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Estimating the Environmental and Economic Effects of Widespread Residential PV Adoption Using GIS and NEMS

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Table of Contents

List of Figures and Tables

Acknowledgments

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Summary

This paper describes a study of the national effects of widespread adoption of grid-connected residential rooftop photovoltaic (PV) systems. A Geographic Information System (GIS) model is used to estimate potential PV system adoption and PV electricity generation and the National Energy Modeling System (NEMS) is used to estimate the national effects of PV electricity generation. Adoption is assumed to occur if levelized PV system cost is less than the local average retail electricity rate at the county level. An estimate of the current "best" scenario (defined by a 6.5% real interest rate, 30-year loan life, $\$6_{1994}$/W system cost, and $\$4_{1994}$/month voluntary premium) results in no adoption. Several scenarios designed to stimulate PV adoption are modeled. As an example, if PV system costs are instead assumed to be $\$3_{1994}$/W, rooftop systems are found to be cost effective in 16% of detached single-family households in the U.S. By 2015 (assuming full adoption of 4-kW systems), this results in 82.1 TWh of annual PV electricity generation, 170 TWh of avoided electricity transmission, distribution, and generation losses, 6 Mt/a of avoided carbon emissions, 50 kt/a of avoided NOx emissions, and 27.3 GW of avoided electricity generating capacity in place.

1.0 Background

This work is intended to demonstrate a possible method for estimating the national consequences of policies intended to stimulate renewable energy and draws from the methodology set forth in Wenger, *et al.* (1996b). The approach is purposefully simple and results in extreme adoption rates. Housing characteristics (such as roof orientation, shading, and area) and buying preferences are neglected. Consequently, the results are not intended as forecasts, but rather as an upper bound on the effectiveness of renewable energy policies.

1.1 Rooftop Photovoltaic Systems

Distributed PV systems have long been competitive with grid power at remote sites where line extensions are costly to install and maintain or grid power is unreliable. Falling costs have now brought PV under consideration as a replacement or supplement to utility power at grid-connected sites.

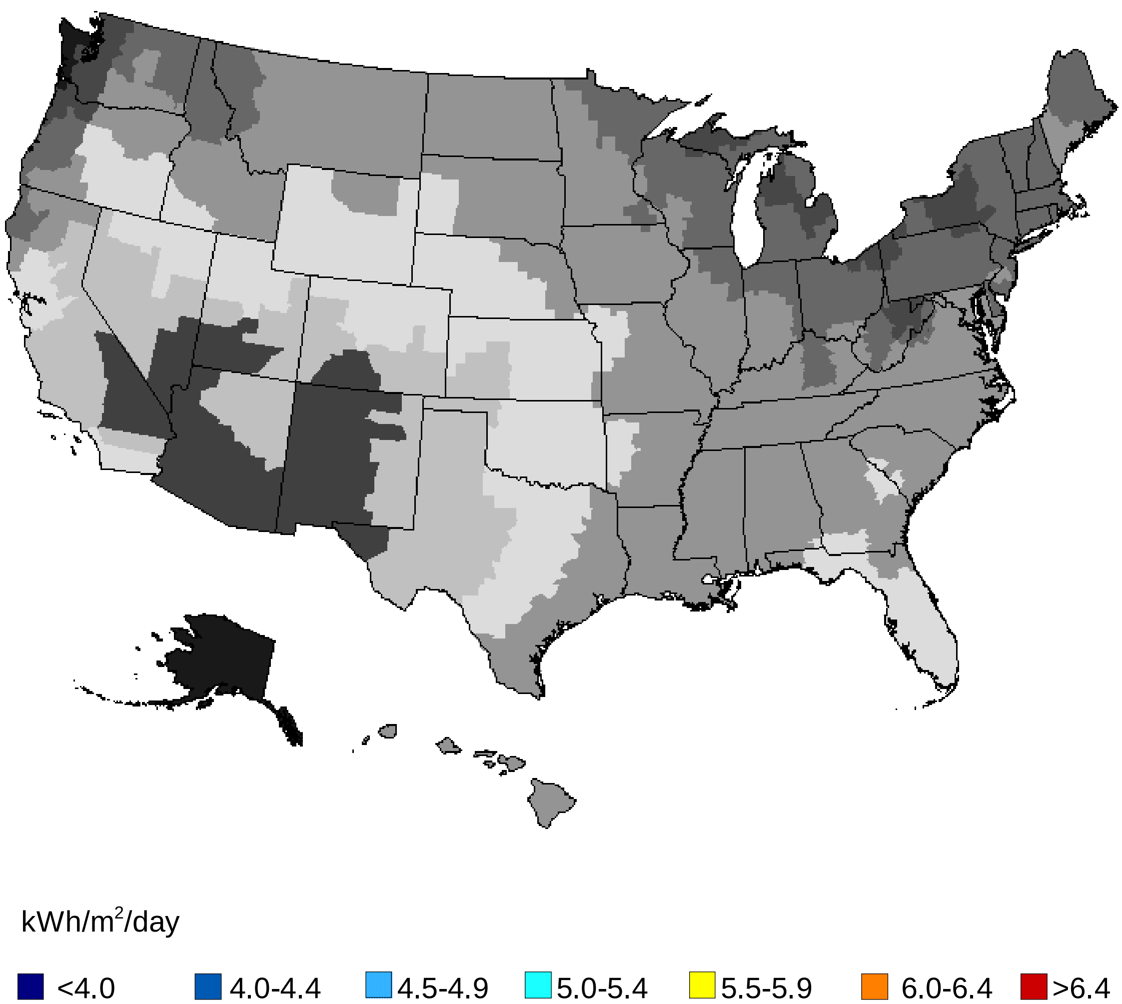
Facing a capacity shortfall and recognizing the potential of distributed rooftop PV electricity generation, the Sacramento Municipal Utility District (SMUD), with 480,000 customers, began a residential rooftop PV commercialization program called PV Pioneers in 1993. Under the program, SMUD installs and maintains the equipment, while the homeowner pays a voluntary premium (currently $4/month). That is, the customer pays for the satisfaction of generating green power, and, further, receives no rent or other benefit for provision of the site to SMUD. In 1995, 80 4.1-kW systems were installed with a turn-key cost of $\$5.98_{1994}$/W, bringing the total power output of all SMUD residential rooftop PV systems up to 1.6 MW (Osborn and Collier 1996). There are currently over 340 of these synchronous systems meeting the requirements for non-utility grid-connected generation installed. SMUD reports the levelized cost of electricity from the latest systems to be approximately $18¢_{1994}$/kWh (Osborn and Collier 1996).

1.2 Geographic Information System

A Geographic Information System (GIS) is software that links attribute data such as population, to geographic space and allows for the manipulation of this spatial data (as points, lines, and polygons) while maintaining the integrity of the attribute data. Solar insolation, electric utility rates, and population spatial databases are used in this study.

Solar insolation data are input into the model for 239 stations across the United States (NREL 1994). Station data for flat-plate collectors facing south at a fixed tilt angle are sorted to find the tilt angle with the highest annual output. Station data are mapped as points and converted to polygons using a linear statistical model. A spatial weighting model is used to estimate county-level insolation data from the polygon data. See Figure 1 for county-level insolation values.

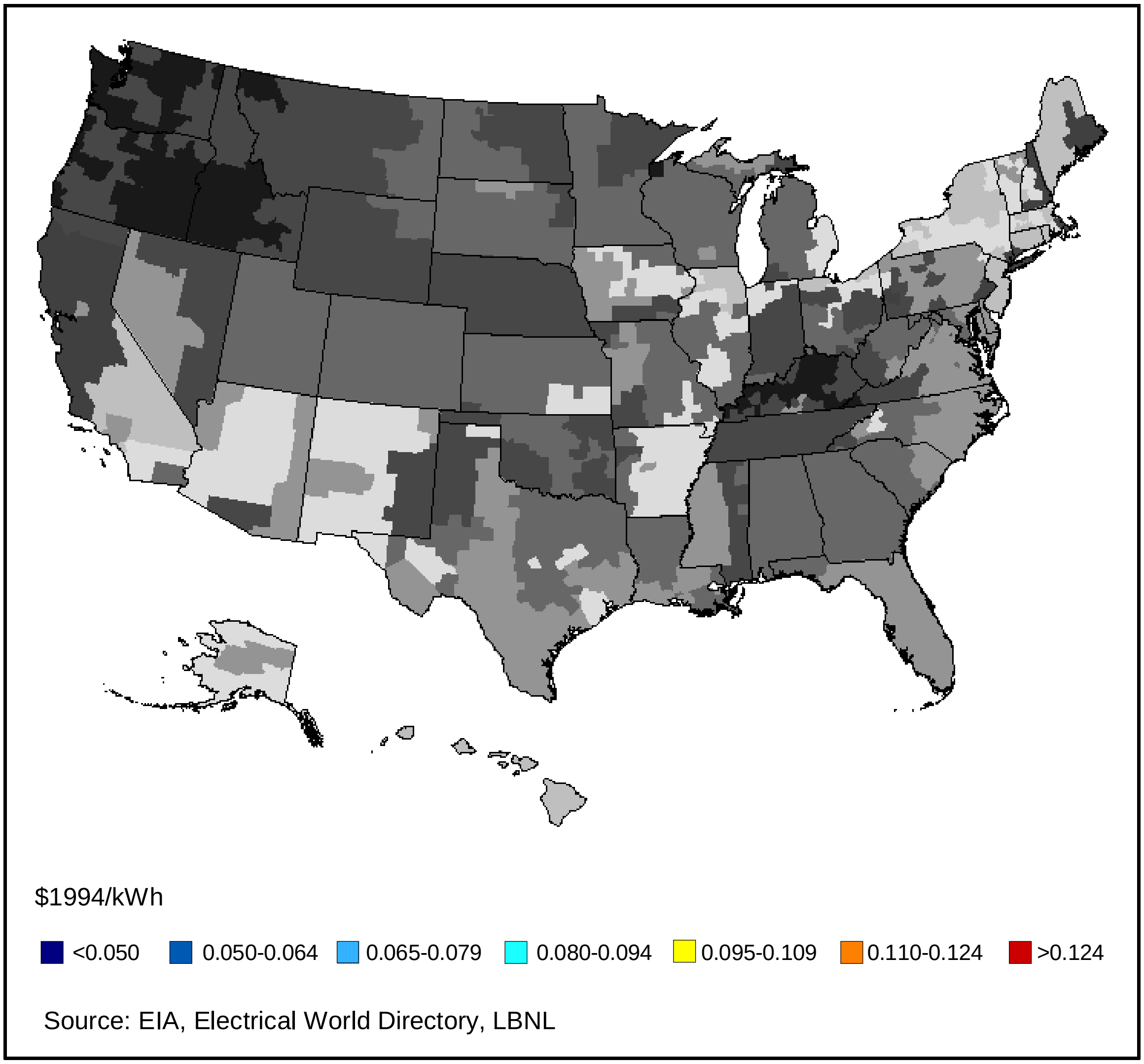
Figure 1. Daily Average Output for Flat Plate Collectors with a Fixed Tilt Angle Chosen for Maximum Annual Output



Source: NREL, modified by LBNL

Retail electricity price estimates are made for utility customers based on published data,[1] assigning each county to the utility which serviced the greatest number of residential customers within the county. Figure 2 shows county-level residential electricity prices and Figure 3 shows single-family detached home densities taken from 1990 Census data.

Figure 2. 1993 Residential Electricity Prices (Adjusted to 1994 $)



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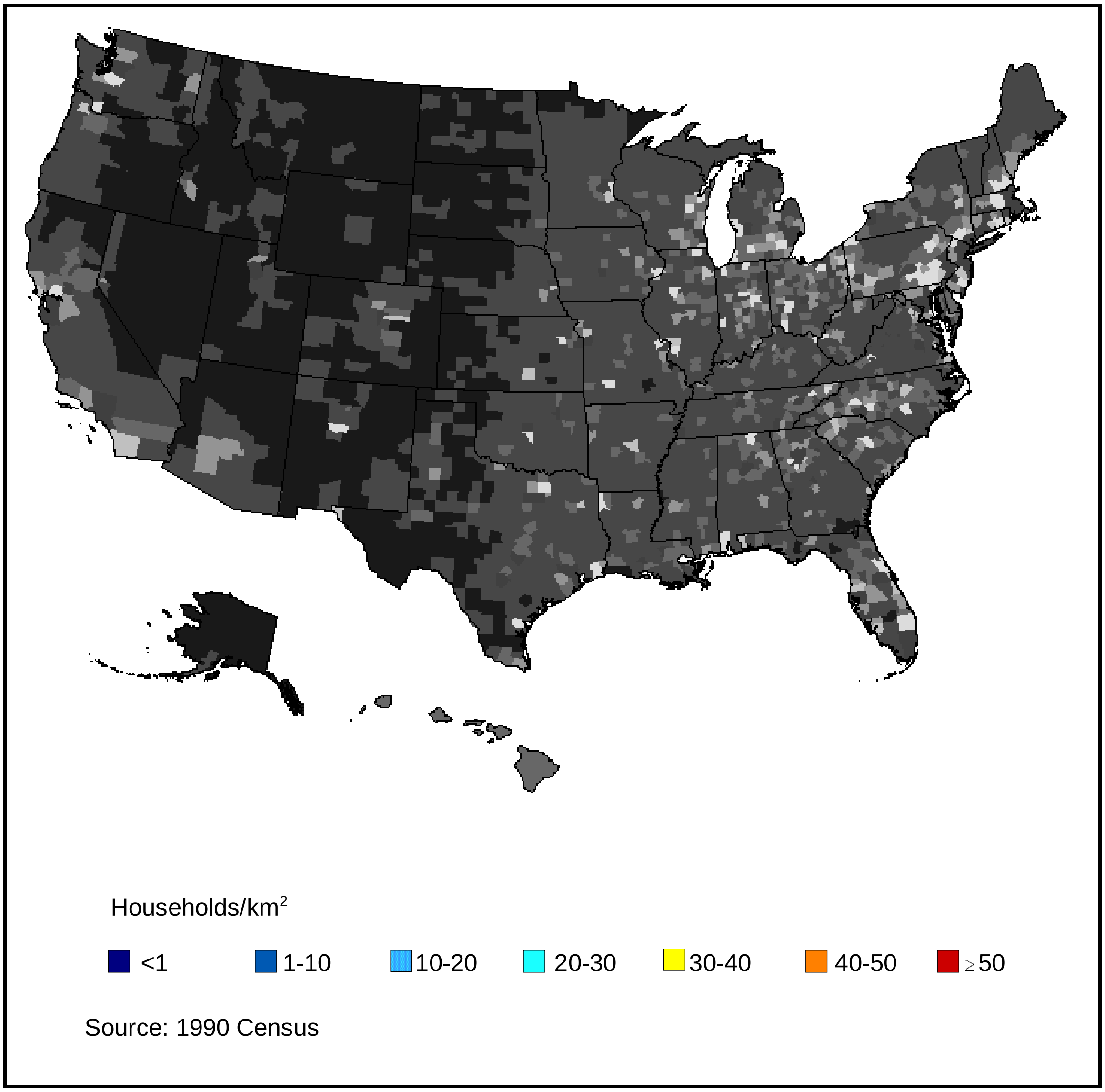
[1] County-level electricity prices were estimated using a combination of data from the Electrical World Directory of Electric Utilities (1993), and Electrical Sales and Revenue (EIA 1993).

Figure 3. Residential Housing Density for Detached Single-Family Homes



1.3 *The National Energy Modeling System*

The National Energy Modeling System (NEMS)[2] is an integrated model of the U.S. energy industry detailing economic, energy-related, and environmental aspects of energy production, distribution, and consumption. NEMS was designed and built over several years by the Energy Information Administration (EIA). The EIA (1996) uses NEMS to forecast U.S. energy production, imports, conversion, price, and consumption to 2015, which is documented in the Annual Energy Outlook (AEO96). Because NEMS models the complex

[2] The version of NEMS used in this analysis was used to produce the 1996 Annual Energy Outlook (EIA 1996).

interactions between energy demand, energy supply, and the economy at large, it is suited to study first-order and second-order effects of changes in electricity demand.

2.0 Approach

The goal of this work is to estimate the national effects of the rapid introduction of customer-sited PV systems at grid-connected homes by programs similar to SMUD's PV Pioneers.

The effect of distributed rooftop PV electricity generation is modeled in two steps: (1) GIS is used to estimate potential household adoption and therefore, potential PV electricity generation; and (2) NEMS is used to estimate the economic and environmental effects stemming from this generation.

In this analysis, adoption is determined by a simple comparison of the levelized cost of electricity from a generic PV system and local residential electricity rates generalized to the county level. The levelized cost is a function of system cost, insolation, loan and equipment life, real interest rate, and voluntary premium. (See Appendix for levelized cost calculation details and assumptions; see Figures 7, 8, 9, 10, and 11 for levelized cost sensitivity to inputs.)

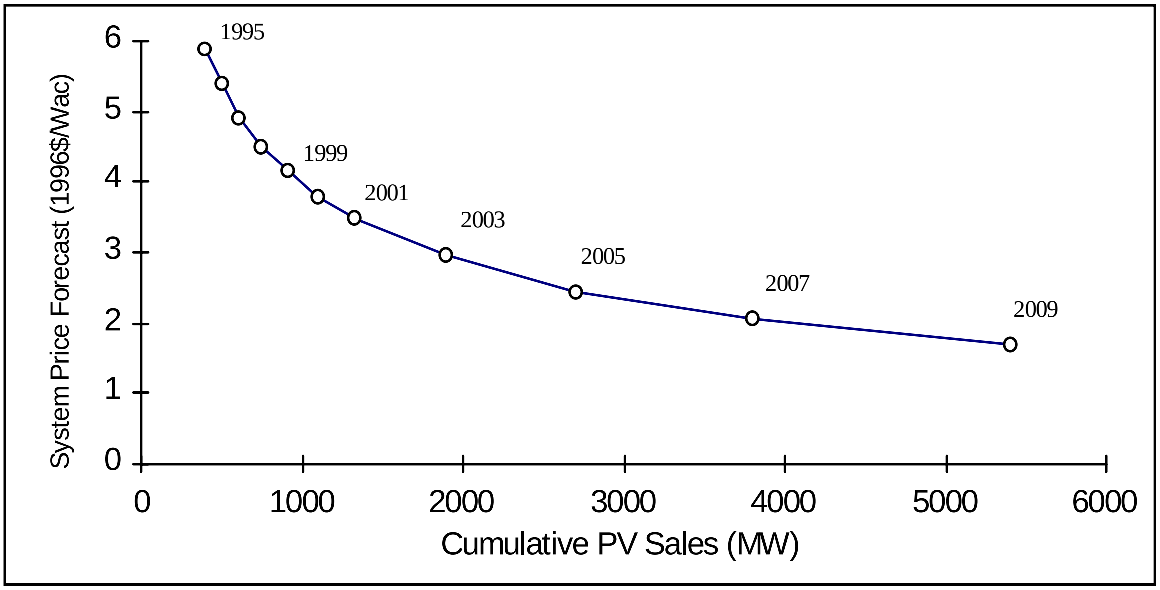
GIS analysis (using county-level insolation and electricity prices) of our current "best" scenario (defined by a $\$6_{1994}$/W system cost, 6.5% real interest rate, 30-year loan life, and $\$4_{1994}$/month voluntary premium) results in no adoption. For example, using an insolation of 5.12 kWh/m^2/d (the average of the station insolation data described in Section 1.2) as a proxy for county-level insolation data, our current "best" scenario yields a levelized cost of 24¢$_{1994}$/kWh. We additionally modeled several alternative scenarios designed to encourage PV adoption, which are described in Table 1.

Table 1. Scenario Characteristics

Scenario	System Cost ($\$_{1994}$/W)	Real Interest Rate (%)	Loan Life (Years)	Voluntary Premium ($\$_{1994}$/month)
Current Best	6	6.5	30	4
Low System Cost	3	6.5	30	4
Low Interest Rate (IR)	6	1.5	30	4
Voluntary Premium (VP)	6	6.5	30	85
Low IR and VP	6	3.5	30	35

In addition, PV system costs (Wenger *et al.* 1996a) are expected to fall with time, as shown in Figure 4, and we modeled the sensitivity of adoption to system cost assuming a 30-year loan life at both 3.5% and 6.5% real interest rates and no voluntary premium. See Section 3.2 for the results.

Figure 4. Forecast of PV System Price Based on Cumulative PV Capacity Sales



Please note that the following assumptions are implicit in our analysis:

(1) all surplus electricity generated by a household sold at the prevailing electricity rate (perfect net metering)
(2) retail electricity costs fixed even though power plant construction is avoided and fuel prices may change
(3) zero operation and maintenance costs for PV[3]
(4) only static adoption determined by GIS
(5) no other non-NEMS benefits of PV included, such as proximity of generation to load (Hoff *et al.* 1996)
(6) equipment life identical to loan life (30 years)
(7) adoption at single-family detached homes only

[3] Jones and Eto (1997) have derived a total operating cost (including O&M, administrative, insurance, and other miscellaneous costs) of $160 per year.

3.0 GIS Model

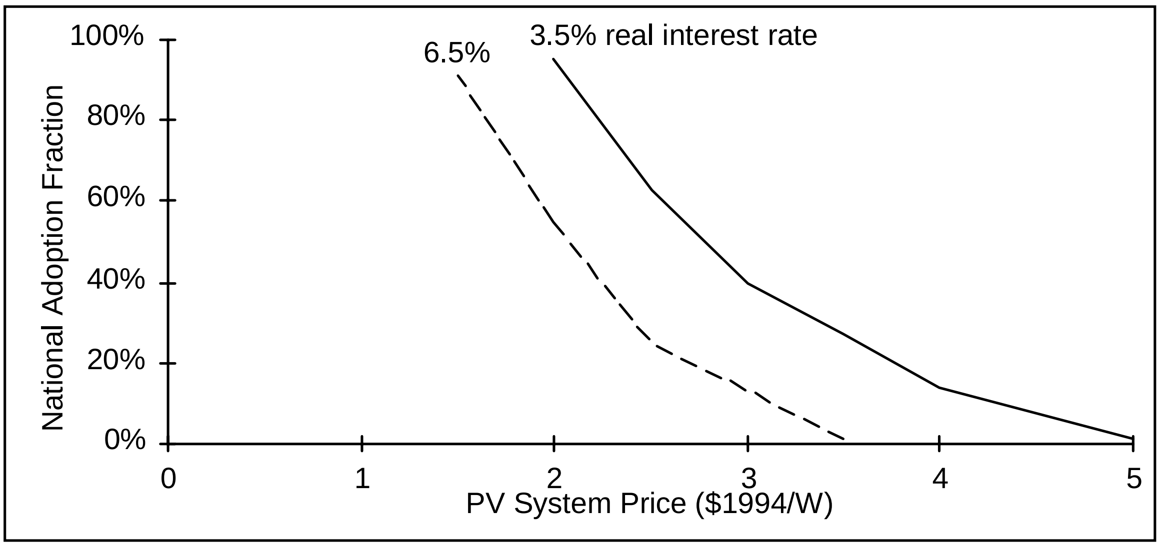
3.1 GIS Methodology

GIS estimates potential household adoption by comparing the hypothetical levelized cost of a system with the prevailing retail electricity price on a county-by-county basis across the U.S. for single-family detached homes only. Potential adoption at a county-by-county level occurs when the levelized cost of the system is less than the retail electricity rate. Potential PV generation is then calculated using potential household adoption, generic system characteristics, and insolation data. County-level results for potential PV generation are aggregated to the Census Division level for entry into NEMS.

3.2 GIS Results

As mentioned above, the effect of falling system cost on adoption is of particular interest. In addition to the scenarios described in Table 1, GIS was used to estimate the sensitivity of adoption to system cost assuming a 30-year loan life at both 3.5% or 6.5% real interest rates and no voluntary premium, as shown in Figure 5.

Figure 5. Sensitivity of Adoption Rate to System Cost



The five scenarios described in Table 1 are modeled with GIS and the adoption patterns of these different scenarios are shown in Table 2. Table 3 shows the potential PV electricity generation values associated with the household adoption patterns shown in Table 2.

Table 2. Household Adoption by Census Division (million households)[4]

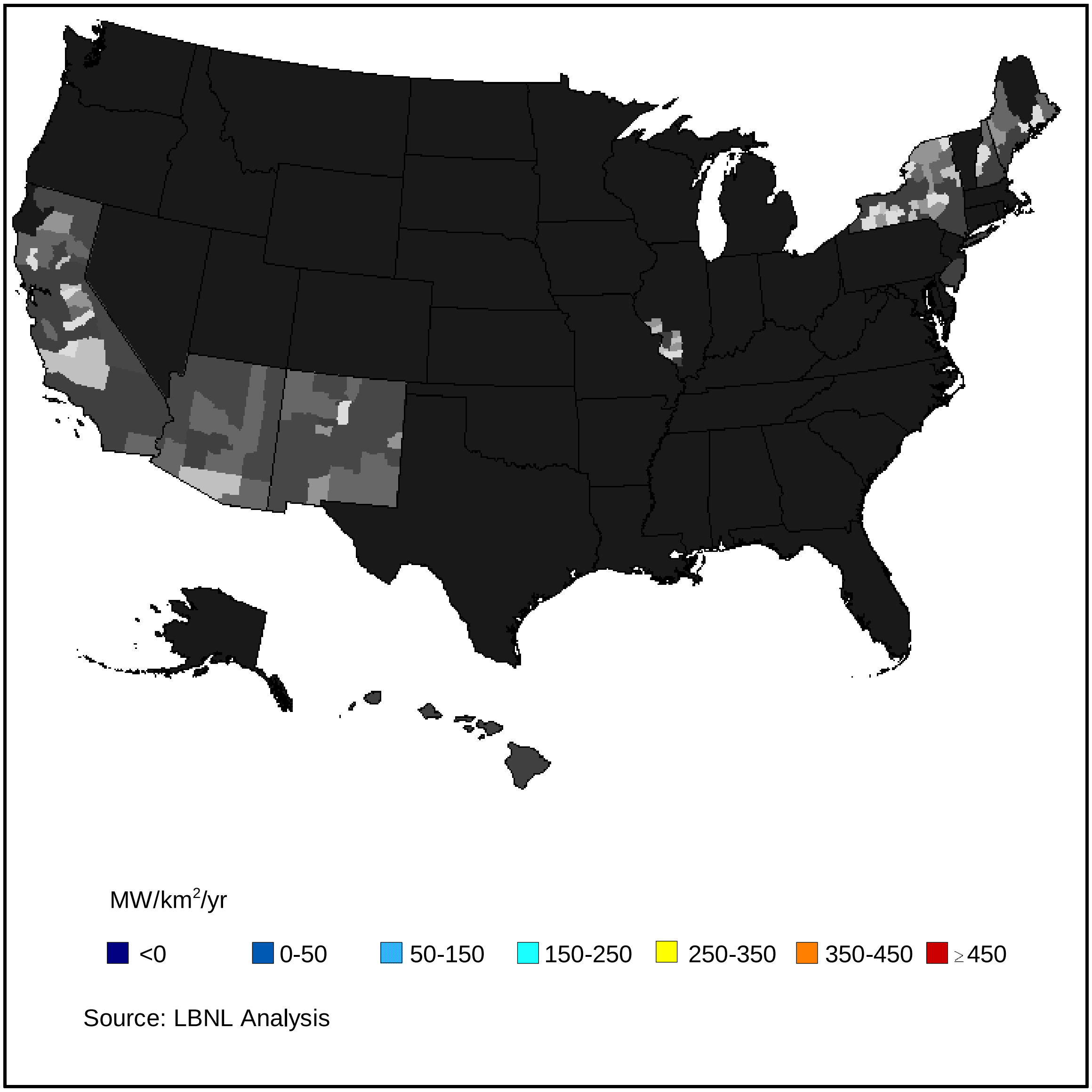
Scenario	Pacific	New England	Mountain	East North Central	Middle Atlantic	Total U.S.
Current Best	0.0	0.0	0.0	0.0	0.0	0.0
Low System Cost	6.2	1.2	0.3	0.0	2.2	9.9
Low Interest Rate (IR)	6.2	0.8	0.0	0.0	0.0	6.9
Voluntary Premium (VP)	6.3	1.3	0.6	0.2	3.5	11.8
Low IR and VP	6.2	1.2	0.0	0.0	2.2	9.6

Table 3. Potential PV Electricity Generation by Census Division (TWh)[3]

Scenario	Pacific	New England	Mountain	East North Central	Middle Atlantic	Total U.S.
Current Best	0.0	0.0	0.0	0.0	0.0	0.0
Low System Cost	54.2	11.8	2.1	0.0	14.9	83.0
Low Interest Rate (IR)	53.9	7.4	0.0	0.0	0	61.3
Voluntary Premium (VP)	54.6	12.2	4.3	1.7	23.8	96.6
Low IR and VP	54.0	11.5	0.2	0.0	14.9	80.6

4 Pacific Census Division is comprised of AK, CA, HI, OR, and WA; New England Census Division is comprised of CT, ME, MA, NH, RI, VT; Mountain Census Division is comprised of AZ, CO, ID, MT, NW, NM, UT, WY; East North Central Census Division is comprised of IL, IN, MI, OH, and WI; and Middle Atlantic Census Division is comprised of NJ, NY, and PA.

Figure 6. Residential PV Electricity Generation Under the Voluntary Premium Scenario



The distribution of potential PV electricity generation under the "Voluntary Premium" scenario is shown in Figure 6.

4.0 National Energy Modeling System

4.1 NEMS Methodology

The NEMS model is used to estimate the economic and environmental impact of distributed PV electricity generation. In NEMS, PV electricity generation is assumed to grow linearly from zero generation in 1995 to potential generation in 2005 (see Table 3 for potential PV electricity generation values.)

Unfortunately, the technology choice logic used by the residential module of NEMS cannot model PV electricity generation at the household level; therefore, PV electricity generation is modeled as a regional reduction in end-use electricity consumption. PV electricity generation is subtracted from the residential cooling consumption end-use because the capacity factor corresponding to the cooling end-use (37%) was closest to the capacity factor for PV electricity generation (20%).[5] A weakness of this approach is that the PV generation is not correctly distributed by time of day and season. However, construction of a new load pattern in NEMS was beyond the scope of this work.

4.2 NEMS Results

We chose the following five NEMS outputs as key indicators of the effect of widespread PV adoption under each of the five scenarios described in Table 1:

- avoided residential electricity sales
- avoided electricity transmission, distribution, and generation losses
- avoided carbon emissions
- avoided NOx emissions
- avoided electricity generating capacity in place

The AEO96 is used as a baseline for comparison. In 2015, AEO96 forecasts 1,418 TWh of residential site electricity use, 2,752 TWh of residential electricity TD&G losses, 1,705 Mt of carbon emissions, 15,500 kt of NOx emissions, and 940.1 GW of total electricity generating capacity in place. Table 4 shows the change in the key indicators under each of the five scenarios in 2015 relative to the AEO96. Table 5 shows the percentage change in the key indicators under each scenario in 2015 relative to AEO96.

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5 Capacity factors for PV electricity generation were calculated from data in Table 3-3 of Photovoltaic Economics and Markets: The Sacramento Municipal Utility District as a Case Study (Wenger *et al.* 1996a). Capacity factor for cooling was calculated from NEMS output.

Table 4. Decrease in Key Indicators in 2015 Relative to AEO96

Scenario	Residential Electricity Sales (TWh)	TD&G Losses (TWh)	Carbon Emissions (Mt/a)	NOx Emissions (kt/a)	Generating Capacity in Place (GW)
Current Best	0	0	0	0	0
Low System Cost	82.1	170.0	6	50	27.3
Low Interest Rate (IR)	61.5	149.5	7	80	16.0
Voluntary Premium (VP)	96.7	187.6	7	70	32.6
Low IR and VP	79.1	167.0	6	70	27.0

Table 5. Percent Reduction in Key Indicators in 2015 Relative to AEO96

Scenario	Residential Electricity Sales (TWh)	TD&G Losses (TWh)	Carbon Emissions (Mt/a)	NOx Emissions (kt/a)	Generating Capacity in Place (GW)
Current Best	0%	0%	0%	0%	0%
Low System Cost	5.8%	6.2%	0.35%	0.32%	2.9%
Low Interest Rate (IR)	4.3%	5.4%	0.41%	0.52%	1.7%
Voluntary Premium (VP)	6.8%	6.8%	0.41%	0.45%	3.5%
Low IR and VP	5.6%	6.1%	0.35%	0.45%	2.9%

5.0 Conclusions

In this study, we examined the national effects of widespread adoption of residential rooftop photovoltaic systems.

Our estimate of the current "best" scenario (defined by a 6.5% real interest rate, 30-year loan life, $\$6_{1994}$/W system cost, and $\$4_{1994}$/month voluntary premium) results in no adoption. We modeled several scenarios designed to stimulate PV adoption. As an example, if PV system costs are instead assumed to be $\$3_{1994}$/W, rooftop systems are found to be cost effective in 16% of detached single-family households in the U.S., located in the Pacific, Mountain, New England, and Middle Atlantic Census Divisions. By 2015 (assuming full adoption of 4-kW systems), this results in 82.1 TWh of annual PV electricity generation, 170 TWh of avoided TD&G electricity losses, 6 Mt/a of avoided carbon emissions, 50 kt/a of avoided NOx emissions, and 27.3 GW of avoided electricity generating capacity in place.

The viability of PV is highly sensitive to local conditions. However, as technology improves and costs decrease, customer-sited photovoltaic systems are a potential supplement to utility generation of residential electricity in some areas of the U.S. PV systems can provide a cost-effective, environmentally attractive, distributed source of electricity at times of high electricity demand, reduce utility-generated electricity, and result in fewer electricity transmission, distribution, and generation losses, carbon emissions, NOx emissions, and electricity generating capacity in place.

6.0 Future Work

Future plans include:

(1) implementing a residential end-use load shape in NEMS for rooftop PV generation

(2) incorporating state tax incentives in GIS analysis

(3) conducting an analysis of utility restructuring and its effect on residential prices and adoption of PV systems

(4) including solar water heating and space-heating options as components of rooftop solar systems

(5) extending the analysis to include commercial buildings

(6) expanding adoption logic to include factors such as household characteristics and income as well as implementing dynamic adoption in GIS

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Appendix: Levelized Cost Sensitivities

Levelized cost ($¢_{1994}$/kWh) is calculated using the following formula:

$$Levelized\ Cost = \frac{\dfrac{Cost \times Capacity \times r \times (1+r)^t}{(1+r)^t - 1}}{(365\ \frac{days}{y}) \times Insolation \times Efficiency \times Size} \times 100$$

where,

Cost	=	System cost in $\$_{1994}$/kW
Capacity	=	System capacity in kW
Efficiency	=	System efficiency
Size	=	*Capacity*/*Efficiency* × (1 m^2/1,000W)
r	=	Real interest rate
t	=	Loan life in years
Insolation	=	Insolation in kWh/m^2/d
Voluntary Premium	=	Annual voluntary premium in $\$_{1994}$

In this work, all calculations are made assuming a 4-kW system and a capacity rating conversion of 1,000 W/m^2. The average of the station insolation data (described in Section 1.2), which is 5.12 kWh/m^2/day, was used as the insolation value in sensitivity calculations. The following figures show the sensitivity of the levelized cost calculation to insolation, system cost, real interest rate, voluntary premium, and loan life. "Default" refers to the values used in the "Current Best" scenario and most values used in the other scenarios. (See Table 1 for complete description of scenario assumptions.)

Figure 7. Sensitivity of Levelized Cost to Insolation

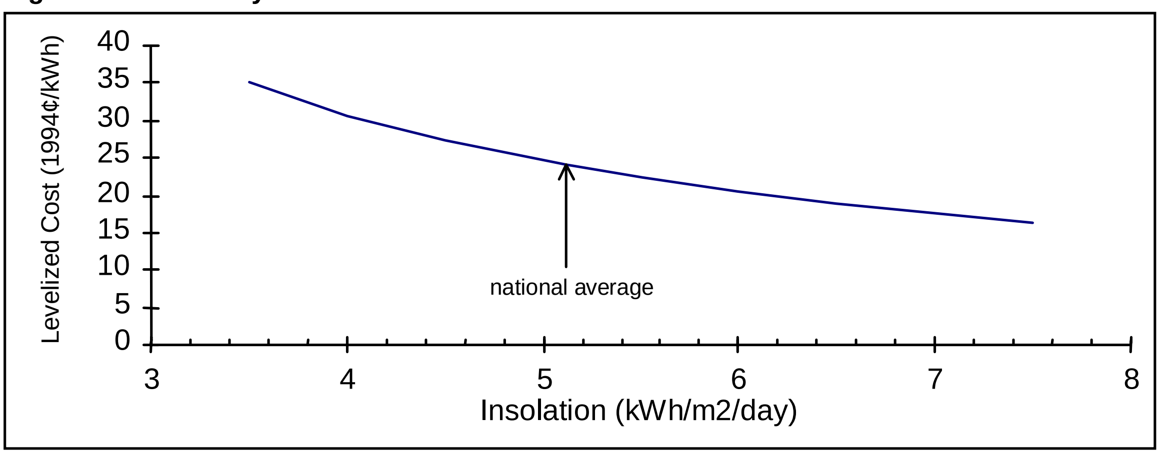

Figure 8. Sensitivity of Levelized Cost to PV System Cost

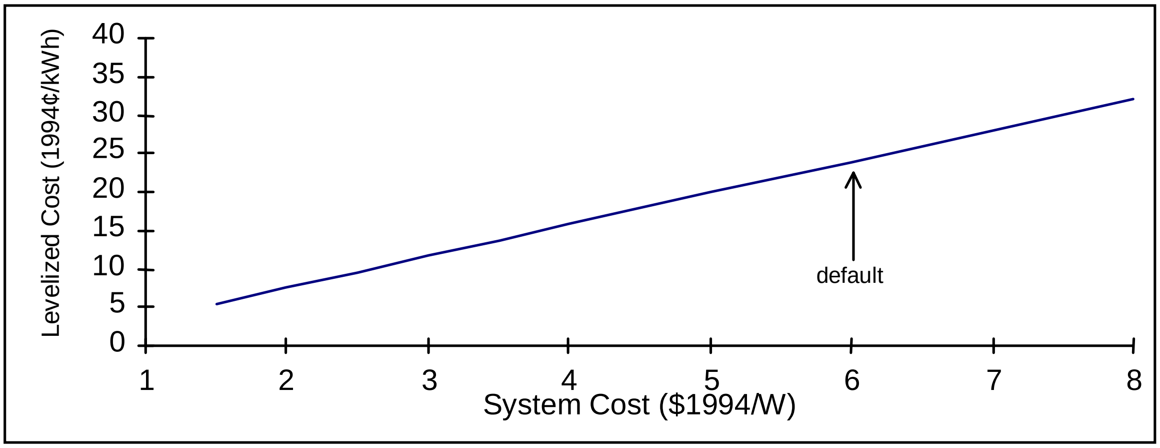

Figure 9. Sensitivity of Levelized Cost to Real Interest Rate

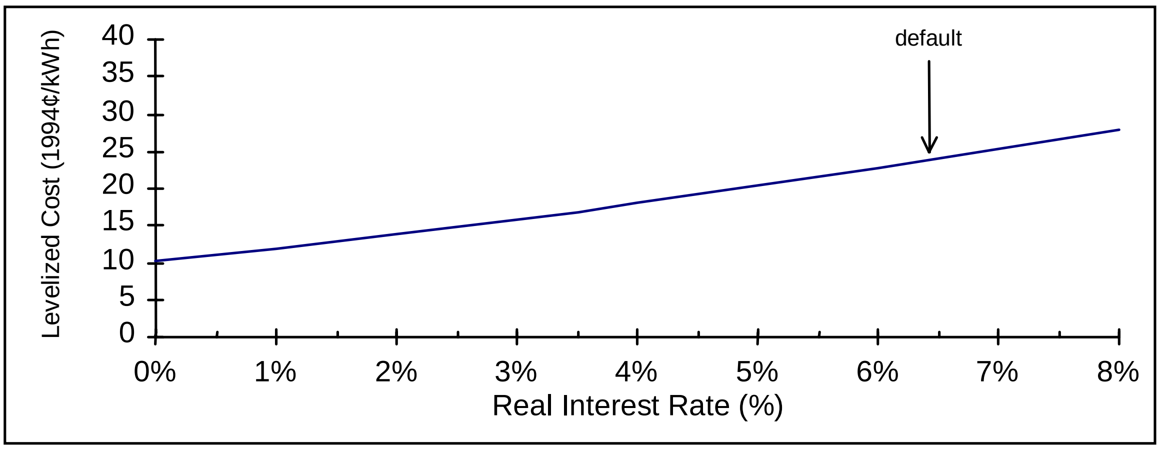

Figure 10. Sensitivity of Levelized Cost to Voluntary Premium

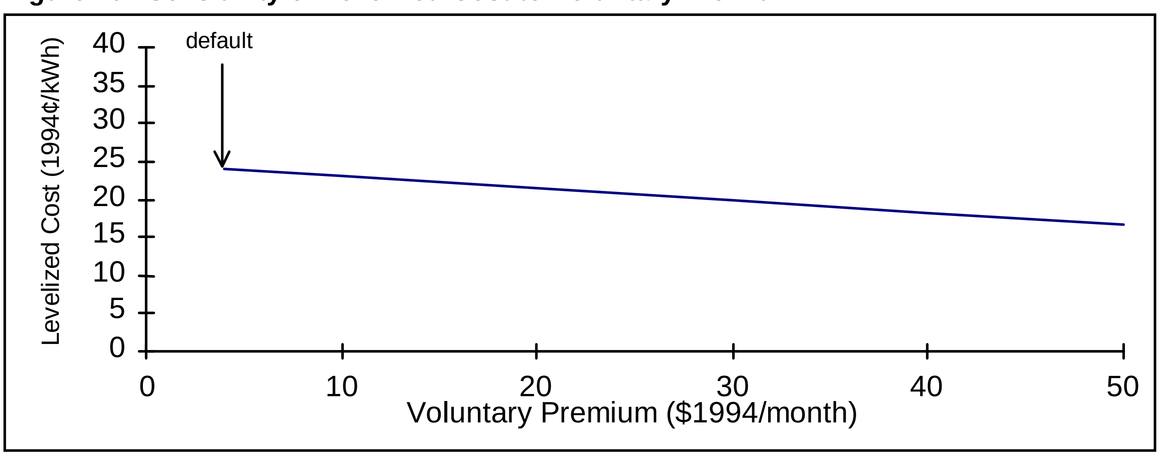

Figure 11. Sensitivity of Levelized Cost to Loan Life