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The Potential of Solar Electric Power for Meeting Future European and U.S. Energy Needs: A Comparison of Projections of PV Generation and European and U.S. Domestic Oil Production

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Abstract - *The paper compares potential energy supply from solar electric power and domestic oil reserves to meet future European and U.S. aggregate energy demand. Such a comparison has practical value since it directly addresses a key policy choice under consideration in the new century, namely, that between mature, but non-renewable, energy sources and rapidly growing renewable ones.*

1. INTRODUCTION

Direct comparison of European and U.S. oil production and potential photovoltaic (PV) output (during the 70-year expected pumping lifetime of the newest oil deposit in these regions) has been neglected in the recent policy debate. In part, this is because oil is widely regarded as a well-established and economical resource, while PV is often seen as a ‘frontier’ technology that is too expensive to supply a significant share of energy demand. As we argue below, policy evaluation is positively served by a direct comparison of the two alternatives since it would force the debate about energy futures to move beyond answers that are constrained by the boundaries of the energy *status quo*. Our analysis of the two options suggests that interesting, if surprising, policy implications flow from such a comparison.

To analyze PV’s future contribution to meeting energy needs, historical trends are fitted with a logistic growth model of the Pearl-Reed form (see Mignogna, 2001).[1] Oil production scenarios are based on exponential function applied to published forecasts by the U.S. Geological Service (or USGS, 2000), the U.S. Energy Information Administration (or EIA, 2002a) and several International Energy Agency country policy reports (IEA, 2001, 2002a, 2002b). The methods for forecasting energy supply from the new sources are described below.

2. METHODOLOGY

2.1 The PV logistic growth model

To project PV’s contribution to national electricity supply, a Pearl-Read logistic growth curve was fitted to empirical data. Logistic growth models have been usefully applied to describe a wide variety of phenomena, from human population growth (first used by Belgian mathematician Pierre Verhulst in 1838 in connection with population studies) to oil development (Hubbert, 1962).

For our study, it was assumed that the contribution of PV to European and U.S. electricity production would grow until it would reach 10-15% of the national total (see section 3. of the paper for justification of this range). We further assumed that annual European and U.S. electricity production growth would be 1.6% and 1.8% respectively for 2000-2020 (based, respectively, on IEA’s 2002c and EIA’s 2001b forecasts). Also it was assumed that European and U.S. total electricity consumption would stabilize by 2050, meaning zero growth in consumption after that year. Thus, for the 2020-2050 period it was assumed that the growth rate of national electricity generation would decline gradually from 1.6% (for Europe) and 1.8% (for U.S.) in 2020 to 0% in 2050[2].

The equation used to project logistic growth of annual electricity generation Q is:

$$Q= U/(1+EXP[-b(t-tm)]) \qquad (1)$$

Maximum annual production from PV is denoted as U, and is set at 10-15% of current European or U.S. electricity generation. Using Laherrere (2000), the slope coefficient (b) for equation (1) is as follows:

$$b=6/d \text{ (to be more precise } b=5.986/d) \qquad (2)$$

where d is the time period needed to reach the maximum production additions rate (or one-half of the maximum production) from 1% of its level. If we take the time period when t=tm–d (that is, the time when the production level is 1% of its possible maximum), then:

$$Q1=U/(1+\exp[-(6/d)*(-d)])=U/(1+\exp6) \qquad (3)$$

After one year,

$$Q2=U/(1+\exp[-(6/d)*(-d+1)]=U/(1+\exp(6-b)) \qquad (4)$$
$Q2/Q1= (1+\exp6)/(1+\exp(6-b))$, for simplification

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[1] It should be noted that the Pearl-Reed curve is identical to the more widely cited Fisher-Pry form (for Fisher-Pry, see their 1971 paper; for the proof of their equivalence, see Mignogna, 2001).

[2] While some may regard a zero growth rate after 2050 to be unrealistic, the real purpose of a zero growth scenario is to ensure a conservative forecast for PV, since continued growth in electricity demand, even with a cap on PV’s share, would lead to higher forecasted growth in PV capacity additions after 2050.

$$K= Q2/Q1 \qquad (5)$$

The known (empirically observed) level of growth in percentage terms is p=(K-1)*100%, from which we can obtain K:

$$K= 1+p/100\% \qquad (6)$$

Simplifying (5) gives:

$$K*exp(6-b)=1-K+exp6 \qquad (7)$$
$$Exp6/expb=(1-K+exp6)/K \qquad (8)$$
$$EXP(b)=K*EXP6/(1-K+EXP6) \qquad (9)$$
$$b=ln[K*EXP6/(1-K+EXP6)] \qquad (10)$$

Thus, after specifying the current level of PV growth p, K can be obtained from equation (6), the slope b can be obtained from equation (10), and the value of d can be obtained from equation (2), which represents the length of time needed for reaching one-half of the maximum production level. Also, by knowing the existing level of PV production, it is possible to find the time needed to reach 1% of the maximum additions level. And by adding this time to d, tm is found. Thus, all required parameters for equation (1) are determined and a forecast of potential PV energy production can be obtained.

2.2 Methodology for oil production forecast

Oil production forecasts for Europe and U.S. relied initially on existing forecasts from IEA country reports (2001, 2002a, 2002b) for Europe[3] through 2010 and on an EIA (2002b) forecast to 2010 for the U.S. For further projections to 2070, a negative exponential growth function was applied to USGS (2000) estimates of remaining and undiscovered (mean) oil reserves in the U.S. and Europe.

This method assumes that after maturation of the oil production areas, and long after passing peak production levels (1970 for U.S. and around 2000 for Europe), annual oil production will decline exponentially. To derive annual decline rates, production levels for the beginning of the forecast period (P) and potential remaining oil reserves (S) at that time were utilized.

Potential remaining oil reserves in these areas during the additional forecast period (i.e. from 2010 to 2070) were calculated by the following formula:

$$S=(R+X)-(H+F) \qquad (11)$$

where S is the remaining potential reserve beyond 2010, R is the USGS estimate of remaining reserves, X is the USGS estimate of undiscovered oil reserves, H is historical cumulative production from 1996 until 2001, and F is cumulative production from the early forecast period of 2002-2010.

It can be shown by the following mathematical manipulation that the rate of decline is:

$$r=P/S \qquad (12)$$

The proof is as follows:

$$P/(1+r)+P/(1+r)^2+ P/(1+r)^3+\ldots=S \qquad (13)$$

Multiplying both sides by 1/(1+r) gives:

$$P/(1+r)^2+ P/(1+r)^3+ P/(1+r)^4\ldots=S/(1+r) \qquad (14)$$

Subtracting (14) from (13) gives:

$$P/(1+r)=S-S/(1+r) \qquad (15)$$

Multiplying both sides by (1+r) gives:

$$S+S*r-S=P \qquad (16)$$

After canceling S terms and dividing both sides by S equation (12) results.

After obtaining r values, annual oil production forecasts for Europe and U.S. were made to 2070.

3. FORECASTING PV CAPACITY ADDITIONS FROM 2000 TO 2070

Using the above method, a forecast of installed PV capacity in Europe and the U.S. between 2001 and 2070 was developed. Key assumptions include: 1.) PV's contribution to European and U.S. electricity supply will reach a maximum of 10-15% by 2050; 2.) growth in European and U.S. electricity supply will stabilize by 2050; and 3.) capacity additions after that year will represent replacement demand only.[4]

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[3] Because the major oil production area in Europe is the North Sea and no other significant petroleum deposits in Europe have been identified by research (see, e.g., USGS 2000), North Sea oil was the only known European deposit included in the analysis. Of course, an estimate of undiscovered reserves in Europe was added.

[4] Of course, competitors to PV technology, as well as more competitive PV designs and applications, can substantially alter long-term growth patterns. Still, it is instructive to consider PV's future in terms of theoretically defined general tendencies for the diffusion of new technologies (see, e.g., Mansfield, 1968; Saad, 2000). This is the approach taken here.

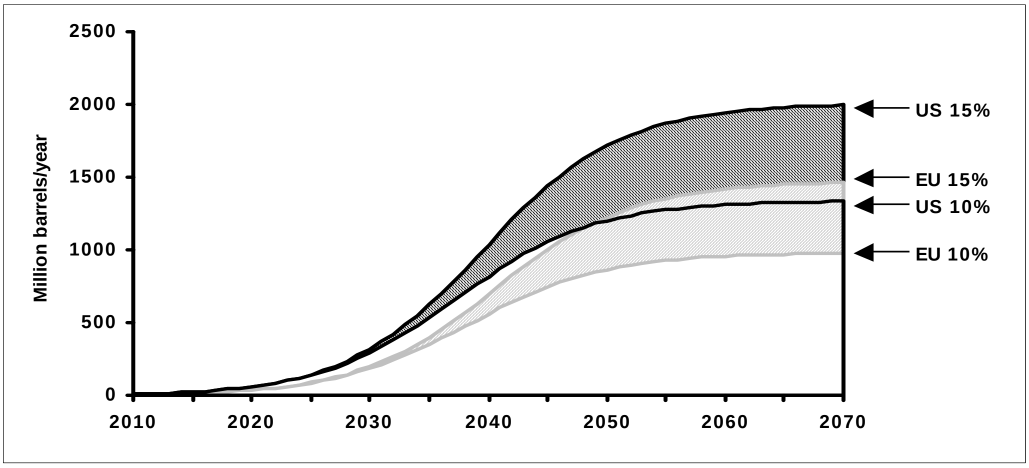

Figure 1. Potential U.S. and European PV supply at 10% and 15% of electricity supply target levels.

The assumption of a 10-15% limit on PV's contribution to future European and U.S. electricity supply is conservative. The technical limit for grid use of an intermittent source of energy is ordinarily thought to be around 30% (e.g., Kelly and Weinberg, 1993), and one researcher has suggested that for PV, specifically, it may be upwards of 20% (Perez et al, 1993). Thus, our 10-15% cap is in the lower range of research projections.

An initial annual growth rate for European and U.S. capacity additions was set at 20%, with the rate declining to zero in 2050 (when electricity generated from PV reaches its 10-15% cap). An initial 20% growth assumption is well sported by historical data and is within the 15-25% range used by NCPV (2001) for their PV industry development road map.

Collectively, assumptions of an initial yearly growth rate of 20%, a 2050 peak for PV generation share, and PV manufacturing for the European and U.S. markets limited after 2050 to replacement demand, are conservative, anticipating slow market maturity for the technology when energy and silicon-based technologies have tended to grow more rapidly and have taken longer to peak than these assumptions allow. For example, Between 1862 and 1911, the average yearly growth rate in U.S. oil production was 25.5% (based on data from U.S. Census Bureau, 1975). Between 1957 and 1977, installed nuclear plant capacity in the U.S. grew at an average annual rate of 36% (Williams and Terzian, 1993). Two silicon-based technologies – personal computers and cellular phones – offer empirical evidence of market growth in time frames that overlap with silicon-based PV. Sales of personal computers in the U.S. between 1982 and 2000 exhibited annual average growth of 22% (U.S. Census Bureau, 1991-2000a; 1994-2001b). Between 1986 and 2000, the annual average growth rate of cell phones in the U.S. was 48.6% (U.S. Census Bureau, 1991-2000a; 1994-2001b; Cellular Telecommunications & Internet Association, 2001).

These comparisons suggest that the 20% initial growth rate used for PV in our forecast is not unreasonable. Studies of sustained growth rates of new energy technologies likewise support the assumptions made in our analysis (e.g., Payne et al, 2001).

Because PV is currently expensive (compared to fossil fuels), a projection such as that in Figure 1 might be regarded as wishful under dramatic price declines occur. However, credibility for our forecast is strengthened if two things can be shown: first, that the break-even price at which PV can be expected to compete favorably in the energy market is likely to be realized in the near future, and second, that PV sales at the break-even price can be expected to be at or above forecasted levels. We address this question using experience curve analysis.

Experience curves can be described by the following equation:

$$\text{Price at year } t = P_0 * X^E \qquad (17)$$

Where P_0 is the price of the first unit of cumulative shipments, X is cumulative shipments at year t and E is the experience index, which determines the inclination of the experience curve. The progress ratio (PR) can be derived from E (or vice versa) given that $PR = 2^E$ (IEA, 2000). The experience curve equation can be used to calculate the breakeven level of cumulative shipments necessary to bring the average selling price to a level that can be expected to be competitive with other energy options.

The average selling price at which PV is reported to become competitive has been debated in the research literature. Forecasts vary from $\$0.50/W_p$ to $\$2.50/W_p$

(Neij, 1997; International Energy Agency, 2000; NCPV, 2001). We adopt \$1.50/W_p as a mid-range value. Using log-linear regression analysis for the period 1985-2001, a PR of 80% is statistically predicted (assuming a breakeven price of \$1.50/W_p). With a PR of 80%, the resulting breakeven level of cumulative worldwide shipments is about 22,000 MW_p. U.S. and Europe on domestic sales are expected by our forecast to reach 22 GW by 2019.[5] Thus it would appear that the forecast in Figure 1 is easily achievable at a breakeven price of \$1.50/W_p.

Forecasted energy generation from PV was converted to barrels of oil equivalent to facilitate comparison with oil production estimates. The conversion formula used for our forecast was as follows: assuming a 30-year lifetime for PV systems and that 1 peak watt of PV annually generates an average of 1.7 kWh (taking into account avoided T&D losses), annual electricity generation from 300Wp of PV = 505kWh = the electricity equivalent of one barrel of oil.

From our model, it is projected that by 2070 cumulative energy supply from PV in the U.S. could be in the 44.2 – 61.8 billion bbl range and for the Europe in the 31.4 – 43.8 billion bbl range (See Figure 1). The difference between the U.S. and European values can be explained by higher levels of electricity consumption in U.S. compared to Europe (around 2,900 TWh annually for Europe, and 3,600 TWh for the U.S. (IEA 2002c)).

4. FORECASTING OIL PRODUCTION FROM 2000 TO 2070

Domestic oil production is expected to decline in the U.S. and Europe. EIA (2002c) has concluded that European oil production peaked in 2000, while historical data from EIA (2002a) indicate that American production peaked in 1970 and continues decline. While undiscovered oil deposits are anticipated in both regions (e.g., USGS (2000) believes that 19.6 billion bbls of oil are still to be found in Europe and 75.6 billion bbls in the U.S.), there will not be sufficient to reveres the decline in domestic oil production in either region.

If we consider the projected energy production value of all current oilfields and potential, but yet undiscovered, oil production areas, and fit an exponential curve to link such a long-term estimate to the 2010 IEA/EIA forecasts, we can find a plausible pathway for domestic oil supply through 2070. Of course forecasting future oil production is a risky analytical enterprise that, understandably, can yield widely varying estimates. The USGS world petroleum assessment (2000) is used to identify U.S. and European potential (undiscovered) and existing (remaining) oil reserves. The controversial category of reserve growth was not included in our analysis.

It was widely recognized in the forecast research literature that (e.g. Hubbert, 1962; Laherrere 2000), after oil production reaches maturity and passes peak levels, annual production gradually declines. Using the methodology described in section 2.2, production forecasts were made for U.S. and Europe (Figures 2 and 3). By 2055, Europe is projected to have fully depleted its domestic reserves. By 2070, the U.S. will have only the most expensive remaining 5% of its domestic reserves to use. Thus, from the perspective of domestic production, the oil era will have concluded by 2070 for the U.S. and Europe.

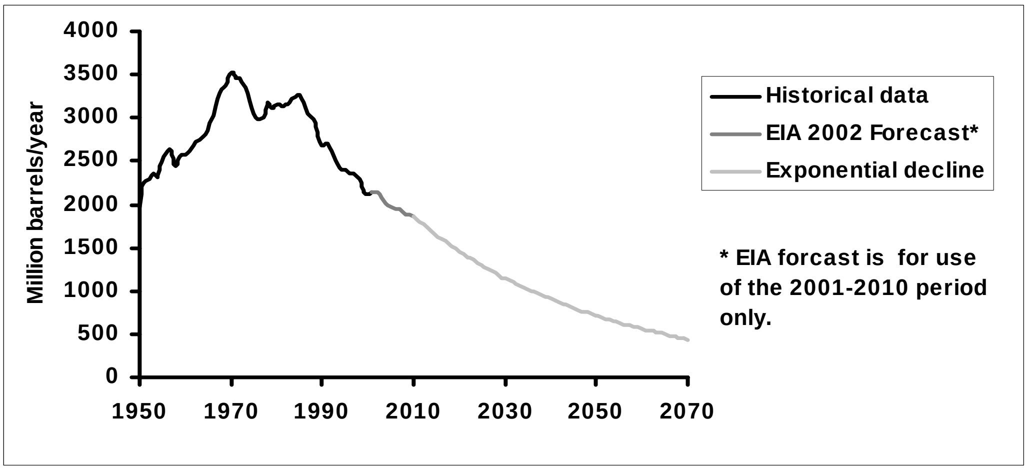

Figure 2. Historical and forecasted U.S. oil production (Data sources: EIA 2002a, EIA 2002b, USGS 2000)

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[5] Actually, the 22 GW break-even level refers to *world* sales. Thus, this market scale is likely to be reached earlier than 2019, which provides even stronger support for the reasonableness of our forecast.

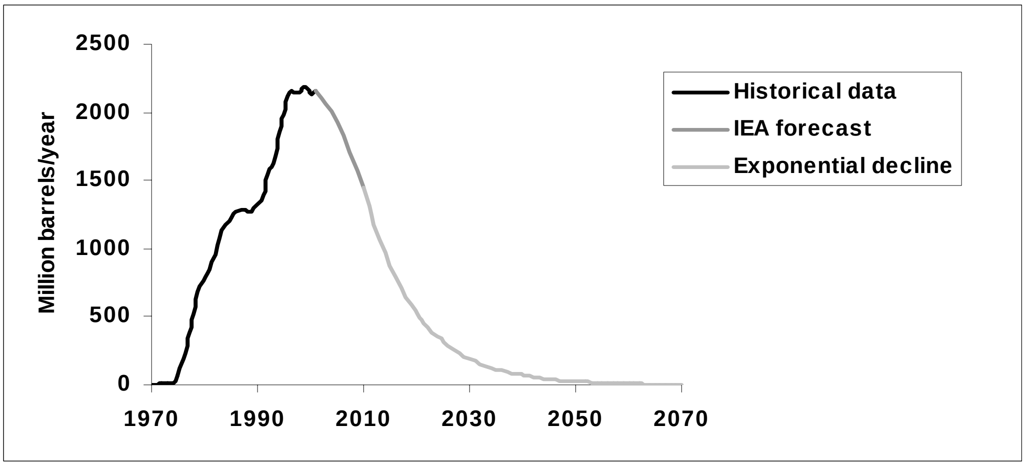

Figure 3. Historical and forecasted European oil production (Data sources: IEA 2001, IEA 2002a, IEA 2002b, USGS 2000)

5. COMPARISON OF POTENTIAL OIL PRODUCTION TO PV

By our calculations, for U.S. cumulative domestic oil production in the U.S. for the period 2010-2070 could amount to 60.2 billion barrels, while PV energy supply in oil equivalent could be between 44.2 and 61.8 billion barrels. Thus, the contribution of PV to U.S. energy supply for 2010-2070 is likely to be comparable to that from oil (Figure 4). If hydrogen becomes a competitive fuel for transport, PV could be strategically valued for its ability to significantly reduce dependence on imported oil.

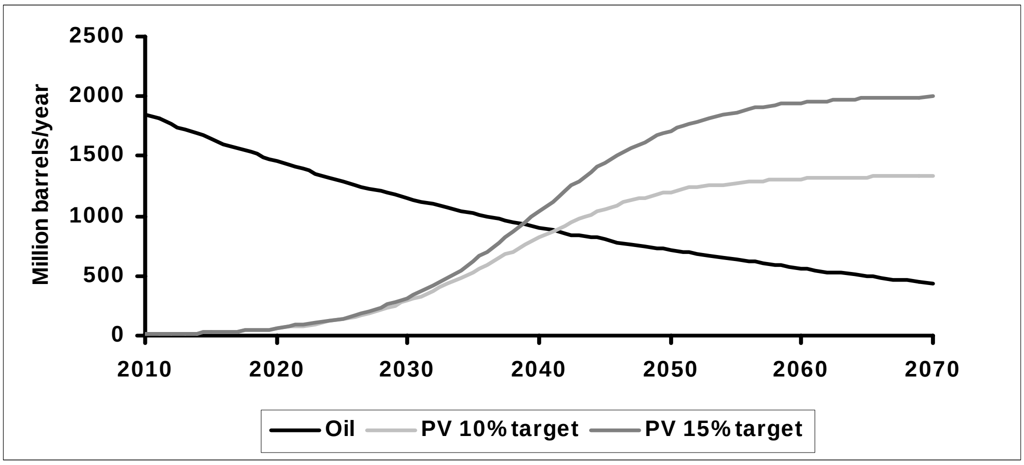

Figure 4. Comparison of forecasts of U.S. PV energy supply and U.S. oil production from existing domestic reserves

For Europe, cumulative domestic oil production could amount to 14.6 billion barrels, while PV energy supply in oil equivalent for the same period could grow to 31.4 to 43.8 billion barrels. Thus, the contribution of PV to European energy supply for 2010-2070 would be 2 or 3 times more than that from oil (Figure 5).

6. CAN PV COMPETE?

Currently, PV systems furnish bulk electric power at roughly \$0.25 per kWh. Compared to electric generation from coal plants of \$0.03-\$0.04 per kWh (uncorrected for adverse environmental effects), it is difficult to imagine that PV can compete with fossil fuels to supply an advanced industrial society's energy needs.

Researchers often evaluate the prospects for PV market viability by comparing it with fossil fuel plants on the assumption that its ultimate market destination is bulk power supply, which is now dominated by utility-owned systems. In this case, PV systems will have to generate electricity at a cost equal to that for electricity generated by natural gas or coal-fired power plants. According to IEA (2000), the breakeven price for PV modules to compete in the electric power market is \$0.50/W$_p$, which is one-third the price we used to justify our forecast.

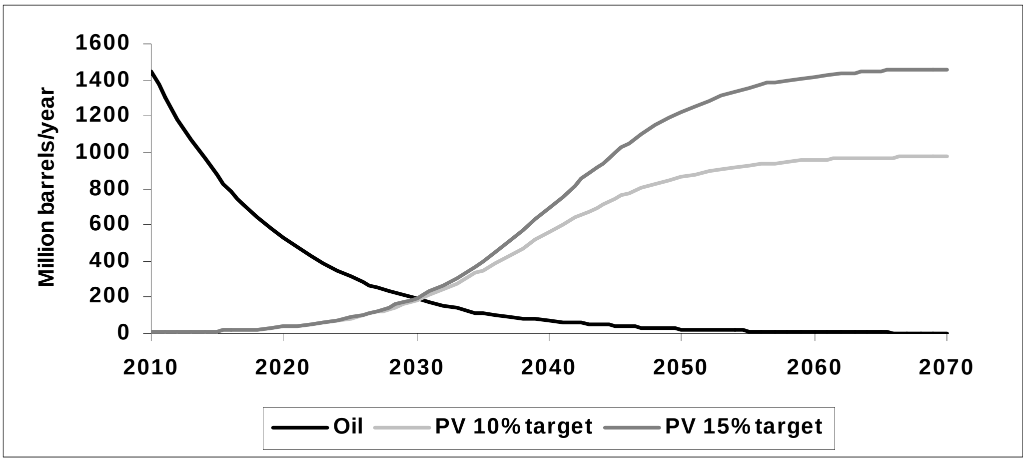

Figure 5. Comparison of forecasts of European PV energy supply and European oil production from existing domestic reserves

However, this argument neglects to consider PV as a self- or co-generation option. Where net-metering is allowed, the cost of electricity generated from a PV system should be compared with the retail price of electricity, rather that the cost of the electricity generated by the utility. In Germany, Italy and specific U.S. states (e.g., California), retail prices for domestic customers (including taxes) reach a level of \$0.15-\$0.25/kWh. When these prices are used to set the 'hurdle rate' for competitive PV, a module price of \$1.50/W_p can be considered as a reliable estimate for a breakeven scenario.

But there is an additional reason to believe that PV can compete on the scale we have forecast. It involves a conceptual question of special importance to the economics of PV. Breakeven analysis of the kind discussed above presumes that PV's principal application will eventually be for bulk power, where it will have steal market share from its fossil fuel competitors. But many researchers (including the authors) dispute this presumption. First, the energy technology sector is experiencing marked change from its traditional architecture of large-scale, centralized supply systems. Unlike as recently as the 1980s, when the economics of power generation seemed to favor large facilities (e.g., 500 to 1,200 MW – see Messing et al, 1979), today's power plants are usually modest in size (often less than 1 MW – see Dunn, 2000) and their profitability is based on the principle of modularity (Hoff and Herig, 1997) rather than economies of scale. PV certainly fits this trend. Thus, traditional cost comparisons based on large bulk power markets may be inappropriate when technology change is leading to the obsolescence of large electric power plants (Hunt and Shuttleworth, 1996: 2).

Second, and perhaps more important, PV is likely to pioneer the development of a new energy services market in which technology does not simply supply energy, but must also meet the demand for such services as energy management (e.g., peak shaving), back-up or emergency power, environmental improvements (for example, reducing pollution that adversely affects air quality and forest growth, or mitigating carbon emissions that are linked to climate change) and fuel diversity (see, especially, Awerbuch, 1995 and Awerbuch et al, 1996). When PV is analyzed in this services context, its economics dramatically improve (see, e.g., Byrne et al, 1996, 1997 and 2000). Indeed, in transmission-constrained locations, PV as a service technology can be competitive at today's module prices (see Letendre et al, 1998).

Evaluated with these economic trends and factors in mind, the current spread in bulk power prices between PV and the fossil fuel family may not be compelling.

Of course, even if the possibility of a PV-led transformation in the electricity market is considered (for argument purposes), there can be a second objection to our analysis. After all, PV would compete in electricity markets, while oil is largely used for transport. In essence, the comparison we have offered can be rejected because it compares 'apples with oranges.'

We believe this objection misses a key factor, namely, the role of policy. While it is likely that PV and oil would compete during much of our forecast horizon to supply distinctly different services,[6] the ability of both sources to serve markets will be not insignificantly dependent on national and international policy. Oil's status as an essential energy source for industrialized society comes

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[6] Of course, there is the possibility that oil and PV could be direct competitors. If a hydrogen economy emerges by 2020 or so, or if breakthroughs in electric vehicle technology (especially with respect to storage) are realized, we would see direct competition between these sources.

with policy obligations that include national and global security commitments, subsidies to relieve users of the need to pay the full social and environmental costs of oil production and consumption, and increasingly favorable treatment for investments in oil extraction (because exploration and drilling will only increase in cost over the next 65-70 years). The oil industry has demonstrated an impressive capacity to obtain needed policy attention in all of these areas in order to sustain its market viability.

For PV to attract even modest policy support (beyond its present treatment as a ‘frontier’ technology deserving ‘market priming’ assistance), it must compete in the very important policy ‘marketplace.’ Comparing PV to oil is essential for PV’s participation in this competition. National and international energy policy largely exists as a fuels policy, rather than a sectoral or user-based policy. The findings of the research reported here can be used to ‘level the playing field’ of policy-making, and provide grounds for challenging the overwhelming pro-carbon bias in energy policy throughout Europe and the U.S. Hopefully, it may also encourage Europe and the U.S. to re-think the meaning of and strategic planning for energy security.

Thus, we think there are sound reasons for comparing the long-term prospects for oil and PV. Both the changing economics of energy markets and the highly important politics of energy policy suggest that the comparison is warranted.

7. CONCLUSIONS

Energy debates usually concern issues of technology and markets. This reflects an implied belief that incremental change will dominate the future. But energy change can often be dramatic and sudden (e.g., MacKenzie, 1997). Moreover, energy choices can be highly affected by policy decisions.

It is wise to evaluate policy alternatives that do not assume the energy status quo, in order to understand the true magnitude of policy choice that is at stake. The direct comparison of PV and oil is an example of a less constrained approach to energy policy analysis. Our findings from this comparison suggest that PV has a realistic potential of providing services in the U.S. that would be comparable in energy value to all known U.S. domestic oil reserves. For Europe, the role may be even more substantial, possibly two to three times as much as the region’s domestic oil reserves.

In light of these results, PV’s treatment in the current energy policy debate as a ‘frontier’ technology is misguided and, almost certainly, inaccurate. Our analysis suggests that it deserves American and European policy attention at least at the level presently afforded to oil.

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