (2005)	Switzerland	30	1100	Poly-Si	On-roof mount	3 kWp, 79 g CO_2-eq/kWh electricity mix	**39–110**
Kannan et al. (2006)	Singapore	25	1635	Mono-Si		2.7 kWp	**217**

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Table 8 (*continued*)

Source	Location	Life (years)	Irradiance (kWh/m²)	Tech	Mounting	Assumptions	Estimate (g CO_2-eq/kWh)
					Aluminum/concrete roof mount		
Kim et al. (2012)	Global	30	2400	a-Si	Ground mount	6.3% efficiency	**20**
				CdTe	Ground mount	10.9% efficiency	**14**
				CIGS	Ground mount	11.5% efficiency	**26**
				a-Si	On-roof mount	6.3% efficiency	**21**
				CdTe	On-roof mount	10.9% efficiency	**14**
				CIGS	On-roof mount	11.5% efficiency	**27**
Manish et al. (2006)	India	20	–	–	–	10-15% efficiency	**50–130**
Pehnt (2006)	Germany	25	–	Poly SOG-Si	–	566 CO_2-eq/kWh electricity mix	**104**
Querini et al. (2012)	Global	30	1204	Mono-Si	45 degree fixed mount		**92**
Reich et al. (2011)	–	30	1300	c-Si	–	no F-gas emissions, renewable electricity mix (1 g CO_2-eq/kWh), 15% efficiency	**1**
						coal electricity mix without CCS (1,000 g CO_2-eq/kWh), 15% efficiency	**218**
Sengul and Theis (2011)	Europe	30	1700	CdSe QDPV	Ground mount	14% efficiency	**5**
Veltkamp and de Wild-Scholten (2006)	Southern Europe	5	1700	Glass – glass (DSC) dye sensitizes	–	8% efficiency	**106.25**
		10	1700		–	8% efficiency	**52.5**
		20	1700		–	8% efficiency	**17.5**

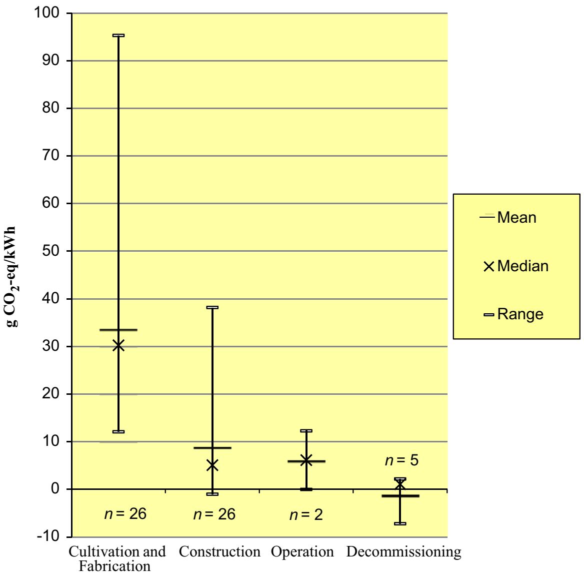

Fig. 4. Lifecycle greenhouse gas emissions for solar PV by lifecycle stage.

and solar PV systems from our “best” sample of studies, substantial disparities do exist, and this section of the study explains how at least eight separate factors play a role in these differences: (1) resource inputs and technology, (2) transportation, (3) manufacturing, (4) location, (5) sizing and capacity, (6) longevity, (7) optional equipment, and (8) calculation methods.

6.1. *Resource inputs and technology*

The material inputs required for wind generation necessarily vary in the literature based upon physical size (capacity and hub height), the location and design of the plant (onshore versus offshore and interconnection distances), and even based upon the type of technology used (floating turbines, turbines with and without gearboxes, etc.). Guezuraga et al. (2012) compares two turbines, one 2 MW geared turbine and one 1.8 MW gearless turbine, and found significantly higher stainless steel, reinforced concrete and total mass calculations (1538 t) for the former, and higher copper requirements, but overall lower mass (360 t) for the latter. Intuitively, these sorts of differences alter the GHG intensity of the manufacturing and construction lifecycle stages. Also, despite presumably greater material inputs required by offshore wind installations to reach the seabed and the general presumption that they are generally larger turbines to take advantage of higher wind speeds, offshore estimates in the literature show decreased emissions intensity. While there was a much larger estimate sample for onshore (31 compared to 6), and some obvious outliers, offshore estimates showed a lower mean intensity illustrated by Fig. 5.

Similarly, PV technologies vary substantially in their emissions profiles, given that they require somewhat different material inputs. Our sample of studies included crystalline silicon technologies such as mono-crystalline (mono-Si), poly-crystalline (poly-Si), multi-crystalline (multi-Si) and ribbon multi-crystalline (ribbon-Si), as well as several thin-film technologies such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper – indium – gallium – diselenide (CIGS). The sample also included other PV types such as micromorph (a-Si and micro-Si hybrid), organic/plastic cells (including indium-tin-oxide, dye sensitized and others), and cadmium selenide quantum-dot photovoltaics (CdSe QDPV). All of these technologies have distinct material and processing requirements,

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Table 9
Summary statistics of qualified studies reporting projected greenhouse gas emissions for solar PV.

	Cultivation and fabrication	**Construction**	**Operation**	**Decommissioning**	**Total**
	(*n*=26)	**(*n*=26)**	**(*n*=2)**	**(*n*=5)**	**(*n*=57)**
Mean	33.67	8.98	6.15	−1.56	49.9
Median	30.25	5.1	6.15	1.1	37.8
Mode	16, 21.3, 33, 36	2	–	2.2	14, 21, 25, 30, 32, 37, 38, 45, 48
Standard Deviation	20.57	10.15	8.7	4.68	43.3
High	95.31	38.2	12.3	2.2	218
Low	12.1	−1	0	−7.2	1
Percentage of total (%)	71.30	19.00	13.00	−3.30	100

Note that the "total" column equals the mean for all lifecycle studies that made it past our screen, not necessarily those that broke emissions down by specific lifecycle stages. "*n*" also refers to number of estimates, not necessarily number of studies.

Table 10
Detailed statistics of qualified studies reporting lifecycle equivalent greenhouse gas emissions for solar PV.

Source	**Cultivation and fabrication**	**Construction**	**Operation**	**Decommissioning**	**Total**
Alsema et al. (2006)	25.4	4.1	–	–	29.5
	28.7	3.3	–	–	32
	31.8	3.2	–	–	35
	18.75	6.25	–	–	25
Beylot et al. (2014)	21.3	38.2	–	−6.1	53.5
	21.3	15.6	–	1.1	38
	20.2	23.2	–	2.2	37.5
	16	24.6	–	2.2	42.8
de Wild-Scholten et al. (2006)	37	1	–	–	38
	33.5	2	–	–	35.5
	33	−1	–	–	32
	33	−0.5	–	–	32.5
	36	5	–	–	41
	36	1	–	–	37
Fthenakis and Alsema (2006)	32.5	4.5	–	–	37
	16	5	–	–	21
	19	6	–	–	25
Glockner et al. (2008)	28.1	2	–	–	30
	20.9	2	–	–	23
Hondo (2005)	28.3	9.8	12.3	–	53.4
Jungbluth (2005)	33.8–95.31	5.19–14.66	0	–	39-110
Querini et al. (2012)	85.6	6.3	–	−7.2	92
Veltkamp and de Wild-Scholten (2006)	75	31.3	–	–	106.25
	36.9	15.6	–	–	52.5
	12.1	5.3	–	–	17.5

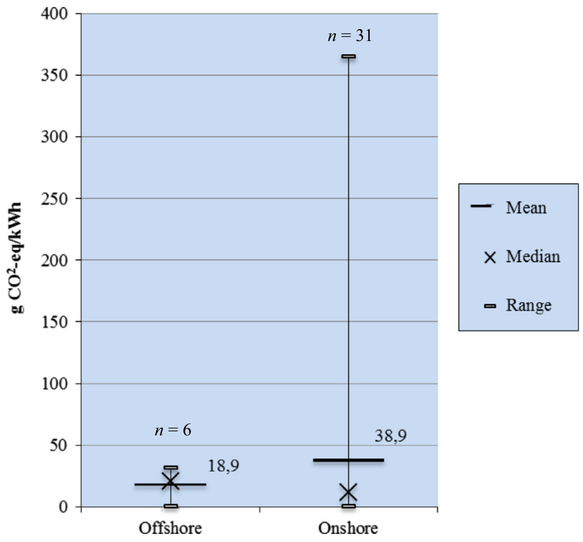

Fig. 5. Differences in greenhouse gas intensity for onshore and offshore wind turbines.

leading to different solar conversion efficiencies in the final product, and thus an exceptional range of emissions possibilities for PV as a whole—statistics reflected in Table 11. Table 11 shows mono-Si to have the highest average estimated emissions and CdSe QDPV ranks as having the lowest emissions, though the sample sizes of the studies behind these claims are small.

6.2. *Transportation*

While transportation – a subcomponent of our construction lifecycle stage – might not seem like a major GHG producing aspect of either wind or solar PV, there is significant variation in the literature. For wind, the highest transportation estimate accounted for 28.3% of total emissions (Mallia and Lewis, 2013), whereas the average percentage share of transportation is significantly lower, at only 11.8%, and the lowest estimates fall to as small as 0.2% (Chen et al., 2011). There are a number of factors that can explain this variation. First, assessments of smaller turbines that include battery backup and additional optional equipment, potentially manufactured and transported separately from different locations, and overall producing less lifetime energy than large multi-megawatt turbines, show a higher than average share of transportation GHGs. For

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Table 11
Differences in greenhouse gas intensity based on solar PV material inputs.

PV technology	Mean	Median	*n*	Mode	Standard deviation	High	Low
Mono-Si	**79.5**	46.5	6	–	70.4	217.0	35.0
Multi-Si	**44.3**	37.5	17	32, 37, 38	23.3	124.0	23.0
Poly-Si	**78.7**	78.7	2	–	35.8	104.0	53.4
Ribbon	**33.9**	29.8	4	–	9.5	48.0	28.0
Total c-Si	**55.3**	40.5	34	30, 32, 37, 38, 45, 48	47.1	218.0	1.0
a-si	**20.5**	20.5	2	–	0.7	21.0	20.0
CIGS	**26.5**	26.5	2	–	0.7	27.0	26.0
CdTe	**19.4**	21.0	7	14, 25	5.6	25.0	12.8
Total thin-film	**20.9**	21.0	11	14	5.2	27.0	12.8
Organic ITO	**47.2**	47.2	2	–	13.4	56.7	37.8
Dye sensitized	**58.8**	52.5	3	–	44.7	106.3	17.5
Total organic	**63.4**	54.6	6	–	37.2	109.8	17.5
CdSe QDPV	**5.0**	5.0	1	–	–	5.0	5.0
Micromorph	**20.9**	20.9	1	–	–	20.9	20.9

example, Fleck and Huot (2009) find a large 78.85 g CO_2-eq/kWh, equating to 21.5% of lifecycle intensity, resulting from transportation for very small 400 W turbines with battery backup. Further transportation discrepancies could arise between onshore and offshore turbines as they necessarily entail different transportation processes, types (boat, airplane, rail, truck) and distances involved.

PV lifecycle studies seemingly focused significantly less on defining the GHG intensity of transportation, which is a clear weakness of the literature as a whole. Although the same theoretical implications as considered for wind systems should apply, the only individual estimate specifically for transportation was that of Querini et al. (2012), which found 6.3 g CO_2-eq/kWh accounting for 6.9% of the total emissions profile.

6.3. Manufacturing

Fabrication and manufacturing are energy intensive processes which may partially depend on direct fossil fuel use, generally for heating processes, but also significantly rely on electricity inputs. One assumption found throughout wind and PV literature relates to the electricity mix of the locale, considering the types of electricity generators (coal, natural gas, nuclear, renewables) which supply the local grid. Depending upon how carbon intensive these sources are, wind and solar estimates vary.

In the case of wind, Guezuraga et al. (2012) showed that the same manufacturing process in Germany would result in less than half of the total emissions that such a process would entail in China. This was primarily due to China's significantly greater dependence on black coal for electricity production in comparison with Germany's much greater reliance on natural gas and nuclear power. Oebels and Pacca (2013) also attributed significant disparity to the location of manufacturing, noting that the Brazilian electricity mix, being as low as 64 g CO_2-eq/kWh (as much as eight times lower than the global average), had a significant effect on their low overall calculation (7.1 g CO_2-eq/kWh). This contrasts with Pehnt (2006) which used a 566 g CO_2-eq/kWh energy mix and returned a 9–11 g CO_2-eq/kWh wind calculation, a 55% increase to Oebels and Pacca (2013).

For PV, this trend again applies as PV manufacturing also depends upon electricity to compose finished modules. Some energy mix assumptions made in the literature include a Danish grid intensity of 420.88 g CO_2-eq/kWh (Espinosa et al., 2011a) and a 566 g CO_2-eq/kWh for Germany (Pehnt, 2006). One study that pays explicit attention to this factor, Reich et al. (2011), concludes that the source of the electricity mix can affect the GHG intensity of a PV installation anywhere from zero g CO_2-eq/kWh (for an all renewable and nuclear mix) to 200 g CO_2-eq/kWh (for coal-only mixes). Manufacturing can also see emissions intensity variation based upon the particular type of PV technology considered and its relevant processing steps. For example, quartz extraction from sand and then processing and refinement are needed to create PV grade silicate for some panels, whereas others such as CIGS may not need silicates at all. Other influential factors include the type of PV technology. For amorphous, multi, and mono PV systems, silicates may need to be converted into different products, such as ingots, wafers, or other components, to form the finished panel (Glockner et al., 2008). Accordingly, the amount of energy and GHG emissions attributable to all of these processes can lead to significant variation.

6.4. Location

Emissions efficiency is directly tied to geographic location and the solar and wind resource base. Essentially, the more of the resource, the more power generation and therefore the lower the GHG intensity. For wind turbines, wind is subject to signification spatial variation, both globally and locally, and also to temporal variation, in terms of seasonal and daily fluctuations. These factors strongly influence the total amount of electricity generated and thus are important variables assumed in the literature to calculate the GHG intensity of wind turbines. Most global average wind speed maps shows that oceans, especially in the far North and South, have higher wind speed averages, along with mountainous and coastal areas (3Tier Inc., 2011b). Furthermore, local topography plays a role in wind speeds and availability, as mountains, manmade structures, and even vegetation (for smaller turbines) can affect airflow. Zimmermann and Gößling-Reisemanna (2012) pay particular attention to this factor and show how different hub heights on the same sited turbine leads to different average wind speeds, from 7.5 m/s to 8.57 m/s, which then leads to fluctuation in overall CO_2-eq/kWh, from 8.3 g to 12.5 g. Despite the critical implications that wind speed can have between otherwise similar turbines, this factor is clearly not the most important consideration (as compared to sizing, on/offshore and lifetime) as the unharmonized statistics taken from the literature do not show an obvious trend.

The location of PV installations has the same implications. Solar resources vary both globally and locally across the world, and again vary on a daily and seasonal basis. Shading problems caused by local geography, vegetation, and structures can thus play a role on solar PV performance (3Tier Inc., 2011a). Therefore, though most studies presumed a solar irradiance value of 1700 kWh/m^2/yr, some in our sample went as low as 1100 kWh/m^2/yr whereas others assumed 2400 kWh/m^2/yr (more consistent with the

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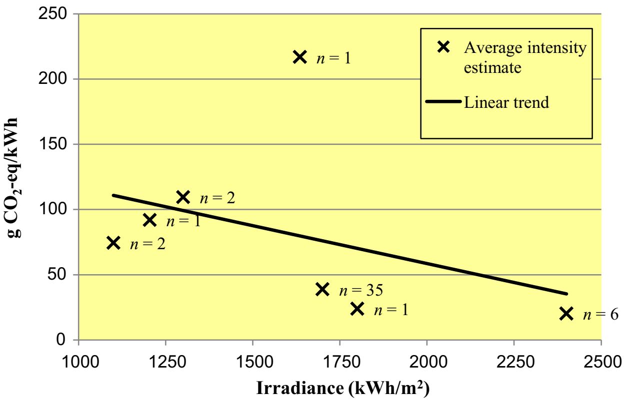

Fig. 6. Differences in greenhouse gas intensity for solar PV based on irradiance.

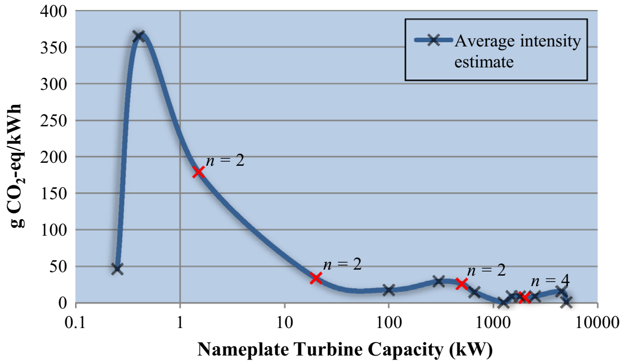

Fig. 7. Differences in greenhouse gas intensity for wind energy based on nameplate capacity. *Note*: to avoid excessive data labels, *n* values are not provided for data points that represent individual estimates from the literature. Instead, only data points that represent an average GHG intensity from multiple estimates in the literature are labeled with the appropriate *n* value, and the data points are presented in red for specificity.

Sahara or the American Southwest). Fig. 6 illustrates how solar irradiance has a direct effect on greenhouse gas intensity.

6.5. *Sizing and capacity*

The literature reveals differences in emissions intensity based upon the physical and nameplate capacity sizes of each system, with a positive trend as sizes increase. Higher capacity wind turbines, both with taller hub heights and larger rotor diameters, correspond to lower GHG intensities. Tremeac and Meunier (2009) compared a 4.5 MW turbine to a 250 W version and found the smaller to have a GHG intensity equal to approximately three times greater than the larger turbine. Kabir et al. (2012) calculates that 20 × 5 kW turbines result in an emissions intensity of 42.7 g, 5 × 20 kW turbines have an emissions intensity of 25.1 g, and one 100 kW turbine has a mere 17.8 g of CO_2-eq/kWh, implying that “bigger is better.” Figs. 7 and 8 plot the relationship between greenhouse gas emissions intensity and nameplate capacity and hub height, respectively.

PV, perhaps oddly, also follows the sizing advantages of wind energy. (We say “oddly” because PV is a modular technology that is supposed to work the “same” regardless of whether ten panels or 100 panels are being used). There do appear to be economy of scale advantages that larger PV installations benefit from, possibly due to efficiency gains in logistics and transportation, and with larger systems being able to access a wider (and more stable) solar resource. Per the logarithmic average shown in Fig. 9, there is a clearly downward trend as installed capacity increases from small distributed generation scale installations to larger utility- and merchant-scale power plant projects.

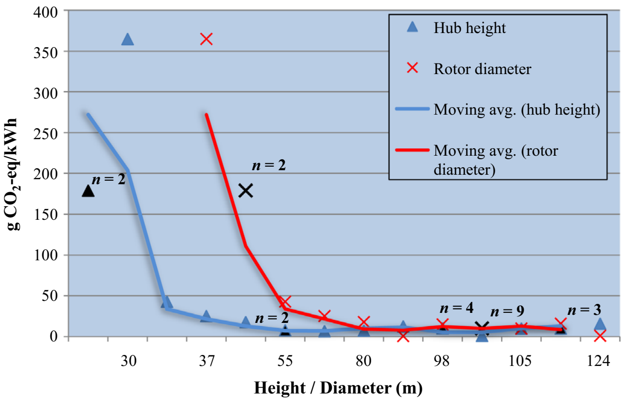

Fig. 8. Differences in greenhouse gas intensity for wind energy based on hub height and rotor diameter. *Note*: to avoid excessive data labels, *n* values are not provided for data points that represent individual estimates from the literature. Instead, only data points that represent an average GHG intensity from multiple estimates in the literature are labeled with the appropriate *n* value, and the data points are presented in black for specificity.

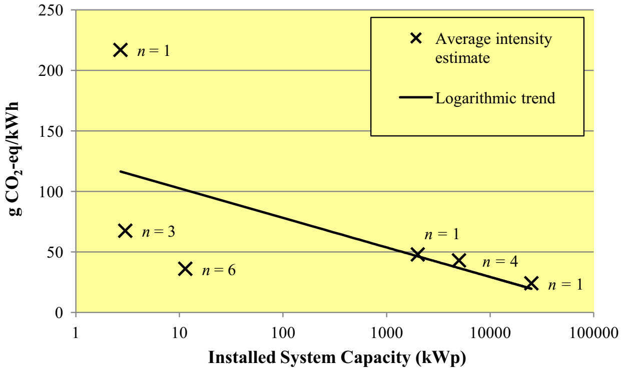

Fig. 9. Differences in greenhouse gas intensity for solar PV based on installed system capacity.

6.6. *Longevity*

Longevity is a fairly obvious factor influencing GHG intensity. Yet it is also an imprecise one because there are a number of unknown considerations, such as how well maintained the generators are, how well they are manufactured, the physical and natural conditions at the installation site, and how quickly the installations and their interconnections degenerate. Furthermore, because most wind and solar systems have not (yet) been deployed for full lifespans, many estimates are little more than educated guesses.

For the wind literature, lifetime estimates vary in 5–10 year increments between the maximum of 30 years and the minimum of 20 years. Despite the fact that Padey et al. (2012) was excluded for its reliance on secondary sources, it is one of the only studies which specifically looks at the effects of life expectancy on the GHG intensity of an otherwise similar turbine, and shows exactly 50% decreases in GHG intensity for doubled life expectancy estimates, and 66% reductions for tripled estimates. This generally makes sense as doubling life expectancy should nearly double total output, however it does not seem to account completely for

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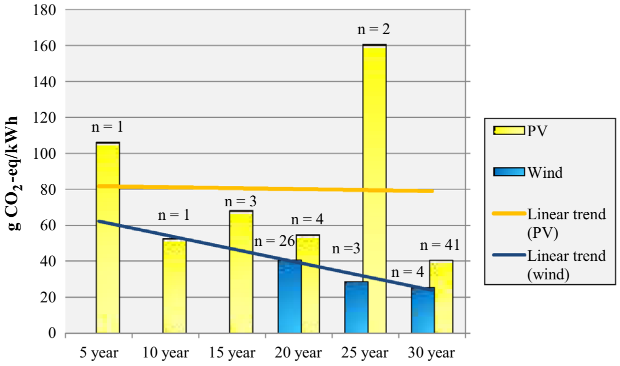

Fig. 10. Differences in greenhouse gas intensity for wind energy and solar PV based on longevity.

Table 12
Differences in greenhouse gas intensity for solar PV based on mounting.

	Roof mount	Ground mount*	Dual axis tracking	Single axis tracking
Mean	48.5	34.5	42.8	42.7
Median	33.8	26	42.8	42.7
n	24	13	1	2
Mode	21, 30, 32	25	–	–
Std. dev.	44.5	21.9	–	7.4
High	217	92	42.8	47.9
Low	14	5	42.8	37.5

* Includes any "fixed mounting" described in the literature not specified as roof.

increased maintenance and any grid curtailment or degradation of the turbine. As a whole, our sample of the wind literature does show a clear trend, where 20 year assumptions result in an average of 40.69 g CO_2-eq/kWh, 25 years decreases the mean intensity to 28.53 g CO_2-eq/kWh, and 30 years drops it to 25.33 g CO_2-eq/kWh.

The same trend is confirmed by our sample of PV literature, which tended to presume systems operated for 30 years. However, Veltkamp and de Wild-Scholten (2006) showed that a 5 year operating lifetime resulted in an emissions intensity of 106.25 g CO_2-eq/kWh, whereas a 20 year lifetime saw emissions drop to 17.5 g CO_2-eq/kWh—emphasizing the importance of maintenance. When our sample of literature is aggregated as a whole, a linear trend line shows a slight decrease in GHG intensity as lifetime increases, which would clearly be more distinct if the 217 g CO_2-eq/kWh provided by Kannan et al. (2006) in the 25 year PV categoy were harmonized. Fig. 10 details these effects both for wind and solar PV.

6.7. *Storage and mounting*

One clear factor influencing lifecycle estimations involved optional energy storage. For example, Khan et al. (2005) found that a turbine integrated with fuel cell electricity storage outputted 59.31 g CO_2-eq/kWh, and Fleck and Huot (2009) found a small wind turbine with battery backup to generate 364.83 g CO_2-eq/kWh. These results of course are well above the mean or median wind GHG intensity numbers in the literature. At least one piece of literature, Browne (2010), did attempt to factor in backup power plants potentially needed to supplement wind systems due to intermittency, however this study was excluded for failure to account for GHG intensity (see Table 1). Otherwise, none of the studies included in further analysis appeared to consider this issue.

Also – and perhaps peculiarly – the PV literature did not discuss the need for supplemental production, nor did it investigate battery backup. The PV literature instead tended to focus on the type of mounting that the system required. Many types of roof mounts appear in the literature, including Schletter hooks, Phonix mounting structures and in-roof options (as opposed to on-roof). Fixed ground mounting is also considered in some studies, with various material options including woods and metals (Beylot et al., 2014). Finally, both single-axis and dual-axis tracking options are considered in the literature, which track the sun over the course of the day to maximize exposure and increase productivity per day. According to one study, even given all of the same conditions and components otherwise, ground mounting results in a solar footprint of 53.5 g CO_2-eq/kWh whereas tracking lowers the footprint to 37.5 g CO_2-eq/kWh, clearly a substantial difference (Beylot et al., 2014). Regardless, the statistics compiled into Table 12 do suggest that fixed ground mounting is generally much lower in terms of GHG intensity than roof mounting, which are in turn slightly better than tracking systems (though the sample of studies with data on tracking was very small).

6.8. *Calculation methods*

Lastly, although not technically related to the "real" GHG emissions intensity of a wind turbine or solar panel, the particular methods utilized in each study were also a cause for variation. Authors from our sample relied on various lifecycle techniques including CML methods (named based upon its founding institution, the Centre for Environmental Studies at the University of Leiden), IO (input – output), hybrid methods, International Organization of Standardization (ISO) methods, and so on. Furthermore, they relied on a variety of different software including different versions of SimaPro and GaBi, as well as different lifecycle and materials databases, such as the popular EcoInvent Database. The best evidence that these different methods result in differing wind estimates is represented in Wiedmann et al. (2011), wherein process analysis, integrated hybrid analysis, and IO hybrid analysis are examined. That study comes to three very different conclusions ranging from 13.4 g CO_2-eq/kWh to 29.7 g CO_2-eq/kWh, all stemming from the particular method used. In the PV literature, none of the studies in our sample specifically addressed this issue, though one article excluded for completeness, Zhai and Williams (2010), contrasted process and hybrid lifecycle methods, finding an end calculation difference of 8 g CO_2/kWh, equivalent to a 38.1% difference in emissions.

7. Conclusions

This study has screened 153 lifecycle studies of greenhouse gas equivalent emissions for wind turbines and solar panels to identify a subset of the 41 most relevant, current, peer-reviewed, original, and complete assessments. It finds a range of emissions intensities for each technology, from a low of 0.4 g CO_2-eq/kWh to a high of 364.8 g CO_2-eq/kWh for wind energy, with a mean value of 34.11 g CO_2-eq/kWh. For solar energy, it finds a range of 1 g CO_2-eq/kWh to 218 g CO_2-eq/kWh, where the mean value is 49.91 g CO_2-eq/kWh. Thus, wind and solar energy are in no way "carbon free" or "emissions free," even though, as Table 13 indicates, they can certainly be called "low-carbon." Based upon these estimates, we make three conclusions.

The first, and perhaps most blatant conclusion, is that lifecycle studies of greenhouse gas emissions associated with the wind and solar energy lifecycles – similar to those for nuclear

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Table 13
Comparative lifecycle estimates for sources of electricity.

Technology	Capacity/configuration/fuel	Mean estimate (g Co_2e/kWh)
Hydroelectric	3.1 MW, Reservoir	10
Biogas	Anaerobic Digestion	11
Hydroelectric	300 kW, Run-of-River	13
Solar Thermal	80 MW, Parabolic Trough	13
Biomass	Forest Wood Co-combustion with hard coal	14
Biomass	Forest Wood Steam Turbine	22
Biomass	Short Rotation Forestry Co-combustion with hard coal	23
Biomass	Forest Wood Reciprocating Engine	27
Biomass	Waste Wood Steam Turbine	31
Wind	Various sizes and configurations	34
Biomass	Short Rotation Forestry Steam Turbine	35
Geothermal	80 MW, Hot Dry Rock	38
Biomass	Short Rotation Forestry Reciprocating Engine	41
Solar Photovoltaic	Various sizes and configurations	50
Nuclear	Various reactor types	66
Natural Gas (Conventional)	Various combined cycle turbines	443
Natural Gas (Fracking)	Combined cycle turbines using fuel from hydraulic fracturing	492
Natural Gas (LNG)	Combined cycle turbines utilizing LNG	611
Fuel Cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy Oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1,050

Note: Wind and solar PV numbers taken from this study. Hydrofracking numbers taken from Hultman et al. (2011), who argue that shale gas has emissions 11% greater than ordinary natural gas. All other numbers taken from Sovacool (2008).

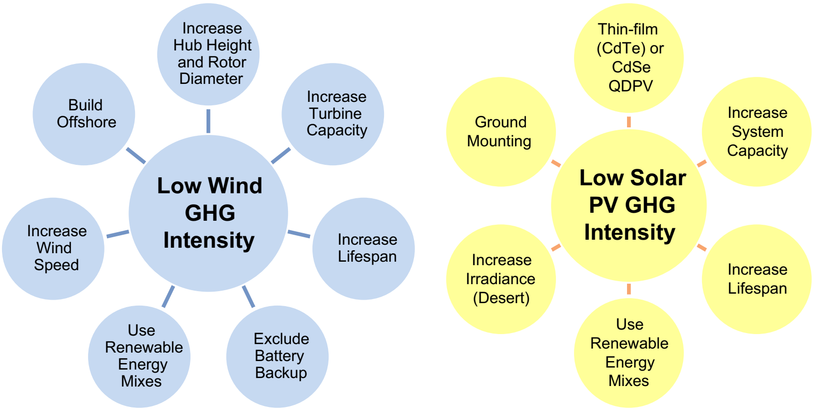

Fig. 11. Low GHG attributes of wind energy and solar PV systems.

power (Sovacool, 2008) – need to become more methodologically rigorous. Of the original 153 articles, 38% were studies that failed to consider greenhouse gas emissions intensity when considering lifecycle impacts. More than 25% of these 153 studies were either outdated, non-peer reviewed, or unoriginal, and another 10% did not consider all greenhouse gases. This left us with only about one-quarter of the available literature. Even within this smaller base of selective literature, the types of lifecycle stages and the ways in which they were defined were dissimilar, and embodied varying assumptions related to a multitude of factors such as resource inputs, manufacturing and fabrication, sizing and capacity, and longevity, among others. Moreover, these studies raise a pressing concern regarding energy storage. On the one hand, storage can alleviate some of the intermittency issues that prevent wind and solar from gaining a greater market share. On the other hand, our analysis suggests that adding storage can increase the GHG intensity of both solar PV and wind energy systems. So if the choice is to be smaller amounts of wind/solar (without storage) and more fossil fuels, or larger amounts of wind/solar (with storage) and less fossil fuels then which option has the overall lower GHG emissions? The current literature leaves this salient question all but unaddressed.

Second, specific configurations of both wind and solar bring with them particular greenhouse gas advantages and disadvantages. A 2 MW wind turbine without battery backup and a 30 year lifetime results in an incredibly low emissions profile of 0.4 g CO_2-eq/kWh. Yet a tiny 400 W, 30 m high, 1.17 m rotor, onshore wind turbine with battery backup and a short 20 year lifetime results in a high emissions profile of 364.8 g CO_2-eq/kWh, approaching that of natural gas. Similarly, a solar PV system produced without F-gasses using an all renewable energy mix was found to have an emissions intensity as low as 1 g CO_2-eq/kWh, whereas a solar PV system produced with F-gasses on a completely coal fired energy mix without carbon capture and storage had an emissions intensity of 218 g CO_2-eq/kWh. These, along with a number of other findings, suggest that the “best” solar and wind systems, those that have the lowest lifecycle greenhouse gas emissions, are those with the attributes characterized by Fig. 11.

Third, and perhaps most important, by looking at these disparities, and drawing from these two conclusions, a number

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of important concepts are revealed about how to most effectively utilize wind and PV to combat climate change. It would appear that wind energy is generally a better option for bulk power, and when it comes to this technology, size is key—bigger truly is better (though not too large as to negate the benefits of decentralization). Utility and merchant-power-plant sized turbines with larger rotors and higher nameplate capacities, as well as those placed higher and out to sea to take advantage of stronger wind speeds, are generally the best performing options (from an emissions standpoint). For solar PV, the GHG intensity benefits seem to lie in more in the use of cadmium telluride, CdSe QDPV, and micromorph technologies, sited in deserts, with ground mounting and possibly single or dual-axis tracking. The literature also suggests that battery and fuel cell electricity storage have a substantially negative implication for emissions intensity of wind systems, and despite the lack of information available for PV, the same logical concerns apply, making grid connection without storage possibly better options (from a greenhouse gas standpoint, again). Better understanding, and researching, these sorts of factors will be critical to enhancing the ability for wind energy and solar PV to effectively mitigate greenhouse gas emissions.

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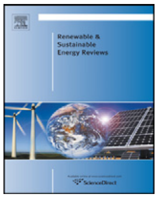

Environmental impacts from the installation and operation of large-scale solar power plants

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ABSTRACT

Large-scale solar power plants are being developed at a rapid rate, and are setting up to use thousands or millions of acres of land globally. The environmental issues related to the installation and operation phases of such facilities have not, so far, been addressed comprehensively in the literature. Here we identify and appraise 32 impacts from these phases, under the themes of land use intensity, human health and well-being, plant and animal life, geohydrological resources, and climate change. Our appraisals assume that electricity generated by new solar power facilities will displace electricity from traditional U.S. generation technologies. Altogether we find 22 of the considered 32 impacts to be beneficial. Of the remaining 10 impacts, 4 are neutral, and 6 require further research before they can be appraised. None of the impacts are negative relative to traditional power generation. We rank the impacts in terms of priority, and find all the high-priority impacts to be beneficial. In quantitative terms, large-scale solar power plants occupy the same or less land per kW h than coal power plant life cycles. Removal of forests to make space for solar power causes CO_2 emissions as high as 36 g CO_2 kW h^{-1}, which is a significant contribution to the life cycle CO_2 emissions of solar power, but is still low compared to CO_2 emissions from coal-based electricity that are about 1100 g CO_2 kW h^{-1}.

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1. Introduction

Solar powered electricity generation is experiencing rapid growth. Current worldwide installed capacity is more than 22 GWp and increasing at ∼40% per year [1,2]. Many state or provincial governmental organizations are enforcing renewable portfolio standards, requiring a percentage of utility supplied power to come from renewable sources. Consequently, large-scale solar projects are expanding into a wide range of locations and ecosystems. For example, New Jersey is pursuing a goal of 22.5% renewable energy by 2021. New York is pursing a 24% renewable energy standard by 2013, and will soon complete a 37 MWp photovoltaic array on Long Island. The Canadian province of Ontario has an 80 MWp solar power plant already in operation. Published research provides a

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good understanding of environmental impacts from the manufacturing and end-of-life phases of solar power equipment [3,4], but such is not the case for the installation and operation phases where little scientific research has been performed. This lack of information is particularly true for solar power applied in forested regions. There is much motivation to improve this situation. Lessons learned during the rapid expansion of wind turbines highlight the benefits of a thorough understanding of environmental impacts from the installation and operation phases [5]. Additionally, a rate-limiting step for construction of large-scale solar power plants is the permitting process for the installation and operation phase. Delays in permitting occur largely because the impacts have not been studied or understood. In this paper we develop an improved understanding of the environmental impacts of the installation and operation phases of solar power. We identify and appraise 31 impacts related to issues of land use, human health and well-being, wildlife and habitat, geohydrological resources, and climate.

Most published investigations of environmental impacts from solar power use a life cycle assessment (LCA) framework, and typically focus on greenhouse gas emissions and energy payback time [4,6–8]. A smaller number of papers consider other impacts, i.e., hazardous materials emissions [3,4,9], land use intensity [10–12], water usage [13], wildlife impacts [14], and albedo effects [15]. The LCA method details mass and energy flows throughout a product's life cycle, from extraction of raw materials, to manufacturing necessary equipment, to installation and operation phases, and finally to disposal or recycling phases. In the case of solar power, the installation and operation phases of the life cycle have received little scientific attention. The few existing studies of the operation phase [16–19] are brief and contain no quantitative information. Several informative environmental impact statements (EISs) have been made public in recent years, most notably the U.S. BLM and DOE Programmatic Environmental Impact Statement (PEIS) [20]. Since tens of thousands of acres of U.S. land are proposed for development into solar power in the upcoming years, the environmental impacts from the installation and operation phases deserve comprehensive research and understanding. For example, the most up-to-date LCA results for CO_2 emissions are 16–40 g CO_2 kW h^{-1} [4,6–8], but these numbers do not account for CO_2 emissions that arise if the power plant is installed in a forested region, in which case the removal of vegetation during installation needs consideration. Further, regarding impacts to wildlife, we are aware of only one report that collected primary data on impacts from a solar power facility, i.e., Ref. [14]. In spite of this lack of previous research, a significant need exists for understanding the environmental impacts. Construction of large-scale solar power plants is currently bottlenecked due to permits needed from local agencies concerned with environmental impacts. Our analysis accomplishes the following: (i) identifies impacts, (ii) assesses each impact relative to traditional power generation, (iii) classifies each impact as beneficial or detrimental, and (iv) appraises the priority of each impact. The results form a comprehensive description of the impacts of installation and operation of solar power, in a variety of climates, and afford a first picture of the impacts of solar power in forested regions.

2. Characteristics of the installation and operation of solar power plants

Solar power plants are being developed in a wide range of locations and ecosystems, ranging from forests in England, to deserts in California, to nearly tropical locations in Florida and elsewhere. The environmental impacts of a solar power plant change depending on its location. In this section we describe the relevant characteristics of location of installation, categorized by biomes as forests, grasslands, desert shrublands, true deserts, and farmland. Latitudes from 0° to 50° are considered adaptable to solar power plants. Section 4 describes that the main environmental parameters affecting solar power plants are solar insolation, biomass density, and biodiversity, and we focus on these parameters here. Biodiversity is measured by species density (species ha^{-1}), and is correlated with sunshine and precipitation [21].

Forests require precipitation of at least 50 cm yr^{-1} and the absence of sustained periods of freeze or drought [22]. Cloud cover in forested regions commonly reduces insolation by factors of 25–50%. Vegetation height ranges from 5 to 100 m, and rooting depths range from 1 to 5 m, with deeper roots occurring in drier soils [23]. Biomass density in temperate or tropical forests ranges from 100 to 500 Mg C ha^{-1} [24], the variation due to the age of the forest as well as tree species and local climate. Tropical rainforests have the greatest biodiversity, as measured by species density, of any biome on the planet, close to doubling any other location. Multivariable regressions show that mean annual insolation and precipitation explain 60% of the global variability of biodiversity [21]. Important natural services provided by forests include generation of wood and pulp, mitigation of flood waters by tempering the runoff hydrograph, filtration of pollutants from rainwater and air, moderation of local air temperatures, creation of scenic and recreational opportunities, and hosting of endangered and protected species [25]. The only burden forests cause on local resources is use of groundwater through evapotranspiration.

Grasslands receive between 30 and 100 cm yr^{-1} of precipitation. Often they experience periods of freeze or drought that prohibit dense populations of trees [22]. Biomass density in grasslands ranges from 10 to 50 Mg C ha^{-1} [26,27] with the majority lying in the soil. Biodiversity is comparable to forests but usually $\sim$25% less. Grasslands offer the same natural services as forests, minus the generation of wood and pulp but with the addition of more livestock grazing capacity.

Desert shrublands receive between 5 and 30 cm yr^{-1} of precipitation. Cloud cover is much lower than in forests or grasslands. Biomass density is also lower, in the 10–30 Mg C ha^{-1} range [28]. Surprisingly, biodiversity in desert shrublands is roughly as high as in grasslands [29]. Desert shrublands offer the same natural services as grasslands, but with less flood risk mitigation and grazing capacity.

True deserts are distinct from desert shrublands, have extremely low rainfall, i.e., less than 3 cm yr^{-1}, and have practically zero biomass or biodiversity [29]. Examples are the Sahara or Arabian deserts. These locations are best suited for solar power since they have nearly zero cloud cover, very little wildlife or biomass, low human populations, and offer few natural services to human interests.

Our final landscape category is farmlands, which is unique because it is manmade. Farmlands can be built in replacement of forests, grasslands, or desert shrublands. Therefore, on farmland, cloud coverage varies over the full range depending on location. However, biomass is usually similar to grasslands, and biodiversity is usually lower than grasslands or shrublands but higher than true deserts. Fig. 1 summarizes the geographic parameters of top importance, i.e., biodiversity, biomass density, and cloud cover. The locations of installation are organized into the biomes: forests, grasslands, desert shrublands, and true deserts. The values in the Fig. 1 are normalized by those that occur in tropical forests, because tropical rainforests have the greatest cloud cover, biomass density, and biodiversity. As shown in Sections 4 and 5 of this paper, environmental impacts of large-scale solar power installations are low when the values of these geographic parameters are low.

Installation of solar power equipment requires removing trees, brush, and root balls [20,30]. Photovoltaic or mirror panels are mounted onto steel and aluminum supports $\sim$1 m above ground level, either on concrete footings or by driving steel posts into the

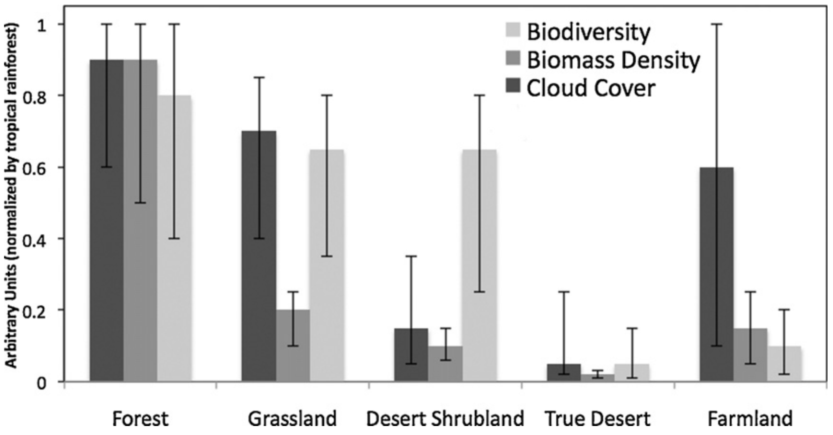

Fig. 1. Geographic parameters of top importance for environmental impacts during the installation and operation are shown. Values are normalized to those in tropical rainforests, which hold the greatest biodiversity, biomass density, and cloud cover. The error bars represent variability that occurs within a particular biome as the latitude or climate conditions change.

ground. The ground slope is usually kept below 5%, by grading, if necessary. After installation of the solar panels, the vegetation is periodically mowed to prevent shading of the panels, which limits vegetation height to below 1 m height. Herbicides are sometimes used instead of mowing [20]. Inverters, transformers, and collector boxes are built for every ~1 MWp of panels, and sit on concrete pads sized at roughly 5 × 5 m. Trenching for electrical and communications cables is usually required. The power plants are currently engineered for a lifetime of 30 years, with most projects anticipating a longer lifetime. With solar-tracking systems and solar thermal power, the panels require washing, which uses water at a rate of roughly 500–1000 gallons per MWp of panels per year [31]. In a forested environment the rainfall will likely reduce the need for washing. Access roads, electrical equipment, and spacing interlace the panel array, causing the power plant footprint to be ~2.5 times great than the area directly overlain by panels. Typically the spatial density of commercial solar power equipment is 35–50 MWp per km^2, i.e., 5–8 acres per MWp [10–12]. Maintenance vehicles travel the access roads between the panels for washing and mowing, a few times per year during normal operation.

3. Metrics for environmental impact categories

Power generation technologies are best compared by use of LCA methods with consistent and transparent metrics for each impact category. A metric is the item tracked by life cycle analysis (LCA), and comprises the physical unit of measurement, the methods of data gathering, and the methods of data analysis. For the creation of accurate LCA comparisons, it is crucial that metrics are as objective and consistent as possible. Some environmental impacts have well-defined metrics that are followed by a majority of LCA practitioners, e.g., kg CO$_2$-eq yr^{-1} for greenhouse gas emissions or decibels above the auditory threshold for noise impacts. Other impact categories do not have well-defined metrics or have no consensus among LCA practitioners. For example, with wildlife and habitat impacts, there is ongoing research on measurement methods for habitat fragmentation, for multiple stressors on the health of individuals, and for risk of collapse of complex ecosystems. Similarly, some of the impacts to human health and well-being are not well understood, particularly those resulting from climate change, e.g., food security or disease release. In Section 4.5 we discuss impacts to geohydrological resources from large-scale power, a topic where no previous research on environmental impact metrics is reported.

The complexity encountered with assessing wildlife and habitat impacts encourages the use of proxy impact categories that are more tractable, such as land use intensity. Land use intensity is therefore an important impact category, but there is not yet a consensus on which metrics best describe the variety of uses of and effect on the land. An analysis of land use metrics is presented in Section 4.2. Although metrics for impacts to ecosystems and geohydrological resources are similarly underdeveloped, we avoid an analysis of possible metrics as this is beyond the scope of this paper. The remainder of our impact categories, have well defined metrics, e.g., albedo effects, noise, or emissions of greenhouse gases, priority pollutants, or heavy metals. Each of these impacts is well defined by "midpoint" metrics, i.e., mass of the pollutant emitted per energy production basis. Also, metrics for impacts to visual resources have been created and managed by the U.S. Forest Service [25], the result being a mixture of qualitative and quantitative methods. Metrics for recreational resources have not been developed but will likely be similar to those for visual resources.

4. Environmental impacts

4.1. Methods

To identify the environmental impacts due to installation and operation of large-scale solar power we reviewed the published science literature and sought expert opinion. We organized our findings into 32 impacts, which are described in the following subsections: Section 4.2 – land use, Section 4.3 – human health and well-being, Section 4.4 – wildlife and habitat, Section 4.5 – geohydrological resources, and Section 4.6 – climate and greenhouse gases. Each subsection holds a table that lists relevant impacts. In the second column of these tables a description is given of the physical effect on the measurable impact indicator that arises from solar power displacing U.S. traditional power. In the third column each impact is appraised in comparison to impacts from traditional U.S. electricity generation, e.g., 45% coal, 23% natural gas, 20% nuclear, 7% hydro, 1% petroleum, and 4% other renewables [32]. This appraisal classifies the impact from solar power as beneficial or detrimental. The justification for a comparative method is that solar electricity generation capacity will displace traditional generation capacity. A comparative approach was also used by the International Energy Agency's assessment of renewable energy technologies [33] and the National Research Council's assessment of wind energy environmental impacts [5]. The fourth column lists a priority for each respective impact. Our determination of priority follows a protocol similar to that of "significance" from the U.S. National Environmental Protection Act, 40 CFR 1508.27 [34], i.e., a "low" priority impact does not require any mitigative action for the project to proceed, a "moderate" priority impact warrants mitiga-

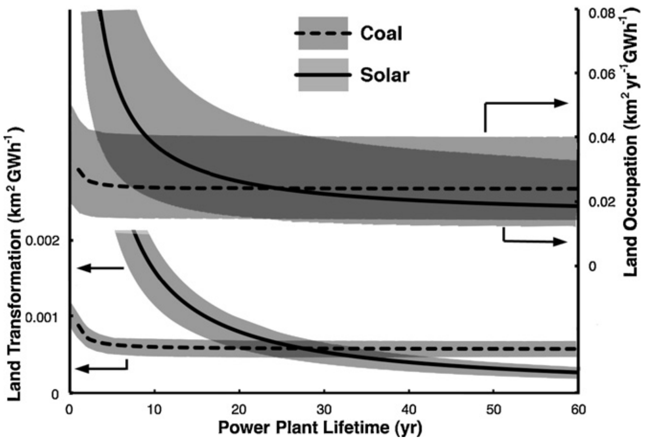

Fig. 2. Comparisons of land use intensity metrics for large-scale solar and coal power. The left ordinate shows land transformation, and right ordinate shows land occupation. For both ordinates the dashed line is the average result for coal powered electricity while the solid line is the average result for solar powered electricity. The gray shaded areas give the range of sensitivity of the calculations as the input parameters are varied over their possible values, as described in the supplemental information.

tion that can be obtained at low cost or can be left semi-mitigated, and a "high" priority impact requires mitigative action that is both costly and required to be fully completed.

When possible we obtain quantitative results and make a numerical comparison with traditional U.S. power generation. For example we use this approach in the next section to compare land use intensity of large-scale solar power plants to coal-fired power plants. In section 4.6 we make a quantitative comparison of CO_2 emissions. We also find previous literature that allows further quantitative comparisons, as in the case of mercury or cadmium emissions.

4.2. Land use

Land use intensity is an important impact because it is often used as a proxy for other impacts. Land-use intensity may be quantified by the following metrics: (i) land area "transformation" per unit of time-averaged power output ($km^2\,GW^{-1}$) or per nameplate "peak" capacity ($km^2\,GWp^{-1}$), (ii) land area transformation per unit of electric energy generated ($km^2\,TW\,h^{-1}$), and (iii) land area "occupation" per unit of electrical energy generated ($km^2\,yr\,TW\,h^{-1}$). The metric "transformation" focuses on the one-time action of changing the physical nature of the land, i.e., installation. Alternatively, the metric "occupation" is a measurement of land being used for a known period of time, defined as land area multiplied by the length of time that the land area is held in use. The length of time needed for the land to recover from use should be included in this length of time. The occupation metric captures the impact from both the installation and operation phases, whereas the transformation metric captures only the installation phase.

Here we compare land use intensity for the life-cycles of photovoltaic power and coal power. Fig. 2 shows the calculations of land transformation and occupation as a function of lifetime of the operation phase. Solar power plants are currently designed for 30+ years of operation. As the lifetime of a solar power plant gets longer, the land transformation per capacity is unchanged, but the land occupation per energy generated decreases. The coal power life-cycle on the other hand requires mining to obtain the fuel. In the United States 70% of produced coal is obtained by strip-mining [35], wherein the land yields a one-time amount of coal per land surface area. Mining for coal can be described as a land transformation per unit of energy generated ($km^2\,TW\,h^{-1}$). Additionally, since the topsoil of mined land takes several decades to restore itself, it can be described as land occupation per unit of energy generated ($km^2\,yr\,TW\,h^{-1}$). Coal power also requires land for the power plant itself, and land for railways to transport the coal from the mine, both of which should be described with either of the previous two sets of units. Land use for solar power, on the other hand, does not require mining for fuel, and is often described with units of land per rated capacity (e.g., $km^2\,GW^{-1}$). However, to compare the two life cycles, both are described herein in units of land occupation or transformation units per energy generated. The land occupation metric captures the most information and allows the best comparison of solar power to coal power.

A calculation of the above metrics requires the following information: (i) the power plant lifetime, (ii) area used for gathering and transporting fuel, e.g., mining and railway, (iii) area used for the generating facilities (e.g., the furnace, turbine, solar panels, etc.), (iv) the land and energy required for manufacturing the components, and (v) the recovery time of land transformed. All input parameters and methods of calculation are described in the supplemental text to this paper, but for example we assume surface-mined typically transforms $0.004\,km^2\,GW\,h^{-1}$ [12], and coal power plants cover an average of $2\,km^2\,GW^{-1}$. We use a 73% capacity factor for coal power [36] and capacities determined by local irradiation for solar power plants. Recent commercial solar power plants cover an average of $25\,km^2\,GWp^{-1}$. Manufacturing of photovoltaic modules typically requires $\sim 3\,kW\,h\,Wp^{-1}$ [37]. Full recovery of the forest following strip-mining requires 50+ years [38–50], thus we assume a 50-year recovery time for soil and ecosystems to return to equivalent value or function as prior to mining. Forest recovery time for a photovoltaic power plant is assumed to average 10 years, as the disturbance is significantly lower than for coal mining. To better understand the parameter sensitivity we make our calculations with a range of input values as described in the supplemental text. Fig. 2 plots the calculations for land use metrics. The results for land transformation show parity between solar and coal at 26 years, whereas those for land occupation show parity at 24 years. The latter is a more informed metric since it includes information about the recovery times of land following disturbance. A 30-year old photovoltaic plant is seen to occupy ~15% less land than a coal power plant of the same age. As the age of the power plant increases, the land use intensity of photovoltaic power becomes significantly smaller than that for coal power. The sensitivity in the calculations, as dependent on input parameters, is shown by the shaded belts in Fig. 2. Land transformation per plant capacity $km^2\,GW^{-1}{}_{ac}$ show parity between solar and coal after 30 years, with a range from 27 to 40 years (data not plotted).

4.3. Human health and well-being

Table 1 lists the impacts to human health and well-being from solar energy in forested regions. Most of the impacts are beneficial, due to a reduction in toxics emissions arising from the combustion of fossil fuels. For example, a recent study found that 49% of lakes and reservoirs in the U.S. contain fish with concentrations of mercury (Hg) above safe consumption limits [51]. Solar power equipment releases 50–1000 times less direct Hg emissions than traditional electricity generation, i.e., $\sim 0.1\,g$ Hg $GW\,h^{-1}$ as compared to $\sim 15\,g$ Hg $GW\,h^{-1}$ from coal [4,52,53]. In the US, at least 65% of the mercury deposited in lakes and reservoirs originates from burning fossil fuels [54]. Photovoltaics made with CdTe emit $\sim 0.02\,g$ Cd $GW\,h^{-1}$ when manufactured with clean electricity, which is 100–300 times smaller than emissions from coal power generation [4,52,53]. Emissions of NO_x, SO_2, and many other pollutants, are orders of magnitude smaller than those from traditional power [4]. Emissions of these toxics and others, including particulates, are significant burdens on human health [55,56]. Carbon dioxide emissions also pose risks to human health and well-being,

Table 1
Impacts to human health and well-being relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Emissions of mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~30× less
Emissions of cadmium	Reduces emissions	Beneficial	High	Solar emits ~150× less cadmium
Emissions of other toxics	Reduces emissions	Beneficial	Moderate	Solar emits much less
Emissions of particulates	Reduces emissions	Beneficial	High	Solar emits much less
Other impacts				
Noise	Reduces noise	Beneficial	Low	Less mining noise; less train noise
Recreational resources	Reduces pollution	Beneficial	Moderate	Cleaner air; cleaner fishing
Visual aesthetics	Similar to fossils	Neutral	Moderate	Solar farms vs. open pit mines
Climate change[a]	Reduces change	Beneficial	High	Solar emits ~25× less g h g
Land occupation	Similar to fossils	Neutral	Moderate	See Section 4.1

[a] We discuss climate change in Section 4.6.

due to climate change and the associated effects: sea level rise, extreme weather, food security, and socioeconomic change [57]. Fossil fuel power plants emit ~64% of greenhouse gases worldwide [58], and most of the remaining emissions are due to petroleum use that can be partly replaced by electricity from clean power sources. Assessment of the greenhouse gas emissions of solar power life cycles are given in Section 4.6.

Impacts on aesthetics and recreational opportunities from solar power are less clear. Recent legislation introduced in California placed large tracts of land out-of-bounds for solar energy plants, partly due to recreational and visual impacts, and partly for ecological concerns [59]. The visual and recreational impacts are difficult, to quantify but much progress has been made by the U.S. Forest Service over the past decades toward appraising visual resources during land development [25]. A similar approach could be used for recreational resources. Regarding recreational resources, note that a switch to solar power would decrease mercury deposition on lakes and rivers, thereby improving their utility for fishing and recreation. Mountaintop mining could also be reduced or displaced by deployment of large-scale solar power, thereby opening vast amounts of highland forest to recreational opportunity.

4.4. Wildlife and habitat

The impact on plant and animal life is a major hurdle for permitting the construction of solar power plants. Solar projects in the desert southwest of the United States generate controversy regarding their disruption to wildlife and habitat, and recent environmental impact statements have estimated impacts to wildlife that require extensive mitigation efforts [60]. Large areas of desert land in California may be excluded from solar energy development due partly to concerns for wildlife [59]. The science behind these ecological impacts is poorly understood, mostly because these large-scale power plants are a new technology.

The majority impact to wildlife and habitat is due to land occupation by the power plant itself. The power plant is typically enclosed by a fence [61], limiting movement by animals. Some fences have openings to allow small animals to enter the facilities. With or without these openings, the habitat of the land changes significantly. Hiding spots, preying strategy, food availability will all be affected. The soil is sometimes scraped to bare ground during construction and kept free of vegetation with herbicide [20], while in other cases the vegetation is allowed to grow but is mowed frequently to keep it below a few feet tall. In either case, a significant alteration to the vegetation occurs. The PV panels themselves will cast shadows and change the microclimate, causing an unstudied effect on vegetation.

The only quantitative study of impacts to wildlife from solar power is that of McCrary et al. [14] who measured death of birds, bats, and insects at the Solar One concentrating solar power tower near Daggett, CA in desert land. Six birds per year died and hundreds of insects per hour were incinerated in the intense light [14]. This impact was concluded to be low compared to other anthropogenic sources of bird and insect fatality. Academic publications contain only hypothetical analyses, and are very brief [16–19]. Several environmental impact statements give more thorough projections of the anticipated impacts. For example, environmental impact statement for the Ivanpah Solar Electric Generating System [60] reported that "significant impact" would occur for the threatened desert tortoise, five special-status animal species, and five special-status plants in the local area. Significant impact is a legal term used in conjunction with the U.S. endangered species act, and denotes the anticipated loss of an amount of habitat that will hinder the recovery of the species. An environmental impact report prepared for the 550 MWp Topaz photovoltaic project in grasslands and abandoned farmlands of central California found the potential for significant impact to dozens of protected animal and plant species in the region. Through extensive mitigation efforts, funded by the solar project itself, these anticipated impacts were reduced to be less than significant [62]. However it should be kept in mind that monitoring of impacts is just beginning.

The impact to wildlife will be tightly correlated to the biodiversity of the land on which the power plant is built. Biodiversity, as measured by species density, is documented most thoroughly by the recent Millennium Ecosystem Assessment [29], which ranked biodiversity in the world's biomes from greatest to least as follows: tropical rainforests, tropical grasslands, deserts and xeric shrublands, tropical/sub-tropical dry broadleaf forests, montane grasslands and shrublands, temperate broadleaf and mixed forests, flooded grasslands and savannas, tropical coniferous forests, temperate coniferous forests, Mediterranean forests and scrublands, boreal forests, and lastly tundra [29]. For our current paper we use fewer numbers of biomes, which are ranked from greatest to least biodiversity as follows: forests, grasslands, desert shrublands, and true deserts. Sunlight and water availability can significantly alter the biodiversity in any of these biomes, by a factor of two, and endangered species can live in any biome. Consequently, a customized study of the wildlife and ecosystem surrounding each power plant is recommended as a best practice.

Although very few measurements of ecological impacts, or mitigation efforts, from large-scale solar projects are published, there is a rich scientific literature for other land disturbances, such as agriculture or suburban sprawl. Farmland management practices have been found to have a large effect on ecological impacts. For example, practices such as crop-rotation, rest-rotation, non-till farming, intercropping, crop-margin habitat maintenance, and mechanical rather than chemical weed management improve biodiversity and habitat quality within the cropland and on nearby lands [63–65]. The main metric for impacts to wildlife will likely be risk of population decline, based on computational models of ecosystem dynamics, e.g., see [66]. An arising concept in restoration ecology is "connectivity" of the land, i.e., how well the wildlife can

Table 2
Impacts to wildlife and habitat of solar energy relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Exposure to hazardous chemicals				
Acid rain: SO NO*x*	Reduces emissions	Beneficial	Moderate	Solar power emits ~25× less
Nitrogen, eutrophication	Reduces emissions	Beneficial	Moderate	Solar emits much less
Mercury	Reduces emissions	Beneficial	Moderate	Solar emits ~30× less
Other: e.g., Cd, Pb, particulates	Reduces emissions	Beneficial	Moderate	Solar emits much less
Oil spills	Reduces risk	Beneficial	High	Note: BP Horizon Spill, Valdez Spill
Physical dangers				
Cooling water intake hazards	Eliminates hazard	Beneficial	Moderate	Thermoelectric cooling is relegated
Birds: flight hazards	Transmission lines	Detrimental	Low	Solar needs additional transmission line
Roadway and railway hazard	Reduces hazard	Beneficial	Low	Road and railway kill is likely reduced
Habitat				
Habitat fragmentation	Neutral	Neutral	Moderate	Needs research and observation
Local habitat quality	Reduces mining	Beneficial	Moderate	Mining vs. solar farms; needs research
Land transformation	Neutral	Neutral	Moderate	Needs research and observation
Climate change[a]	Reduce change	Beneficial	High	Solar emits ~25× less greenhouse gases

[a] We discuss climate change in Section 4.6.

move across tracts of land and interact. Connectivity is a promising metric to gauge disturbance to a habitat from regional patterns in land use [67], and will be particularly important for large-scale solar energy development.

Recovery of the soil and ecosystem following disturbance can require many years or decades. Coal strip mining, for example, disturbs the land to such a degree that recovery takes 50–100+ years [68], mostly because the soil takes several decades to regenerate. The recovery following solar power production will likely occur more quickly because less soil is removed, but this hypothesis needs further research and primary observations.

It is important to consider that positive effects for wildlife are possible, similar to those found in artificial reefs in marine environments [69]. In many cases a large-scale solar power project provides funding for mitigation actions throughout the lifetime of the power plant, which builds potential for the project to be a benefit to local wildlife rather than a burden [66]. Recent regulatory requirements from the US-BLM and US-DOE call for extensive monitoring of wildlife on solar power plant properties, and for habitat restoration if the wildlife shows signs of stress [20]. Examples of such benefits are elimination of invasive or overpopulating species, construction of suitable habitat for endemic species, the exclusion of recreational off-highway vehicles, or increased monitoring of the state of the ecosystem. Furthermore, as noted in Section 4.2, displacement of coal power with solar power leads to less land occupation per kW h on time scales beyond 27 years, and also less deposition of mercury, NO*x*, and sulfates [51,56]. Land use during the life cycle of solar power is typically less hazardous than that during the life cycle of fossil power, e.g., less mining, railway transport, cooling water intake, and global warming potential. Table 2 summarizes ecological impacts of solar power plants displacing power generated by the traditional U.S. technologies.

4.5. *Geohydrological resources*

Table 3 lists anticipated impacts to geohydrological resources, again relative to traditional power production in the United States. Possible impacts to geohydrological resources include the erosion of topsoil, increase of sediment load or turbidity in local streams, reduction in the filtration of pollutants from air and rainwater, the reduction of groundwater recharge, or the increased likelihood of flooding [70,20]. For example, mitigation plans for storm flow surface water were required for the 400 MW Ivanpah power plant in California [60], and the U.S. BLM and DOE require [20]. If solar power plants are built on slopes, access roads between the panels could produce erosion similar to that seen in vineyards [71]. For example, soil infiltration rates, runoff ratios, and evapotranspiration typically change by factors of two or three when the native vegetation is replaced with agriculture [72–77]. Lessons from forestry give caution to removal of trees on sloping hillsides. Recent solar power plants in Spain are expanding into high slope terrain, 10% slopes or greater, and rack mounting manufacturers are pushing the market space in this direction. Forests offer many other natural services, e.g., flood water reduction or stream bank protection. If the forest's capacity to purify water is degraded then additional municipal purification facilities may need construction. Recent assessment of these issues [20] finds that mitigation of these impacts are easily achievable. However, since these assessments are based on scientific projections rather than measurements, studies and monitoring are recommended for conservation of the local hydrological and soil resources.

4.6. *Impacts on climate, and greenhouse gas emissions*

A major motivation for deploying solar power is to reduce emissions of carbon dioxide from traditional power generation. When installing solar power in forested regions, this motivation needs further research because, as mentioned earlier, trees and brush must be removed to prevent shading of solar panels. Typically, any plant taller than ~0.5 m is cut or removed, and tree roots are removed to allow posts to be driven into the ground [20]. In this subsection we estimate the CO_2 released by the removal of vegetation, and present a full life cycle CO_2 emission rate for large-scale solar power. At the end of the subsection, we discuss possible climate impacts from surface albedo and heat island effects.

The average biomass density in a forest, including soil, ranges from 100,000 kg C ha^{-1} to 500,000 kg C ha^{-1} [24,78] depending on age of the forest and local climate. The soil and root mass accounts for roughly 50% of this carbon [24]. Boreal forests hold considerably more carbon in soils, but we are not considering them as viable locations for large-scale solar technology. The removed timber, brush, and woody debris can be: (i) turned to mulch, (ii) burned, or (iii) used as lumber for construction or in another long-lived wood product. A portion of the third case may be considered carbon sequestration. In the first two cases, a release of CO_2 is made to the atmosphere, whereas in the third case, the release of CO_2 is delayed for decades or centuries. For this study we define carbon sequestration in the context of the 100-year global warming potential (GWP) [79], i.e., a net transfer of carbon out of the atmosphere, or net avoidance of emission to the atmosphere, for which the transfer or avoidance persists for at least 100 years. A study of the Oregon forestry industry found that roughly 20% of forest biomass cut for forestry products is sequestered on long time scales [80,81]. Studies of sawmill operations confirm this view, and show

Table 3
Impacts to land use and geohydrological resources relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Soil erosion				
During construction	Less soil loss	Beneficial	Low	Existing mitigation is sufficient
During routine operation	Unknown	Unknown	Moderate	Needs research and observation
Surface water runoff				
Water quality	Improves water quality	Beneficial	Moderate	Needs research and observation
Hydrograph timing	Unknown	Unknown	Low	Needs research and observation
Waste management				
Fossil fuels waste spills	Eliminates waste stream	Beneficial	Moderate	Solar avoids fly ash spills and oil spills
Nuclear waste stream	Eliminates waste stream	Beneficial	High	Solar avoids need for waste repositories
Groundwater				
Groundwater recharge	Unknown	Unknown	Moderate	Needs research and observation
Water purity	Improves water quality	Beneficial	Moderate	Needs research and observation

more than 50% of roundwood is lost as waste at the sawmill or put into short-lived products such as paper [82,83]. For our present analysis we assume that between 25% and 50% of the deforested carbon is sequestered or is used in products that offset emissions elsewhere, and the remaining 50–75% becomes a new emission of CO_2 to the atmosphere. These same numbers also cover the scenario that the cut vegetation becomes firewood, in which case we assume that 25–50% of the deforested carbon displaces firewood production from elsewhere.

The removal of the forest changes the land's natural carbon sequestration rate. Understanding of the sequestration rate is improved due to recent radiocarbon measurements [84,85], measurements of the volume of wood in lumber and other forest products [86,87], and observations of ecosystem chronosequences [24]. The studies show the net exchange of carbon with the atmosphere to follow these phases: (i) carbon emission to the atmosphere occurs for the first 10–20 years following deforestation due to respiration of unsupported soil matter, at a rate of 400–2000 kg C $ha^{-1}\,yr^{-1}$ [85,88], (ii) carbon sequestration occurs for the subsequent ~75 years due to growth of trees and soil horizons, at a rate of 500–3000 kg C $ha^{-1}\,yr^{-1}$ [85,86,88], (iii) a reduction to near zero net carbon exchange sets in after the forest age reaches past ~100 years age, to rates of ±20 kg C $ha^{-1}\,yr^{-1}$ [85,89–91]. The range in these numbers is due to differing forest species and forest climate conditions. Recent publications suggest roughly half of the sequestered carbon is quickly returned to the atmosphere via rivers and lakes [92–94]. If a solar power plant is operating on the land then the trees and biomass cannot produce the middle stage of high sequestration, because the vegetation is continually trimmed and the clippings are oxidized back to the atmosphere. For our present study we assume the land will emit carbon for the first 15 years at 400–2000 kg C $ha^{-1}\,yr^{-1}$, then subsequently drop to zero net emissions for the remainder of the power plant lifetime. At the power plant's end-of-life, the solar power facilities are removed and the land may reforest, allowing carbon sequestration, but we do not account for these carbon flows in our present study because they occur many decades in the future.

We calculate the emissions of CO_2 per kW h of delivered electricity. To accomplish this we assumed that the solar power plant operates for 30 years, under insolation of 1700 kW h $m^{-2}\,day^{-1}$, with module conversion efficiency of 13%, a performance ratio of 80%, a land to GW_p ratio of 20 km^2 per GW_p, and a degradation rate of 0.5% per year in the module's performance. These numbers are typical for LCAs of CO_2 emissions from solar power [4], and give ~72 GW h $km^{-2}\,yr^{-1}$ as time-averaged generation for the plant. Emissions of CO_2 from the remainder of the life cycle of solar power are 16–40 g CO_2 kW h^{-1} for 1700 kW h $m^{-2}\,yr^{-1}$ insolation [4,6–8], A description of the calculations of CO_2 emissions per kW h is given in this paper's supplementary text. The results, which are summarized in Table 4, show the following: (i) the avoidance of ~650 g CO_2 per kW h of delivered electricity (average U.S. power emissions from Kim and Dale [95] and the DOE [96]), (ii) the emission of between 0 and 36 g CO_2 kW h^{-1} due to the initial removal of vegetation, iii) the emission of between 0 and 2 g CO_2 kW h^{-1} during the 10 years following deforestation, (iv) the emission of between 0 and 9 CO_2 kW h^{-1} due to the loss of the forest's natural sequestration, and (v) the emission of 16–40 g CO_2 kW h^{-1} due to the life-cycle of the solar system excluding vegetation considerations. The net emission results in Table 4 shows that solar power is still a very low carbon alternative to traditional U.S. power generation.

Methane and nitrous oxide are also important greenhouse gases released by coal power plants. For comparison, the radiative forcing of CO_2, methane, and nitrous oxide, respectively, are 1.7, 0.5, and 0.2 W m^{-2} [79], and fossil fuel combustion contributes 73%, 27%, and 8% of the respective amounts [97]. Emissions of CH_4 and NO_2 from the life cycle of solar power in forests are likely to be much lower than from fossil fuels, suggesting another GHG benefit for switching electricity generation from fossil to solar power.

Land use affects local climate, microclimate, and surface temperatures, e.g., urban heat islands exist near metropolitan areas. Solar panels have low reflectivity and convert a large fraction of insolation into heat, which leads to concern that they may affect global or local climate. Nemet [15] investigated the effect on global climate due to albedo change from widespread installation of solar panels and found the effect to be small compared to benefits from the accompanying reduction in greenhouse gas emissions. Nemet did not consider local climates or microclimates.

Table 5 lists the environmental impacts from solar energy in forested regions. The presence of the forest affects most of the impacts, particularly the CO_2 emissions. Field research is needed to establish the effect of the power plant on local climate and microclimates.

5. Net environmental impact

We aggregated the information in Section 4 to produce the net environmental impacts of large-scale solar power displacing grid electricity. Considering Tables 1–5, the following observations are made: (i) twenty two of the thirty two net impacts are beneficial,

Table 4
Emissions of CO_2 from the life cycle of large-scale solar power.

	Carbon dioxide emissions (g CO_2 kW h^{-1})	
	Best case	Worst case
Loss of forest sequestration	+0.0	+8.6
Respiration of soil biomass	+0.0	+1.9
Oxidation of cut biomass	+0.0	+35.8
Other phases of the life cycle	+16.0	+40.0
Total emissions of solar	+16.0	+86.3
Fossil fuel emissions avoidance	−850.0	−650.0
Total including avoidance	−834.0	−563.7

Table 5
Impacts to climate change from solar power, relative to traditional U.S. power generation.

Impact category	Effect relative to traditional power	Beneficial or detrimental	Priority	Comments
Global climate				
CO_2 emissions	Reduces CO_2 emissions	Beneficial	High	Strong benefit
Other GHG emissions	Reduces GHG emissions	Beneficial	High	Strong benefit
Change in surface albedo	Lower albedo	Neutral	Low	The magnitude of the effect is low
Local climate				
Change in surface albedo	Lower albedo	Unknown	Moderate	Needs research and observation
Other surface energy flows	Unknown	Unknown	Low	Needs research and observation

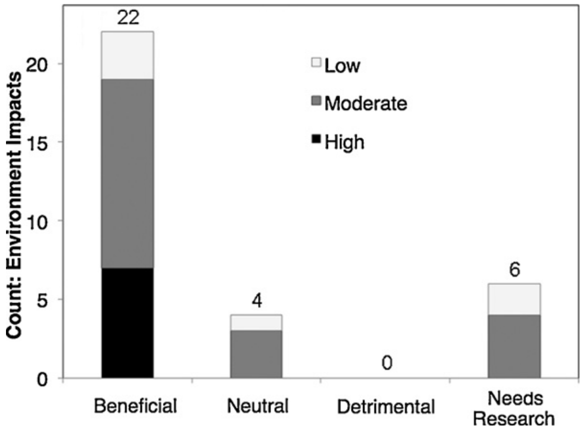

Fig. 3. Summary of the aggregate impact of solar power in forested environments compared to traditional U.S. power generation.

seven of which have high priority, twelve of which have moderate priority, and three of which have low priority, (ii) four of the thirty two net impacts are neutral, three of which have moderate priority and the remaining one has low priority, (iii) none of the net impacts were detrimental relative to traditional power, and (iv) the final six net impacts need further research before they can be classified. Fig. 3 presents these results graphically. In "true desert" regions the benefits of solar power would be more intense, and many of the net impacts would change from neutral (or unknown) to beneficial. These desert locations have the additional benefit that wintertime power generation is considerably stronger than in cloudier, or more polar, locations.

6. Conclusions

We identified and appraised the environmental impacts of large-scale solar power plants. Solar technology is concluded to be much preferable to traditional means of power generation, even considering wildlife and land use impacts. We identified 32 environmental impacts for solar power plants, and found that 22 are beneficial relative to traditional power generation, 4 are neutral, none are detrimental, and 6 need further research. All high-priority impacts are favorable to solar power displacing traditional power generation, and all detrimental impacts from solar power are of low priority. We find the land occupation metric to be most appropriate for comparing land use intensity of solar power to other power systems, and find that a solar power plant occupies less land per kW h than coal power, for plant lifetimes beyond ~25 years. The land transformation rate of solar power is lower than that of coal power for plant lifetime's beyond ~27 years. When comparing deployment of solar power plants in forests to that in grasslands or deserts, there are clear differences. Our calculations shows solar power in forested regions will release significantly more CO_2 than in desert regions, by a factor of 2–4, with a total emission of between 16 and 86 g CO_2 kW h^{-1}, due mainly to clearing of vegetation to make room for the solar power plant but also partly to the reduced insolation in forests due to clouds. All of the environmental impacts per kW h are heightened by the lower insolation in cloudy or high-latitude regions, because less kW h of electricity is generated from the life cycle of the power plant. Solar power plants located in true deserts, and other locations where solar insolation is intense and wildlife is absent, have the most beneficial environmental impact.

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IRRIGATION RETURN FLOW OR DISCRETE DISCHARGE? WHY WATER POLLUTION FROM CRANBERRY BOGS SHOULD FALL WITHIN THE CLEAN WATER ACT'S NPDES PROGRAM

BY

ANDREW C. HANSON[*] & DAVID C. BENDER[**]

Despite license plates proclaiming it as the "dairy state," Wisconsin is the top cranberry producing state in the nation. Cranberry operations are unique in that they are agricultural operations that require vast quantities of water. Water discharged to lakes, wetlands, and rivers through ditches and canals during the production process can contain the phosphorus fertilizers and residues of pesticides that were applied during the growing season, which can cause serious water quality problems. Although the cranberry industry has not historically been subject to the Clean Water Act, cranberry bog discharges appear to fit squarely within the purview of the National Pollutant Discharge Elimination System (NPDES) program under that statute. In 2004, the Wisconsin attorney general filed a public nuisance lawsuit against a cranberry grower, alleging that the grower discharged bog water laced with phosphorus to the lake. However, provided that cranberry bog discharges do not fall within the "irrigation return flow" exemption from the Clean Water Act, the NPDES permit program may be a more cost-effective approach to addressing the water quality problems that can be caused by cranberry bog discharges.

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May 23, 2018, 12:28pm EDT

If Solar Panels Are So Clean, Why Do They Produce So Much Toxic Waste?

Michael Shellenberger Contributor ⓘ ⊕

Energy

I write about energy and the environment.

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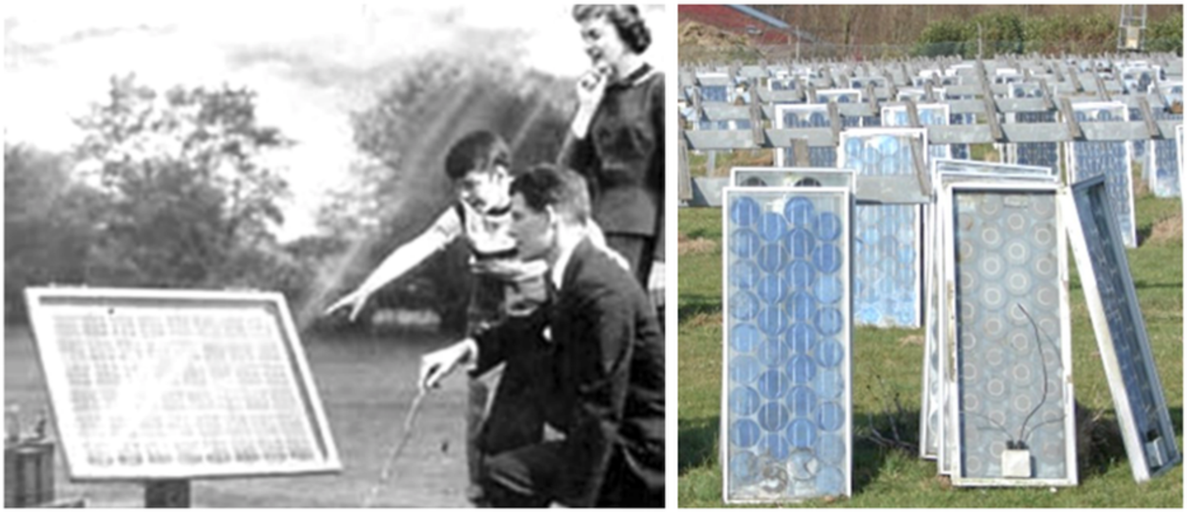

Bell Labs, 1954. Solar Panel Waste, 2014 BELL LABS & PV CYCLE

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- The problem of solar panel disposal "will explode with full force in two or three decades and wreck the environment" because it "is a huge amount of waste and they are not easy to recycle."
- "The reality is that there is a problem now, and it's only going to get larger, expanding as rapidly as the PV industry expanded 10 years ago."
- "Contrary to previous assumptions, pollutants such as lead or carcinogenic cadmium can be almost completely washed out of the fragments of solar modules over a period of several months, for example by rainwater."

Were these statements made by the right-wing Heritage Foundation? Koch-funded global warming deniers? The editorial board of the *Wall Street Journal*?

None of the above. Rather, the quotes come from a senior Chinese solar official, a 40-year veteran of the U.S. solar industry, and research scientists with the German Stuttgart Institute for Photovoltaics.

With few environmental journalists willing to report on much of anything other than the good news about renewables, it's been left to environmental scientists and solar industry leaders to raise the alarm.

"I've been working in solar since 1976 and that's part of my guilt," the veteran solar developer told *Solar Power World* last year. "I've been involved with millions of solar panels going into the field, and now they're getting old."

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at the end of that year. IRENA projected that this amount could reach 78 *million* metric tonnes by 2050.

Solar panels often contain lead, cadmium, and other toxic chemicals that cannot be removed without breaking apart the entire panel. “Approximately 90% of most PV modules are made up of glass,” notes San Jose State environmental studies professor Dustin Mulvaney. “However, this glass often cannot be recycled as float glass due to impurities. Common problematic impurities in glass include plastics, lead, cadmium and antimony.”

Researchers with the Electric Power Research Institute (EPRI) undertook a study for U.S. solar-owning utilities to plan for end-of-life and concluded that solar panel “disposal in “regular landfills [is] not recommended in case modules break and toxic materials leach into the soil” and so “disposal is potentially a major issue.”

California is in the process of determining how to divert solar panels from landfills, which is where they currently go, at the end of their life.

California's Department of Toxic Substances Control (DTSC), which is implementing the new regulations, held a meeting last August with solar and waste industry representatives to discuss how to deal with the issue of solar waste. At the meeting, the representatives from industry and DTSC all acknowledged how difficult it would be to test to determine whether a solar panel being removed would be classified as hazardous waste or not.

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"The theory behind the regulations is to make [disposal] less burdensome," explained Rick Brausch of DTSC. "Putting it as universal waste eliminates the testing requirement."

The fact that cadmium can be washed out of solar modules by rainwater is increasingly a concern for local environmentalists like the Concerned Citizens of Fawn Lake in Virginia, where a 6,350 acre solar farm to partly power Microsoft data centers is being proposed.

“We estimate there are 100,000 pounds of cadmium contained in the 1.8 million panels,” Sean Fogarty of the group told me. “Leaching from broken panels damaged during natural events — hail storms, tornadoes, hurricanes, earthquakes, etc. — and at decommissioning is a big concern.”

There is real-world precedent for this concern. A tornado in 2015 broke 200,000 solar modules at southern California solar farm Desert Sunlight.

"Any modules that were broken into small bits of glass had to be swept from the ground," Mulvaney explained, "so lots of rocks and dirt got mixed in that would not work in recycling plants that are designed to take modules. These were the cadmium-based modules that failed [hazardous] waste tests, so were treated at a [hazardous] waste facility. But about 70 percent of the modules were actually sent to recycling, and the recycled metals are in new panels today."

And when Hurricane Maria hit Puerto Rico last September, the nation’s

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Destroys Solar Farm in Puerto Rico BOB MEINETZ

Many experts urge mandatory recycling. The main finding promoted by IRENA's in its 2016 report was that, "If fully injected back into the economy, the value of the recovered material [from used solar panels] could exceed USD 15 billion by 2050."

But IRENA's study did not compare the value of recovered material to the cost of new materials and admitted that "Recent studies agree that PV material availability is not a major concern in the near term, but critical materials might impose limitations in the long term."

They might, but today recycling costs more than the economic value of the materials recovered, which is why most solar panels end up in landfills. "The absence of valuable metals/materials produces economic losses," wrote a team of scientists in the *International Journal of Photoenergy* in their study of solar panel recycling last year, and

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Post, “their products can end up being more expensive than new raw materials.”

Toshiba Environmental Solutions told Nikkei Asian Review last year that,

> Low demand for scrap and the high cost of employing workers to disassemble the aluminum frames and other components will make it difficult to create a profitable business unless recycling companies can charge several times more than the target set by [Japan’s environment ministry].

Can Solar Producers Take Responsibility?

In 2012, First Solar stopped putting a share of its revenues into a fund for long-term waste management. "Customers have the option to use our services when the panels get to the end of life stage," a spokesperson told *Solar Power World*. “We’ll do the recycling, and they’ll pay the price at that time.”

Or they won’t. “Either it becomes economical or it gets mandated. ” said EPRI’s Cara Libby. “But I’ve heard that it will have to be mandated because it won’t ever be economical.”

Last July, Washington became the first U.S. state to require manufacturers selling solar panels to have a plan to recycle. But the legislature did not require manufacturers to pay a fee for disposal. “Washington-based solar panel manufacturer Itek Energy assisted with

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Milliman, is that it increases the risk of more financial failures like the kinds that afflicted the solar industry over the last decade.

> [A]ny mechanism that finances the cost of recycling PV modules with current revenues is not sustainable. This method raises the possibility of bankruptcy down the road by shifting today's greater burden of 'caused' costs into the future. When growth levels off then PV producers would face rapidly increasing recycling costs as a percentage of revenues.

Since 2016, Sungevity, Beamreach, Verengo Solar, SunEdison, Yingli Green Energy, Solar World, and Suniva have gone bankrupt.

The result of such bankruptcies is that the cost of managing or recycling PV waste will be born by the public. "In the event of company bankruptcies, PV module producers would no longer contribute to the recycling cost of their products," notes Milliman, "leaving governments to decide how to deal with cleanup."

Governments of poor and developing nations are often not equipped to deal with an influx of toxic solar waste, experts say. German researchers at the Stuttgart Institute for Photovoltaics warned that poor and developing nations are at higher risk of suffering the consequences.

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Maharashtra, India, 2014 DIPAK SHEELARE

> Dangers and hazards of toxins in photovoltaic modules appear particularly large in countries where there are no orderly waste management systems... Especially in less developed countries in the so-called global south, which are particularly predestined for the use of photovoltaics because of the high solar radiation, it seems highly problematic to use modules that contain pollutants.

The attitude of some solar recyclers in China appears to feed this concern. "A sales manager of a solar power recycling company," the *South China Morning News* reported, "believes there could be a way to dispose of China's solar junk, nonetheless."

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panels to make up for their low performance. Everyone is happy with the result.”

In other words, there are firms that may advertise themselves as "solar panel recyclers" but instead sell panels to a secondary markets in nations with less developed waste disposal systems. In the past, communities living near electronic waste dumps in Ghana, Nigeria, Vietnam, Bangladesh, Pakistan, and India have been primary e-waste destinations.

According to a 2015 United Nations Environment Program (UNEP) report, somewhere between 60 and 90 percent of electronic waste is illegally traded and dumped in poor nations. Writes UNEP:

> [T]housands of tonnes of e-waste are falsely declared as second-hand goods and exported from developed to developing countries, including waste batteries falsely described as plastic or mixed metal scrap, and cathode ray tubes and computer monitors declared as metal scrap.

Unlike other forms of imported e-waste, used solar panels can enter nations legally before eventually entering e-waste streams. As the United Nation Environment Program notes, “loopholes in the current Waste Electrical and Electronic Equipment (WEEE) Directives allow the export of e-waste from developed to developing countries (70% of the collected WEEE ends up in unreported and largely unknown destinations).”

A Path Forward on Solar Panel Waste

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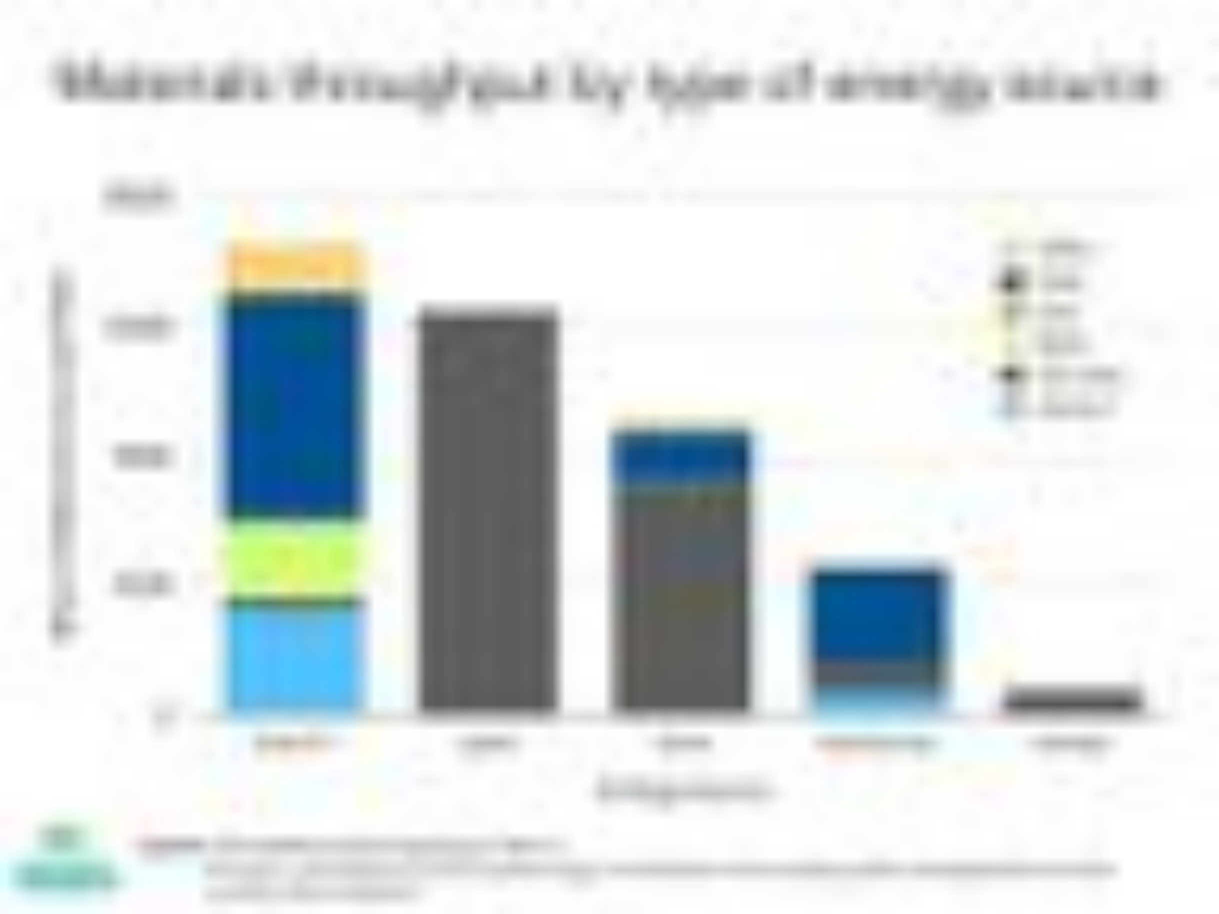
collectors to capture and convert the sun's rays into electricity. Those large surface areas, in turn, require an order of magnitude more in materials — whether today's toxic combination of glass, heavy metals, and rare earth elements, or some new material in the future — than other energy sources.



Solar requires 15x more materials than nuclear EP

All of that waste creates a large quantity of material to track, which in turn requires requires coordinated, overlapping, and different responses at the international, national, state, and local levels.

The local level is where action to dispose of electronic and toxic waste

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secondary market for solar shows, ultimately there needs to be some kind of international regulation.

The first step is a fee on solar panel purchases to make sure that the cost of safely removing, recycling or storing solar panel waste is internalized into the price of solar panels and not externalized onto future taxpayers. An obvious solution would be to impose a new fee on solar panels that would go into a federal disposal and decommissioning fund. The funds would then, in the future, be dispensed to state and local governments to pay for the removal and recycling or long-term storage of solar panel waste. The advantage of this fund over extended producer responsibility is that it would insure that solar panels are safely decommissioned, recycled, or stored over the long-term, even after solar manufacturers go bankrupt.

Second, the federal government should encourage citizen enforcement of laws to decommission, store, or recycle solar panels so that they do not end up in landfills. Currently, citizens have the right to file lawsuits against government agencies and corporations to force them to abide by various environmental laws, including ones that protect the public from toxic waste. Solar should be no different. Given the decentralized nature of solar energy production, and lack of technical expertise at the local level, it is especially important that the whole society be involved in protecting itself from exposure to dangerous toxins.

“We have a County and State approval process over the next couple months,” Fogarty of Concerned Citizens of Fawn Lake told me, “but it has become clear that local authorities have very little technical breadth

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in its panels is not water soluble. That claim has been contradicted by the previously-mentioned Stuttgart research scientists who found cadmium from solar panels “can be almost completely washed out…over a period of several months…by rainwater.”

Third, the United Nations Environment Programme’s Global Partnership for Waste Management, as part of its International Environmental Partnership Center, should more strictly monitor e-waste shipments and encourage nations importing used solar panels into secondary markets to impose a fee to cover the cost of recycling or long-term management. Such a recycling and waste management fund could help nations address their other e-waste problems while supporting the development of a new, high-tech industry in recycling solar panels.

None of this will come quickly, or easily, and some solar industry executives will resist internalizing the cost of safely storing, or recycling, solar panel waste, perhaps for understandable reasons. They will rightly note that there are other kinds of electronic waste in the world. But it is notable that some new forms of electronic waste, namely smartphones like the iPhone, have in many cases replaced things like stereo systems, GPS devices, and alarm clocks and thus reduced their contribution to the e-waste stream. And no other electronics industry makes being “clean” its main selling point.

Wise solar industry leaders can learn from the past and be proactive in seeking stricter regulation in accordance with growing scientific evidence that solar panels pose a risk of toxic chemical contamination. “If waste

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If the industry responds with foresight, Mulvaney notes, it could end up sparking clean innovation including “developing PV modules without hazardous inputs and recycled rare metals." And that's something everyone can get powered up about.

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Michael Shellenberger is the best-selling author of *Apocalypse Never: Why Environmental Alarmism Hurts Us All* (Harper Collins), a Time Magazine “Hero of the Environment,”... **Read More**

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