An Assessment of the Environmental Impacts of Concentrator Photovoltaics

and

Modeling of Concentrator Photovoltaic Deployment Using the SWITCH Model
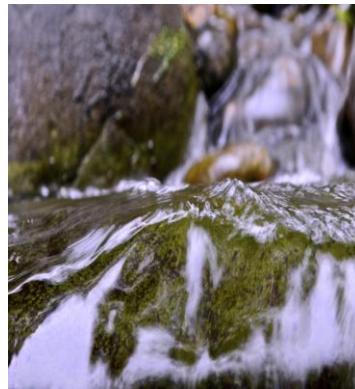
Conducted by the
Renewable and Appropriate Energy Laboratory
http://rael.berkeley.edu/
Energy and Resources Group
University of California at Berkeley

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GLOSSARY OF TERMS

CPV	Concentrator Photovoltaics
RAEL	Renewable and Appropriate Energy Laboratory University of California Berkeley
LCA	Life Cycle Assessment: environmental impact of any technology incorporating all impacts from inception to retirement
GHG	Green House Gases
CSP	Concentrating Solar Power, also referred to as Solar Thermal
EPBT	Energy Payback Time defined as time in years it takes for a technology to produce as much energy as it takes to create and dispose of the device
SWITCH	Electric power system capacity expansion model of Western North America that plans long-term grid investments while minimizing cost of electricity in a given policy context; developed and maintained by RAEL at University of California Berkeley
WECC	Western Electricity Coordinating Council

PREFACE

About Dr. Daniel Kammen

Dr. Kammen brings to the analysis of national and international energy policy an understanding of the technology as well as of the economics and the policy landscape.

He sees value in greater emphasis on renewable energy sources, such as solar and wind power and biomass, not only because it is better for the environment, but also because it would improve our nation's security by lessening reliance on imported oil. Renewables also would produce more jobs than an equivalent investment in fossil fuel energy sources, according to a recent study by Kammen. He also argues that renewables are a better investment than highly touted but uncertain exotic new technologies such as hydrogen fuel.

He has testified before U. S. House and Senate committees on energy and environmental issues. He has advised the New Apollo Energy Project, an initiative spearheaded by Sen. Maria Cantwell, D-Wash., and Rep. Jay Inslee, D-Wash., to replace the energy bill now languishing in Congress with a new bill emphasizing energy independence and weaning the country from a reliance on imported fossil fuels by 2010.

Kammen has been a guest on National Public Radio's Science Friday and has been interviewed by CNN and numerous local television and radio stations on energy, environmental and risk policy issues, and current events. He is very comfortable in front of the camera, and recently was interviewed by Alan Alda for an upcoming Scientific American Frontiers program called Future Car, set to air in May 2004.

Kammen advises the United States and Swedish Agencies for International Development, the World Bank, the American Academy of Arts and Sciences, the African Academy of Sciences and the President's Committee on Science and Technology, and is a member of the Intergovernmental Panel on Climate Change.

Overview of the Renewable and Appropriate Energy Laboratory

The Renewable and Appropriate Energy Laboratory (RAEL) is a unique new research, development, project implementation, and community outreach facility based at the University of California, Berkeley in the Energy and Resouces Group and the Department of Nuclear Engineering. RAEL focuses on designing, testing, and disseminating renewable and appropriate energy systems. The laboratory's mission is to help these technologies realize their full potential to contribute to environmentally sustainable development

in both industrialized and developing nations while also addressing the cultural context and range of potential social impacts of any new technology or resource management system.

The work in RAEL is guided by the principles of use-inspired basic research, interdisciplinary approaches to the needs that energy services can provide, and a dedication to understanding and addressing the opportunities and risks in the implementation of novel energy generation and management programs. At one level, the goal for RAEL is to update, integrate and nurture a collaborative synthesis of E. F. Schumacher's *Small is Beautiful* appropriate technology and development philosophy with the energy industry as it exists today. On another level, it is to promote sustainable development that includes deep cuts in greenhouse gas emissions and resource consumption.

RAEL will study how to evolve the current energy infrastructure through analysis of coal, oil, and integrated fossil-fuel/fuel cells systems, biomass energy, and combinations of energy-efficiency and renewables, as well as entirely new long-term energy options for industrialized, decentralized, and rural energy needs.

Today, over one billion people obtain most of their energy services from wood, charcoal, agricultural wastes and dung (biomass fuels), over two billion people have no access to electricity, and several hundred million more only have recourse to a limited, unreliable, or impossibly expensive supply. Despite the tremendous social, economic, health, and environmental benefits of widespread access to environmentally clean energy, many nations are unable to maintain even their current electrical grids, let alone afford the cost of extending electrical capacity to service the majority of their populations. The lack of basic energy resources and inefficient and unsustainable energy practices are perhaps the largest contributors to human, environmental, and global health problems today.

INTRODUCTION

The environmental and societal benefits of deploying renewable energy technologies at utility scale must be considered alongside the concomitant costs and alternatives in order to properly evaluate the social return on investment of each technology.

The benefit of evaluating the environmental impact of a technology *before* large-scale deployment cannot be stressed enough. The United States wind industry has learned difficult lessons from its deployment of wind turbines at the Altamont pass in California, where windmills have been found to kill at least one bird per year per turbine (Ritter 2005). Had there been a proper environmental impact study of the area, 4000 turbines would not have been sited in an important bird migration route, and the wind industry would not have received negative press surrounding the harmful environmental impacts of a prominent green technology. Mitigation efforts for new wind projects such as using radar to detect flocks of birds and furl turbine blades are now underway (Iberdrola 2009), but this type of technology could have been used from the inception of wind deployment.

The first part of this report touches on important environmental areas that must be considered when deploying Concentrator Photovoltaics (CPV). It does not attempt to evaluate the best sites for CPV development on an environmental basis. Rather, CPV is compared to other solar technologies and more broadly, to other electric power generating technologies with respect to key life cycle environmental metrics.

In the second part of this report, the possible future deployment of CPV is investigated using UC Berkeley's SWITCH model, and the emissions benefits of including CPV in the future Western United States electric power system are discussed.

AN ASSESSMENT OF THE ENVIRONMENTAL IMPACTS OF CPV

To accurately portray the environmental impact of any technology, all impacts from inception to retirement must be taken into account. Life Cycle Assessment (LCA) methodology considers three distinct phases in the life cycle of CPV: (1) fabrication of CPV modules and deployment in the field on two-axis tracking systems (2) energy production (3) recycling and disposal at end of life. Here, four LCA environmental impact metrics are discussed in the context of CPV: energy, emissions, water use and land use.

Embodied Energy and Emissions

The production of photovoltaics is an energy-intensive process. As most current forms of energy-intensive processes use greenhouse gas (GHG) intensive fuels, it is important to quantify the effect of the production of photovoltaics on our energy supply and on the stock of GHG in our atmosphere. The LCA community refers to the energy used and GHGs emitted in the production and disposal of a product as 'embodied energy' and 'embodied emissions' respectively.

By concentrating sunlight on highly efficient photovoltaic material, CPV systems minimize the amount of active photovoltaic material that must be mined, refined and purified into the final device. However, additional components related to light concentration and sun tracking must be included in CPV systems, thereby making the net embodied energy and emissions of light concentration in photovoltaic devices uncertain. Here we review LCA literature on CPV embodied energy and emissions and compare the results to other electric power generators.

A dominant LCA energy metric is the Energy Payback Time (EPBT), which denotes the time in years it takes for a technology to produce as much energy (net) as it takes to create and dispose of the device. EPBT is a measure of energy efficacy - for an energy technology to be a worthwhile investment from an energy production perspective, the EPBT should be much less than the lifetime of the device. In the past, the fast-paced solar industry has been plagued with outdated literature values of EPBT in the range of 3 - 11 years for a technology with a lifetime of 20 - 30 years (Alsema 1998, Alsema 2007), leading to fallacious conclusions that solar energy doesn't warrant deployment due to large energy demands in production. Figure 1.1 shows recent EPBT values for a range of solar technologies, all of which are less than or equal to two years.

EPBTs are calculated (eq. 1) by adding up all energy used in fabrication and installation of an electric power device, as well as disposal/recycling at the end of life, and then dividing this Cumulative Energy Demand (CED) by the yearly net energy during operation. The yearly net energy during operation is expressed in units of *primary* energy per year, thereby giving the EPBT in years.

$$EPBT = \frac{CED}{Yearly\,Operational\,Net\,Energy} = \frac{E_{Fabrication} + E_{Installation} + E_{EndOfLife}}{\dfrac{P_{GeneratedNet}}{GridEfficency} - P_{O\&M}} \qquad \textbf{(1)}$$

The conversion from yearly net electricity generated by the device $P_{GeneratedNet}$ to primary energy terms is accomplished by dividing $P_{GeneratedNet}$ by the efficiency of electric power grid at converting primary energy into electricity at the site of deployment of the device. This conversion represents the input energy that would have been used to create a unit of electricity from other electric power generators, had the device in question not been installed. The primary energy used in operations and maintenance $P_{O\&M}$ is subtracted from the denominator to obtain the yearly operational net energy.

Embodied GHG emissions are calculated by adding up all GHGs emitted throughout the life cycle of an electric power device and then dividing by the total electricity produced by the device, giving units gCO_2-eq/kWh. EPBT and embodied GHGs are plotted in Figure 1.1 for a variety of solar energy technologies. Figure 1.2 puts LCA GHG emissions from solar technologies in the broader context of other electric power generators.

As shown in Figure 1.1, the EPBTs of CPV systems are comparable with those of non-concentrator PV systems. CPV systems have EPBTs of 0.7 to 1.9 years, whereas non-concentrator PV systems have EPBTs of 0.8 to 1.8 years. This broad range of EPBTs for both non-concentrator and CPV technologies reflect differences in methodology and scope of each LCA study; consequently comparisons as in Figure 1.1 should be taken with a note of caution. One of the largest sources of inconsistency between studies is the site at which each solar system is assumed to be installed, causing the incident insolation and hence power production to vary by up to 30 % from study to study. The power conversion efficiency from primary energy to grid electricity also varies significantly from site to site.

The embodied emissions of CPV systems are higher than those of most non-concentrator PV systems. This is primarily due to the tracking system necessary for CPV technology, which contains large amounts of GHG-intensive steel. Redesigning tracking mechanisms to reduce wind susceptibility and thus the need for steel could help to reduce the GHG footprint of CPV.

CPV modules have made large gains in efficiency in the past three years, relative to other solar technologies (Hartsoch 2011). Many of the studies cited in Figure 1.1 were performed in the 2008-2010 timeframe, and therefore the efficiency of CPV systems in these reports is lower than is found today. While a complete life cycle assessment with using these new efficiency values is out of the scope of this work, it is clear that these efficiency gains will translate into reduced EPBTs and GHG emissions for CPV.
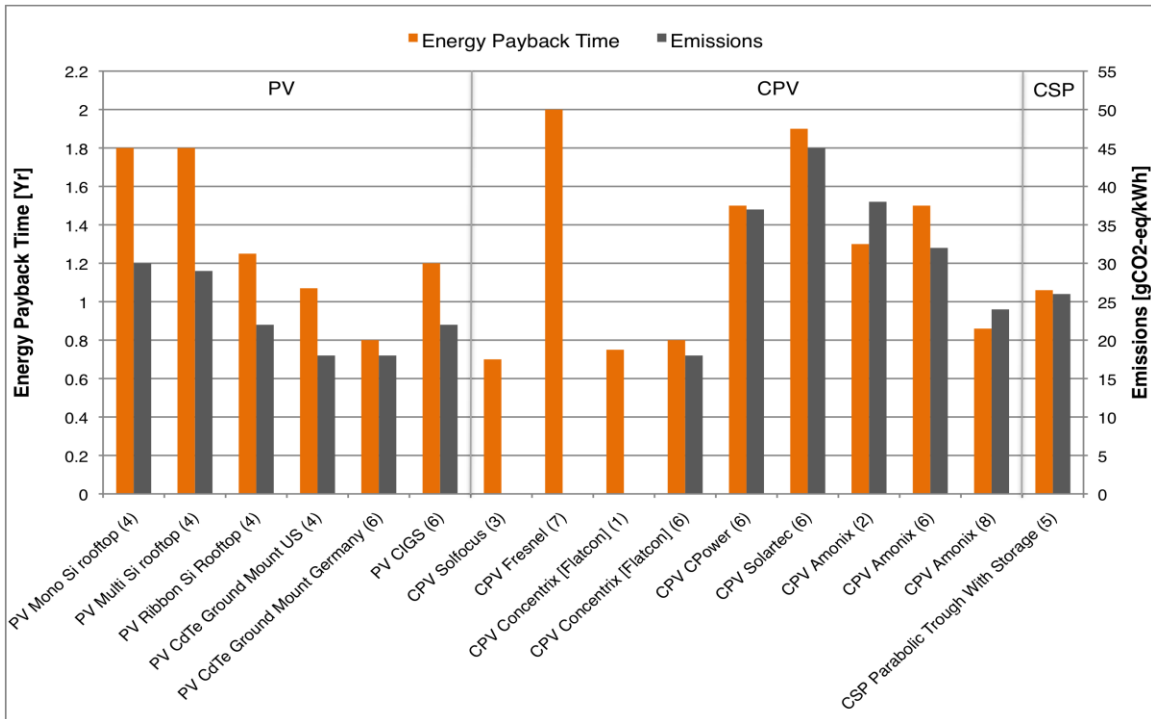
Figure 1.1: Energy Payback Time and Life-cycle GHG Emissions for various solar technologies. Where blank, emissions data was not available. Sources cited above: Peharz and Dimroth 2005 (1), Kim and Fthenakis 2006 (2), Reich-Weiser et al. 2008 (3), Fthenakis et al. 2009 (4), Burkhardt et al. 2010 (5), de Wild-Scholten et al. 2010 (6), Nishimura et al. 2010 (7), Fthenakis and Kim 2010A (8).
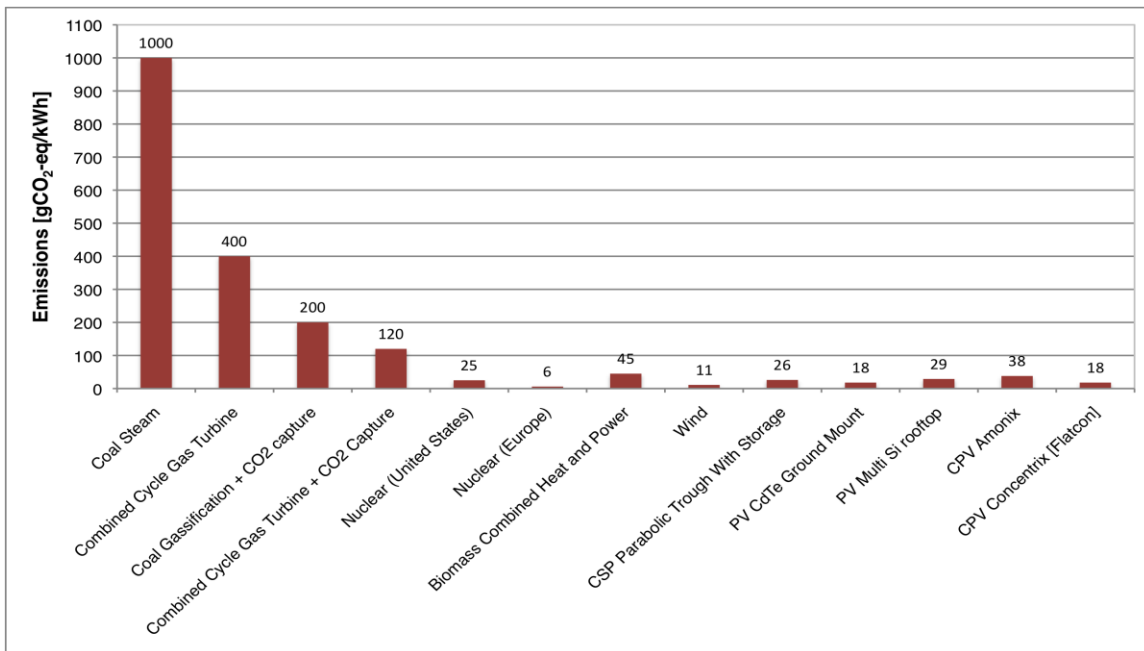

Figure 1.2. Life cycle GHG Emissions for electric power generators. Sources: Alsema and de Wild-Scholten 2005, Alsema et al. 2006, de Wild-Scholten et al. 2010.

Owing to the steel tracking systems, CPV systems are consequently heavier than non-concentrator PV systems and therefore require more energy to transport, incurring more GHG emissions along the way. Transportation can account for up to 20 % of GHG emissions along the CPV supply chain (Reich-Weiser et al. 2008), a value that has recently been reduced by collocating CPV component manufacturing sites with areas of high direct normal insolation (Phoenix Business Journal 2009, Amonix 2010).

Changing the electricity supply mix during CPV system manufacturing could also significantly decrease the embodied energy and emissions of CPV. Roughly one quarter of life cycle GHG emissions originate from electricity used in CPV module production (Reich-Weiser et al. 2008). If instead of manufacturing CPV modules using the average emissions of the electric power system – a GHG emissions-heavy system which in the United States is fueled in large part by coal and natural gas – the CPV panels were instead manufactured using electricity generated by existing solar power plants, the emissions attributed to electricity used in module production could be reduced to a fraction of the current value. This concept is known as the PV breeder concept (Fthenakis *et al.* 2008).

The embodied energy of solar thermal Concentrating Solar Power (CSP) systems has received much less attention than that of photovoltaics, but recent estimates put the EPBT of a parabolic trough system with six hours of thermal storage at 1.06 years (Burkhardt *et al.* 2010). While both the EPBT and GHG emissions values for solar thermal (without natural gas backup) are within the range of estimates for CPV, other environmental factors such as water use must be taken into account when considering solar thermal systems. Using dry cooling technology in the above solar thermal plant raises the CED by 8% and the GHG emissions by 7%. A comparison of water use of these plants can be found below.

Other Embodied Emissions

LCA studies of solar technologies are in the nascent phase of incorporating emissions of substances other than GHGs (e.g. cadmium) into their sustainability metrics (Fthenakis *et al.* 2008). A recent study compares CPV to multicrystalline PV using one unified metric that includes fossil fuel depletion, global warming potential, water and air pollution, acid rain, etc (Nishimura *et al.* 2010). It was found that CPV has roughly double the environmental impact of multicrystalline PV, with most of the added environmental stress coming from embodied pollutants in the tracking system. Strategies for reducing the environmental intensity of the CPV tracking system are discussed above.

Water Use

Water use represents an important environmental impact of electricity generation, especially in the context of growing demand for water and ever more limited supplies (Fthenakis and Kim 2010B). Currently 41 % of all water withdrawals in the United States come from electricity generation (Burkhardt *et al.* 2010). Water is consumed prior to power plant operation during the energy-intensive manufacturing of power plant components and is also used by thermal power plants during power production for cooling. As manufacturing and power production may not be collocated, the local effect of water withdrawal may differ substantially between these two phases.

For solar thermal generation technologies, water usage for cooling purposes during electricity production may be an important limiting factor to tapping high quality solar resources, as these tend to be located in arid areas with severe water shortages. Note the overlap in concentrating solar resource (direct normal insolation) in Figure 1.3 and water-constrained areas in Figure 1.4.
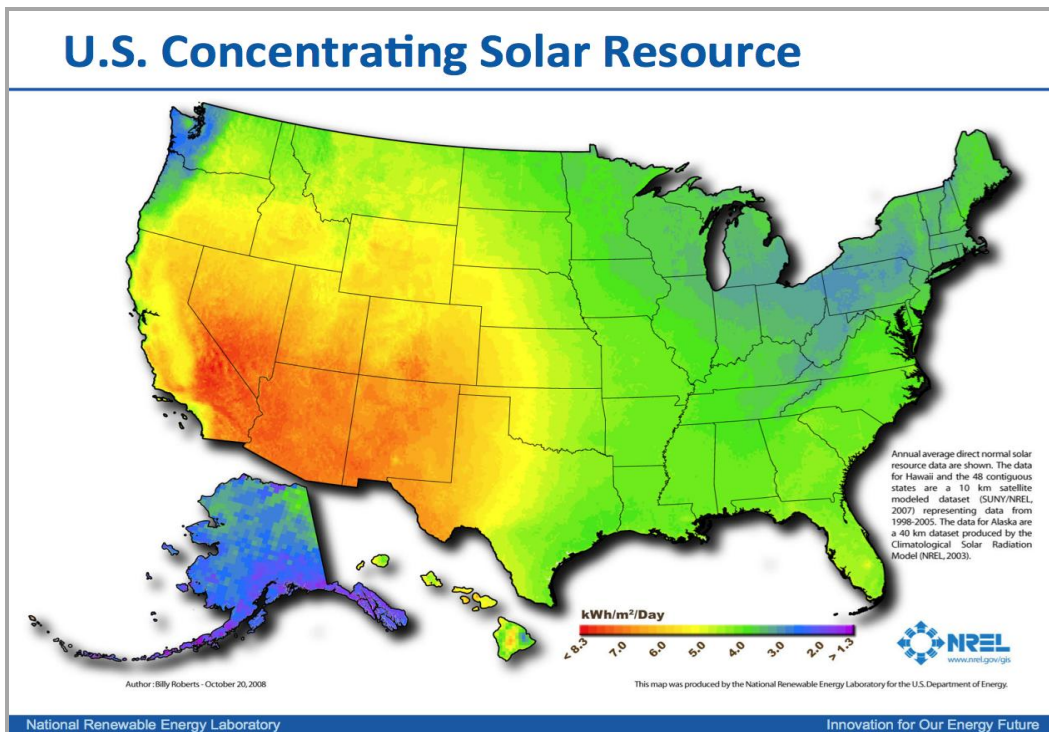

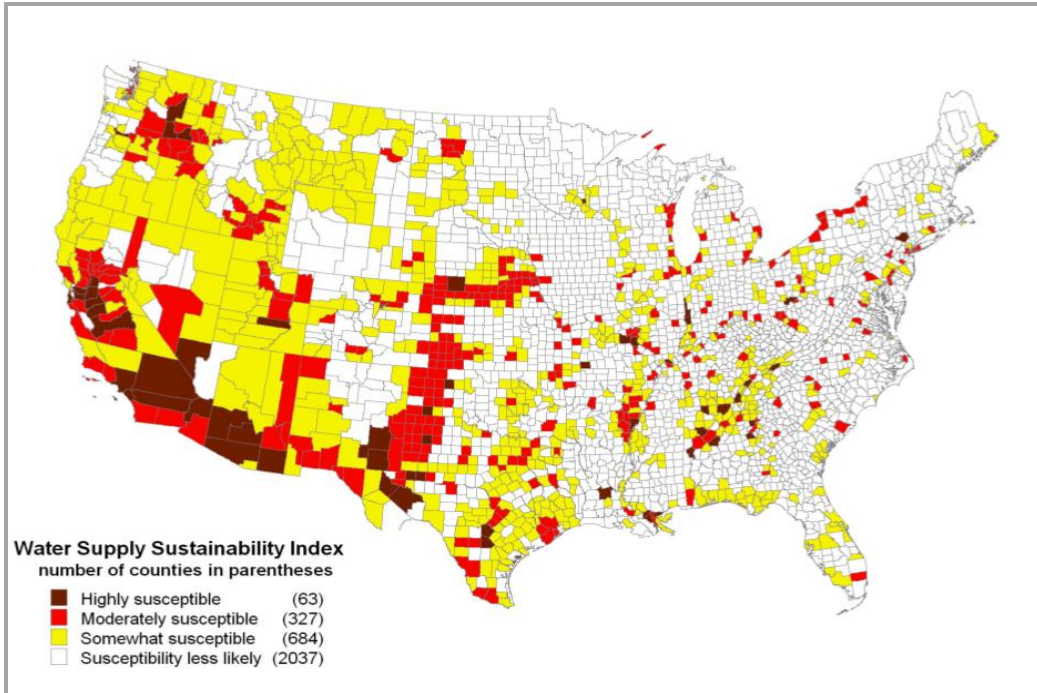**Figure 1.3**. United States direct normal radiation (National Renewable Energy Laboratory 2009).

Figure 1.4. Water supply sustainability in the United States by county (Electric Power Research Institute 2003).

Upstream Water Use

Limited data is available on the upstream water usage for materials manufacturing and solar power plant construction as LCA water use methodologies are in their infancy (Koehler 2008). Fthenakis and Kim (2010B) note that water consumption requirements during the manufacturing stages of a power plant can be difficult to determine because of the lack of information on the extent of water recycling during these stages, thereby obscuring the amount of water is actually consumed.

For non-concentrator silicon PV, the amount of water withdrawn (but not necessarily consumed) throughout the system fabrication process is about 2000 L/MWh (Fthenakis and Kim 2010B). Most of this water is withdrawn for producing high-purity silicon, accounting for 66 % and 68 % of the total upstream water use for multi- and mono-Si respectively (derived from Fthenakis and Kim 2010B). The considerably lower photovoltaic material requirement of thin film CdTe PV, combined with a less energy-intensive fabrication process, results in a lower water withdrawal value of about 800 L/MWh.

To date, quantification of upstream water withdrawal by CPV is not present in the literature. The energy and hence water demand from CPV semiconductor production is likely to be lower than for silicon PV as the concentration of light allows CPV to minimize semiconductor material requirements. However, the effect of the additional

concentrating optics and tracking system on upstream water use will add significantly to the total upstream water demand of CPV. Because upstream water use tends to be correlated with energy used in fabrication and because PV and CPV have comparable manufacturing energy uses, it is unlikely that CPV upstream water use differs by more than a factor of two from that of PV.

The upstream water withdrawal from other generation technologies is outside the scope of this review, but thermal power plants, including solar thermal, generally have upstream water withdrawal values within a factor of about three of PV (Harto *et al.* 2010, Fthenakis and Kim 2010B). Water withdrawn during manufacturing is considerably less important than water use during power plant operation, as operational water demands are necessarily situated at the site of the power plant, which may be located in a water-constrained region.

Water Use During Power Plant Operation

Photovoltaic generators require water to wash dust and dirt off of the front of modules, as cell efficiency is reduced when the modules are dirty. Fthenakis and Kim (2010B) estimate that the water use during PV and CPV plant operation is 15 L/MWh, and this estimated is corroborated for CPV by Hartsoch (2010). Schell (2009) estimates that CPV water usage during operation to be similar to be 7.2 L/MWh, with the value for non-concentrator PV be double the CPV value because of the larger module area requiring maintenance relative to CPV. These PV and CPV values are small compared to the water consumed by thermal generators (Figure 1.5).
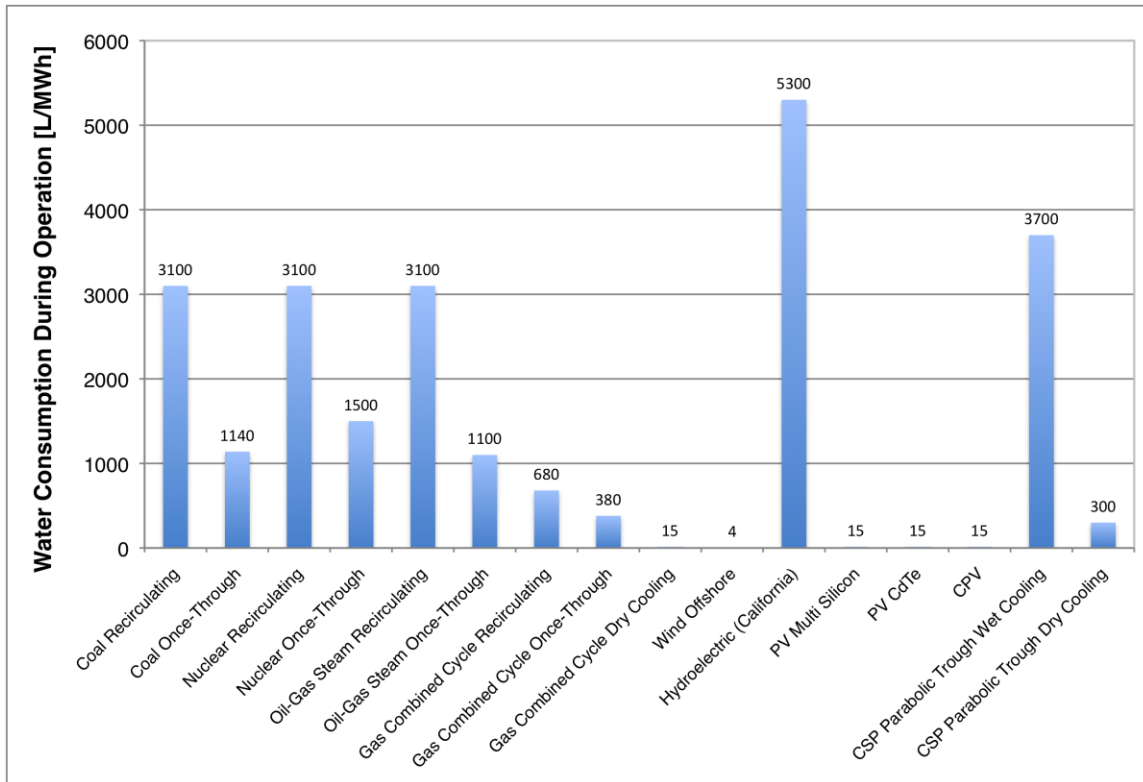
Figure 1.5. Water consumption for various power generation technologies during the operational phase of the power plant life cycle. Values are chosen to represent median cases for each technology. Source: Fthenakis and Kim 2010B.

As mentioned above, solar thermal CSP may encounter significant water constraints in desert environments. Stoddard et al (2006) note that water usage at CSP plants will depend on the specific design and configuration of the system, estimating water consumption at about 2800 L/MWh if wet cooling is used. Fthenakis and Kim (2010B) estimate the water consumption of a wet-cooled CSP parabolic trough system to be between 3100 and 3800 L/MWh. Dry cooling – using ambient air for cooling instead of water – is another option, as dry cooling is estimated to reduce water consumption by more than 90 percent (Turchi *et al*. 2010). The remaining water consumption is for the steam cycle and mirror washing. Concomitant with water consumption benefits, dry cooling increases the plant construction costs by 3 to 6 % and decreases plant performance by 5 to 9 %, raising the overall cost of CSP electricity by 10 percent or more (Pihl 2009, Stoddard *et al.* 2006, Schell 2009), potentially making dry cooling CSP a less attractive than other central station solar options.

Similarly to CSP, the cooling option greatly affects the water use levels during operation at thermal power plants. A review by Fthenakis and Kim (2010B) finds that once-through cooling requires water withdrawal on the order of 10^5 L/MWh, but the water consumed by the thermal plant is roughly two orders of magnitude less. Water

consumption values range between 242 and 4430 L/MWh for coal power plants, between 530 and 3400 L/MWh for nuclear power plants, and between 341 and 3100 L/MWh for oil and gas-steam power plants. Figure 1.5 shows typical water consumption values for these generators.

Land Use

Solar power has long been criticized for using vast amounts of land relative to conventional generation sources. When mining and transportation and disposal of non-renewable, conventional fuels are taken into account, the land requirements for solar are comparable to those of non-renewable fuels. Life cycle land use is well covered in Fthenakis and Kim (2009), the results of which are summarized in Figure 1.6 below.
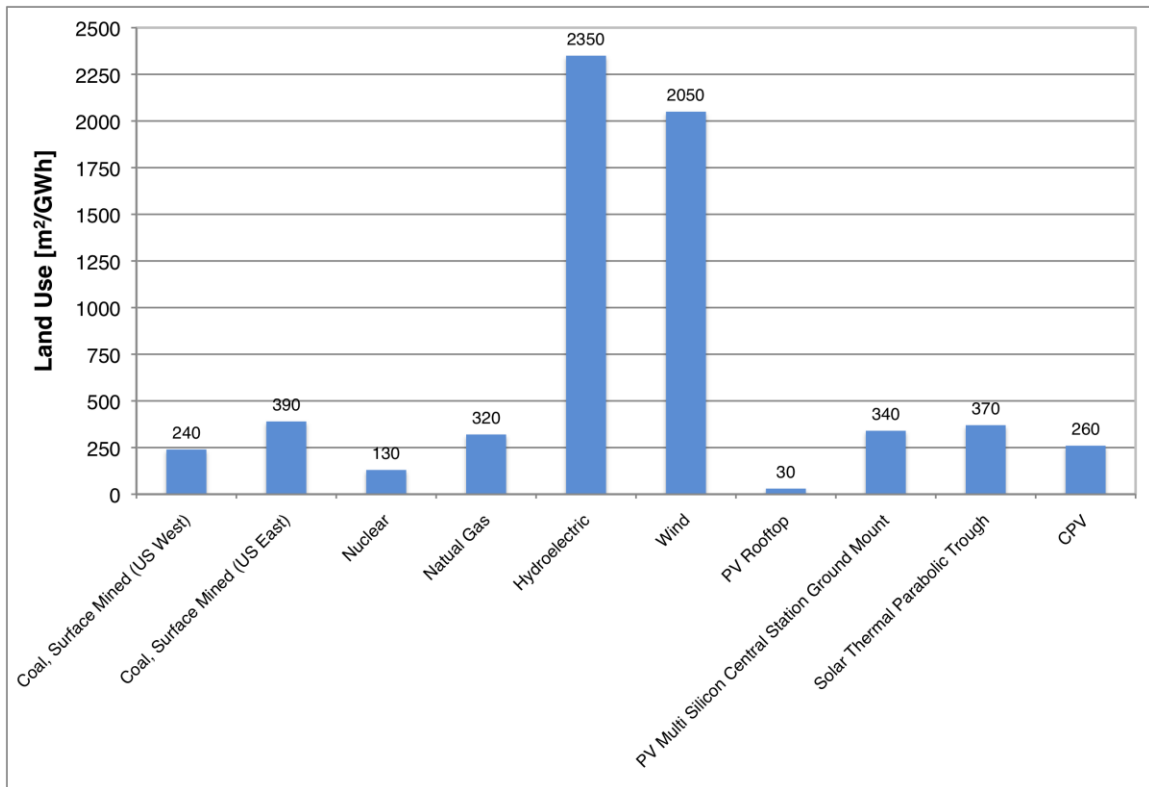

Figure 1.6. Land use by technology. Values are inclusive of direct and indirect land use, and are chosen to represent median cases for each technology. Source: Fthenakis and Kim (2009).

The decreased land demand for CPV systems with respect to non-concentrator, ground mounted PV systems is due to the high power conversion efficiency of CPV. CPV systems require more land per square meter of module area than non-concentrator PV due to spacing requirements imposed by the two-axis tracking system, but this effect is more than offset by CPV's high power conversion efficiency, leading to lower overall land use.

Rooftop PV installations have the least land use of any technology considered in Fthenakis and Kim (2009), as rooftop PV installations are situated on land already disturbed by the building on which they sit. While these installations provide land use and transmission benefits, the added cost of rooftop PV relative to central station PV may preclude utility-scale deployment. Central station solar is needed alongside rooftop PV to cost effectively meet the rapidly increasing demand for solar energy.

Minimizing central station solar power plant land use has the important effect of decreasing effects on local plant and wildlife habitat. Central station solar projects in the American desert southwest have recently come under fire for disturbing fragile desert tortoise habitats (CNBC 2009), and as the deployment of solar increases, these concerns are only likely to increase. CPV enables minimal land disturbance per unit of energy produced and hence is a good choice when deciding between different central station solar options.

Most CPV system designs offer potential additional land use benefits by virtue of being mounted above the ground on a tracking pole. As an example, the land occupied by the tracking pole support of a SolFocus CPV system is 2.5 % of the module area (Hartsoch 2010). This opens up the possibility of retaining desert ecosystem under and around the CPV modules, especially considering that the tracking system does not permanently shade any one part of the underlying ground. Additionally, tracking pole technologies such as CPV do not require major earthwork and accompanying ecosystem disruption; land does not need to be flattened to mount poles. Ecosystems will be disrupted during site development, but developers can choose to allow plants and small animals to return and remain undisturbed after construction. If the site was sufficiently degraded before development this practice could improve ecosystem conditions.

It should be noted, however, that maintaining the desert under CPV modules would be a shift for central station solar development. Many solar project developers flatten the desert floor and erect fences around major solar plants, as depicted by images of the world's ten largest central station solar plants (Tulloch 2010). Developers do currently perform environmental impact studies, move endangered or threatened species off of disturbed land, and set aside pristine parcels of land to compensate for the loss of habitat. New security and module maintenance methods are needed to retain the desert land directly below CPV installations, with the benefit of keeping valuable wildlife corridors open and preserving desert plants at the site. CPV has been a leader thus far in keeping the land below modules open, and the climate of land use protection found in the CPV community will hopefully continue this trend as CPV scales up to utility-scale generation.

MODELING OF CPV DEPLOYMENT USING THE SWITCH MODEL

Overview

- SWITCH is an electric power system capacity expansion model of Western North America that plans long-term grid investments while minimizing the cost of electricity in a given policy context.
- We used the SWITCH model to project how CPV could be integrated into the grid. SWITCH is a good tool for this evaluation because it considers many factors necessary for integrating renewable energy sources. These factors include:
  - Matching hourly intermittent power output with hourly load
  - Optimizing the location of renewable energy sites with respect to the grid
  - Building traditional generators to "firm up" intermittent power output
  - Building new transmission to move renewable power to loads
  - Planning grid operations to fully use available intermittent energy
- Our results show that:
  - It would be economical to install between 12 and 43 GW of CPV by 2030 in the United States Desert Southwest
  - Including CPV allows for deeper CO_2 reductions in the electric power system
  - CPV displaces natural gas generation on the margin
  - Strong carbon policy increases the deployment of CPV

SWITCH Model Description

Current capacity expansion models of the electric power system struggle to incorporate the intermittent nature of solar and wind power plants, as doing so properly requires the sampling of hundreds or thousands of possible conditions under which a future electric grid must operate. The Renewable and Appropriate Energy Laboratory (RAEL) at UC Berkeley has recently made advances in the integration of an hourly operational model of the electric power system into a traditional capacity expansion model (Fripp 2008, Fripp and Nelson 2011).

SWITCH – a loose acronym for Solar, Wind, Hydro, and Conventional generation and Transmission Investment model – is a mixed-integer linear optimization program whose objective function is to minimize the cost of generation, storage and transmission capacity expansion of the electric power system in western North America over the upcoming decades while also ensuring that electricity demand is met cost-effectively and reliably. SWITCH has unprecedented spatial and temporal resolution in the area overseen by the Western Electricity Coordinating Council (WECC) - over 1000 existing generators are included, and SWITCH can also choose to install roughly 10,000 new renewable and conventional generators. SWITCH also operates existing and builds new transmission and storage. Investment in new power system infrastructure is performed

in four four-year long investment periods: 2014-2017, 2018-2021, 2022-2025 and 2026-2029.

Optimization of generation, transmission and storage installation is performed concurrently with hourly dispatch of these grid assets, thereby determining the value of each asset to the electric power system on an hourly basis. Load must be met in each of the 576 study hours considered by the SWITCH optimization in each of 50 balancing areas throughout the WECC.   By employing time-synchronized hourly load and intermittent generation profiles, the model is capable of capturing and evaluating many of the effects of intermittent solar and wind generation on grid operation.

The WECC is the ideal place to study the depolyment of CPV, as it has the highest quality CPV resource in the United States (Figure 1.3). The WECC also has large demand for renewable generation through the state mandated Renewable Portfolio Standards (RPS) (Database of State Incentives for Renewables and Efficiency 2011), which are included in all simulations presented here.

For this study, Concentrating Photovoltaics (CPV) were added to the possible list of generators between which SWITCH can choose to build in order to meet load. Land suitable for large-scale solar development was derived using land exclusion criteria from Mehoz and Perez (2005). In total, the hourly output of 2373 distinct CPV sites are given as inputs to the optimization. The hourly capacity factors of each of these CPV projects were calculated by the National Renewable Energy Laboratory's Solar Advisor Model (National Renewable Energy Laboratory 2010) using paramaters for a SolFocus CPV system.

Capital costs for CPV are derived from projections provided by the CPV Consortium and are compared to SWITCH capital costs for other generators in Figure 2.1. Operations and maintenance, as well as fuel costs are also included in SWITCH optimizations, but not shown here for brevity.
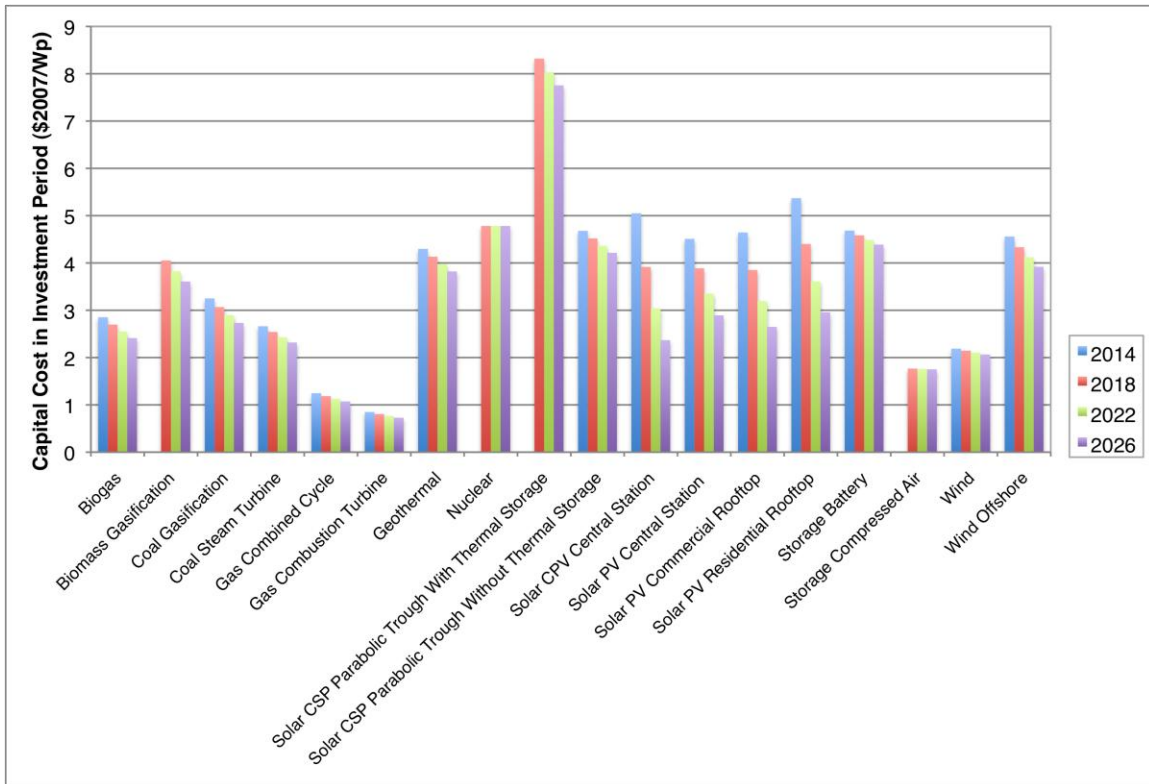
Figure 2.1. Capital cost projections for generation and storage options in SWITCH, by year operational. Missing values for 2014 denote new projects that could not be completed by the start of 2014 if planning and construction were to start in 2011.

In this study we analyse the effect of a carbon price on the depolyment of CPV in the WECC. This price on carbon emissions can either represent an explicit tax on carbon emissions, or the price of carbon credits at market equilibrium under a carbon cap and trade program. The carbon price is held constant over all of the four four-year long investment periods of the study. Six different SWITCH model runs are presented at carbon costs of $0, $20 and $40 per ton of CO_2, with and without the option to deploy CPV.

SWITCH CPV Results

CPV is included in the optimal power system at any cost on carbon emissions investigated here, starting in 2022 and continuing through 2029. This demonstrates the economic viability of CPV as a power generation technology in the WECC, subject to CPV achieving future capital cost targets. CPV outcompetes rooftop and central station PV (Figure 2.2) to achive deployment in the United States Desert Southwest, with 12 GW installed by 2026 absent a price on carbon.
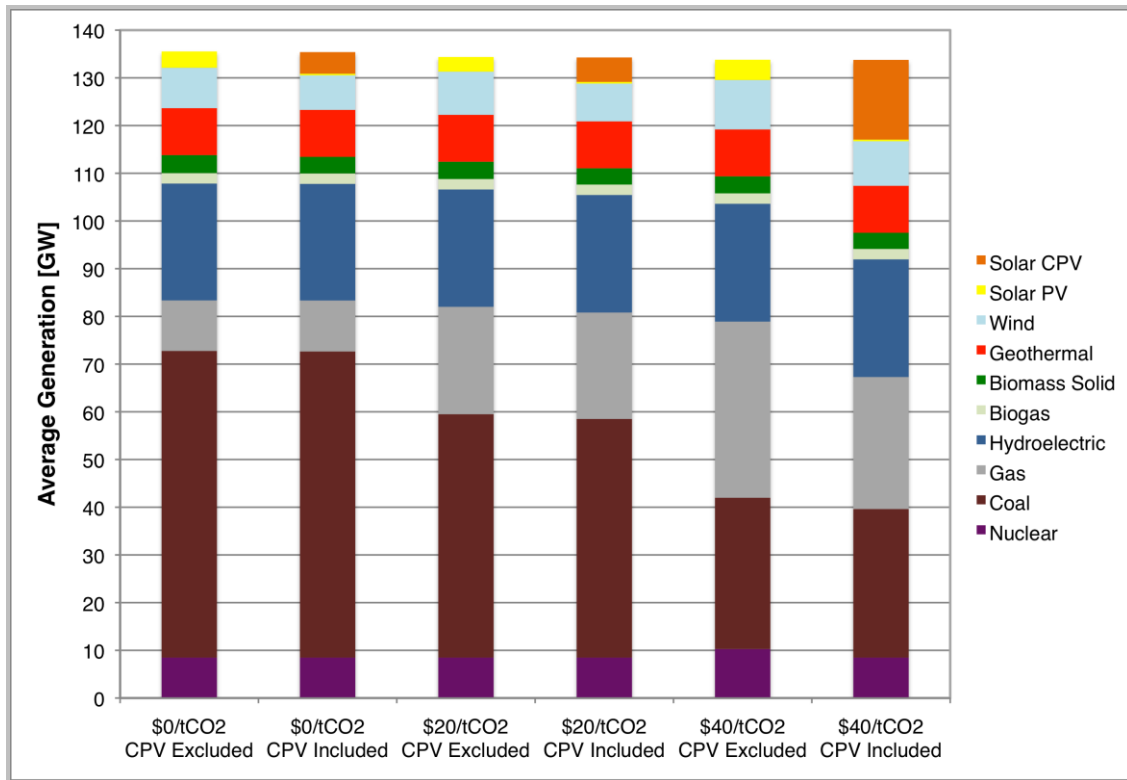
Figure 2.2. Average contribution of each fuel to the generation mix of the WECC between 2026 and 2029 as a function of carbon price and CPV deployment.

The removal of new coal generation from the optimal power mix at $40/tCO$_2$ represents a large opportunity for CPV, as the amount of CPV depolyed increases to 43 GW by 2026, generating 12 % of the WECC's electricity between 2026 and 2029. CPV is included in the optimal power mix to serve load throughout Nevada, Arizona, New Mexico and Northern Baja Mexico, as well as to meet Califorina's high demand for renewable resources via imports from the surrounding states (Figure 2.4).

Figures 2.3C and 2.3D show hour by hour generator dispatch as optimized by SWITCH. As carbon policy strengthens – represented by an increasing carbon cost – CPV supplants natural gas primarily in the hours of peak load, which tend to coincide with the maximum CPV output. Figure 2.4 shows that this fuel switching occurs in the Desert Southwest where the highest quality CPV resources is located.
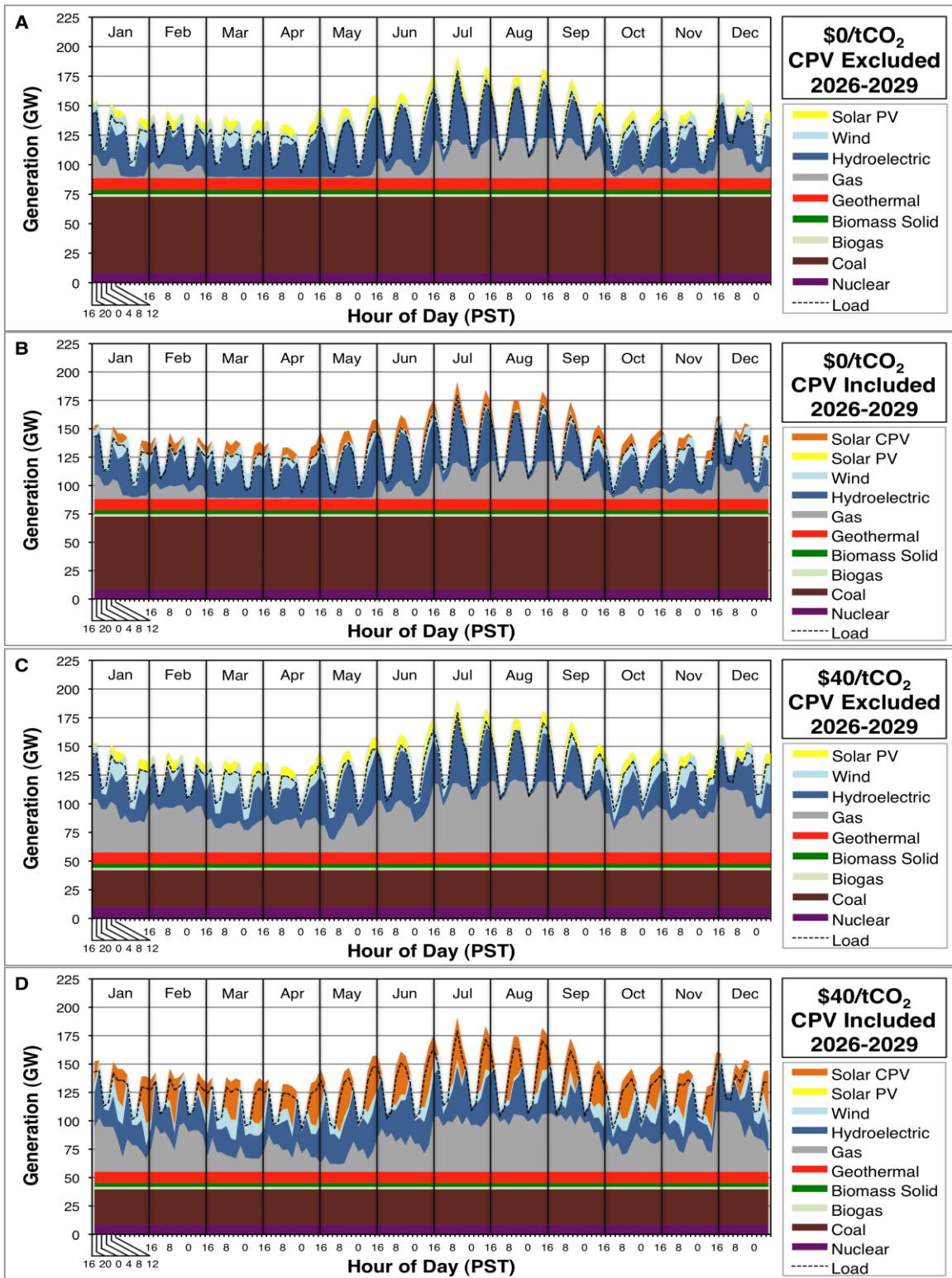
Figure 2.3. Hourly dispatch by fuel between 2026 and 2029 at $0/tCO_2$ and $40/tCO_2$, with CPV excluded and included. Load is below generation due to system losses, primarily in the distribution system. No new electricity storage capacity is built and is hence not depicted here. Pumped hydroelectric storage is included with 'Hydroelectric'.
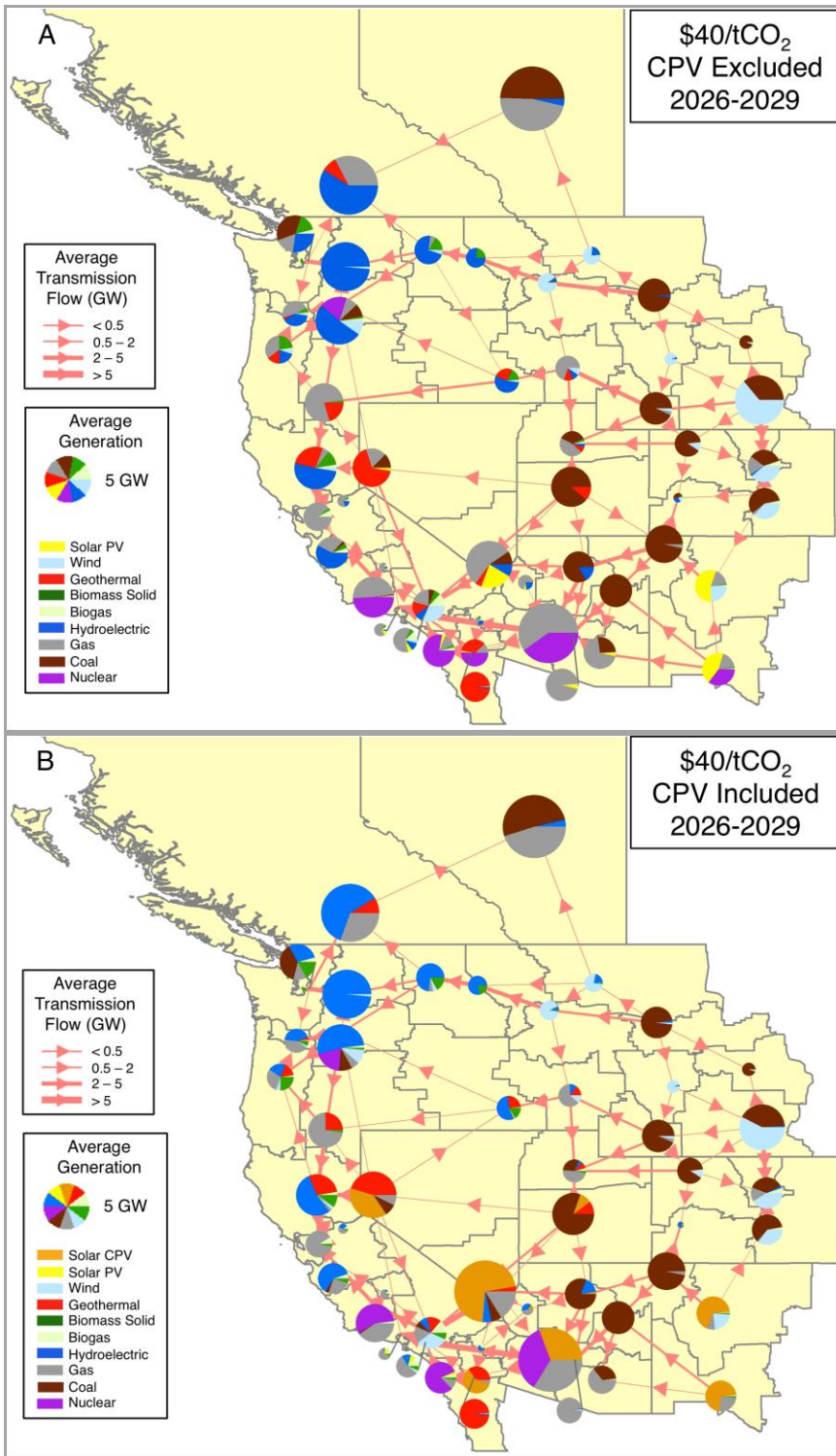
Figure 2.4. Spatial portrayal of average transmission and average generation by fuel between 2026 and 2029 at $40/tCO_2$, with CPV (a) excluded and (b) included, showing the increased deployment of solar in the Desert Southwest states of Nevada, Arizona and New Mexico, as well as in Northern Baja Mexico, with the inclusion of CPV.

The reduction in carbon emissions from the inclusion of CPV in the power system are small if no carbon policy is in effect (Figure 2.5), as CPV substitues for traditional PV (Figure 2.2), both of which are low carbon generation sources. The reduction in carbon emissions effected by the inclusion of CPV becomes significant at a carbon price of $40/tCO_2$, as CPV substitutes for gas-fired generation on the margin. This change represents a WECC-wide reduction in carbon intensity of 32 gCO_2/kWh. When this difference is attributed to CPV (as the only thing changed to induce this reduction in carbon emissions was inclusion of CPV in the optimization), this translates to a reduction in carbon intensity of 260 gCO_2 per each kWh produced by CPV. The ~ 35 gCO_2/kWh of emissions incurred to produce CPV (Figure 1.1) is thereby more than offset by the cost-effective displacement of fossil-fueled generation by CPV.
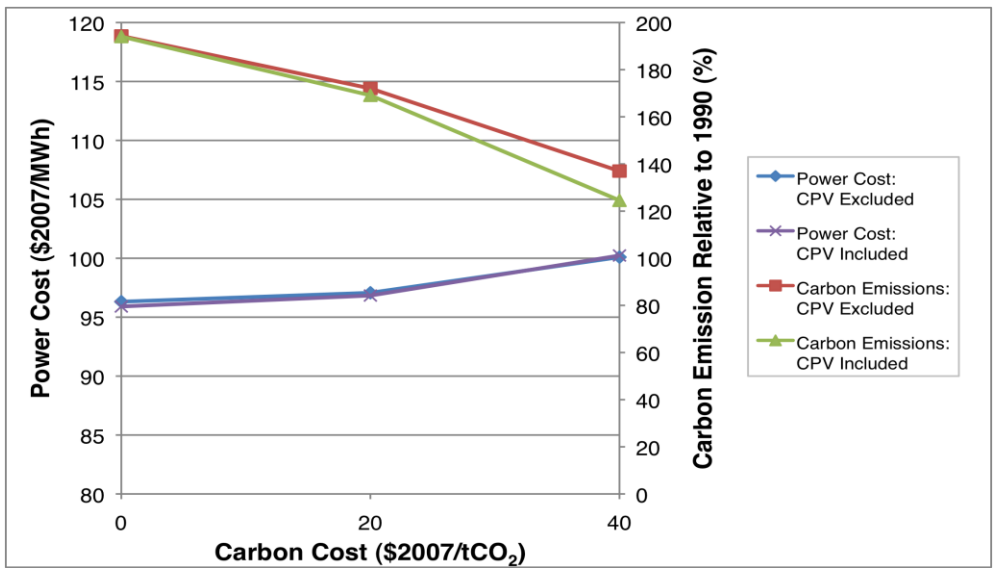

Figure 2.5. Power cost and carbon emissions between 2026 and 2029 as a function of carbon price and CPV deployment.

Conclusions

The cost of including CPV in the optimal power mix is minimal. For all investment periods and carbon prices, not just for 2026-2029 as depicted in Figure 2.5, the power cost difference between the CPV excluded and CPV included scenarios is less than 1 %, with CPV lowering the cost of delievered power in many cases. Should CPV meet its cost targets, it is poised to reduce the carbon intensity of the electric power system at no added cost.

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