

The Role for Solar in the Long-Term Outlook of Electric Power Generation in the U.S.

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In this paper we examine the potential role for central and distributed solar energy technologies in the U.S. over the long-term, i.e., through 2050. We discuss how we developed and used a modified version of the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS) to produce a range of solar energy technology and policy focused scenarios. The extension of NEMS to 2050 required a series of assumptions about technology and energy service trends. We modified key modules of NEMS to reflect the longer term horizon, although no significant new energy sources (i.e. hydrogen) were added. In addition, the focus on solar technologies led us to revise the representation of distributed photovoltaics (PV) in the residential and commercial modules of NEMS. Using this extended version of the model we developed and evaluated a set of solar focused technology and policy cases. Our analysis indicates that with a combination of enhanced R&D and policies, solar energy could become a significant contributor to the U.S. generation system by the year 2050.

1 INTRODUCTION

This paper explores the implications of aggressively developing and deploying solar energy technologies over the next 50 years. Specifically, we examine what it would take for solar energy to become a dominant source of energy in the U.S. by the year 2050, and estimate the cost effectiveness of pursuing such a path. We explore a range of solar futures – from a solar baseline scenario to an enhanced R&D with aggressive policies scenario.

In carrying out our analysis, we drew heavily on data and models from the DOE's Energy Information Administration (EIA). In particular, we used EIA's Annual Energy Outlook 2003 high renewables and high technology demand cases as a starting point for our analysis, and we created an extended version of EIA's National Energy Modeling System (NEMS) to conduct our analysis. We used this extended version of NEMS to create a series of scenarios to determine the key factors that are likely to drive solar energy technology adoption over the next 50 years. Through the process of defining and refining scenarios, we evaluated the sensitivity of our results to changes in key assumptions in the model, examined various limitations of the model, and estimated the return on investing in solar R&D and policies.

Our analysis indicates that solar energy could become a dominant U.S. energy resource by the year 2050, however, achieving this vision will require setting aggressive but realistic R&D goals, as well as implementing policies aimed at increasing the penetration of solar energy technologies into the marketplace. Below we present the details of our analysis. First, we provide a brief overview of how we modified NEMS. Second, we discuss the definition of and results from four distinct solar scenarios: the solar baseline scenario, the solar baseline with carbon value scenario, the solar advanced R&D with moderate policies scenario, and the solar advanced R&D with aggressive policies scenario. Third, we present our estimates of the cost of achieving these scenarios. Fourth, we discuss issues related to the large-scale integration of solar energy technologies with the electricity grid. And finally we present summary conclusions from our analysis.

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2 EXTENDING NEMS TO 2050

National Energy Modeling System (NEMS) is the engine used by EIA to develop projections published in its Annual Energy Outlook. As our starting point, we used the version of NEMS employed in the *Annual Energy Outlook 2003* (AEO2003), which was designed to project energy demand and supply through 2025 (EIA 2003). Because we were interested in exploring the role of solar technologies in the U.S. energy economy through 2050 we developed an extended version of NEMS. In extending the model we focused on selected modules of NEMS, primarily those with solar technology markets. These modules included the residential demand module, the commercial demand module, the electricity market module, the coal market module, and the renewable fuels module.

The other parts of the energy system were represented through exogenous assumptions. For example, projections of electricity demand and cogeneration sales from the industrial sector and oil and natural gas prices for all sectors were extrapolated to 2050 and used as fixed inputs. The industrial demands were extrapolated from the AEO2003 High Technology case, consistent with the use of the High Technology case assumptions used in the buildings sectors. Wellhead natural gas prices were assumed to be approximately \$0.50 per mcf higher than in the AEO2003 to reflect current trends and expectations. Coal prices were projected within the model, and mining productivity improvements were assumed to saturate post-2025.

The macroeconomic forecast was extended for variables such as population, residential housing starts, commercial floorspace, and interest and inflation rates. Because the population growth rates in the AEO2003 were from the 2000 Census Middle Series, the same forecast was used for the 2025 to 2050 period. Residential housing starts, and commercial floorspace were extended assuming that their growth rate trends would follow those of population. Over the 50 year time period population was projected to increase by about 50%, while commercial floorspace doubles.

Extending projections to 2050 also required reviewing capital stock retirement and aging issues that may not have been relevant for the AEO2003 2025 mid-term horizon, but would gain in importance in the long-term. The AEO assumption that older power plants face higher O&M costs as they age was extended to include an increase of \$25/kW-year after the age of 60 in addition to a \$5/kW-year increase at age 30. Nuclear power plants were assumed to have 40 year operating licenses that could be extended for one 20 year period. No second relicensing of nuclear plants was considered.

With respect to distributed photovoltaic (PV) systems the AEO2003 version of the model was designed for a 25 year timeframe and with low levels of adoption expected. As a result, several algorithms required modifications to accommodate the longer timeframe and higher penetration rates. For example, we added stock accounting with retirements, modified the algorithm for adoption rates, increased the average system size from 2kW to 4kW for residential systems and 10 kW to 100 kW for commercial systems, added the capability for system sizes to change over the forecast period, increased the maximum penetration rates for single family homes and commercial buildings, and added multi-family homes as an option for distributed PV systems. The treatment of solar water heaters was also modified, and an active solar space heating option was added to the residential module.

3 DETAILED SCENARIO ASSUMPTIONS AND RESULTS

We used the extended version of NEMS, described above, to develop four distinct scenarios: the solar baseline scenario, the solar baseline with carbon value scenario, the solar advanced R&D with moderate policies scenario, and the solar advanced R&D with aggressive policies scenario. The difference between the two baseline scenarios is that the solar baseline scenario does not place a monetary value on carbon while the carbon value scenario has a value for carbon that is phased in over time (from \$0 per metric ton carbon in 2015 to \$100 per metric ton carbon in 2040). In the baseline with carbon case we assume that a market-based approach would be used to value carbon in the energy economy. This carbon value is also included in the enhanced R&D and policies scenarios.

In the enhanced R&D with moderate policies scenario, accelerated solar technology R&D leads to further and more rapid cost reductions and performance improvements, a production tax credit (1.8 cents per kWh) is put in place for central station solar, the average size of distributed photovoltaic (PV) systems is assumed to increase by 50% over time (reflecting higher cell efficiencies), and an investment tax credit (30% in 2005) is adopted for distributed PV, solar water heating, and solar space heating. In addition, when moving from the moderate to the aggressive policies scenario, the production tax credit for central station solar is increased (to 2.7 cents per kWh) and is applied over a longer period of time (20 years), the financing period for central station solar is increased to 30 years, the average size of distributed PV systems is assumed to double over time, and the constraint on adoption of PV in existing buildings is relaxed slightly. There is no change in the R&D targets between the moderate and aggressive policy scenarios. Below we will discuss in detail the assumptions used in, and the results obtained from, each of the scenarios.

3.1 Solar Baseline Scenario

In the solar baseline scenario we used technology cost projections that are consistent with the existing targets from the U.S. Department of Energy's Solar Energy Technology Program for photovoltaics (PVs), Concentrating Solar Power (CSP) and Solar Water Heating (SWH). The near- and mid-term targets (i.e., through 2020-2025) were drawn from the Solar Program's recently published Multi-Year Technology Plan (DOE 2004). In order to define a set of consistent long-term targets going out to 2050, a multi-lab, multi-technology team was assembled. This team produced technology cost projections for use in both the baseline and the accelerated R&D scenarios.

In the solar baseline scenario we used EIA's high renewables and high technology demand cases assumptions for energy efficiency and non-solar renewable energy technologies. These assumptions were extended from 2025 to 2050 with no significant discontinuities. For all other energy technologies in the baseline scenario we used EIA's reference scenario assumptions. Again, these assumptions were extended from 2025 to 2050 with no significant discontinuities. Other important assumptions used in creating the solar baseline scenario included adopting business-as-usual economic assumptions (i.e., related to population, economic growth, housing stock, commercial floor space, etc.), assuming that existing nuclear plants retire after 60 years in operation (i.e., are allowed one re-licensing), and assuming that no carbon policies are adopted in the U.S. These assumptions are consistent with EIA's reference case. We did depart from EIA's reference case in one important respect: natural gas prices were assumed to be roughly \$0.50 per MMBtu higher than in EIA's reference case. This reflects a growing consensus among analysts that future natural gas prices are likely to be higher than those projected in EIA's Annual Energy Outlook 2003.

As shown in Figure 1(a), in the solar baseline scenario, coal continues to be the dominant source of electricity generation accounting for roughly two-thirds of generation in 2050. In this scenario solar is projected to provide 7% of electricity generation in 2050. While solar is not a dominant source of energy in this scenario, it does begin to make an important contribution to the energy economy during the later part of the projection. This business-as-usual projection illustrates the immense inertia in the energy system. The simple message of this scenario is that given the long lifetimes of existing energy technologies, in a business-as-usual world, replacing existing technologies with renewable, advanced-fossil or advanced-nuclear technologies will take many decades to accomplish.

Underlying this relatively static projection, however, there are hints of dynamic change. As shown in Figure 2(a), if we look at the share of new generation added in five-year increments, we see that through 2010 new capacity is primarily supplied by gas technologies, and while post-2020 coal continues to dominate new additions, we also find that wind and geothermal provide a significant share of new generation through 2025, and that distributed PV and CSP make important contributions during the second half of the scenario. What is most troubling about the solar baseline scenario, however, is that in this scenario carbon emissions are projected to increase by roughly 70% between 2005 and 2050. Pursuing a

path that involves such a large increase in carbon emissions may be risky from an environmental perspective. Further, it is inconsistent with President Bush's goal to "slow the growth of our greenhouse gas emissions and, as science justifies, to stop and then reverse the growth of emissions" (Bush 2003).

3.2 Solar Baseline with Carbon Value Scenario

The potential liabilities inherent in the solar baseline scenario prompted us to create an alternative solar baseline scenario. In this scenario, the baseline with carbon case, we imposed a carbon value rising linearly from \$0 per metric ton carbon in 2015, to \$100 per metric ton carbon in 2040. Such a carbon trajectory was chosen because it roughly stabilizes buildings and electricity carbon emissions through 2050. This relatively modest carbon value is consistent with levels that many analysts believe would be sufficient to stabilize carbon emissions through market mechanisms, yet not overly burdensome on the U.S. economy. In addition, we have chosen to phase the carbon value in over 25 years to allow the economy to adjust gradually over time.

As shown in Figure 1(b), with a \$100 per metric ton carbon value, coal-fired generation and capacity remain roughly constant throughout the scenario; however, coal's share of generation declines from roughly one-half in 2000, to about one-third in 2050. Meanwhile, the solar share of electricity generation reaches 17% by 2050, and the share of generation from other renewables also increases substantially. The increased contribution from solar energy in a carbon-constrained world illustrates the value of investing in solar energy technologies as part of a broad-based carbon insurance policy.

The dynamics of the baseline with carbon value scenario are very different than the baseline scenario. As shown in Figure 2(b), new electricity generation capacity through 2025 is dominated by natural gas technologies. In terms of renewables, wind is the first technology to expand rapidly. By 2020, however, wind reaches a saturation of the best resource sites.¹ After 2020, biomass and solar begin to gain significant market shares. The expansion of biomass and solar is tied to both the declining costs of these technologies and the increasing value of carbon. Interestingly, after 2040, sequestered coal and nuclear plants begin to enter the mix.

The solar baseline with carbon value scenario illustrates the potential for a very significant role for solar in a carbon constrained world. In this scenario, solar accounts for roughly half of all new electricity generation added to the energy economy after 2035. Clearly the transition to a solar economy is beginning to emerge during the later part of this scenario. Next we will discuss two scenarios aimed at encouraging this transition to occur more rapidly.

3.3 Solar Advanced R&D with Moderate and Aggressive Policies Scenarios

The multi-lab, multi-technology team that defined the long-term cost targets for the solar baseline scenario also produced a set of long-term cost targets for use in the advanced R&D scenarios. Example targets are shown in Figure 3. The Solar R&D budget in this scenario is assumed to be set as follows: \$250 million per year between 2005 and 2010, and then declining to \$0 per year in 2035. This level of support would require a total investment in Solar R&D of \$4.6 billion between 2005 and 2035.

Key areas where additional resources would be focused include: driving down the cost of crystalline silicon and thin film PV technologies; developing new generations of PV technologies (e.g. nanotechnology, quantum dots, organic and polymer cells); integrating solar technology into the roofs of homes and into the roofs, walls, windows, and parking lots of commercial buildings; exploring solar hydrogen production methods including electrolysis, thermochemical, and direct production methods, as well as possible storage mediums for solar-produced hydrogen; developing a new generation of solar concentrators using super-thin glass and space frame construction; developing thermal storage systems using new salt formulations possessing very high temperature capability, enabling higher system efficiencies; developing new solar space heating and cooling technologies; and developing advanced solar lighting technology to bring sunlight into the interior rooms of a building.

Expanding the resources available for R&D is critical but alone is not sufficient to achieve a significant increase in the market penetration of solar energy technologies. In addition, policies aimed specifically at increasing the penetration of solar technologies into the marketplace across a broad spectrum of applications will be required. In our analysis we have defined two sets of policies: a moderate and an aggressive set of policies.

In the advanced R&D with *moderate* policies scenario, we included the following *new* policies: a federal production tax credit (PTC) for central station solar, and an investment tax credit (ITC) for distributed PV, solar water heating, and solar space heating. The PTC would be set at 1.8 cents/kWh in 2005, have a 10-year duration, be inflation adjusted through 2020, and then be phased out between 2020 and 2030. A PTC for solar at this level is included in the energy bill currently moving through Congress. The ITC would be set at 30% in 2005, decline linearly to 10% in 2030, and then be held at 10% through 2050. In addition, we assumed that the existing 10% ITC and the accelerated depreciation for central station solar would remain in place through 2050, and the average size of PV systems on buildings would increase by 50% between 2005 and 2030 (reflecting higher cell efficiencies).

In the advanced R&D with *aggressive* policies scenario, we included the following *additional* changes. For central station solar we increased the PTC from 1.8 cents/kWh to 2.7 cents/kWh in 2005, we increased the duration of the PTC from 10 to 20 years, and we increased the financing period from 20 to 30 years. With respect to distributed PV we relaxed the constraint on adoption of PV in existing buildings slightly, and assumed that the average size of PV systems on buildings would increase by 100% between 2005 and 2030 (reflecting higher cell efficiencies and an increased emphasis on integrating solar into buildings). The ITC and depreciation assumptions were not modified between the moderate and aggressive policies scenarios.

As shown in Figures 1(c) and 1(d), by 2050 the solar share of electricity generation increases substantially, to 23% in the moderate case and 32% in the aggressive case. In addition, there is a dramatic shift towards distributed generation, with 30% and 33% of demand in 2050 being supplied by distributed resources in the moderate and aggressive cases, respectively. The radical change taking place in the electricity sector in these scenarios is even more apparent in Figures 2(c) and 2(d). Here we see that PV and CSP begin to capture a significant share of new generation after 2020 in the moderate case, and after 2015 in the aggressive case. In fact, CSP accounts for roughly half of new generation between 2021 and 2025, and PV dominates additions after 2030.² The transition to a solar economy has clearly been accelerated in both of these scenarios.

4 EVALUATION OF POLICY COSTS

There are several ways to measure the costs and benefits of achieving the scenarios described above. One direct measurement of cost is the Federal government budget outlays for R&D and tax incentives. Another is the impact on consumer costs, both in terms of energy and capital expenditures. A third is the total energy system costs, in this case focused on the electric generation system as defined by central station plants, transmission, distribution, and distributed generators.

The annual incremental government expenditures in the moderate policy case relative to the solar baseline with carbon value case range from \$1 to 3.5 billion per year. The largest cost component in the moderate case is the investment tax credit (ITC) for distributed PV systems. In the aggressive policy case, the costs rise substantially to the \$8 to \$14 billion per year range for many years. The majority of the cost in the aggressive case is due to the production tax credit (PTC). This PTC is paid to central solar generators at a level of 2.7 cents per kWh for 20 years of production. Because we have assumed that the PTC is phased out between 2020 to 2030, in the aggressive case, the costs in 2040 are only for those plants constructed prior to 2030. In the aggressive case the cost of the distributed PV ITC is higher as well, as there is greater investment in PVs.

Private sector investment costs can be expressed either annually or as a net present value (NPV) over the scenario period. The NPV approach has the advantage of collapsing the annual values into one

metric that also weights the costs appropriately across time. Of course, the discount rate selected can have a significant effect. We estimate that the incremental government costs (policy case minus carbon case) between 2005 and 2050 has a NPV (using a 7% real discount rate) equal to \$70 billion in the aggressive case vs. \$20 billion in the moderate case.

The full costs and benefits should include any significant secondary impacts on the energy system beyond direct investments and energy savings. However, because the extended version of NEMS used in our analysis is not a fully integrated model, some of the secondary impacts cannot be included. Most importantly, natural gas prices are fixed in our scenarios. Therefore, the benefit of lower natural gas prices that would be anticipated from lowering gas demand as much as 3 quads per year or 15% in the aggressive policy case is not reflected in the cost estimates shown here. Another element that is not included is the cost of environmental externalities other than those associated with carbon emissions.

The costs for transmission and distribution (T&D) and for central generation are reduced in both policy scenarios. The T&D and central generation costs are reduced due to greater adoption of distributed PV, and thus a reduced need to invest in new central T&D and generation. On the other hand, consumer investments are increased substantially. When these costs and the government R&D and subsidy costs are included, the NPV of total system costs (between 2005 and 2050 using a 7% real discount rate) are slightly positive in the moderate policy case and roughly \$50 billion in the aggressive policy case. When the value of reduced carbon emissions is incorporated as well, the moderate policy case yields a slight negative cost (i.e. a net benefit) and the aggressive policy case cost drops to \$24 billion. Again it should be noted, that these costs do not reflect other environmental or security benefits.

5 INTEGRATION ISSUES

Due to the intermittent nature of sunshine, integrating large quantities of solar energy into the electricity grid, for example at the levels envisioned in the moderate and aggressive policy cases, is very challenging. The prospects for integrating significant amounts of CSP into the electricity grid is aided by the expectation that CSP will evolve with significant storage capabilities. PV systems, on the other hand, will need to rely on a combination of on-site storage, load management, and electric grid adaptations. These integration strategies are beyond our modeling capability at this point, and therefore were not explicitly represented in our analysis.

One option for addressing the intermittency issue is the integration of solar with the emerging hydrogen economy. This would allow solar to broaden its impacts to additional fuel markets. There are two primary solar-hydrogen options: local electrolysis from rooftop PV systems and thermo-chemical production via distributed dishes or central power towers. Each has advantages and disadvantages. The advantage of the rooftop systems is that they are distributed which would avoid the need for a hydrogen distribution system (i.e., for automobile use). However, these systems would need to compete with other uses (i.e., electricity generation and heating) for limited rooftop space. The advantages of thermo-chemical production are that there is a very large resource base particularly in the Southwest, the technology has the potential to achieve high conversion efficiencies, and economies of scale could potentially lead to lower costs. Of course, the disadvantages of a centralized approach include the land requirements and the need for adequate infrastructure for hydrogen distribution.

The electric grid itself is expected to continue to evolve in ways that will make solar an increasingly attractive option. An increased emphasis on reliability, security, and environmental concerns is likely to drive a number of new technologies into the marketplace. Among these technologies are improved storage technologies, new load management techniques, smart metering and time-of-use pricing, and intelligent control systems. These types of technologies could significantly change the pattern of electricity demand and facilitate the use of conventional technologies to “firm up” solar generation. Again, while these were not explicitly analyzed in our modeling analysis, these factors will likely enable solar to become an integral part of the electric grid.

6 CONCLUSIONS

Our analysis indicates that solar energy is well suited to become a major contributor to the U.S. national energy portfolio over the next 25-50 years. We find that placing a modest value on carbon emissions (rising over time to \$100 per metric ton) would provide solar energy technologies with a significant increase in market opportunities. This increased role for solar in a carbon-constrained world highlights the value of investing in solar energy technologies as part of a broad based carbon insurance strategy.

We also find that an increased investment in solar energy technology R&D, coupled with a set of moderate or aggressive solar focused policies, could result in a dramatic increase in solar market share. For example, in the advanced R&D with aggressive policies case described above solar energy accounts for over half of new electricity generation capacity added after 2025, and roughly 50% of the electricity demanded in buildings by 2050. This would include a radical shift towards a distributed electricity system with up to a third of all electricity provided outside the central grid.

Finally, we find that the incremental cost of pursuing an aggressive vs. moderate set of policies, however, would be significant. In our analysis we estimated the NPV cost between 2005 and 2050 using a 7% real discount rate. Using this approach the incremental government cost was estimated at \$70 billion in the aggressive case vs. \$20 billion in the moderate case; while the incremental system-wide cost was estimated at \$50 billion in the aggressive case vs. slightly positive in the moderate case. If one includes the value of carbon abatement, then the system-wide cost drops below \$25 billion in the aggressive case, and there is a net fiscal benefit in the moderate case.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

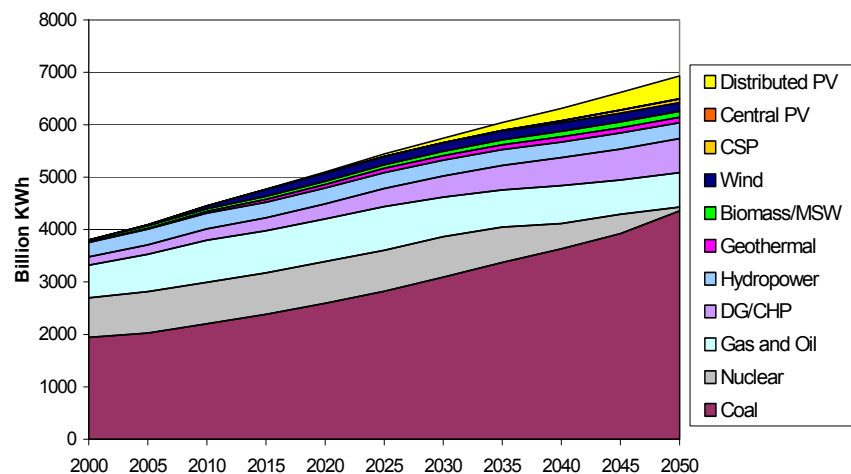
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¹ One could argue that this saturation effect is an artifact of the way wind is modeled in NEMS. In particular, NEMS constrains cross-regional transfers of electricity to current levels. This constraint also limits the growth of CSP. We did not relax this constraint for two reasons: (1) we were concerned about possible conflicts with land-use issues in expanding long-distance transmission, and (2) adding expanded trading to NEMS would have required an effort beyond our available resources. NEMS also has regional resource multipliers that substantially increase the cost of wind as more is developed.

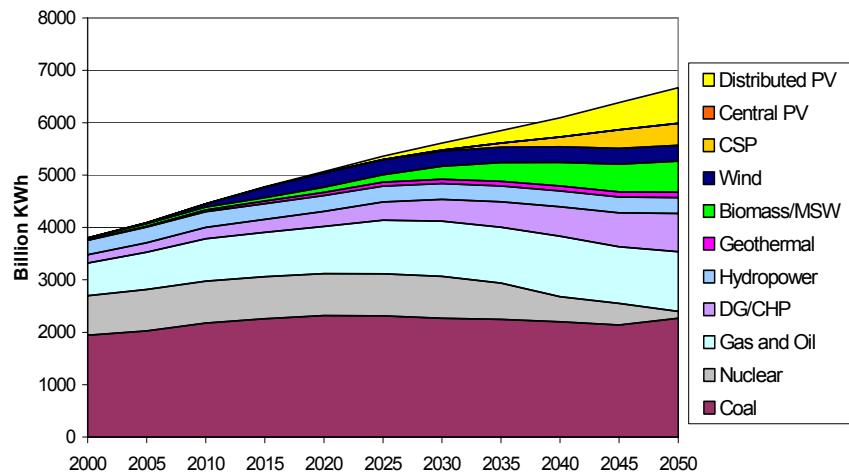
² The CSP share is capped in part by the assumption that cross-regional transfers of electricity are constrained. Also, as distributed PV gains market share there is less need for new central station power plants.

Figure 1: Electricity Generation by Fuel

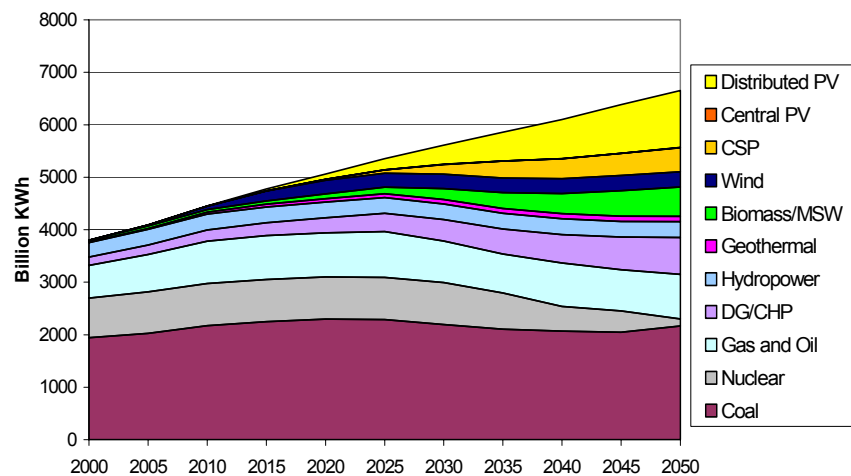
(a) Solar Baseline Scenario



(b) Solar Baseline with Carbon Value



(c) Enhanced R&D with Moderate Policies



(d) Enhanced R&D with Aggressive Policies

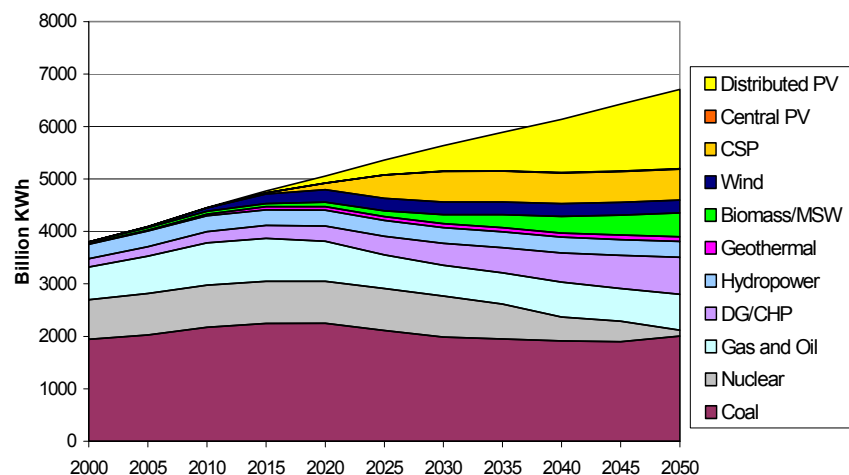
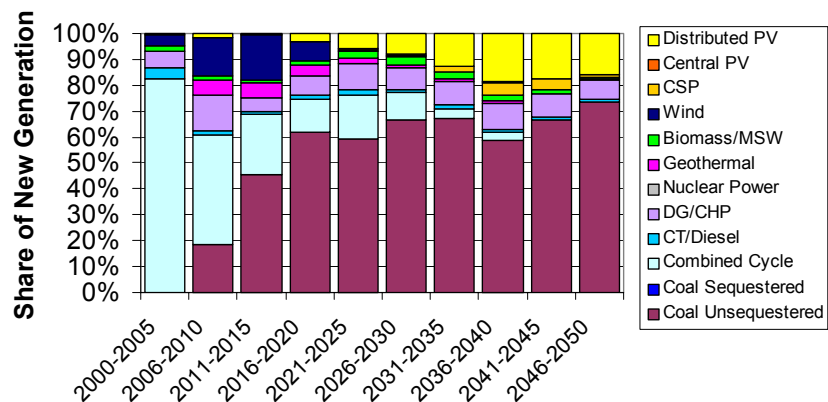
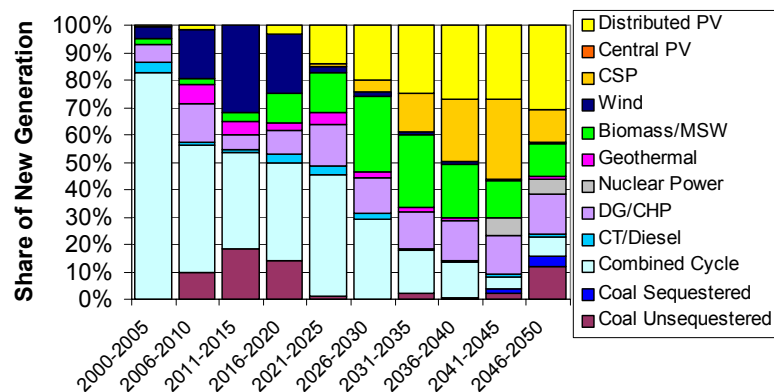


Figure 2: Shares of New Generation by Fuel*

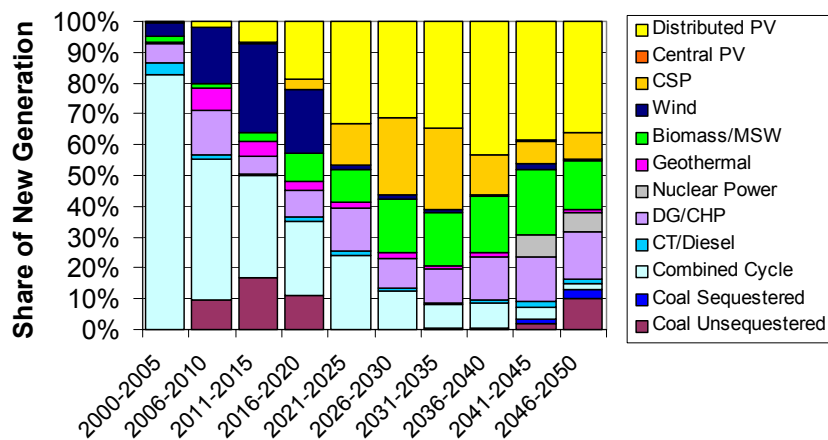
(a) Solar Baseline Scenario



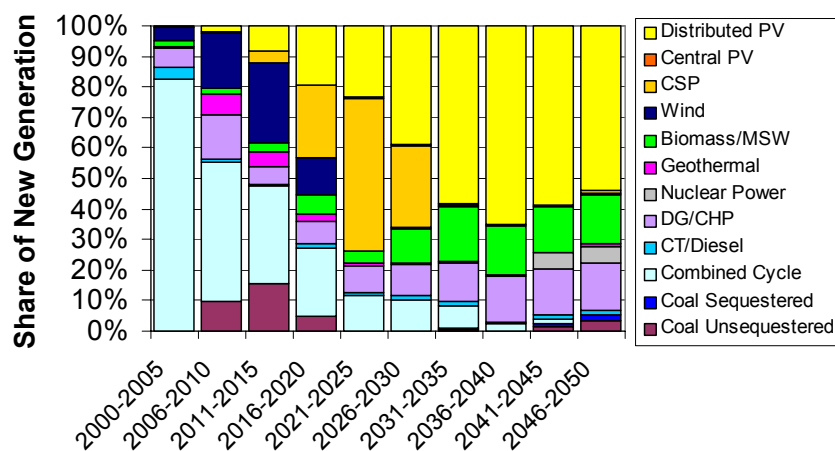
(b) Solar Baseline with Carbon Value



(c) Enhanced R&D with Moderate Policies



(d) Enhanced R&D with Aggressive Policies



* The capacity additions per five year period shown in these figures have been adjusted by the average capacity factor for each fuel.

Figure 3: Installed System Cost Targets for Selected PV, CSP and Solar Water and Space Heating Technologies

