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The potential of solar electric power for meeting future US energy needs: a comparison of projections of solar electric energy generation and Arctic National Wildlife Refuge oil production

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Abstract

This paper compares the potential contribution of solar electric power in the form of photovoltaics to meet future US energy demand with the projected volume of oil estimated to be available in the Arctic National Wildlife Refuge. Such a comparison has practical value since it directly addresses a key policy choice under consideration in the new century, namely, that between one of the most promising untapped oil deposits in the world and one of the most rapidly growing renewable energy options.

Keywords: Solar energy forecasting; Energy futures analysis; PV-ANWR comparison

Direct comparison of Arctic National Wildlife Refuge (ANWR) oil production and potential photovoltaics (PV) output (during the 70-year expected pumping lifetime of the ANWR deposit) has been neglected in the recent US 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 current 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] ANWR production scenarios are based on published forecasts by the US Geological Service (or USGS, 1998) and the US Energy Information Administration (or EIA, 2000). After reporting the results of this comparison, PV-based energy supply is more broadly considered in relation to future energy supply from known US oil reserves as a means of gauging this technology's relevance to the country's energy future.

1. Observed trends in US installed PV capacity and PV shipments

PV shipments from the US between 1986 and 2001 grew exponentially at an average annual rate of 20% (EIA, 2001a). Market growth in the most recent years has been accelerating, with the average rate for 1998–2001 being 28%. Although most PV modules manufactured in the US are sold in overseas markets, growth in installed PV capacity has been robust and mirrors rates for shipments. Many forecasts suggest that both PV shipments (including exports) and PV additions to installed capacity in the US will continue to grow exponentially for decades (e.g., NCPV, 2001; NREL, 2001). However, it is clear that the pattern of exponential growth will eventually be replaced by slower rates of increase brought on by market saturation. At that point, growth rates will decline and then reach a constant rate of replacement growth.

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[1] The appendix describes the forecasting model used to depict future additions of PV installed capacity. It should be noted that the Pearl-Reed curve adopted in the model is mathematically identical to the more widely cited Fisher-Pry form (for Fisher-Pry, see Fisher-Pry (1971); for the proof of their equivalence, see Mignogna, 2001).

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2. Forecasting US PV capacity additions from 2000 to 2050

A forecast of installed PV capacity in the US between 2001 and 2050 was developed using a logistic growth model (discussed in the appendix). Key assumptions include: (1) PV's contribution to US electricity supply will reach a maximum of 10% by 2050; (2) Growth in US electricity supply will stabilize by 2050; and (3) Capacity additions after that year will represent replacement demand only.[2] The assumption of a 10% limit on PV's contribution to future US 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% cap on PV-generated electricity is in the lower range of research projections. The assumption of a 2050 peak for PV generation share and thereafter that PV manufacturing for the US market is limited to replacement demand are likewise conservative. Together they anticipate slow market maturity for the technology when energy and silicon-based technologies have tended to grow more rapidly and take longer to peak than these assumptions allow (see Section 3 for details).

Two scenarios were developed based on these assumptions. In a 'rapid growth' scenario, the initial growth rate for US capacity additions is assumed to begin at 30%, and then decline to zero in 2050, when electricity generated from PV would amount to 10% of total electricity generation.[3] In a 'moderate growth' scenario, the initial growth rate was set at 20% and declines until 2050, when electricity generation from PV would provide 10% of national electricity supply.

US electricity demand is projected by EIA (2001b) to increase at an annual rate of 1.8% from 2000 to 2020. After 2020, we assumed that energy demand growth would gradually decline to zero by 2050.[4] Forecasted energy generation from PV was converted to barrels of oil equivalent to facilitate comparison with ANWR production estimates.[5] Potential oil production from ANWR was taken from the USGS median case (1998) at a market price of $20/bbl, according to which this oil field is expected to produce 3.2 billion bbl over its 65-year production life. In addition, the EIA 'optimistic case' of the US was used which estimates that at $20/bbl, approximately 7.2 billion bbl is economically recoverable (EIA, 2000). Then, applying the methodology from EIA's forecast for yearly ANWR production (2000) to both the EIA and USGS scenarios, peak output from the deposit is expected by 2034 and would average 120 million bbl per year in the USGS case and 270 million bbl per year under the EIA scenario.

Fig. 1 depicts the two PV and ANWR oil scenarios. Based on differences in initial assumed growth, production from PV in 2034 ranges from 480 million to 1130 million bbl. Thus, even in the moderate initial growth case of 20%, PV can be anticipated to supply 1.5–4.0 times more energy than ANWR by the latter's peak production year.

Cumulative energy supply from PV capacity in the US is expected to be 44.3 billion bbl by 2070 under our moderate growth scenario and 58.8 billion bbl under our rapid growth alternative. In the same period, the ANWR field will yield a cumulative output of 3.2–7.2 billion bbls, considerably below that from PV.

If we consider the projected energy production value of all current US oilfields and then add ANWR production, PV's domestic contribution can be placed in clearer perspective. Forecasting future US oil production is a risky analytical enterprise that, understandably, can yield widely varying estimates. For example, Laherrere (2000), using Hubbert's (1962) new classic methodology, projects a rapid decline in output from the lower 48 states and Alaska (see Fig. 2). By contrast, EIA (2000) forecasts declining US oil production for 2001–2020, but at a much slower pace.

Relying on a USGS (2000) report used by the EIA to prepare its 2001–2020 forecast, we completed the forecast for the same period as Laherrere's (again, see Fig. 2). A substantial difference results.

It should be noted that these forecasts ultimately depend on assumptions about future US oil discoveries. Laherrere (2000) uses statistical data on past US oil discoveries to establish this value, a conservative method; while EIA's forecast embraces the more optimistic approach of a technically recoverable resource base (EIA, 2000, p. 242) taken from the USGS World Petroleum Assessment 2000. A middle case scenario of future US oil production can be derived by

[2] 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, 1993; Saad, 2000). This is the approach taken here.

[3] Specifically, for the period 2021–2050, it was assumed that growth in electricity supply would gradually decrease and then stabilize in 2050, when total US electricity consumption would reach 6.8 GWh.

[4] 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 fuel mix over the next 50 years. But the real purpose of a zero growth scenario is to ensure a conservative forecast for PV, since a 10% cap on PV use would lead to *higher* forecasted growth in PV capacity additions if electricity demand continued to grow after 2050.

[5] 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 in the US annually generates an average of 1.7 kWh (taking into account avoided T&D losses), annual electricity generation from 300 Wp of PV = 505 kWh = the electricity equivalent of one barrel of oil.

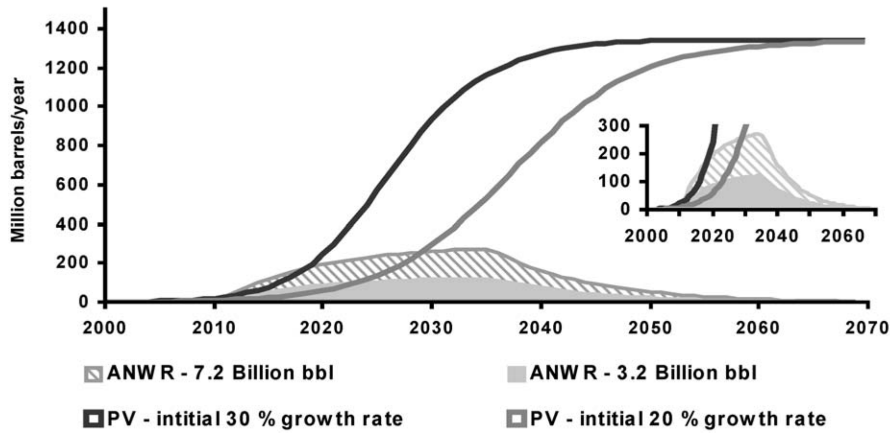
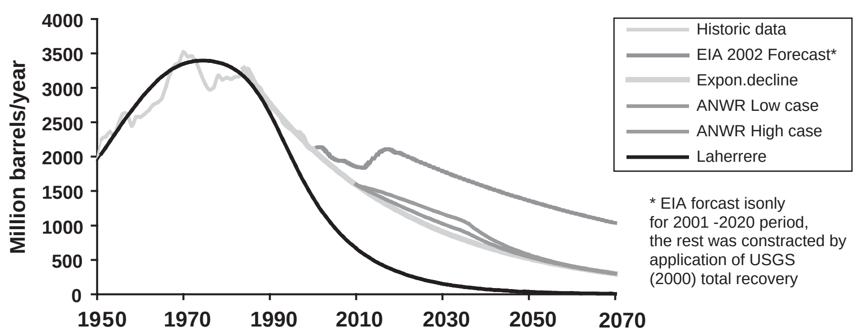


Fig. 1. Comparison of potential US PV energy supply and ANWR oil output.



Data sources: EIA 2002a, EIA 2001b, EIA 2000, USGS 2000, USGS 1998, Laherere 2000

Fig. 2. Comparison of forecasts of US oil production from existing domestic reserves. Data sources: EIA (2002a), EIA (2001b), EIA (2000), USGS (2000), USGS (1998) and Laherere (2000).

applying statistical regression methods to production trend data for the 1985–2001. When we followed this procedure, an exponential decline between that of Laherrere and the EIA results. We added the USGS and EIA's projected ANWR production values to establish a comparable forecast to that of Laherrere and the EIA.

For the current study, we rely upon the middle case scenario for comparison with our PV forecast. Fig. 3 summarizes the results of the exercise for the period of 2010–2070 when ANWR is proposed to supply oil to the market (see National Energy Policy Development Group, 2001). By our calculations, cumulative oil production for the period would range from 51 to 55 billion barrels, while PV energy supply in oil equivalent for the same period would range from 44 to 59 billion barrels. Thus, the contribution of PV to national energy supply for 2010–2070 would be the same as that from oil (Fig. 3) and could help to significantly reduce dependence on imported oil if hydrogen becomes a competitive fuel for transport.

3. Observed historical trends in other energy sources and silicon-based products

For our analysis, initial growth rates of US PV production are assumed to be 20% and 30% per year. It might be argued that these are too optimistic and cannot reasonably be expected to continue for the 15 or so years assumed in our forecast.

In order to assess whether these growth rates for PV energy production are realistic, we examined historical trends in market growth for three energy sources (oil, natural gas, and nuclear power) and two silicon-based products (personal computers and cell phones). The comparison with oil and natural gas was based on annual data for the first 50 years of US development of

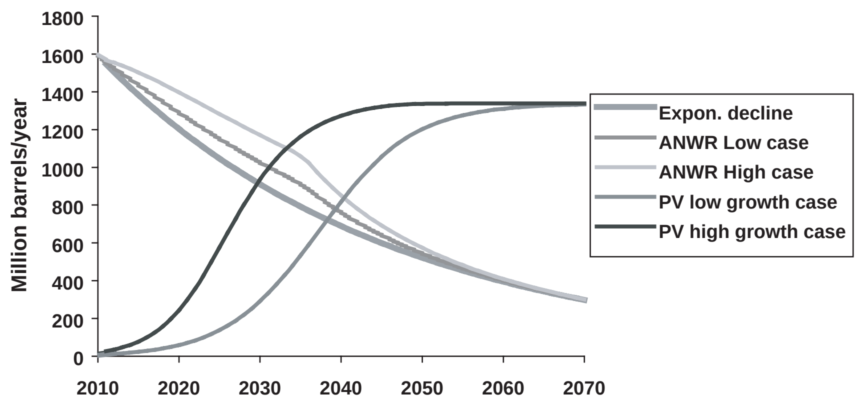


Fig. 3. Comparison of forecasts of potential US PV energy supply and US oil production from existing domestic reserves.

these energy sources. The comparison with nuclear power, cell phones and personal computers is less robust since only the first 15–20 years of production in the US is available. However, our forecast is built on double-digit growth in PV capacity additions for only 20 years (2001–2020) and, therefore, comparing this assumed pattern with empirical ones for nuclear power, personal computers and cell phones can be helpful in gauging the plausibility of our approach to PV forecasting.

Between 1862 and 1911, the average yearly growth rate in US oil production was 25.5% (based on data from US Census Bureau, 1975). Oil production began in 1859, but the growth rates of 1860 and 1861 were not included in the analysis because of their very high values (25,000% in 1860 and 322% in 1861). Natural gas production in the US grew between 1901 and 1950 at an average yearly rate of 8.57% (US Census Bureau, 1975), which is lower than the average rates used in our forecast for PV. The historical growth rate of nuclear power in the US is similar to that for oil. Between 1957 and 1977, installed nuclear plant capacity in the US grew at an average annual rate of 36% (Williams and Terzian, 1993).

Two silicon-based technologies—personal computers and cellular phones—offer empirical evidence on market growth in time frames that overlap with silicon-based PV. Sales of personal computers in the US between 1982 and 2000 exhibited annual average growth of 22% (US Census Bureau, 1991-2000; US Census Bureau, 1994-2001). Cell phones experienced the highest rates of growth among all products that we considered. Between 1986 and 2000, the annual average growth rate of cell phones in the US was 48.6% (US Census Bureau, 1991-2000; US Census Bureau, 1994-2001; Cellular Telecommunications & Internet Association, 2002).

These comparisons suggest that growth rates used for PV in our forecast are 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).

4. PV prices and market share

Currently, PV systems furnish bulk electric power in the US 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.

But such a prognosis neglects the empirical evidence for expecting continued declines in PV prices. For example, average selling prices of PV modules have decreased from \$55/W_p (in 2001 dollars) in 1976 to approximately \$3.50/W_p in 2001 (Harmon, 2000; Maycock, 2002). For our analysis, we set the breakeven price of PV modules at \$1.50/W_p, which is within the range reported in the research literature on PV market penetration (e.g., Payne et al., 2001). PV modules can be expected to reach a real price of \$1.50/W_p by 2012, based on price trends to date.[6]

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 some of the estimates published in the literature, this breakeven level of electricity cost can be obtained with a price of PV modules between \$0.50/W_p and \$1.00/W_p (Neij, 1997; International Energy Agency, 2000).

However, such research 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 several industrialized

[6] Some suggest that PV can be competitive at module prices above \$2.00/W_p (see NCPV, 2001).

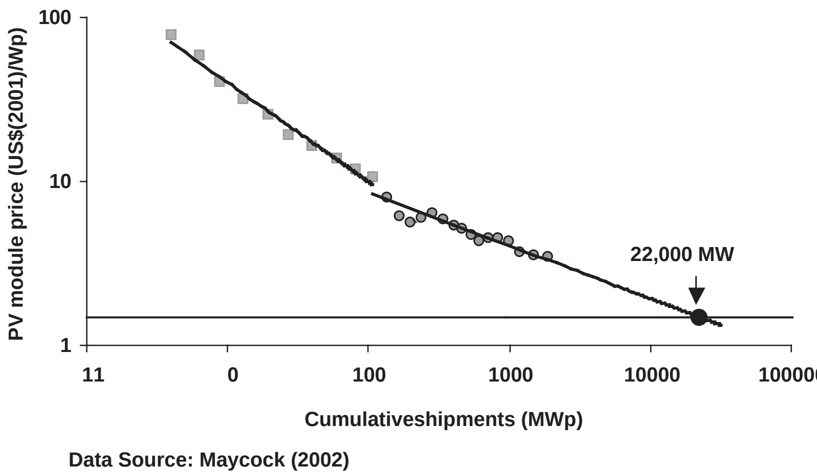


Fig. 4. PV experience curves for 1976–2001 and projection to a breakeven price of $1.50/W$_p$. Data sources: Harmon (2000) and Maycock (2002).

countries (e.g., Germany and Italy) and specific US 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. Assuming that balance of system costs will account for 50% of total cost, the breakeven price for PV systems would then be $3.00/W$_p$.

Using a $1.50/W$_p$ breakeven module price, we estimate that this could occur with a level of worldwide cumulative shipments of about 22,000 MW$_p$ (see Appendix A and Fig. 4). This level of breakeven cumulative shipments could be attained between 2011 and 2019, without a significant technology breakthrough, provided that the average market growth rate will be between 15% and 30%. This forecast applies the standard methodology of experience curves for the analysis of market penetration of emerging technologies (see, e.g., Williams and Terzian, 1993; Neij, 1997; International Energy Agency, 2000; Harmon, 2000). In our breakeven analysis, a 'progress ratio' (PR) of 80%[7] is statistically estimated (again, see appendix for details).

There is a conceptual matter that deserves attention at this point. Breakeven analysis of the kind described above presumes that PV's market will eventually be the bulk power service market of 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 that take advantage of significant economies of scale. Unlike as recently as the 1980s when the economics of power generation seemed to dictate the building of large facilities (e.g., 500–1200 MW—see Messing et al., 1979), today's power plant is typically modest in size (often less than 1 MW—see Dunn, 2000) and its economics 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 misleading when technology change is leading to the obsolescence of large electric power plants (Hunt and Shuttleworth, 1996, p. 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 instead meet the demand for such services as energy management (e.g., shaving peak loads of users), back-up or emergency power, environmental improvements (e.g., reducing pollution that adversely affects air quality and forest growth or mitigating so-called 'greenhouse gases' that are linked to climate change) and fuel diversity (see, especially, Awerbuch, 1995; Awerbuch et al., 1996). When PV is analyzed in this *services* context, its economics dramatically improve (see, e.g., Byrne et al., 1996, 1997, 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 factors in mind, the current spread in bulk power prices between PV and the fossil fuel family may not be compelling. When PV creates benefits that oil, natural gas or coal plants cannot (e.g., environmental improvements and fuel diversity), and when it generates high-value services more attractively than fossil fuels can (e.g., energy management and back-up or emergency power), price comparisons that neglect

[7] 1−PR denotes the rate at which prices decline for every doubling of cumulative production. Thus, a PR of 80% indicates that prices decline by 20% with every doubling of cumulative production. The 80% PR is based on regression analysis of historical data on PV shipment volumes and module prices.

these economic and social contributions are likely to be misleading on the question or market development.

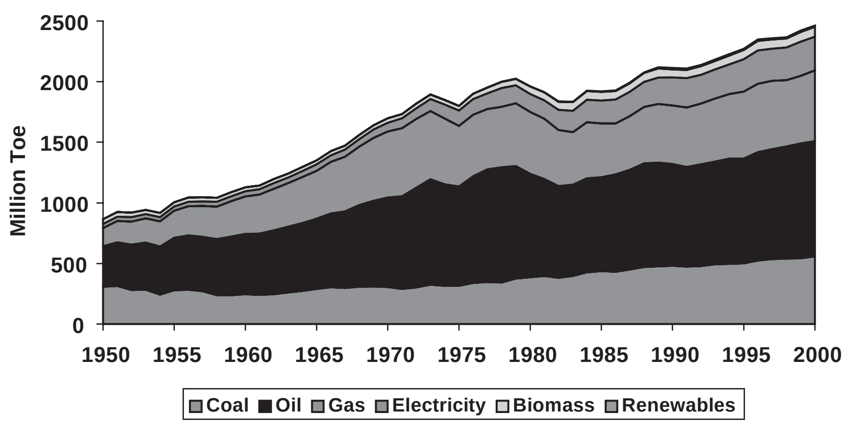
5. PV's past and its future

Hesitation is likely to remain about the premise that PV will play a major role in the energy future of the US and global economy. In part, this may be due to realistic recognition of the sizable policy and institutional interests that favor the energy status quo. These interests represent potent barriers to the development of PV and other emergent energy technologies.

When judged in terms of the recent past, PV and other renewable energy options appear destined to remain 'frontier' technologies for some time. A common depiction of energy supply—a fuel mix graph over the last 50 years (see Fig. 5)—reinforces this view. The thin, pencil-line contribution of renewables to US energy supply discourages an expectation that their role will change in the next 10–20 years.

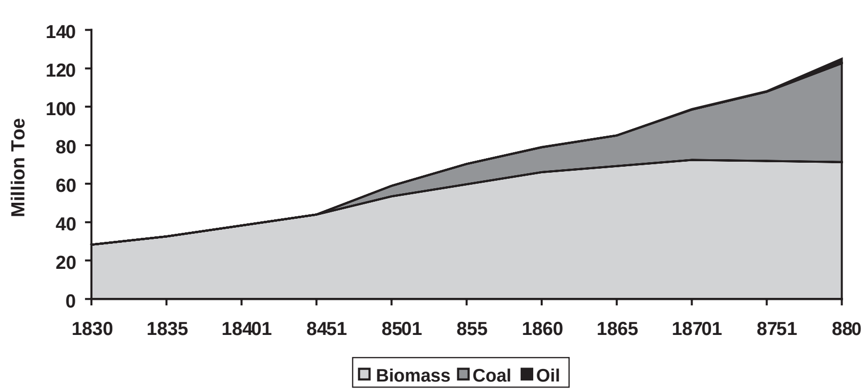
But applying the future-as-revised-past hypothesis would mean that the rise of fossil fuels in the 20th century would be judged as unreasonable. Consider, e.g., the US energy supply by fuel in the 19th century (Fig. 6). There was no hint in this energy past of its oil-dependent future. Nor would one have imagined the extraordinary rates of increase in energy use throughout the 20th century. Just as Fig. 6 is no predictor of Fig. 5, the latter offers little knowledge for the purpose of evaluating the content and implications of Fig. 1.

Instead, PV's future will almost certainly be different from its past and, in this respect, the forecast of Fig. 1 is more likely conservative (because of its reliance on past growth patterns and a 10% cap on penetration of the electricity market) than optimistic. As two of the coauthors of this study (Barnett and Byrne) suggested nearly 20 years ago in a volume edited for the American Association for the Advancement of Science, the solar energy transition will have little to do with the energy *status quo* and, therefore, will be more affected by policy and environmental considerations than competition for market share in traditional energy applications (Rich et al., 1983). We think that this remains true.



Data source: EIA 2002b

Fig. 5. US fuel mix for the last 50 years. Data source: EIA (2002b).



Data source: EIA 2002b

Fig. 6. US fuel mix from 1830 to 1880. Data source: EIA (2002b).

6. Energy policy analysis—thinking beyond the status quo

Energy policy debates are often shaped by current prices, technologies, applications and markets. The ongoing debate as to whether ANWR should be opened for oil extraction is illustrative of this tendency. Yet, experience indicates that energy change can often be dramatic and sudden (e.g., MacKenzie, 1996 and Figs. 5 and 6). Moreover, energy choices can be highly affected by policy decisions. Indeed, the entry and diffusion of nuclear power into energy markets appears to have been largely policy-driven (Byrne and Hoffman, 1996).

As the above analysis shows, 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 solar electric power and oil on a 70-year time scale suggests that PV has a realistic potential of providing energy services in the US that, in energy units, could be 8–15 times more than ANWR oil and approximately the same as all known US domestic reserves.[8] Considered in this light, PV's status in the current energy policy debate as a 'frontier' technology is misguided and, almost certainly, inaccurate.

Admittedly, any long-term forecast of energy options will be mistaken with respect to future quantities. But it is equally important to recognize that analyses focused on short-term likelihoods are able to accurately project tomorrow's numbers only by risking the possibility of being altogether blind to transformative events. The policy relevance of the type of analysis offered here lies not in its numerical projections but in the comparison it allows. Only when analysis focuses on the long-term and compares 'unusual'[9] options can we have any hope of discovering a surprising result.

Our analysis has found a policy surprise—PV is likely to be much more important to the energy future of the US than oil. It supports the adoption of an aggressive strategy to deploy PV on the ground that its 21st century potential is comparable to that of the remaining known US reserves of oil. Surely, that raises an interesting policy question.

Appendix A

A.1. Methodology for developing the PV logistic growth model

For projecting PV's contribution to US electricity supply, a logistic growth curve was fitted to empirical data. The logistic growth model has been applied widely to describe various 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 US electricity production would grow until it would reach 10% of the national total (see NCPV, 2001). We further assumed that annual US electricity production growth would be 1.8% for 2000–2020 (based on EIA's 2001b forecast). Also, it was assumed that US 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 1.8% in 2020 to 0% in 2050.

The equation for logistic growth of annual electricity generation Q is

$$Q = U/(1 + \exp[-b(t - tm)]). \tag{A.1}$$

Maximum annual production from PV is denoted as U, and is set at 10% of current US electricity generation. Using Laherrere (2000), the slope coefficient (b) for Eq. (A.1) is as follows:

$$b = 6/d (\text{to be more precise } b = 5.986/d), \tag{A.2}$$

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:

$$Q_1 = U/(1 + \exp[-(6/d)(-d)]) = U/(1 + \exp 6). \tag{A.3}$$

After 1 year,

$$Q_2 = U/(1 + \exp[-(6/d)(-d + 1)]) = U/(1 + \exp(6 - b)), \tag{A.4}$$

$$Q_2/Q_1 = (1 + \exp 6)/(1 + \exp(6 - b)),$$
$$\text{for simplification } K = Q_2/Q_1. \tag{A.5}$$

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

$$K = 1 + p/100\%. \tag{A.6}$$

Simplifying (5) gives

$$K \exp(6 - b) = 1 - K + \exp 6, \tag{A.7}$$

$$\exp 6/\exp b = (1 - K + \exp 6)/K, \tag{A.8}$$

$$\exp(b) = K \exp 6(1 - K + \exp 6), \tag{A.9}$$

$$b = \ln[K \exp 6/(1 - K + \exp 6)]. \tag{A.10}$$

Thus, after specifying the current level of PV growth p, K can be obtained from Eq. (A.6), the slope b can be obtained from Eq. (A.10), and then the value of d can be obtained from Eq. (A.2), which represents the length of

[8] This finding is based on widely cited price forecasts, namely those of EIA and USGS for oil and NCPV for PV modules.

[9] We prefer the term 'under-investigated'.

time needed for reaching half of the maximum production level. Also, by knowing current level of production it is possible to find the time needed to reach 1% of the maximum addition level. And by adding this time to d, tm is found. Thus, all required parameters for Eq. (A.1) are determined and a forecast of potential PV energy production can be obtained.

A.2. Methodology for determining break-even year

Experience curves can be described by the following equation:

$$\text{Price at year } t = P_0 X^E, \tag{A.11}$$

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 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. Using log-linear regression analysis for the sample period of 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 shipments is about 22,000 MW_p (see Fig. 4).

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