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Chapter 2

Beyond Oil: A Comparison of Projections of PV Generation and European and U.S. Domestic Oil Production[1]

by

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Abstract

The chapter analyzes the potential contribution of photovoltaics (PV) to meet part of European and U.S. future electricity needs. A logistic growth model based on historical trends of PV markets was utilized in order to forecast electricity generation from PV between 2005 and 2070. Historical growth of other energy sources (e.g., oil, natural gas) and other silicon-based commodities (e.g., cellular phones, personal computers) were also analyzed in order to assess whether the projected growth rates for PV capacity that result from the model can be considered realistic. The PV forecasts are also compared with projections of other researchers. The forecasted energy generated from PV is then compared in energy units (barrels of oil equivalent) with forecasted European and U.S. domestic oil production. Our conclusion is that cumulative energy production from PV will be higher than domestic oil output for both regions for the forecast period. The role of European and U.S. national energy policies promoting PV development is examined in light of this finding.

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[1] An early version of parts of the argument appearing in this chapter is published in a recent issue of the journal *Energy Policy* (see Byrne et al., 2004). The earlier article included only an analysis of the U.S. case. Several additions and detailed improvements have been made to the argument and methodology that we believe further demonstrate the importance of comparing PV and domestic oil while expanding the scope of the analysis to Europe and considerably strengthening the empirical support for our findings.

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1. Introduction

To realize the potential of solar electric power, improvements in photovoltaic (PV) technology will be needed. While certain peak-shaving and so called "distributed utility" (see Weinberg et al., 1993) applications can be competitive at today's module prices (Byrne et al., 1996, 1997, 1998, 2000 and 2002, as discussed below), as can a full range of off-grid uses, wider market penetration of PV will depend on further technical and economic advances. Without considering the costs of externalities, current costs preclude PV from competing with fossil fuel-fired generation technology and wind energy and hydroelectric systems for the supply of low-cost bulk power to grid users.

Partly due to this fact, PV's future is often discussed, even by its promoters, as largely a matter of technology and markets. Forgotten in this treatment are three interrelated factors of equal or greater significance: 1) the major changes underway in the electricity sector; 2) an even larger set of changes in how societies assess energy services; and 3) the influence of past and future policies on PV's (and its competitors') development. Briefly, electricity technologies and economics are shifting from a nearly exclusive focus on the provision of large amounts of kWhs via centralized production systems to a service architecture that emphasizes modular development of electricity capacity when and where different needs arise (see, e.g., Hunt and Shuttleworth 1996). As discussed in section 4 of the chapter, comparison of PV to busbar costs of thermal plants using fossil fuels will become less and less relevant as this trend accelerates. Just as the lower per minute cost of land line telephone communication did not decide the fate of the cellular phone industry, it is unlikely that PV's prospects will rest upon competitive bulk power rates.

Possibly more significant is the trend in many societies to evaluate energy services according to new yardsticks that include environmental performance, health impacts, effects on local control and security implications. With the energy sector now understood to contribute to a variety of environmental ills from climate change to urban smog and acid rain, and with linkages now being drawn between its emissions and health problems (such as higher incidences of cardiovascular and respiratory diseases), there is a growing social consensus that changes are needed in the types of fuels used, the pricing of energy services and the general expectations of energy systems. With regard to the latter, the recent California energy crisis (in the wake of its electricity deregulation policy) and the persisting volatility in fossil fuel prices and international energy politics have likewise strengthened the interest of many communities in increasing the use of local renewable energy sources. Often, renewable energy generally, and PV specifically, reduces social risk and adds local control benefits (both for communities and companies) to energy service provision (Awerbuch, 1995; Lovins and Lovins, 1982).

These rising social concerns have led to a plethora of policy initiatives to incentivize renewable energy development, especially in the U.S. and Europe (discussed in some

detail below). Not willing to let short term costs and benefits entirely determine their energy future, several communities in both jurisdictions have adopted regulations and employed policy tools to speed up the entry of renewables into the marketplace and, in some cases, have authorized taxes to discourage continued reliance on fossil fuels (see section 7 below). While the initiatives are embryonic, the new policy environment appears to seek change in the social structure of energy service, which if effective would raise doubts about the validity of benchmarking PV's performance against the energy *status quo*.

Thus, there are empirical reasons (discussed more fully below) why PV's future likely cannot be judged by existing technical and economic considerations alone. This should encourage research and policy analysis that canvasses wider opportunities for the technology than its ability to substitute for conventional systems. Yet there is very little research of this kind. In the interest of opening the PV research agenda to broader questions and in an effort to build a more complete analytical portrait of the technology's potential, we consider a question that is ordinarily neglected, namely, if and how PV could have the equivalent importance of a major energy source for the U.S. and Europe in the 21st century. Oil continues to be widely regarded as a major energy source for the American and European economies, while PV – both in the policies and investment patterns of the two jurisdictions[2] – is treated as a 'frontier' technology. Our question probes, rather than accepts, the validity of this treatment.

Thinking beyond conventional energy wisdom is actually grounded on a well-established feature of energy transitions. As with the contemporary cases of coal, large hydro, oil, natural gas and nuclear power, energy transitions are typically sudden and substantial (see, e.g., Smil 2000). The rapid change that defines them is closely linked to policy shifts, which often spur technical and economic change (Byrne and Rich, 1983). Therefore, understanding PV's potential will require us to ask not only technically and economically innovative questions, but policy questions as well.

2. Forecasting PV Electricity Generation

2.1 A logistic Growth Model

Energy forecasting is a well-established and widely used tool by private and public sector organizations to gauge market trends in this strategic sector. Typically, forecasts link physical (e.g., geology), economic and social information, often in mathematical models, in order to produce near-term (less then one year), short-term (1-5 years), medium-term (5-10 years) and long-term projections (more then 10 years) of energy supply and demand (EIA 2002b, IEA 2001, 2002a, 2002b, 2002c). For reasons

[2] As we discuss later in the chapter, recent changes in policy strategy and investments are evident in Europe and the U.S. If these changes continue to accumulate, it is possible that a shift in policy objectives–and energy investment outcomes–will result. See section 7 for details.

described below, we have adopted a logistic growth approach for forecasting PV market development in the U.S. and Europe. This methodology is commonly used to anticipate the entry of new technology generally (Fisher and Pry, 1971; Mignogna, 2001; Woodall, 2000) and new energy technologies specifically (e.g. EWEA, 1999; Roethle Group, 2002).

Logistic growth models have proven to be accurate tools for forecasting a wide range of phenomena, from human population growth (used by Belgian mathematician Pierre Verhulst in 1838) to oil development (Hubbert, 1962 and Laherrère, 2000). A logistic growth curve, according to Laherrère (2000) and Mignogna (2001), can be represented by the following equation:

$$Q = \frac{U}{1 + e^{-b(t - t_m)}} \qquad \text{(Eq. 1)}$$

where:

Q is the forecast variable (e.g., annual or cumulative energy production or the number of new users in the case of technologies like cellular phones and personal computers);
U is the saturation (maximum) level for Q;
b is the slope term, reflecting the initial growth rate;
t is time (in years); and,
t_m represents the midpoint of the logistic curve.

Variable Q in equation (1) can represent annual energy production in the case of renewable energy technologies, cumulative energy production in the case of oil and natural gas, and the number of users in the case of silicon–based technologies such as cellular phones or personal computers. U represents the maximum level of energy production from renewable energy (based on known or assumed economic, technical, and physical restrictions). Alternatively, U represents the physical resource limit for nonrenewable sources such as oil and natural gas (i.e., ultimate feasible production in a given geographic area), and the maximum number of potential customers in the case of cellular phones or personal computers. The slope term b is a constant and represents the rate of growth per unit of time. In equation (1), t_m is the time it takes for Q to reach the midpoint of its logistic growth trajectory.

Rearranging terms in Eq. 1 renders:

$$\frac{U - Q}{Q} = e^{-b(t - t_m)} \qquad \text{(Eq. 2)}$$

which offers an easy means of defining in functional form the parameters of interest. Taking the logarithm of both sides gives:

$$\ln(\frac{U-Q}{Q}) = -b \times t + b \times t_m \qquad \text{(Eq. 3)}$$

Grouping variables, we then obtain:

$$Y = \ln(\frac{U-Q}{Q})$$

This yields the familiar linear equation:

$$Y = \alpha + \beta \times X \qquad \text{(Eq. 4)}$$

where:

X=t

parameter $\alpha = b * t_m$

and parameter $\beta = -b$

Applying statistical regression methods to Eq. 4, the parameters α and β can be robustly estimated.

Noting that $t_m = -\alpha/\beta$ and $b = -\beta$, Eq.1 can be presented as:

$$Q = \frac{U}{1 + e^{\beta(t + \frac{\alpha}{\beta})}} \qquad \text{(Eq.5)}$$

Equation 5 and the linear regression method used to estimate parameters in Eq. 4 are consistent with the classic Fisher-Pry form of a logistic growth curve widely used to model technology diffusion (Fisher and Pry, 1971).[3]

In this way, a forecasting model can be built on empirical experience to date with the technology of interest (PV, in this case) and, equally important, the parameter values adopted for forecasting purposes can be benchmarked against experience with comparable technologies and market conditions. As discussed below, regression results enable the use of a growth rate in the forecast that is selected on objective grounds and can be compared to historical experience with other energy sources and technologies.

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[3] As Mignogna (2001) has shown, the approach we have taken here is mathematically identical to the Fisher-Pry logistic growth model.

2.2 Validity of Using a Logistic Curve Model to Predict Growth in Use of Energy and Silicon-based Technologies

To validate the use of the logistic growth curve, historical data on growth patterns for selected energy and silicon based technologies were analyzed. Results from a regression analysis conducted for the cellular phone industry in the U.S. are shown for illustrative purposes in Figures 1 and 2. After obtaining regression parameters (Figure 1), a logistic growth curve is constructed for the period from market entry to diffusion of this technology (see Figure 2). The coefficient of determination for this regression (R^2=0.9942) indicates that over 99% of the variance in sales data for 1986-2003 is accurately predicted by the logistic growth model. The saturation level (U) is estimated to be 200 million subscribers.[4]

Similarly, an analysis of cumulative oil production shows the versatility of a logistic model to describe energy market development. Maximum oil reserves (U) were set at 216 billion bbl. This is the midpoint between the 210 billion bbl limit used by Laherrère (2000) and the 222 billion bbl maximum employed by Bartlett (2000). Using this (U) value, the regression for the U.S. cumulative oil production produced a quite high R^2 value (see Figure 3a).

Using estimates from the U.S. Geological Survey (1995; 1998) and Mineral Management Service (1996) for measured (proved) reserves and their estimates of "undiscovered" but economically recoverable resources[5] yields a higher estimate of maximum recoverable reserves (229 billion bbl). Figure 3b offers a logistic curve fit for historical oil production data (see US Census Bureau (1975) and Energy Information Administration (2002a)) based on this alternative U value. Inputting obtained regression parameters for the two scenarios yields actual versus estimated scatter plots (see Figures 4a and b).

Table 1 summarizes regression analysis results for the selected technologies and markets. All of the regressions use an underlying logistic growth curve and produce high R^2 values. Naturally, differences in units of the Q variable for each technology and energy option (i.e., subscriptions vs annual electricity generation vs cumulative production in tons or cubic meters) lead to differences in intercept values (the α's). Slope coefficient differences (the β's) reflect the particular economic, technical and physical factors influencing the development of these energy and technology alternatives. Notwithstanding these evident differences, Table 1 demonstrates the ability of a logistic growth model to accurately project market development. It is this feature that encouraged our use of the method.

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[4] According to Telecompetition (2003), the maximum penetration rate of cellular phone subscriptions in the U.S. market is expected to be in the 70-75% range of the population, which is 281 million according to the last U.S. Census (2000). Applying a mid-point value of 72.5% yields 200 million. We use this value for the U term to create the regression results in Figure 1.

[5] See below for a discussion of these terms.

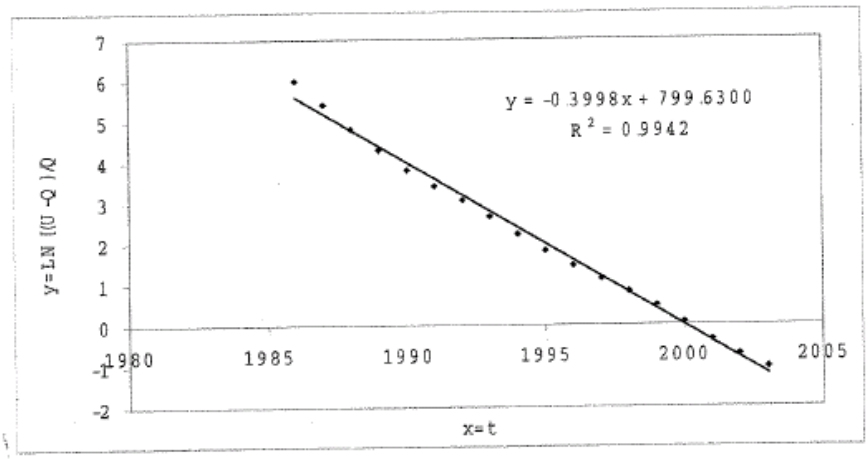

Figure 1. Regression analysis, using a logistic growth model, for cumulative U.S. cellular phone subscriptions with saturation level realized at 200 million subscriptions (Data sources: CTIA 2003).

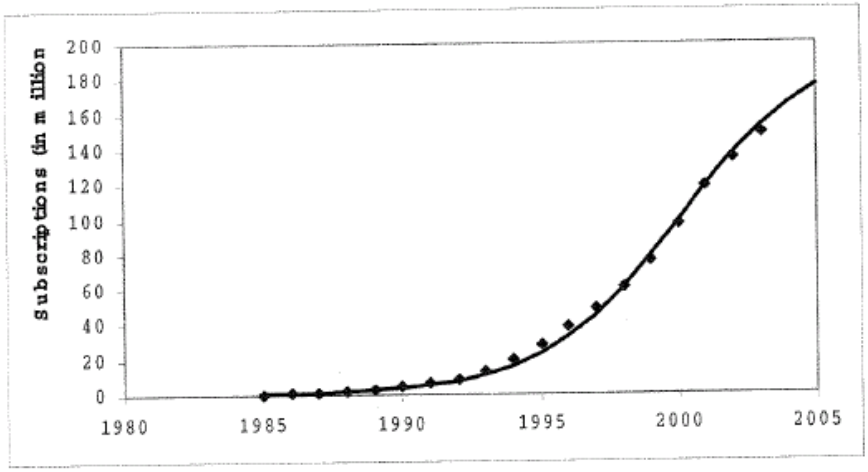

Figure 2. Resulting logistic curve for actual numbers of annual cellular phone subscriptions in the U.S. during 1985-2000 (Data source: CTIA 2003).

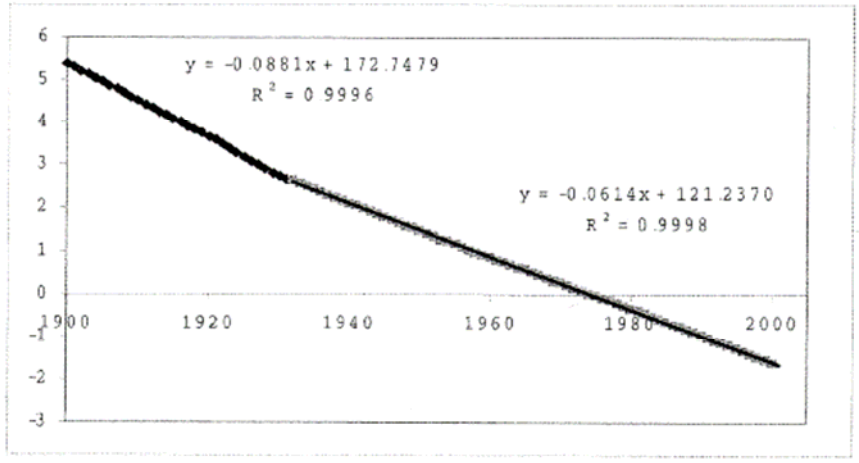

Figure 3a. Regression analysis, using a logistic growth model, for cumulative U.S. domestic oil production with ultimate oil reserves of 216 billion bbl - based on Bartlett (2000) and Laherrere (2000). (Data sources: US Census Bureau 1975, EIA 2002a).

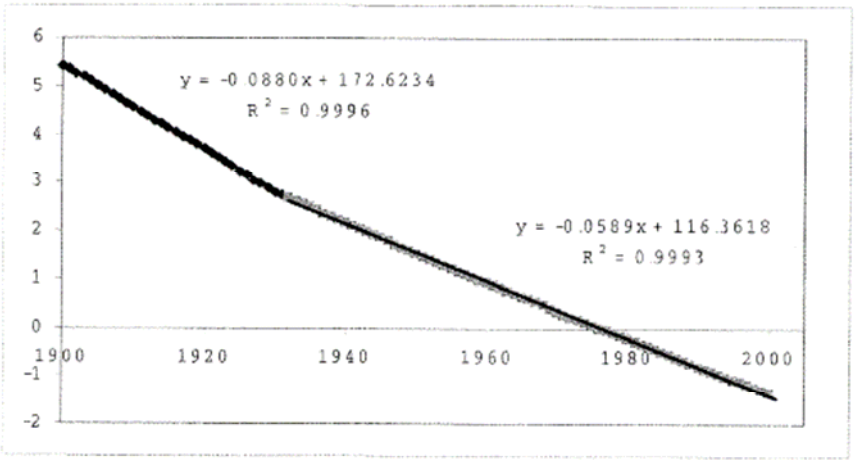

Figure 3b. Regression analysis, using a logistic growth model, for cumulative U.S. domestic oil production with ultimate oil reserves of 229 billion bbl - based on USGS (1995; 1998) and MMS (1995) (Data sources: US Census Bureau 1975, EIA 2002a).

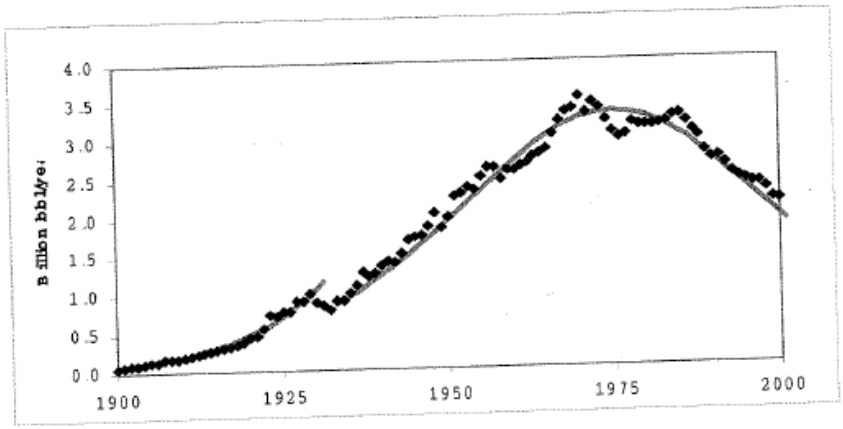

Figure 4a. U.S. domestic annual oil production (diamonds = actual and solid line = estimated) with ultimate oil reserves of 216 billion bbl.

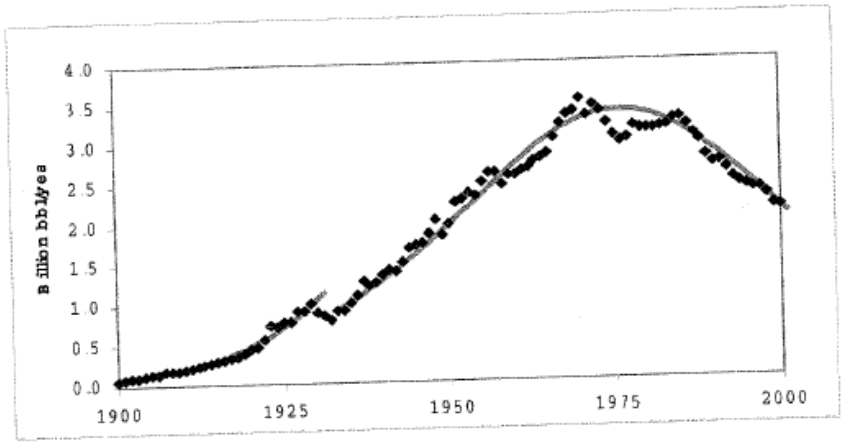

Figure 4b. U.S. domestic annual oil production (actual and estimated) with ultimate oil reserves of 229 billion bbl.

Table 1. Statistics for logistic curves fitting oil and natural gas production, cellular phone subscriptions, personal computer sales, and PV shipments.

Technology/Energy Option	α	β	R^2
Cumulative oil production (1900-1931 period)*	172.75	-0.0881	~100%
Cumulative oil production (1932-2000 period)*	121.24	-0.0614	~100%
Cumulative oil production (1900-1931 period)**	172.62	-0.0880	~100%
Cumulative oil production (1932-2000 period)**	116.36	-0.0589	~100%
Cumulative natural gas production	141.13	-0.0711	~100%
Cellular Phone industry # of subscribers	799.63	-0.3998	99%
Cumulative PC sales	413.42	-0.2071	~100%
Cumulative PV shipments in the US at 10% cap	363.2004	-0.1783	~100%
Cumulative PV shipments in the US at 15% cap	363.5500	-0.1782	~100%
Cumulative PV shipments in the EU at 10% cap	365.3638	-0.1793	~100%
Cumulative PV shipments in the EU at 15% cap	365.7169	-0.1793	~100%

* A U value of 216 billion bbls is assumed (based on Bartlett (2000) and Laherrère (2000)).
** Based on the maximum reserves estimate of 229 billion bbls (assuming a $30 selling price see USGS, 1995; 1998 and MMS, 1996).

2.3 Forecast of PV Generation: 2000-2070

For the U.S. and EU,[6] we assumed initial PV domestic sales growth to average 20% per year. This is consistent with regression results for the period 1984-2002 for the U.S. and EU domestic PV markets (see Figures 5a and 5b).[7] We also assumed that the contribution of PV to European and U.S. electricity supply would grow until, in each case, it reached a level of 10-15% of total electricity supply.

These assumptions, when applied in a logistic growth model, mean that PV annual domestic sales are expected to be approximately 20% until 2020 or so, at which point slower rates of growth appear and by 2040 single digit increases are projected. As discussed in section 2.4, there are sound empirical reasons to expect such a growth path.

We assumed that annual EU and U.S. electricity generation growth would be 1.1% and 1.8%, respectively, for the period 2001-2020. The rates were chosen be-

[6] For data consistency, only the current 15 members of the European Union (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom) and Norway (a major European oil producer) are included in our analysis. Thus, the abbreviation "EU" hereinafter includes the original 15 members plus Norway.

[7] The slope terms in the regressions in Figure 5a and b can be converted, as follows, to gain the estimated initial annual growth rates in PV domestic generation: $e^{\beta}-1$= annual growth rate. For β=0.1783 (U.S.) and β=0.1793 (EU), initial annual growth in PV generation is approximately 20% for the 1984-2002 period.

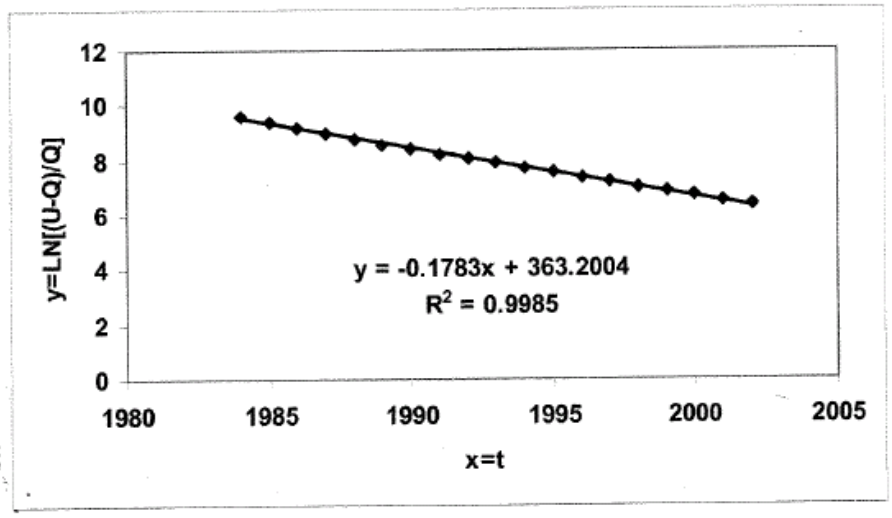

Figure 5a. Regression analysis, using a logistic growth model, for cumulative PV shipments in the U.S. during 1984-2002 (Data source: Maycock, 2002).

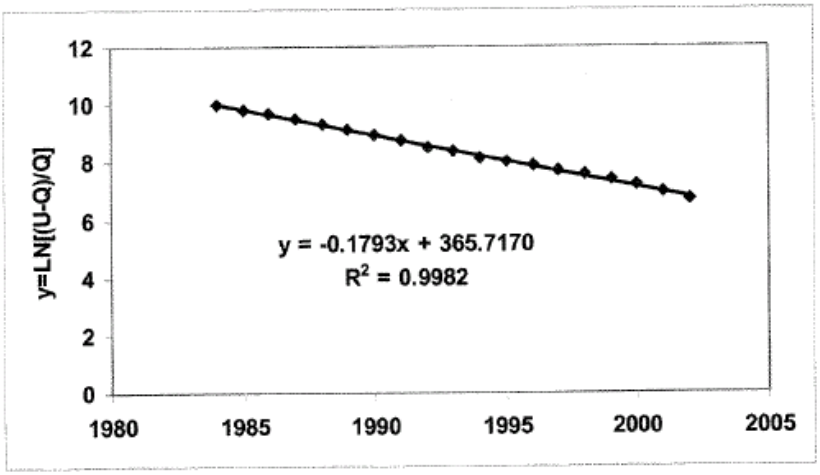

Figure 5b. Regression analysis, using a logistic growth model, for cumulative PV shipments in the EU during 1984-2002 (Data source: Maycock, 2002).

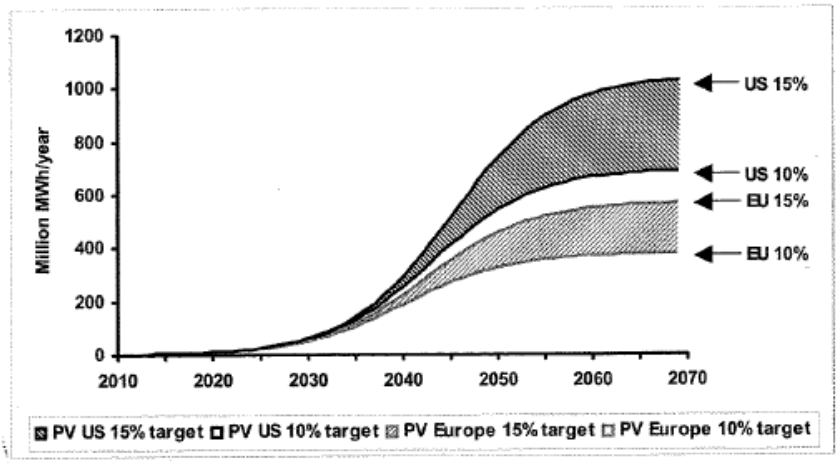

Figure 6. Potential U.S. and European PV supply at 10% and 15% of electricity supply target.

cause they are the ones used by IEA for the EU and EIA for the U.S. (IEA, 2002c and EIA, 2002b). We also assumed that both the EU and U.S. total electricity consumption would stabilize by 2050. Since the demand for PV generation is linked in our forecast to national/regional electricity demand, this has the effect of assuming that electricity demand growth declines gradually from 1.1% (for Europe) and 1.8% (for U.S.) in 2020 to 0% in 2050.[8]

Figure 6 provides our forecast of domestic PV market sales for the EU and U.S. that result from the assumptions described above. We expect PV generation into the EU and U.S. grids to remain quite small until 2025 when the level of output from domestic installations begins to be noticeable. By 2050, we project PV generation to diffuse into the electricity market and to represent a 10 to 15 % share of the generation mixes of both jurisdictions.

Because ours is a long-term forecast (70 years), many uncertainties are associated with the forecast. In the following section, we consider these uncertainties as part of an effort to benchmark our forecast with empirical experience from the energy and silicon-based technology markets. Specifically, we compare our PV forecast with actual diffusion patterns of oil, natural gas, cellular phone and personal computers.

[8] While some may regard a zero growth rate after 2050 to be unrealistic, it is useful to consider that substitutes for conventional grid electric service (including fuel cells and/or "knowledge improvements") may change the electricity services market over the next 50 years. But 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 otherwise lead to *higher* forecasted growth in PV generation demand after 2050.

3. Reasonableness of the Forecasts

The annual compound growth rate for PV shipments from the U.S. and EU companies over the last two decades has averaged 20%.[9] As shown in Table 2, this growth level is not unusual for the range of technologies we examined. While fossil fuels diffused at slower rates, these energy options entered U.S. and European markets early in the 20th century, when modernization was still at an early stage. By contrast, silicon technologies have diffused much more rapidly. Naturally, the economic context of their diffusion is contemporary with PV, but they share additional features with PV of being service oriented and decentralized in their applications. By contrast, the fossil fuels are built on large-scale, manufacturing-focused applications.

Past experience shows that growth rates were quite stable for these diverse energy options and technologies until 1% of saturation levels were reached. At that point, growth rates gradually declined for all comparable cases examined here. Thus, our assumption of an initial annual growth rate of 20% is both statistically (Table 1) and empirically supported by technology and energy market experience (Table 2).

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 group of researchers has suggested that for PV, specifically, it may be upwards of 20% (Perez et al., 1993). According to an EPIA (1996) study, PV on rooftops, without considering other PV applications, can provide more than 17% of electricity supply in the U.S. and 16% in the EU. Thus, our 10-15% cap is in the lower range of research projections and technical limits.

A 2050 peak for growth in PV installations in European and U.S. markets, as well as an assumption that, after 2050, growth is limited to replacement demand, are likewise conservative. Both anticipate slow market maturity for the technology when silicon-based technologies have tended to grow more rapidly than these assumptions allow (see Table 2). Studies of the diffusion of new energy technologies suggest that higher growth and market share could be assumed than we have in our analysis (e.g., Payne et al., 2001).

The reasonableness of our PV forecast can be additionally established by comparing historical experience of energy options and silicon technologies with our projection of growth in PV demand at strategic points in the logistic growth pathway. The early phase of logistic growth can be divided into two key segments–the growth pattern as an option reaches 1% of saturation and the growth pattern as it reaches 10% of saturation. Indicators in units of time and percent growth for both saturation levels are reported in Table 2 in order to establish a basis for comparison. An inspection of these data reveals our PV forecast anticipates conservative to mid-range performance for both segments of early logistic growth.

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[9] The National Center for Photovoltaics of the U.S. Department of Energy's National Renewable Energy Laboratory uses a 15-25% range of annual growth for its American PV "roadmap."

Table 2. Market growth rates for different technologies.

Technology	Number of years for reaching 1% of saturation level	Annual growth rate	Number of years for reaching 10% of saturation level from the 1% level	Annual growth rate	Number of years for reaching 90% of saturation level from the 10% level
Cumulative U.S. oil production	50	9%	30	6%	~70
Cumulative U.S. natural gas production	40	8%	35	7%	~60
Cellular Phone industry # of subscribers	4	49%	6	43%	11
Cumulative PC sales	2	160%	4	21%	21
PV US* at 10% electricity cap	34	20%	13	18%	24
PV US* at 15% electricity cap	36	20%	13	18%	24
PV EU** at 10% electricity cap	31	20%	13	18%	24
PV EU** at 15% electricity cap	33	20%	13	18-20%	24

* 1% of saturation to be reached in 2018-2020, and 10% in 2031-2033

**1% of saturation to be reached in 2015-2017 and 10% in 2028-2030

PV is projected to take 30-35 years to reach 1% of saturation, a time interval consistent with the fossil fuels and significantly longer than the experience of silicon technologies such as the cellular phone and the PC. The rate of annual market growth for PV during this early period of development in our model (20%) is well below the empirically experienced range of the silicon options.

In the second segment of logistic growth, we project PV to take an additional 13 years to reach 10% of saturation, well within the 5-35 year range of the selected cases reported in Table 2. The decline in annual market growth during this period to 18% is consistent with the declines in growth experienced by oil and natural gas. Likewise, silicon technologies have experienced declines in the early phases of their diffusion. But it is notable that the projected growth for PV is quite a bit lower than its silicon-based counterparts and is only modestly faster than its energy competitors. As to the latter, it is important to consider that we have capped demand for PV-based generation at 10-15% of national/regional electricity demand and, further, we have assumed that national/regional electricity demand will reach an *absolute* peak in 2050. Both assumptions mean that PV is assumed *not* to realize annual energy demand levels as substantial as the fossil fuels. This can explain the difference in growth rates to some degree: PV is being forecasted to approach a comparatively small demand level, while oil and natural gas grew to reach a much larger eventual value. In this

instance, it is not unreasonable for PV to be projected to experience more rapid early growth than the fossil fuels as it realizes a moderate level of energy demand.

A third method for assessing the reasonableness of our PV forecast is to compare it to the projections of other researchers. While the amount of research on this topic is limited, we were able to identify forecasts by organizations whose work is typically regarded as credible in the energy field. These include for the U.S., the National Renewable Energy Laboratory's National Center for Photovoltaics (NCPV), Tellus Institute and Brookhaven National Laboratory; for Europe, we relied on forecasts from the EU Energy Commission and consultants to that commission. Because these forecasts reported their projections in units of installed capacity, we converted our PV generation forecast into capacity units, using an average capacity factor of 18.5% for the U.S. and 16% for the EU (see Wenger et al., 1996 and Sinke, 2001 for support for our assumed capacity factors). Tables 3 and 4 summarize the results.

Clearly, our projected capacity additions are well within those of similar assessments by other reputable researchers for the initial 20 to 30 years of the forecast period. We were not able to find another rigorous long-term forecast of the length of our analysis in the research literature, except a study conducted by the International Institute for Applied Systems Analysis (IIASA) (Christiansson, 1995). That effort forecasts PV generation at the end of this century at 1,800 TWh for North America and at 1,293 TWh for Europe. Our forecast, for comparison, is between 694-1,042 TWh for the U.S and between 380-571 TWh for Europe. Supportive evidence of our shorter term forecast of PV-based electricity generation is found in the U.S. EIA's recent projection of distributed generation, which anticipates electricity from PV in the U.S. ranging from 1.0 to 7.0 billion kWh in 2010 (its reference case) and 2.0-16 billion kWh in 2020 (assuming a 40% tax credit for PV and advanced technological improvements-see EIA, 2000). In our own model, PV is forecasted to produce 1.7 billion kWh in 2010 and 10.3 billion kWh in 2020. Thus again, our forecast appears to be conservative.

4. Current and Competitive PV Prices

Because electricity generation via PV for grid service (i.e., the supply of kWhs to an electric grid) is currently expensive compared to thermal power plants, a projection such as that in Figure 6 may be judged by some to be unrealistic. Unless PV generation costs decline dramatically, skeptics might argue that the technology will continue to be uncompetitive and unable to realize even the modest amount forecasted by us. To address this issue, we consider evidence regarding the time frame in which PV is likely to reach its break-even price, such evidence speaks directly to the question of when PV can compete favorably in the energy market. We also consider the volume of PV domestic sales necessary to realize a break-even price and compare it to our forecast levels in order to evaluate our projection by this key economic criterion. We address both questions using experience curve analysis.

Table 3. Forecasted Installed Photovoltaic Capacity in U.S. (In GW_p).

	2010	2020	2025	2030
Our Forecast	1.0	6.4	15.5	36.8 – 37.9
NCPV Roadmap		15.0		
Tellus Institute – 5%	1.7			
Brookhaven National Laboratory	1.2	11.9	36.6	111.9

Table 4. Forecasted installed Photovoltaic Capacity in Europe (In GW_p).

	2010	2020	2030
Our Forecast	1.2	7.1	38.8 - 40.8
EC 1997 White Paper	3.0		
EurObserv'ER 2003, PV Barometer	1.4		
EPIA & Greenpeace	2.8	54.0	
Jäger-Waldau, "PV Status Report 2003"	3.0	15.0	30.0

Experience curve analysis is often used to evaluate market entry issues related to new technologies. In essence, the price of a new technology (or its services) is conceived to be an inverse function of production and application experience. As makers of the technology learn about factors that affect production and use, adjustments are made which improve efficiency in both dimensions and enable production and application volumes to be increased. Unit costs decline over time and applications are discovered at these lower costs that widen the market, thereby reinforcing trends toward lower prices and/or higher market value (see, e.g., Mansfield, 1993; IEA, 2000).

Experience curves can be described by the following equation:

$$\text{Price at year } t = P_0 * X^E \qquad \text{(Eq. 6)}$$

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 sets the rate of change in the price-production relationship of the experience curve).

The experience index can be derived from what is termed a "progress ratio" (PR) (or vice versa) given that $PR = 2^E$ (IEA, 2000). With a reasonable value for E established (see below), 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 options.

The average selling price for modules at which PV should become competitive has been extensively 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; Zwann and Rabl, 2003). 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 estimated (assuming a break-even price of \$1.50/W_p). With a PR of 80%, the resulting break-even level of cumulative worldwide shipments is about 22,000 MW_p (Byrne et al., 2004). U.S. and European sales are expected by our forecast (see Figure 6) to reach 22 GW before 2025. Thus it would appear that the forecast in Figure 6 is easily achievable at a break-even price of \$1.50/W_p. These results are not far from those of other researchers. For example Poponi (2003), who uses a PV *system* break-even price of \$3.20/W_p and market growth rates[10] of 15-30% anticipates the break-even year to occur between 2011 and 2017. And EIA (2000) expects that PV prices will reach a break-even price of \$3.00 per Wp between 2010 and 2014.

But there is also a broader issue at stake, namely, whether PV is properly conceived as a fuel/technology substitute *within* the existing energy system; or whether PV is to be forecasted as an option that could significantly alter the architecture and function of future energy systems. If it is the former, then PV's price should be compared to existing energy prices. In this case, the current cost of \$0.30 per kWh of PV-generated electricity compares unfavorably to the \$0.03-\$0.05 per kWh for power from natural gas or coal fired plants (Gross et al., 2002).[11] The break-even price for the above analysis would be approximately \$0.10 per kWh, still twice that of thermal plants. While it is plausible that PV could find competitive opportunities in special grid service applications equivalent to the GWs forecast in Figure 6, realizing such a scale would be difficult and, in this instance, there would be grounds for skepticism.

However, if PV is instead regarded as a new type of service technology intended to facilitate the transition to a decentralized energy architecture, the above approach is ill-conceived. In this case, PV can be considered to compete in several markets. For example, PV can be used as a source of on-site generation with its output wholly or partly consumed by its owner. Where net metering is allowed,[12] PV costs should be compared to retail electricity prices (with an adjustment for avoided transmission and distribution (T&D) losses). Under this scenario, PV systems that sell for \$3.00/Wp (i.e., module prices of \$1.50/W_p) would be competitive in several U.S. and European markets (notably, Germany, Italy, California and New York). No longer a technology

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[10] Typically, the PV component of an installed system (which additionally includes an inverter, power conditioning, a small amount of buffer storage, and wiring and array structure) represents 50% of system cost. Thus, for comparison to our module cost of \$1.50 W_p, Poponi's system cost is the equivalent of \$1.60 W_p for PV modules.

[11] This does not include the health and environmental costs of fossil fuel use. When these are taken into account, some argue that electricity from fossil fuel-fired plants is more expensive than PV (e.g., Hohmeyer, 1992)

[12] Currently, 36 states within U.S. require utilities to purchase generation surpluses from PV and other qualified renewable energy (UCS, 2003)

for specialized markets, PV would be economical as an option for retail electricity markets. Of course, the possibility of competing in retail markets depends upon policy interventions that require open access to customers. Further, it would be important that PV is properly credited for the benefits of avoided T&D losses that its use would create.

PV can also provide a range of services that large power plants cannot. These include: peak-shaving and load control (what has elsewhere been termed "energy management"–see Byrne et al., 1996; 1997; 1998 and 2000), emergency/back-up power (Byrne et al., 1996; 1997; 1998) T&D decongestion (see Letendre et al, 1996), environmental improvements (e.g., reducing pollution that leads to urban smog and acid rain, and mitigating carbon emissions that are associated with climate change) and fuel diversity (see, especially, Awerbuch, 1995). When the values of these services are incorporated, PV can compete in *new* markets not served (or only partly served) by the current energy system. In particular, these services coincide with the shift to a decentralized energy system in which the economics of modularity (Hoff and Herig, 1997; and Dunn 2000) replaces the traditional scale–based economies of fossil and nuclear fuels (Messing et al, 1979; Hunt and Shuttleworth, 1996) in guiding technology and market development of the energy sector. Again, policy frameworks are needed that enable social and market institutions to accurately evaluate these benefits.

In this respect, PV's future may be only partly gauged by cost and price comparisons with the existing energy system. A wider consideration of PV applications may be required to realize an accurate portrait of its potential. Furthermore, the role of policy in creating conditions for fair and full competition would need to be addressed.[13] If a broader approach is granted, then we are confident that our PV forecast for the U.S. and Europe is reasonable.

5. Forecasting Oil Production

Oil production forecasts for Europe and the U.S. are regularly prepared by government and independent research sources. We relied on forecasts from IEA country reports (2001, 2002a, 2002b) for Europe[14] through 2010 and on an EIA (2002b) forecast to 2010 for the U.S. For further projections to 2070, a logistic growth function

[13] The role of policy in shaping PV's future is discussed in detail in section 7 of this chapter.

[14] 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, prepared by the USGS, was added.

was applied to USGS (2000) estimates of remaining and "undiscovered" but economically recoverable oil reserves in the U.S. and Europe.[15] This method assumes that after maturation of known and expected (so-called "undiscovered") production areas, and long after passing peak production levels (1970 for U.S. and around 2000 for Europe–see below), annual oil production will decline exponentially.

Our approach follows the methodology pioneered by M.K. Hubbert (1962), whose well-known forecast for Shell Oil has proved to be quite accurate. It is also consistent with the methodological refinements developed by Laherrère (2000), a contemporary of Hubbert. To derive annual declining rates, production levels for the beginning of the forecast period (P) and potential remaining oil reserves (S) at that time are utilized. Potential remaining oil reserves (including "undiscovered" deposits) during the 2010-2070 forecast period are calculated by the following formula:

$$S=(R+X)-(H+F) \qquad \text{(Eq. 7)}$$

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 1995 to 2001
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:

$$r=P/S \qquad \text{(Eq. 8)}$$

The proof is as follows:

$$P/(1+r)+P/(1+r)^2+ P/(1+r)^3+\ldots=S \qquad \text{(Eq. 9)}$$

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

$$P/(1+r)^2+ P/(1+r)^3+ P/(1+r)^4\ldots=S/(1+r) \qquad \text{(Eq. 10)}$$

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[15] The term "undiscovered" is used by the USGS to capture new on-shore oil findings that are not now known. It is predicated on experience throughout the 20th century in which new oil reserves were frequently found, even in extensively explored areas. In addition, it includes oil that could be found as a result of technology improvements. The concept is not without controversy and some researchers believe that it is being incorrectly used in current forecasts (Bentley, 2002). The USGS then divides its "undiscovered" oil estimates into "economically recoverable" and "uneconomical" deposits. The same method is adopted by MMS for the off-shore case. Our oil forecast includes on- and off-shore, economically recoverable "undiscovered" deposits, as well as the remaining oil in already known on- and off-shore reserves.

Subtracting (10) from (9) gives:

$$P/(1+r)=S-S/(1+r) \quad \text{(Eq. 11)}$$

Multiplying both sides by (1+r) gives:

$$S+S*r-S=P \quad \text{(Eq. 12)}$$

After canceling S terms and dividing both sides by S, equation (8) results.

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

Domestic oil production is expected to decline in the U.S. and Europe. IEA (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 to decline. While undiscovered oil deposits are anticipated in both regions,[16] these will not be sufficient to reverse the decline in domestic oil production in either region. The controversial category of reserve growth was not included in our analysis.[17]

If we consider the projected energy production value of all current oilfields and potential, but as yet undiscovered, oil production areas, and fit a logistic curve to link them to 2010 IEA/EIA forecasts, we can find a plausible pathway for domestic oil supply through 2070.[18] Using the methodology described above, production forecasts were made for U.S. and Europe (Figures 7 and 8). By 2055 and by 2070, respectively, Europe and the U.S. are projected to have fully depleted their domestic reserves. Thus, from the perspective of domestic production, the oil era will have concluded by 2070 for both jurisdictions.

6. Comparison of the Energy Values of Future Oil Production and PV Systems

Forecasted energy generation from PV is converted into barrels of oil equivalent to facilitate the comparison of energy from PV with the oil production forecasts developed above. For our conversion, we made the following assumptions: a 30-year lifetime for PV systems; and 1 peak Watt of PV generates an average of 1.6 kWh[19] of electricity annually in the U.S. and 1.4 kWh in Europe (taking into account avoided

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16 USGS (2000) believes that 19.6 billion bbls of oil are still to be found in Europe and USGS (1998) and MMS (1996) believes that 37.4 billion bbls can be economically recovered at $30 per bbl in the U.S. from this category.

17 Because this category of oil additions is disputed by many in the forecast community (Laherrère, 1999; Bentley 2002), we decided to exclude it from our analysis.

18 Of course, forecasting future oil production is a risky analytical enterprise that, understandably, can yield widely varying estimates.

19 According to Wenger et al., 1996, the capacity factor for U.S. is 17-20%, with a mid-point of 18.5%. According to Sinke (2001), for Europe the capacity factor is 8-24%, with a mid-point of 16%. These capacity factors yield 1.6 kWh and 1.4 kWh of annual generation per 1 Wp of installed PV, respectively for the U.S. and EU.

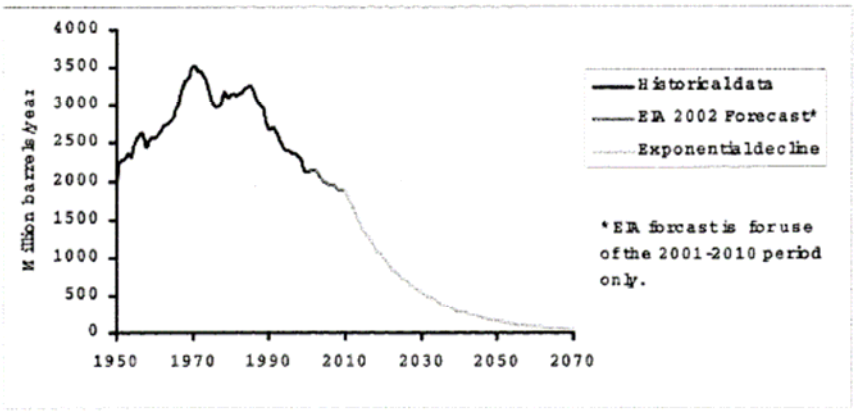

Figure 7. Historical and forecasted U.S. oil production (Data sources: EIA 2002a, EIA 2002b, USGS 2000).

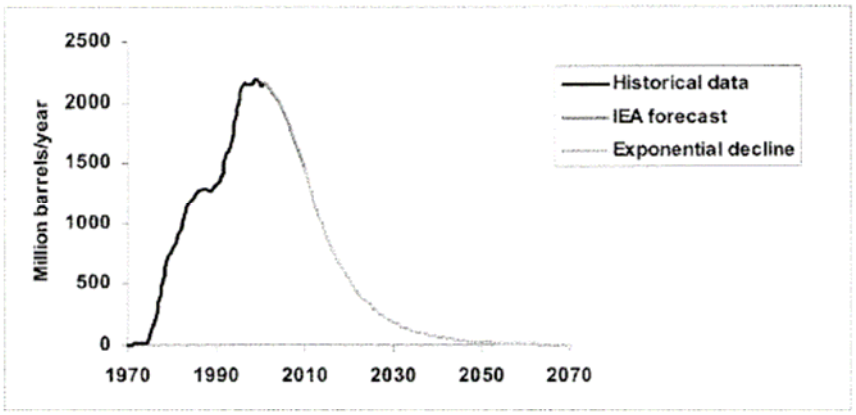

Figure 8. Historical and forecasted European oil production (Data sources: IEA 2001, IEA 2002a, IEA 2002b, USGS 2000).

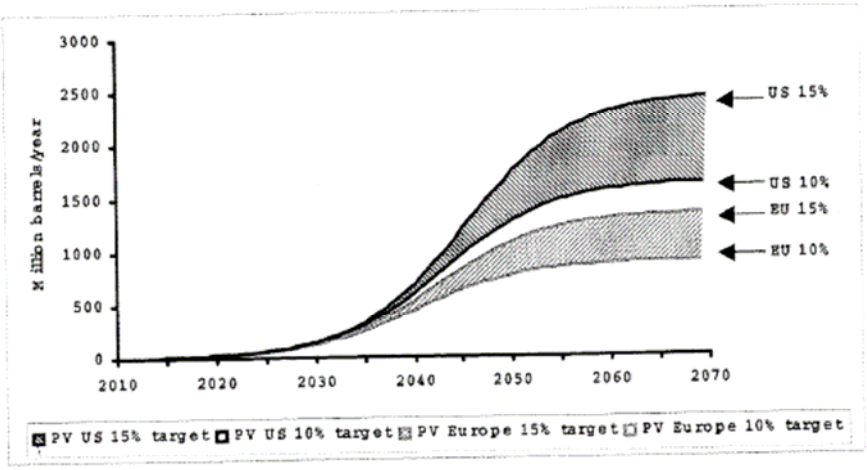

Figure 9. Potential U.S. and European PV supply at 10% and 15% of electricity supply target expressed in barrels of oil.

T&D losses). According to the Society of Petroleum Engineers (SPE, 1984) 1 barrel (bbl) of crude oil = 6.12×10^9 J. Using 1 kWh = 3.6 10^6 J and taking into account a typical efficiency of an internal combustion engine of approximately 25%,[20] 1 bbl of crude oil is equivalent to 425 kWh of electricity. Our PV forecast, converted to oil equivalent, is presented in Figure 9.[21]

By our calculations, U.S. cumulative domestic oil production for the period 2010-2070 could amount to 30.3 billion barrels.[22] PV energy supply in oil equivalent is forecasted to be between 45.0 and 62.2 billion barrels. Thus, the contribution of PV to U.S. energy supply for 2010-2070 is likely to be 1.5 to 2.0 times that from domestic oil (Figure 10). 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 between 27.5 and 38.2 billion barrels. Thus, the contribution of PV to European energy supply for 2010-2070 would be at least twice that from domestic oil (Figure 11).

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20 Typical energy efficiency for internal combustion engines under test conditions ranges from 20% to 40%, with the higher end for diesel engines (Plint and Martyr, 1995). Under real operating conditions, depending on the type of engine, efficiency can range from 15% to 30% (Lumley, 1999). Consequently, an efficiency of 25% was assumed for the current research. ICC technology was selected for this conversion because the principal use of oil in the U.S. and EU is to power vehicles and stationary engines.

21 Figure 9 is identical to Figure 6, except for the energy unit used to map PV market development.

22 This estimate assumes the higher U value of 229 billion bbls–see section 5 above.

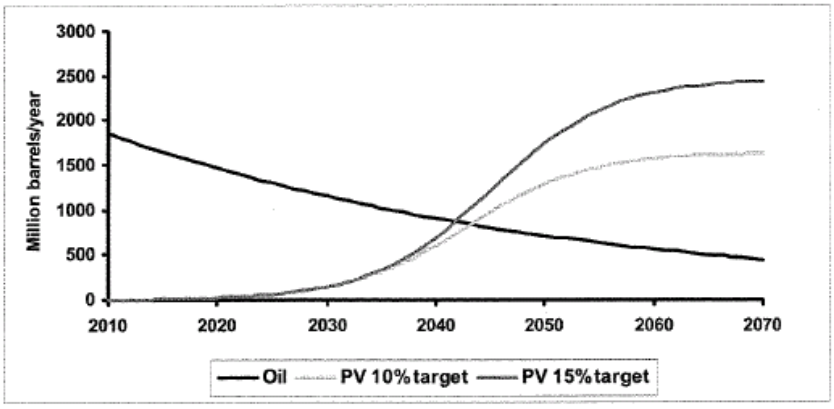

Figure 10. Comparison of forecasts of U.S. PV energy supply and U.S. oil production from existing domestic reserves.

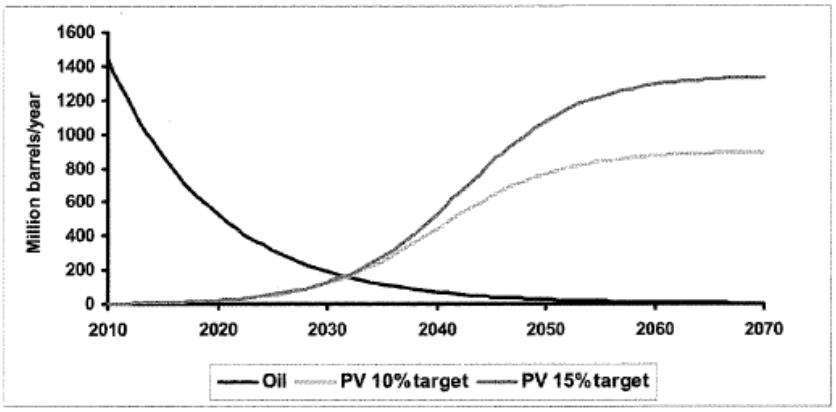

Figure 11. Comparison of forecasts of European PV energy supply and European oil production from domestic reserves.

7. The Role of Policy in PV's Future

Of course, even if our PV forecast is thought to be plausible, there remains an important objection to our analysis. Specifically, some might challenge the comparison itself, arguing that PV would compete in electricity markets, while oil is largely used for transport. In essence, the analysis we have offered might 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,[23] the ability of both sources to serve markets will be significantly dependent on national and international policy. Oil's status as an essential energy source for industrialized society comes 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-focused 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 current 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. Not only the changing economics of energy markets, but the highly important role of energy policy suggest that the comparison is warranted. That said, we now turn our attention to a discussion of energy policy in Europe and the U.S. in order to consider the sorts of tools that might be used to promote PV investment and uses. In this way, it is possible to consider if an operational policy path is emerging that, in effect, might "realize" our forecast.

7.1 Leveling the Playing Field

Historically, national and regional policies have greatly influenced energy development. The creation of state monopolies to shelter fossil fuels, hydropower, nuclear energy and electricity development, the use of infrastructure subsides to pay for pipe-

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[23] 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 could see direct competition between these sources.

lines, ports and T&D systems, and the authorization of a wide range of preferential tax treatments to favor investment in and consumption of selected energy sources and technologies are examples of how policies have shaped the current energy system. Globally, policy support for fossil fuels, hydropower and nuclear energy is estimated to total more than $240 billion annually (van Beers and de Moors, 2001), creating an obvious market advantage for the energy *status quo*.

While fossil fuels and, especially, oil receive disproportionate energy policy attention in Europe and the U.S. and garner the bulk of the yearly world energy subsidy of $240 billion, there is evidence that renewable energy is beginning to attract modest policy support. Below we describe the evolving policy contexts in both jurisdictions with respect to renewable energy generally and PV specifically. Policy will likely prove to be critical to PV's long-term market development. This is because energy market distortions of the magnitude that now exist can only be overcome by policy action.

But equally important, PV promises basic change in the nature and type of energy services available in a society (see above) and it promises to change the political and economic character of energy production and consumption. The environmentally unsustainable and socially inequitable features of the present system, as well as the "abundant energy" ideology that has justified it (Byrne and Rich, 1986) are all challenged by PV, which is environment-enhancing and inherently decentralized, thereby offering opportunities for democratic management of energy systems (Lovins, 1977; Byrne and Rich, 1992;Flavin, 1994). Even ardent advocates of the fossil fuel era have recognized that oil, natural gas and coal systems tend to be technocratic and centralized in character (Burton, 1980).

7.2 U.S. PV Policy

A variety of policies have been and will be important to the growth of PV use in the U.S. Besides net-metering (which has been adopted by 36 U.S. states), interconnection standards, tax credits, renewable portfolio standards and public benefit charges have been key to market development for PV in the U.S.

Interconnection remains a barrier to PV use in the U.S. because no national standard exists and requirements among utilities are diverse and inconsistent. The lack of a uniform standard is a burden for PV installers and creates additional transaction costs, increasing the overall cost of a PV system (Beck and Martinot, 2004). Adoption of a national standard would appear to be essential for long-term development of PV.

The federal energy investment tax credit, a product of the 1992 Energy Policy Act, provides a 10% tax subsidy to companies that purchase certain renewable energy systems including PV (DSIRE, 2003). The tax credit has been a significant incentive for installing PV systems. However, a limitation is that it only benefits companies with appropriate tax liability. Making the tax credit both tradable and available to all parties would create a wider incentive for the use of PV.

The policy mechanism providing the greatest potential for future growth of installed PV capacity in the U.S. is the Renewable Energy Portfolio Standard (RPS). An RPS requires that a certain percentage of all electricity generated in a jurisdiction is provided from qualified renewable sources of energy (typically, solar thermal and electric, wind, some forms of biomass, and geothermal). Sixteen states have adopted renewable portfolio standards, which will result in 14 GW of new renewables by 2012. But to date, a national RPS has not been passed (UCS, 2003).

Recently, two bills on a national RPS appeared in the U.S. Senate and one in the U.S. House. Senator Jim Jeffords' Renewable Energy and Energy Efficiency Investment Act called for renewable resources to account for 20% of U.S. electricity supply by 2020, while Senators Tom Daschle and Jeff Bingaman's Energy Policy Act included an RPS of 10% by 2020. Congressman Mo Udall's H.R. 1294 included an RPS of 20% by 2025. A national study conducted by Tellus Institute concluded that an RPS would have a significant impact on the growth of PV capacity in the U.S. Using the National Energy Modeling System (NEMS) created by the U.S. Energy Information administration, Tellus found that 5% of renewables needed to reach a national RPS of 10% by 2010 would come from solar (Bernow et al., 1997).

Another key policy tool widely used in the U.S. is the public benefit charge (PBC), which assesses a small fee per kWh sold by utilities (usually $0.001-$0.003 per kWh). Accrued funds from PBCs are then auctioned in a competitive bidding process to companies and non-profit organizations for the promotion of energy efficiency and renewable energy projects. Thirty-one states currently employ these charges and 14 have specific set asides, for renewable energy development. Through 2012, these 14 states are obliged to spend at least $4.3 billion for PV, wind and other qualifying renewables (see UCS, 2003).

To ensure that PV is able to enter and transform the U.S. energy market, national RPS and PBC policies, interconnection standards and investment tax credits are probably needed. States have already taken the lead in this effort to ensure both diversity and success in their energy policies. Realization of our U.S. PV forecast would undoubtedly be significantly advanced if such a policy paradigm were adopted at the national level.

7.3 European PV policy

The European Commission's 1997 White Paper called for a doubling of renewables in EU energy consumption, from 6 percent in 1997 to 12 percent by 2010. A 2001 directive called for 22.1 percent of electricity to be derived from renewables, also by 2010 (European Parliament, 2001). For photovoltaic applications, the specific target is 3 GW of installed capacity (which is a little less than 1% of current EU generation capacity) (European Commission, 1997 and 2003).

The EU has pursued its expressed goals for PV development through a number of measures, including the "Campaign for Take-Off" that set targets for the installation of 650 MWp of PV capacity in domestic markets by 2003 (EurObserv'ER, 2001).

Building on partnerships with industry, associations and public officials, the EU has also supported scientific research and demonstration projects in order to increase PV's technological competitiveness and market penetration. To better coordinate research and technology development among countries in the region, the European Commission in partnership with national government agencies and research organizations has established the "PV-EC-NET" project (PV-EC-NET, 2003).

These policies reflect growing momentum due to Europe-wide public support for the technology. Such support has resulted in impressive recent gains for PV. Thus, by the end of 2002, member states' installed PV capacity reached 392 MWp, more than doubling the EU's total of 188 MWp in 2000 (EPIA, 2002). However, of that total capacity, some 278 MWp were installed in Germany. This uneven installation pattern among member states demonstrates how Europe's overall success in PV development can largely be traced to particular policies, tied to specific and long-running support, at national levels.

Germany is the undisputed leader in European PV development. German support for PV has been operationalized through tax incentives and low investment loans, as well as a net metering program that rewards developers with sizable feed-in tariffs, recently equal to approximately $0.60 per kWh (Sijm, 2002). The country's "1,000 Roofs Program" started in 1991 to subsidize PV-electricity generation costs (IEA, 1998). The program's 1999 follow-up, the "100,000 Rooftops Solar Electricity Program," called for the installation of 300 MWp through low-interest loans for solar energy equipment (IEA, 2002d). The country is on track to meet its target (European Commission, 2003: 53). At the same time, the Renewable Energy Sources Act, passed in 2000, altered PV feed-in tariffs to include percentage reductions over time (IEA-PVPS, 2003). However, PV development should remain strong in Germany, as the Federal Environment Ministry and the Federal Ministry of Economics have agreed to provide additional payments (beyond basic feed-in tariffs) for PV systems installed on buildings and facades. These measures are specifically designed to "compensate for the expiry of the successful 100,000 roofs solar electricity program," which ended in June 2003 (Federal Environment Ministry, 2003).

The Netherlands, Italy, Spain, and France are also using feed-in tariffs and additional measures to stimulate investor interest in PV electricity generation (de Vries et al., 2003; ENER-IURE 2002a and 2002b). However, many of these programs are relatively new, having been implemented only in the last two to three years. For example, Italy's version of a solar PV rooftop program, adopted in 2001, provides investment subsidies to support the installation of 10,000 mainly small-scale PV units (EurObserv'ER, 2003 and European Union, 2001).

Goals and projections for installed PV capacity in Europe, while somewhat different in their results, point to continued and sometimes very significant growth in coming decades. In its April 2003 report, the EurObserv'ER Photovoltaic Barometer cautions that future growth in installed PV capacity in the EU remains "very much centered on Germany" (EurObserv'ER, 2003). Because the long-term contributions of policies in France, Italy, and Spain remain uncertain, the Barometer suggests that EU installed

capacity may only reach 1,400 MW in 2010. By contrast, the European Photovoltaic Industry Association (EPIA), in a joint effort with Greenpeace, has projected annual growth rates of 27 percent until 2009 and 34 percent between 2010 and 2020. Their scenario holds that PV can supply 10 percent of Europe's electricity needs in 2020 (EPIA, 2001). But a European Commission report on global prospects for PV offers that the EPIA-Greenpeace target is overly ambitious, as it would require an estimated 54 GW of installed solar electrical capacity in the EU by 2020. Building on the 1997 White Paper's target of 3 GW installed capacity by 2010 with a growth scenario of 17 percent per year, Jäger-Waldau (leading author of the updated study) provides a more cautious projection of 15 GW of installed capacity in 2020 (Jäger-Waldau, 2003). Even so, this is twice the level that our forecast expected for 2020 (see Table 4). Thus, slower growth than the optimistic EPIA-Greenpeace scenario could nevertheless lead to PV playing a greater role in Europe's energy future than the region's oil reserves.

The diversity of targets in Europe suggests the need for robust implementation of existing policies in member states, as well as a need to increase policy support beyond Germany in order for the region to make use of the option. In particular, a regional Renewable Energy Portfolio Standard (RPS) implemented at the EU level would seem to be a worthwhile policy option. Under this framework, targets would be allocated among different types of renewable energy technologies, including PV, in order to ensure their market development and penetration while also encouraging "cost-reducing innovations" and a "genuine EU-wide level playing field" among renewable electricity producers (Jansen, 2003). Greater parity in installed capacity throughout the region could help the PV sector become less vulnerable to changes in particular markets and assume a stronger role in EU-wide electricity generation.

8. From Forecast to Policy

Energy debates are usually dominated by issues of technology and markets. This reflects an implied belief that incremental change will characterize the future. But energy change often is dramatic and sudden (e.g., MacKenzie, 1997). Moreover, energy choices can be highly affected by policy decisions. It is wise, therefore to evaluate policy alternatives that do not assume the energy *status quo,* in order to understand the true magnitude of policy choices that are 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 1.5 to 2.0 times that of all U.S. domestic oil reserves. For Europe, the role may be even greater, possibly more than twice as much as the region's domestic oil reserves.

These findings highlight the disjuncture between energy potential and energy policy in our current situation. Indeed, energy policy in both the EU and the U.S. assumes that oil will be a major source for reliably and economically meeting social needs well into the future, while PV is presently regarded in policies of the two jurisdictions as

something between an R&D project and a niche technology to fulfill specialized needs. Recent policies have taken tentative steps to broaden the role of PV in the energy systems of the two areas. But more will be needed to overcome the disjuncture between potential and existing market development.

While we are confident that the future will prove PV's skeptics to be wrong, we are nevertheless concerned that the chasm between the potential and current policy unnecessarily hinders the ability of the EU and the U.S. to move forward. In this regard, we worry that many technologists, economists and policy makers still seek an understanding of our energy future by an investigation of its past. Forecast and policy offer tools to avoid the error in this way of thinking. Through both, we can depict where we have been and also how we might arrive at a different destination, if we are willing to act beyond the limits of the *status quo*. All energy transformations, as far as we can tell, occurred when societies were able to do precisely this.

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