Emissions Reductions from Solar Photovoltaic (PV) Systems

Estimating potential reductions across the United States by looking at the combined dynamics of solar resources and fossil unit dispatch

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National Assessment of Emissions Reduction of Photovoltaic (PV) Power Systems

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Executive Summary

Project Motivation

Electricity generated from renewable resources, especially sun and wind, are attractive since they are non-polluting, particularly on an air emissions basis. However, the amount of pollutant emissions they avoid by reducing centralized fossil generation is highly variable. This project focused on the determination of avoided emissions resulting from solar photovoltaic (PV) generation across the contiguous forty-eight United States, using historical PV and/or solar insulation data, coupled with hourly electricity demand and fossil unit operation and emissions data.

The majority of PV systems deployed in the USA in recent years are grid-connected, customer sited systems. There are significant daily and seasonal variations in the solar resource, and therefore how much electricity is generated by a PV system varies by time of day, time of year, and weather conditions (cloudiness, temperature, and wind). Additionally, different power systems have different mixtures of coal, oil, natural gas and other centralized generation sources. Individual fossil generators may be used more during different times of day or year, and may use different fuels in certain seasons. Therefore, avoided emissions from PV must be calculated on both an hourly and regional basis, consistent with both solar resource and power system fossil unit control and dispatch.

Results

The emissions reduction potential of a grid-connected PV system depends more on the characteristics of the regional electricity system than on the available solar resource. A detailed analysis of historical PV generation, fossil generation, and fossil emissions data for each region reveals that it is characteristics of a regional electricity system, like fuel portfolio and demand pattern, that determine the magnitude of emission reductions.

The use of PV systems lowers the electricity demand seen by a regional grid. Broadly speaking, the units that are affected by PV generation are those units that are following variations in regional load. To quantify the PV systems' emission reductions, the question that must be asked is: Which specific fossil generating units are affected by the reduction in demand and what are the emissions characteristics of those units? Another question is: Does PV generation in a particular region reduce generation from the above average or below average polluting fossil units (i.e. the coal-fired units or the natural gas-fired units), and how does that change from season to season, when natural gas prices are high, or when less non-fossil generation (nuclear and hydro power) is available?

This analysis empirically determined the fossil units that were offset by PV generation in each region and in each hour for the years 1998 through 2002. PV systems only generate power during daylight hours and the analysis found that PV systems often reduced emissions from natural gas peaking

units because they are used in many regions to meet peak (usually daytime) electricity demand.

Some higher level conclusions regarding avoided emissions from PV, and avoided emissions in general, include:

- PV systems installed in the regions where higher emitting units follow changes in demand during the daytime hours will reduce more emissions than PV systems installed where there is more solar resource but where fossil units with lower emissions (natural gas units) follow changes in demand.
- Grid-connected photovoltaic systems do not generally affect the fossil generating units with the highest emission rates (e.g. coal-fired baseload generation). Economic dispatch dictates that the highest cost units are dispatched last and in many regions these are natural gas peaking units. PV systems do not offset power production from baseload units that are often large, coal-fired generation units.
- The emissions rates of units that follow demand in the evening and nighttime hours are higher than the emission rates of units that follow demand during the day. Strategically, stored non-emitting generation (pumped storage), targeted demand side management, and possibly wind generation, might affect these units more than PV generation that only produces power between sunrise and sunset.
- In most regions, a number of fossil units operate at inefficient output levels (between 5% and 55% of seasonal capability) for a significant portion of all operating hours. Thermal inertia (large fossil power plants take time and to turn on and off), and grid stability and contingency support are the primary reasons. Operation at these "sub-optimal" load levels leads to higher emission rates. Small penetration of renewable generation, especially PV, can do little to alleviate these aspects.

Summary

Introduction

The emission reduction potential of photovoltaic systems is dependent on the amount of solar resource in a given geographic location, as well as on the PV system's configuration, orientation, and performance. A lesser-studied relationship is the role of PV systems in regional electricity grids and how the system as a whole determines emission reductions from PV. Emission reductions depend on characteristics of the regional electricity grid to which the PV system is connected. Regional fuel portfolios, electricity demand, and operation rules and procedures all influence a PV system's impact on emissions. This report assesses the emission reduction potential of grid-connected PV systems by considering them as a part of the electricity system to which they are connected.

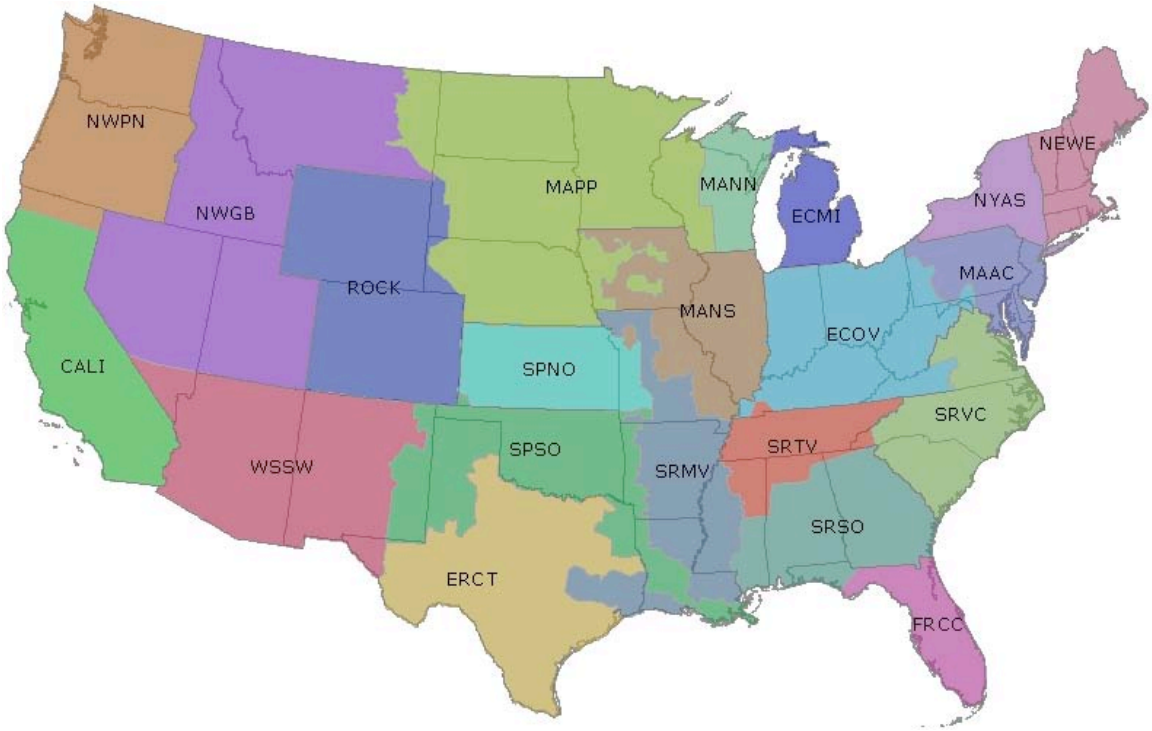
The project was undertaken following US EPA Solicitation No. PR-CI-01-12087. The analysis utilized the EPA's Acid Rain/Ozone Transport Commission (OTC) Program Hourly Emissions Data and the EPA's eGrid summarization data and documents. Information on solar resource and PV system performance came from Solar Electric Power Association (SEPA) and Schott Applied Power (formerly Ascension Technology) installations, which include several EPA-sponsored sites.

Methodology

In order to understand the emissions reductions from grid-connected PV systems this project's analysis sought to empirically determine which individual generating units within power plants were most likely affected by the PV generation. Distributed grid-connected PV systems are on the demand-side of the electricity system, so the centralized power systems sees them as a reduction in demand. A number of difference methods are used by the grid operators to respond to changes in demand. Automatic generation control (AGC) responds to small changes. Central generators are turned up and on (or down and off) in response to larger, slower changes.

In the absence of an hourly historical record of system operation (e.g. which units were running AGC in each hour) for every region in the country, we used empirical methods to identify units that were "following load" in any given hour and therefore likely to be affected by PV generation in that hour. We used the North American Electric Reliability Council's (NERC) definition of subregions as our load following, dispatch regions. These twenty-one regions, and their letter code abbreviations, are given in Figure ES.1. Due to the relative small size of PV systems in relation to overall electricity demand and the size of conventional power plants, we assume fossil units are not turned *off*, but turned *down* in reaction to PV generation.

Figure ES.1. NERC Subregions and Their Abbreviations



	Code	Region
(1)	CALI	California
(2)	NWPN	Pacific Northwest
(3)	NWGB	Great Basin
(4)	WSSW	Southwest
(5)	ROCK	Rockies (CO, WY)
(6)	ERCT	ERCOT (Texas)
(7)	MAPP	Northern Plains

	Code	Region
(8)	SPNO	Kansas
(9)	SPSO	Oklahoma
(10)	SRMV	Mississippi Valley
(11)	SRTV	Tennessee Valley
(12)	SRVC	Virginia-Carolinas
(13)	SRSO	Southeast
(14)	FRCC	Florida

	Code	Region
(15)	MANN	Wisconsin
(16)	MANS	Illinois
(17)	ECMI	Michigan
(18)	ECOV	Ohio Valley
(19)	MACC	Mid Atlantic (PJM)
(20)	NYAS	New York
(21)	NEWE	New England

Analyzing the time-series of total regional demand and generation of the units in the region, a load following unit's generation should follow the shape of the regional demand. That is, if the total system demand is increasing so should the unit's load and similarly for decreasing system load. If a unit's output changes in the opposite direction of the regional demand, that unit is not following load. In this manner, explained in detail in Chapter 1, units in any given hour were designated as "load shape following" (LSF). The emissions rates of the load shape following units in each hour were used to determine the emissions reductions from PV generation.

The assessment showed large variations in the emissions reductions across regional power systems. Reasons for variations span many system characteristics including:

- Solar resource
- PV system upkeep
- Shape and size of daily electricity demand
- Seasonal electricity demand changes
- Quantity of units responding to demand changes
- Fossil unit dispatch patterns
- Operation patterns of likely "turned down" units
- Regional fuel use patterns
- Seasonal fuel use patterns
- Fuel use of load shape following units
- Generation portfolio changes due to competition

Understanding the actual and potential emissions reductions requires an understanding of these and other electric power system variations.

Conclusions

The benefits of this methodology lie in its straightforward and flexible application. Only an operator's knowledge of the system in each subregion, or an historical account, could determine which units were dispatched at what times in response to load. The load shape following logic estimates this dynamically from the generation and demand data themselves.

Generation and Demand

Regional electricity demand determines the units that are utilized in any given hour and the manner in which they are dispatched. Demand itself is shaped by geography, meteorology, demographics, and the economy of the region. Non-dispatchable renewable technologies, like PV, affect the system when their resources are available. Key questions such as whether a PV resource is available during times of peak demand in a regional power system can be answered through analysis of hourly regional generation, demand, and renewable resource data. Analysis of these data also reveals which types of non-emitting generation might be best utilized to reduce peak demand in a subregion. Trends in load-growth and emissions reductions can also be gleaned by inspecting the time-series data.

Emissions

Load shape following emission rates, the emission rates of those units that can be affected by PV generation, depend on a multitude of generation unit and power system characteristics. These include the fuel and technology types of the generators that follow load as well as their load levels, combustion temperatures and operating efficiencies, and pollution control devices. LSF emission rates are by no means consistent from day to day, month to month, or hour to hour. The use of natural gas peaking units, for example, affects the load shape following emission rates. Natural gas units

are turned on during times of peak demand in many regional power systems; Texas (ERCT) and the Mississippi Valley (SRMV) are good examples. The amount of SO_2 in natural gas is significantly less than that in coal or oil and thus the SO_2 LSF emission rates during peak-demand hours in many power systems that utilize natural gas peaking units are significantly lower than the LSF emission rates at other times of day in the same power system. The LSF emission rates in these instances are also significantly different than the average emission rates of all the fossil units generating at the time.

Analysis of the hourly emission rate profiles of subregions also shows the effects of generator and pollution control technology choices. Emission rates in California, which is a heavily regulated region, are substantially lower than those in other regions. The least variation in pollutant emission rates among subregions is in CO_2 emission. The carbon contents of coal, oil, and gas vary only by a factor of two, contributing to the relatively small variability in CO_2 emission rates. Also, SO_2 and NO_x emissions, unlike CO_2 emissions, are regulated, so pollution control equipment on some units, but not others, can create large differences between generators' emissions rates. For SO_2, a range of 48 to 1 existed between the highest regional LSF emission rate (MAAC-Mid-Atlantic) and the smallest (CALI-California) in 2002. For NO_x LSF emission rates in 2002 this ratio is 4:1 and for 2002 CO_2 LSF emission rates it is 2:1 (both for the WSSW-Southwest and CALI-California).

PV Generation and Emission Offsets

Two types of analysis are necessary to understand the emissions reductions from PV systems and the regional variation in PV emissions reduction potential:

- Actual PV system analysis using hourly PV generation data
- Simulated PV system analysis using hourly solar resource data

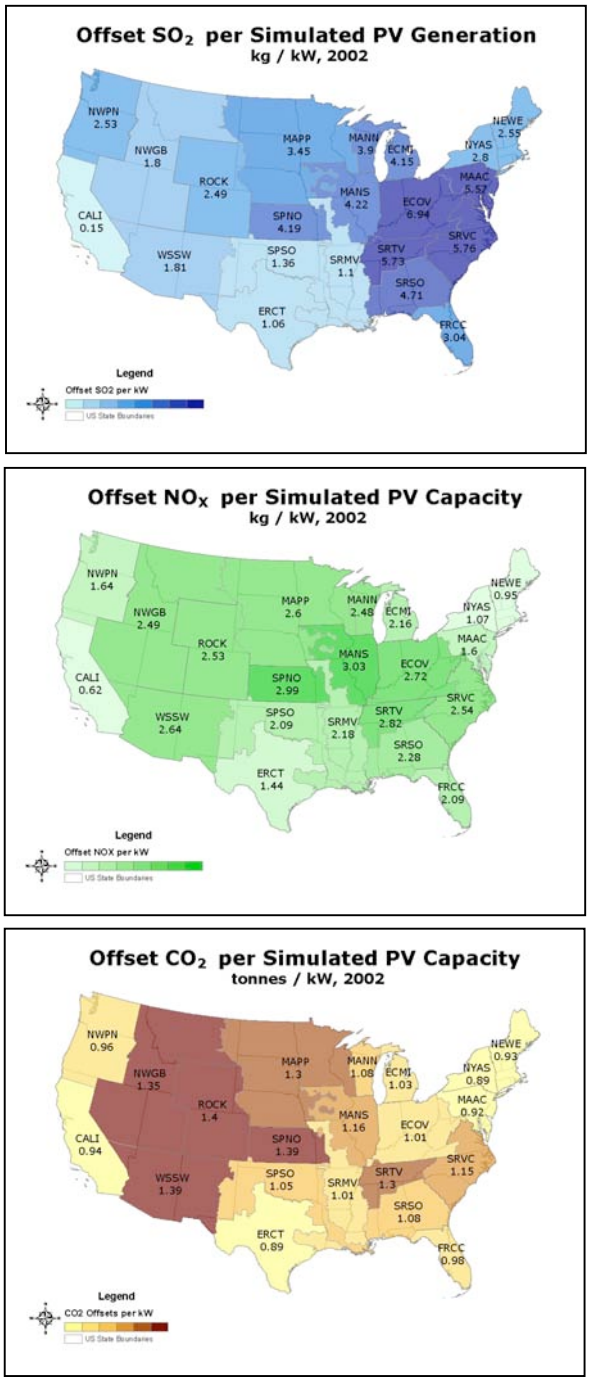
The solar resource available in a region and the performance (e.g. annual generation) of the PV systems are related, but PV system performance also depends on maintenance and upkeep. The upkeep and maintenance of PV systems is critical for emissions offsets: regardless of the resource in a subregion, if a PV system does not operate it cannot offset fossil unit emissions. The monitored (actual) PV sites in the Pacific Northwest were plagued with downtime during the five-year study period, and the emissions offsets in that region suffer as a result. Quantifying the emission reductions from actual grid-connected PV systems serves two purposes. First, it assesses the emissions impacts of the particular systems as they were installed and kept. Second, it informs a practical understanding of emissions reductions. *Real* systems break and they always will: how to the emissions reductions of real PV systems compare to ideal (simulated) PV systems?

Regional solar resources vary in magnitude and in seasonal and daily patterns. The patterns in weather and sunrise/sunset (diurnal and annual pattern) that contribute to the available solar resource also influence the demand for electricity and fossil generator utilization. It is important to analyze real PV systems and their impact in the electricity grid as it simultaneously responds to changes in weather. If this is unavailable, analysis of PV-related emissions reductions using simulated PV system generation *must* use solar resource data that are regionally and temporally coincident with demand, generation, and emissions data (as opposed to typical meteorological year (TMY) data).

Even so, we found the use of simulated PV systems to be necessary to obtain consistent regional comparisons. A region-to-region comparison using actual PV systems was not useful because of the inconsistent upkeep of installed PV systems, and its impact on avoided emissions calculations.

The maps in Figure ES.2 show annual emissions reductions per installed kW of PV using simulated PV systems. Because the simulated sites use hourly regional solar resource data the emissions reductions in the figures represent the emissions reductions expected from a kW of well maintained, and oriented, PV capacity[1].

Figure ES.2. Maps of 2002 SO_2, NO_X, and CO_2 annual offsets per kW of simulated PV capacity



[1] Baseline comparisons of monitored PV systems and simulated PV systems in the same region find that annual production for actual PV systems is about 10 to 20% lower than simulated systems for fairly well maintained actual sites. This difference is offset in the calculation of avoided emissions by comparing PV system generation with the gross power output of fossil generators. eGrid fossil unit power production is reported before taking into account electricity consumption at the generation unit (auxiliary power consumption), as well as additional losses in the transmission and distribution of electricity to the end-user. Higher

The darker regions on the maps indicate higher levels of emissions reductions per kW of installed PV. The maps emphasize the finding that PV installed in regions with less solar resource but higher LSF emission rates can have higher annual emissions reductions than PV systems in regions with better sun, but lower LSF emission rates. Table ES.1 ranks the subregions in order of decreasing annual PV production per installed kW (simulated) and compares annual avoided emissions per installed kW (simulated) for 2002.

Table ES.1. Annual PV production and avoided emissions per kW of Installed PV capacity (simulated).

NERC Subregion	*Photovoltaic Generation*		*Avoided SO2 LSF Emissions*		*Avoided NOx Emissions*		*Avoided CO2 Emissions*	
WSSW	**1784**	**1**	1808	16	2636	5	**1394**	**2**
ROCK	**1701**	**2**	2492	15	2534	8	**1404**	**1**
NWGB	1672	3	1805	17	2490	9	1351	4
CALI	1631	4	152	21	617	21	937	17
SPSO	1553	5	1355	18	2091	14	1053	11
SPNO	1553	6	4192	7	**2988**	**2**	1388	3
MANS	1438	7	4216	6	**3029**	**1**	1155	7
MAPP	1435	8	3453	10	2605	6	1295	6
SRMV	1397	9	1095	19	2178	12	1015	14
SRVC	1391	10	**5765**	**2**	2539	7	1150	8
SRSO	1384	11	4710	5	2283	11	1081	9
MANN	1352	12	3900	9	2479	10	1075	10
SRTV	1349	13	5730	3	2821	3	1302	5
ERCT	1330	14	1056	20	1438	18	892	21
FRCC	1309	15	3045	11	2087	15	984	15
ECOV	1271	16	**6943**	**1**	2715	4	1015	13
NYAS	1271	17	2799	12	1071	19	894	20
NEWE	1256	18	2549	13	946	20	930	18
MAAC	1254	19	5566	4	1602	17	921	19
ECMI	1242	20	4149	8	2160	13	1028	12
NWPN	1070	21	2532	14	1635	16	964	16
(2002)	(kWh/kW)	(Rank)	(g/kW)	(Rank)	(g/kW)	(Rank)	(kg/kW)	(Rank)

The solar resource and its correlation with demand and emission profiles is an influential factor on the emissions avoided by PV. The solar resource is generally well matched to times of peak demand, but times of peak demand are often characterized by the cleanest LSF emissions. The variation between regional power systems in this regard is significant especially for SO_2 and NO_X emissions that vary more by fuel type and technology type than do CO_2 emissions. The solar resource is intense in California (CALI) and Texas (ERCT), for example; but the annual SO_2 offsets are small because the load shape following emission rates in these regions during daylight hours are

simulated PV system generation is therefore offset by the conservative calculation of fossil unit avoided emissions rates. These factors are further explained in Chapter 2.

low. In this regard, the variability in fuels and technologies used in a subregion eclipse the variability in solar resource in determining the total emissions avoidable by PV systems. PV systems in the sunniest regions do not necessarily offset the most emissions per installed capacity; a subregion's LSF emission rate profile is considerably more influential.

With these factors in mind, access to detailed information regarding PV generation *and* electric system operation and emission is essential in order to get an accurate and informative picture of the emission reduction potential of PV (and other non-dispatchable options). Unless informed by this level of analysis, traditional more aggregate "slice of system" approaches will likely overestimate the emissions reduction benefits from PVs, and perhaps underestimate the emissions reduction potential of other renewables, such as windpower, which avoid higher emitting off-peak kWhs.

As the photovoltaic technology and industry continue to mature and grow, the case for PV (and other non-dispatchable technologies) as an emission reduction option, suitable for inclusion in emission trading markets or State Implementation Plans (SIPs) will strengthen. The ability to analyze power generator emissions down to the unit-hour level can provide greater insight into the effectiveness of a broad range of emission reduction policies and practices.