Estimating Carbon Displacement by Solar Deployment

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First Solar, Sustainable Development

ABSTRACT

Solar energy offers the highest global technical potential for electricity generation among renewable energy sources [1] and is therefore an important technology for climate change mitigation and development of a low carbon economy. Documenting power output and carbon displacement from solar deployment involves assumptions regarding solar irradiation, performance ratio, degradation rate, project lifetime, and grid greenhouse gas (GHG) emissions intensity, as well as equivalents such as household electricity consumption, passenger vehicle GHG emissions, and carbon uptake from trees. Case studies are discussed in which regional and global average assumptions and project-specific assumptions are used. GHG displacement methodologies considering grid average versus marginal power and life cycle versus operating emissions are considered. The case studies illustrate the importance of stating assumptions when estimating power output and carbon displacement from solar deployment. Since beginning commercial operation and through 2013, First Solar has manufactured over 8 GW of modules. Using world average assumptions, deployment of these modules results in the following, per GW: over 1.3 TWh/yr power production per GW, enough to power approximately half a million world average households per year; displacement of approximately 700,000 metric tons of CO_2e per year per GW using world average grid assumptions, which is the equivalent of removing over 140,000 world average cars from the road per year or planting approximately 18 million trees per year.

INTRODUCTION

In its Special Report on Renewable Energy Sources [1], the Intergovernmental Panel on Climate Change (IPCC) documents the rapid increase in deployment of renewable energy in recent years. Looking ahead, the IPCC also evaluates the future potential of renewable energy sources and documents that the total global technical potential for renewable energy production is substantially higher than global energy demand. In particular, the potential for solar energy is highest among renewable energy sources, as the energy in sunlight striking the earth every hour exceeds global annual energy consumption [2].

In documenting the mitigation of climate change by solar energy deployment, the system's power output and associated displacement of fossil-fuel generated grid electricity are estimated. For an accurate representation of the carbon displacement, it is important to use power output (kWh) rather than the system's capacity (kW) because output from a given capacity varies considerably as a function of solar irradiation. The methodologies for power output and grid electricity displacement are provided here and demonstrated with four case studies:

- World average deployment
- U.S. average deployment
- European average deployment
- Project-specific deployment.

Carbon displacement from solar deployment is estimated and related to more commonly understand equivalents such as homes powered, cars removed, and trees planted.

METHODS

Power output is estimated conservatively by quantifying first year output and then applying linear annual degradation over the project life. Power output (kWh) from the first year of deploying a solar project (PO_{Year1}) is estimated with Equation 1.

$$PO_{Year1} = W \times I \times PR \qquad (1)$$

where:

W = direct current (dc) wattage in kilowatts (kW); project-specific

I = plane-of-array solar irradiation in kWh/m^2/yr; site-specific

PR = performance ratio (ratio between final yield and in-plane radiation); project-specific with default value of 0.80 for ground-mount systems and 0.75 for roof mount systems [3].

Linear annual degradation following the first year of deployment is assumed over the project life (default value of 25 years based on warranty life) and used to estimate average annual power output over the project life. The annual degradation rate is based on the type of PV technology and the location of the installation. For the photovoltaics (PV) industry, linear annual degradation of approximately 0.67% per year is generally assumed [3].

Carbon displacement associated with average annual power output is estimated with project-specific local utility grid greenhouse gas (GHG) emissions intensities (g CO_2e/kWh) when available, and otherwise with United States Environmental Protection Agency (USEPA) eGrid subregion-average factors for U.S. deployment [4] and from the International Energy Agency (IEA) country-average factors for the rest of the world [5].

Note that to more accurately represent net displacement, a life cycle management approach is taken in the case of CdTe PV, where displacement factors are adjusted by subtracting from them the life cycle greenhouse gas emissions associated with manufacturing, deploying, and decommissioning of CdTe PV modules (e.g., 16-21 g CO_2e/kWh for roof and ground-mounted CdTe PV installations in Southern Europe with plane-of-array solar irradiation of 1700 kWh/m^2/yr) [6] [7].

Estimated power output and carbon displacement are related to the following equivalents for public communication:

- Annual households powered
- Annual cars removed from the road
- Equivalent number of trees planted

When deployment is characterized on a general (non-project specific or non-geography specific) basis, power output and carbon displacement may be estimated with global average assumptions:

- Plane-of-array solar irradiation (I): world average value of 1846 kWh/m^2-yr (population-weighted average) [8]
- Household electricity consumption: world average value of 227 kWh/month; based on world total electricity consumption for the residential sector [9] divided by world total number of households [10]
- Grid GHG emissions intensity: world average value of 536 g CO_2e/kWh [5]
- Passenger vehicle GHG emissions – world average value of 4980 kg CO_2e/passenger vehicle-yr; based on world total CO_2 emissions [11], percent of world CO_2 emissions from light-duty vehicles [12]), and world total number of passenger vehicles [13]
- Trees planted: average value of 0.039 metric tons CO_2/tree planted-yr for medium growth coniferous trees planted in an urban setting (not densely planted) and allowed to grow for 10 years [14].

When deployment is characterized for a specific project or for multiple projects in a specific region, the above global average assumptions can be made region-specific, as discussed below. In addition, project-specific power output and degradation rates may be used when available.

RESULTS AND DISCUSSION

First Solar has rapidly increased annual module production from 2005 (21 MW/yr) to 2013 (1628 MW/yr). Power output and carbon displaced through deployment of these modules has been estimated using the world average assumptions noted above (Figure 1). Note that it is assumed that modules produced in a given year are deployed in the same year.

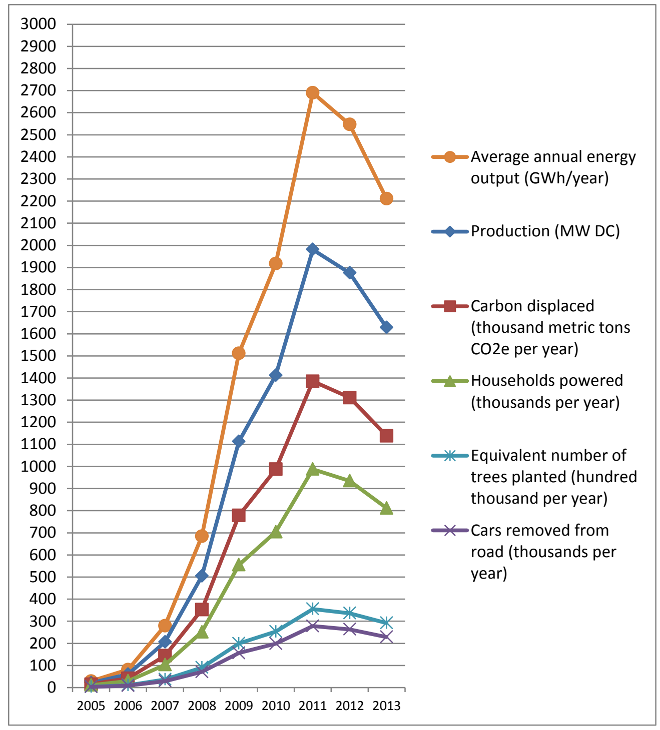

Figure 1. Power output and carbon displacement from First Solar module production (2005-2013) based on average annual electricity output over 25 year project lifetime with linear annual degradation of 0.67%, performance ratio of 80%, and global average assumptions for solar irradiation, household electricity consumption, grid electricity GHG emission intensity, passenger vehicle GHG emissions, and trees planted.

Since beginning commercial operation and through 2013, First Solar has manufactured over 8 GW of modules. Using world average assumptions, deployment of these modules results in the following, per GW: over 1.3 TWh/yr power production per GW, enough to power approximately half a million world average households per year; displacement of approximately 700,000 metric tons of CO_2e per year per GW using world average grid assumptions, which is the equivalent of removing over 140,000 world average cars from the road per year or planting approximately 18 million trees per year.

This approach of quantifying power output and carbon displacement using world average assumptions can be contrasted with project-specific estimates that use regional assumptions, providing a more accurate project specific prediction. For example, the Topaz Solar Project is a 550 MW ac First Solar project in San Luis Obispo County, California. When fully operational, the project will support California in reaching its goal of having one-third of its electricity come from renewable sources by 2020.

Table 1 documents how assumptions for power output and carbon displacement for this specific project differ from the global average assumptions used in the prior example. For reference, average assumptions for the United States and

Europe are also considered, as these are major global markets for solar deployment.

Table 1. Project-specific versus U.S., Europe, and world-average assumptions for estimating power output and carbon displacement from solar deployment for a fixed-tilt ground-mount project. For Europe, solar irradiation and corresponding homes powered and cars removed from the road are also provided in parenthesis for southern Europe.

	Topaz (Southern California)	U.S. Average	Europe Average	World Aver-age
Fixed-tilt plane-of-array solar Irradiation ($kWh/m^2/yr$)	2,073 [24]	1,796 [8]	1,448 (1700) [8] [19]	1,846 [8]
Household electricity consumption (kWh/month)	573 [15]	1005 [18]	292 [10] [20]	227 [9] [10]
Grid GHG emissions intensity (g CO_2e/kWh)	178 [16]	503 [5]	290 [5]	536 [5]
Passenger vehicle GHG emissions (kg CO_2e/passenger vehicle-yr)	5,200 [17|	5,200 [17]	2,689 [21]	4,980 [11] [12] [13]
Equivalent homes powered (per MWdc)	220	110	300 (360)	500
Equivalent cars removed from the road (per MWdc)	50	130	60 (70)	140

Solar irradiation, household electricity consumption, grid GHG emissions intensity, and passenger vehicle emissions can vary considerably by region. In Table 1, although the Topaz project is located in the United States, the project's equivalent homes powered and cars removed from the road more closely resemble that of a European average calculation than a U.S. average calculation. This is because household electricity consumption and grid GHG emissions intensity in California differ considerably from U.S. average values. Note that use of U.S. average assumptions results in high-end estimates of equivalent cars removed and low end estimates of homes powered. This is due to the relatively high U.S. grid GHG emissions intensity and high U.S. household electricity consumption, respectively.

In the above examples, displacement of local and average grid emissions for a given geography is considered. However, when power output from solar PV is incremental to baseload power, it displaces marginal power instead of average grid power. In California, it is commonly assumed that marginal power will come from electricity generated by natural gas generation. The California Air Resources Board (ARB) has therefore considered a grid carbon displacement factor of 830 lb CO_2e per MWh (377 g CO_2e/kWh) for renewable generators, based on displacement of natural gas marginal power [22]. For reference, this factor is comparable to the average European grid GHG emissions intensity (Table 1). The U.S. average grid carbon displacement factor is 690 g CO_2e/kWh for non-baseload generation [18].

Note that the ARB displacement factor is only for operating emissions from natural gas generation, excluding upstream emissions from natural gas extraction and transport. From a life cycle analysis (LCA) perspective, in addition to the operating emissions, there are upstream emissions from raw material (fuel) acquisition and downstream emissions from plant decommissioning at end of operating life. In the above example of displacing natural gas marginal power, a LCA approach would result in displacement of 400-439 g CO2e/kWh [23], compared to 377 g CO2e/kWh considering only operating emissions.

The latter example of marginal power displacement illustrates the importance of understanding the base case when estimating carbon displacement by renewable energy. In this example, by establishing a base case where marginal power is provided by fossil fuel generation and displaced by renewable generation, it is possible to characterize what specific emissions would expect to be avoided as a result of a renewable project.

Green power accounting guidelines addressing GHG displacement methodologies are under development by the World Resource Institute (http://pdf.wri.org/GHGProtocol-Electricity.pdf). Establishing the base case and evaluating displacement on an LCA basis are important methodological considerations. Overall, the above examples illustrate the importance of stating assumptions when estimating power output and carbon equivalents from solar deployment.

REFERENCES

[1] Edenhofer, O., et al., 2011: Summary for Policy Makers. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, New York, NY, USA.

[2] Zweibel, K., J. Mason, and V. Fthenakis, 2008. A Grand Plan for Solar Energy. Scientific American, January, 2008.

[3] V. Fthenakis, R. Frischknecht, M. Raugei, H. C. Kim, E. Alsema, M. Held and M. de Wild-Scholten. 2011. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 2nd edition, IEA PVPS Task 12, International Energy Agency Photovoltaic Power systems Programme.

[4] United States Environmental Protection Agency (USEPA), 2014. eGRID 9th edition (V. 1.0). Year 2010

eGRID Subregion Emissions - Greenhouse Gases. (Available at: http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html).

[5] International Energy Agency (IEA), 2013. CO2 Emissions from Fuel Combustion – Highlights. CO2 emissions per kWh from electricity generation. Year 2011 data. (Available at: http://www.iea.org/publications/freepublications/publication/co2emissionsfromfuelcombustionhighlights2013.pdf).

[6] M. de Wild-Scholten. 2013. Energy payback time and carbon footprint of commercial photovoltaic systems, Solar Energy Materials & Solar Cells 119, 296-305.

[7] Held, M., and R. Ilg. 2011. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Prog. Photovolt: Res. Appl., 19:614-626.

[8] Breyer, C. and J. Schmid. 2010. Population Density and Area Weighted Solar Irradiation: Global Overview on Solar Resource Conditions for Fixed Tilted, 1-Axis and 2-Axes PV Systems. 25th EU PVSEC, Valencia, Spain, pp. 4692 - 4709. Table 1, 0-axis fixed tilted, population weighted data.

[9] IEA, 2011. Electricity/Heat in World in 2008. Final Consumption, Residential. (Available at: (http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=29)

[10] Dorling, D. 2007. Worldmapper Dataset 191: Households. (Available at: http://www.worldmapper.org/display.php?selected=191).

[11] IEA, 2010. CO2 Emissions from Fuel Combustion – Highlights. CO2 emissions: Sectoral Approach. World, Year 2008. (Available at: http://www.iea.org/co2highlights/)

[12] DeCicco, J. and F. Fung, 2006. Global Warming on the Road. Environmental Defense. (Available at: http://www.edf.org/documents/5301_Globalwarmingontheroad.pdf).

[13] Dorling, D. 2006. Worldmapper Dataset 031: Passenger Cars. (Available at: (http://www.worldmapper.org/display.php?selected=31)

[14] Energy Information Administration (EIA), 1998. Method for Calculating Carbon Sequestration by Trees in Urban and Suburban Settings. United States Department of Energy. (Available at: (ftp://ftp.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/sequester.pdf)

[15] EIA, 2013. Residential Average Monthly Bill by Census Division, and State. Residential, California, Average Monthly Consumption, Year 2012 data. United States Department of Energy. (Available at: http://www.eia.gov/electricity/sales_revenue_price/)

[16] PG&E. Greenhouse Gas Emission Factors: Guidance for PG&E Customers, April 2013. Year 2011 data.. (Available at: http://www.pge.com/includes/docs/pdfs/shared/environment/calculator/pge_ghg_emission_factor_info_sheet.pdf).

[17] USEPA, 2005. Greenhouse Gas Emissions from a Typical Passenger Vehicle. Office of Transportation and Air Quality. (Available at: http://www.epa.gov/otaq/climate/420f05004.pdf)

[18] USEPA, 2014. Greenhouse Gas Equivalencies Calculator. (Available at: http://epa.gov/cleanenergy/energy-resources/calculator.html#results).

[19] Joint Research Centre. Solar radiation and photovoltaic electricity potential country and regional maps for Europe. European Commission. (Available at: http://re.jrc.ec.europa.eu/pvgis/cmaps/eur.htm).

[20] Eurostat. Electricity consumption of households. European Commission (Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/themes).

[21] European Commission. TREMOVE: an EU-wide transport model. (Available at: http://ec.europa.eu/environment/air/pollutants/models/tremove.htm).

[22] California Air Resources Board (ARB). 2010. Staff Report: Initial Statement of Reasons, Renewable Electricity Standard, Environmental Assessment, Appendix D.

[23] Fthenakis, V. and E. Alsema, 2006. Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status. Prog. Photovolt: Res. Appl., 14:275–280.

[24] County of San Luis Obispo. Topaz Solar Farm Project Final Environmental Impact Report. Appendix 8A. Department of Planning and Building.