MARKAL ANALYSIS OF PV CAPACITY AND CO_2 EMISSIONS' REDUCTION IN THE US

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ABSTRACT

This analysis compares market penetration of grid-connected PV in the U.S. in the context of a fully competitive market. The MARKAL-MACRO integrated energy-environmental-economic model was used to simulate the US energy capacity for the next 30 years. Photovoltaic technologies were assumed to compete on cost alone with 52 other energy generation technologies in the US, in a deregulated environment. It was shown that PV can become cost-effective in both distributed and central power applications in the US, if current expectations of performance and cost reductions materialize. The predictions of this analysis compare well with the goals of the US Photovoltaic Industry Roadmap.

1. INTRODUCTION

Several models are used for integrated energy environmental economic analyses of the future US energy outlook. The Energy Information Administration (EIA) of the US Department of Energy (DOE) uses primarily the National Energy Modeling System (NEMS) for such forecasting [1]. The US MARKAL-MACRO (MARKAL) is used by the US-DOE Policy Office and 35 other countries. The two models were compared, using the Annual Energy Outlook (AEO) assumptions for performance and cost in the future 20 years [2]. The comparison entailed the whole electric supply sector in the US, electric generating capacity, primary energy use, carbon emissions and price of electricity. It was shown that there were only minor differences between the two models in their projections for renewable energy. In this paper we present predictions for PV and wind penetration produced by MARKAL, under the price assumptions of the US Roadmap [3] and those produced jointly by the DOE and the Electric Power Research Institute [4]; these assumptions are listed are shown in Table I.

Table I. Assumptions of PV System Cost ($/W).

Source	2005	2010	2015	2020	2025	2030
PV Roadmap	4.27	3.00	2.12	1.50	1.12*	1.0*
DOE/EPRI 1999	2.9	1.5	1.3	1.1	1.0	0.9
O&M (cents/kWh)	0.3	0.3	0.2	0.2	0.1	0.1

*The Roadmap lists costs only for 2000-2020; the 2025-2030 prices are arbitrary extrapolations
Life=30 years

2. THE MARKAL MODEL

MARKAL is a demand-driven, multiperiod, linear programming model that captures the complex interrelationships of energy systems and their environmental emissions across the spectrum from energy resources to ultimate energy services [5, 6]. MARKAL selects technologies to enter the solution based on minimizing cost. The model minimizes total energy system cost over a multi-year period, subject to constraints, such as limitations on pollution emissions or limitation on growth rates of technologies. Although only the electricity sector results are presented here, the model analysis included the entire energy system, from extraction of resources; processing operations such as refineries; electric, gas, and oil transmission and distribution operations, and end-use technologies such as lighting, industrial heat production, and transportation technologies (from automobiles to ships and airplanes). MARKAL also projects emissions of environmental pollutants based on characteristics of technologies selected by the model.
All energy resources on both supply and demand sides, as well as energy efficiency and conservation technologies, compete in an even-handed manner. There is a total of 922 technologies in the MARKAL database. These include demand devices such as residential heating, commercial refrigeration, and lighting. The database includes 52 electricity-generating technologies.

3. ASSUMPTIONS

In 1999 a major workshop brought together experts from the PV industry, universities and government research programs. This workshop produced the PV Roadmap [3], and established the goal of a 25% per year rate of growth for the U.S. industry. The expected mix for future market penetration at this rate is one-sixth (17%) AC wholesale generation, one-half (50%) AC distributed generation, and one-third (33%) DC and AC value applications.
Our analysis excludes non-grid connected PV because the competitive energy model in MARKAL does not apply there. Thus our analysis includes the central and distributed energy uses predicted by the Roadmap; that is 67% of the total predicted capacity. MARKAL and its associated database are continually upgraded. This analysis was based on the 2001 MARKAL database, designed to closely match the U.S. Energy Information Administration's Annual Energy Outlook 2001, with the exception of PV and wind data that were used from the US Roadmap and the DOE/EPRI (1999) database, correspondingly. The Roadmap only projected system costs up to 2020. We extrapolated the forecast to 2030 by assuming a continuing price decline trend. We assumed that the peak electricity demand largely overlapped the

peak power demand. These input data for PV are shown in Table I and for wind category 5-7 in Table II.

The only constraint on the model was the upper bound on growth of 25%/year. Average US solar insolation of 1800 kW/hr-m^2 was assumed; the PV penetration in the high solar insolation regions could be much higher than the average.

Table II. Assumptions of Wind 5-7 System and Operating Costs.*

Cost	2005	2010	2015	2020	2025	2030
Capital ($/W)	0.72	0.67	0.66	0.65	0.64	0.63
Fixed O&M ($/kW)	18.2	18.2	18.2	18.2	18.2	18.2

* Source: DOE/EPRI 1997/1999.
Life=30 years; Capacity factor=0.4; Contribution to peak=0.3

4. THE METHOD

The US Roadmap prices were introduced into the model. The model output then displayed the capacities (GW) and output (TWh) of technologies that entered the model. The capacity of PV technologies was compared with the capacities in the 25 % per year planned growth rate in the Roadmap. Distributed PV was assigned 50% of the total Roadmap values and central station PV was assigned 17%. Distributed PV has (in MARKAL) a slight cost advantage, because is not charged a fee for distribution, which is charged on central PV. We assumed that all distributed generation is grid-connected (e.g., through reverse metering) and therefore, subject to the same economic competition as central-station generation. Only grid connected PV was included in this analysis.

The model determined emissions of carbon, nitrogen oxides, PM10, and sulfur oxides produced by electric generators. These were compared with the EIA's Annual Energy Outlook (AEO) forecast values for verification purposes. Finally, emissions displaced by PV (carbon, PM10, SO_2, and NOx) were calculated from the MARKAL output.

5. RESULTS

5.1 Market Penetration

The MARKAL results closely match the Roadmap capacity projections for the 30-year period for distributed PV (Table III). MARKAL does not develop projections year by year, but considers the entire future available to it. It sees the decreasing costs of PV over a 30-year period and finds it worthwhile to build the smaller amounts of capacity in the early stages to obtain the later benefits. The annual growth limit forces the model to build capacity in the early years in order to achieve the desired higher capacity levels in later years. With only a 20-year future before it, however, the model does not see the later low prices of PV and does not meet the Roadmap projections (Table IV). The 30-year projection with the MARKAL Roadmap costs projects 9.38 GW in 2020, while the 20-year projection predicts only a capacity of 0.96 GW. MARKAL selects technologies by discounting all costs for all time periods back to the first period. The high capacity achieved in the latter periods of the 30-year projection is sufficient to keep PV in the solution at a substantial level. In the 20-year projection, MARKAL never sees the opportunity for high capacity later. The result is that the 20-year projection remains near the AEO projection

Thirty years is a reasonable horizon and is generally used in MARKAL analyses. Beyond 30 years in the future, there are likely to be new technologies, not fully understood today.

Table III. Cumulative Capacity of Grid Connected Distributed PV, 30-year projections (GW).

	2005	2010	2015	2020	2025	2030
MARKAL Roadmap	0.28	0.96	3.04	9.38	28.73	87.79
MARKAL DOE/EPRI	0.56	1.8	5.58	17.13	52.37	148.
Roadmap*	0.17	0.57	1.97	6.65	21.48	66.25

*These are Roadmap projections assuming a 25% growth per year.

Table IV. Cumulative Capacity of Grid Connected Distributed PV, 20-year projection (GW).

	2005	2010	2015	2020	2025	2030
MARKAL Roadmap	0.06	0.06	0.28	0.96	--	--
Roadmap*	0.17	0.57	1.97	6.65	--	--

*These are Roadmap projections assuming a 25% growth per year.

The same applies to central PV generation. The 30-yar MARKAL projections closely match the Roadmap capacity projections (Table V), whereas the 20-year projections fall well below the Roadmap values.

Table V. Cumulative Capacity of Grid Connected Central PV, 30-year projection (GW).

	2005	2010	2015	2020	2025	2030
MARKAL Roadmap	0.04	0.23	0.80	2.55	7.87	24.11
MARKAL DOE/EPRI	0.25	0.87	2.75	8.5	26	26
Roadmap*	0.06	0.19	0.66	2.26	7.30	22.52

*These are Roadmap projections assuming a 25% growth per year.

Table VI shows the total central and distributed PV in the 30-year horizon. Under the price assumptions of the Roadmap, PV steadily increases its contribution in electricity generation to the maximum level of 8.9 % of the US capacity by the year 2030.

Table VI. Total US Electrical Power Capacity and Contribution of PV (MARKAL Roadmap Case)

	2005	2010	2015	2020	2025	2030
Total Capacity	821	895	972	1033	1129	1252
PV Capacity	0.32	1.19	3.84	11.93	36.6	111.9
% PV	0.04	0.1	0.4	1.1	3.2	8.9

5.2 Displacement of Fossil Emissions by PV

Carbon emissions are an important part of the model output. The following results correspond to the MARKAL-Roadmap case. PV steadily increases its displacement of carbon emissions and over the seven 5-year time periods, PV is projected to displace over 128 million metric tons of carbon (469 million tons of CO_2). In 2030 alone, the carbon dioxide displacement is projected to be about 62 million tons (Table VI). In addition, large quantities of toxic pollutants will be prevented (Table VIII).

Table VII. Displacement of carbon dioxide emissions by PV (million metric tons/year)

	2005	2010	2015	2020	2025	2030
Carbon displaced	0.22	0.77	2.35	7.26	21.23	62.4

Table VIII. Displacement of fossil pollution emission by PV (thousands of tons/year)

	2005	2010	2015	2020	2025	2030
NOx	0.44	1.64	2.81	13.07	33.95	58.15
PM10	0.02	0.07	0.25	0.84	2.80	9.16
SO2	0.71	2.59	8.33	25.87	79.37	242.32

5.3 Competing Technologies

Three technologies competing with PV were selected as a comparison. These were an advanced combined cycle, a central station technology; microturbines, a distributed technology; and wind 5-7, a renewable technology. Results of the capacity of these technologies are given in Table IX.

Table IX. Capacities of emerging competing technologies (GW).

	2005	2010	2015	2020	2025	2030
Advanced combined Cycle	15.8	71.7	116.	173.1	234.6	234.4
Micro turbine	1.7	4.9	7.1	10.2	14.7	21.2
Wind 5-7	6.6	7.13	11.6	19	30.9	50.0

MARKAL predicts a relatively high penetration for advanced combined cycle turbines and a smaller one for microturbines and wind. It is shown that Wind 5-7 systems, corresponding to installations up to 10 miles away of the grid, becomes cost competitive with conventional energy generation technologies early in the considered period. Wind-4 installations, which carry a higher transmission cost than Wind 5-7, do not enter the picture within the 30-yr horizon. Although the capital cost of Wind-4 installations is lower than that of PV, wind installations have a higher operating cost and do not contribute on peak shavings as much as PV does.

6. DISCUSSION

This MARKAL analysis for the period 2000-2030, verified the predictions of the US PV Industry Roadmap for a 25% per year rate of growth in domestic grid-connected PV installations. The MARKAL analysis validated that portion of the Roadmap goal under a competitive model, given that the cost of PV would continue to decrease. The 25 percent per year growth over an extended period is exceptional, but appears to be realistic. It is noted that from 1997 through 2002, the annual production of PV cells and modules has increased by 35% per year.

It is noted that the model "sees" the decreasing costs of PV over a 30-year period and finds it worthwhile to build the smaller amounts of capacity in the early stages to obtain the later benefits. The model builds capacity in the early years in order to achieve the desired higher capacity levels in the later years. This happens when a 30-year horizon is specified; with only a 20-year horizon, however, the model does not see the later low prices of PV and does not meet the Roadmap projections.

The continuing increase of PV capacity can make a significant impact in preventing future emissions of pollutants and carbon dioxide from fossil fuel power plants. Photovoltaic grid installations in the United Sates at the 2030 predicted levels, would prevent the emissions of $62x10^6$ tons of carbon dioxide per year, 242,000 tons of $SO_{2\ per}$/year, 58,000 tons of NO_X/year and 9,000 tons/year of fine particulates.

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