Characterizing Emerging Industrial Technologies in Energy Models

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ABSTRACT

Conservation supply curves are a common tool in economic analysis. As such, they provide an important opportunity to include a non-linear representation of technology and technological change in economy-wide models. Because supply curves are closely related to production isoquants, we explore the possibility of using bottom-up technology assessments to inform top-down representations of energy models of the U.S. economy.

Based on a recent report by LBNL and ACEEE on emerging industrial technologies within the United States, we have constructed a supply curve for 54 such technologies for the year 2015. Each of the selected technologies has been assessed with respect to energy efficiency characteristics, likely energy savings by 2015, economics, and environmental performance, as well as needs for further development or implementation of the technology.

The technical potential for primary energy savings of the 54 identified technologies is equal to 3.54 Quads, or 8.4% of the assumed 2015 industrial energy consumption. Based on the supply curve, assuming a discount rate of 15% and 2015 prices as forecasted in the Annual Energy Outlook 2002, we estimate the economic potential to be 2.66 Quads — or 6.3% of the assumed forecast consumption for 2015. In addition, we further estimate how much these industrial technologies might contribute to standard reference case projections, and how much additional energy savings might be available assuming a different mix of policies and incentives. Finally, we review the prospects for integrating the findings of this and similar studies into standard economic models. Although further work needs to be completed to provide the necessary link between supply curves and production isoquants, it is hoped that this link will be a useful starting point for discussion with developers of energy-economic models.

Introduction

The record of U.S. model-based energy forecasting yields evidence that such models provide biased estimates that inadequately inform policy-makers about the impact of innovative policies (Laitner, et al 2003; DeCanio 2003). Several recent studies suggest that an inadequate characterization of technological change and rates of change contribute to these results (Sanstad et al 2003; Craig et al 2002). Indeed, technology representation is a challenge for most integrated energy-economic models. Supply curves are one opportunity to include a non-linear representation of technology and technological change in aggregated models. As shown by Stoft (1995) and Blumstein and Stoft (1995), there appears to be a complementary relationship between conservation supply curves and production isoquants that depict the different combination of inputs that can be used to produce a specific level of service or output. In this paper, we explore that relationship to determine whether new studies of emerging industrial technologies can be used to upgrade or enhance energy models of the U.S. economy.

Supply Curves and Production Isoquants

Supply curves and production isoquants are common tools that are used to reflect technology cost and performance characterization in economic policy models. In the 1970s, conservation supply curves were developed by energy analysts as a means of ranking energy conservation investments alongside investments in energy supply in order to assess the least cost approach to meeting energy service needs (Meier et al., 1983). Production isoquants, in the case of energy services, show the specific investments and operating expenditures needed for a given level of energy and economic output (Stoft 1995).

Conservation supply curves rank energy efficiency measures by their "cost of conserved energy" (CCE), which accounts for both the costs associated with implementing and maintaining a particular technology or measure and the energy savings associated with that option over its lifetime. The CCE of a particular option is calculated as:

$$\text{CCE} = \frac{\text{Annualized Investment + Annual Change in O\&M Costs}}{\text{Annual Energy Savings}}$$

The annualized investment is calculated as: $\text{Capital Cost} \times \frac{d}{(1-(1+d)^{-n})}$

where d is the discount rate and n is the lifetime of the conservation measure. CCEs are calculated for each measure that can be applied in a certain sector or subsector (e.g. steelmaking) and then ranked in order of increasing CCE (Koomey et al., 1991). Once all options have been properly ranked, a conservation supply curve is constructed by plotting the CCEs in ascending order.

The conservation supply curve is a snapshot of the total annualized cost of investment for all of the efficiency measures being considered at that point in time. The width of each option or measure (plotted on the x-axis) represents the annual energy saved by that option. The height (plotted on the y-axis) shows the CCE for each of the options. Defining "cost-effective" involves choosing a discount rate that reflects the desired perspective (e.g. customer, society). Then all measures that fall below a certain energy price, such as the average price of energy for the sector, can be defined as cost-effective.[1]

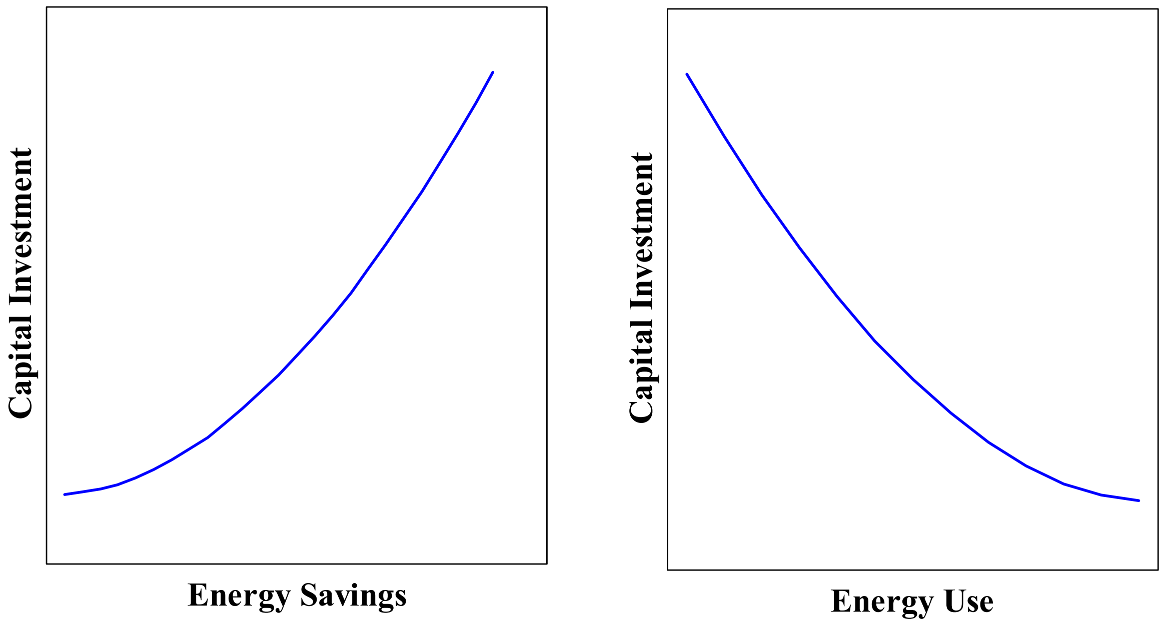
The advantage of using a conservation supply curve is that it provides a clear, easy-to-understand framework for summarizing a variety of complex information about energy efficiency technologies, their costs, and the potential for energy savings. The curve can avoid double counting of energy savings by accounting for interactions between measures, is independent of prices, and also provides a framework to compare the costs of efficiency with the costs of energy supply technologies.

This conservation supply curve approach also has certain limitations. In particular, the potential energy savings for a particular sector are dependent on the measures that are

[1] For examples of conservation supply curves in the buildings, transportation, and industrial sectors, see Meier et al., 1983; Ross, 1990; Ledbetter and Ross, 1989; Difiglio et al., 1990; EPRI, 1990; Blok et al., 1993; Interlaboratory Working Group, 2000; Koomey et al., 1991; Krause et al., 1995; Rosenfeld et al., 1991; DeBeer et al., 1996; National Academy of Sciences, 1992; and Worrell, 1994.

listed and/or analyzed at a particular point in time. There may be additional energy efficiency measures or technologies that are not included in an analysis, so savings may be underestimated. Also, most supply curves are based on the performance of commercially available technology, while emerging or advanced technologies are found less often in supply curves (for other industrial examples, see Worrell et al., 1999; Martin et al., 1999; Martin et al., 2000a; Einstein et al., 2001).

Figure 1. Similarity of Conservation Supply Curves and Production Isoquants



As suggested in Figure 1, there is a strong theoretical relationship between conservation supply curves shown in the graph on the left, and production isoquants shown on the right. While supply curves show the rising level of investment needed to increase energy savings, the isoquants show the combination of capital and energy necessary to meet a given level of economic output. With a change in the label of the x-axis, isoquants can be seen pictorially as the reverse of a supply curve.

Identifying and Characterizing Emerging Technologies

Because it is difficult to foresee what technologies will be available in the future, or even the very near future, representing emerging technologies in a supply curve is a difficult exercise. Reasons include a lack of knowledge of new technologies under development and learning-by-doing. Additionally, performance data of these new technologies are not available or not necessarily representative for the whole industry. For example, costs may come down after some time due to learning by doing effects, while energy savings may be overestimated due to unforeseen process interactions. Still, energy and climate modelers typically use long-term scenarios and hence need to model long-term technological change. For that reason, we try to capture emerging technologies in a supply curve representation as a first step in providing information to the modeling community.

The supply curve representation that we describe next is based on a recent report on emerging industrial technologies and energy savings within US industries (Martin at al., 2000b). Based on a literature review and the application of initial screening criteria, the report characterized 54 technologies, out of an initial set of 180 emerging technologies. The technologies ranged from highly specific ones that can be applied in a single industry to more broad, crosscutting ones that can be used in many industrial sectors. Each of the selected technologies has been assessed with respect to energy efficiency characteristics, likely energy savings by 2015, economics, and environmental performance, as well as what's needed to further the development or implementation of the technology. The technology characterization includes a two-page description and a one-page table summarizing the results for the technology.

Table 1 provides an overview of the 54 emerging energy-efficient industrial technologies. For the most part, the technologies in Table 1 are additional to currently available commercial technologies identified in earlier studies. However, there may be some overlap due to competition between emerging and commercially available technologies. While it is difficult to estimate the size of any potential overlap, the authors of the emerging technologies report assumed only limited market penetration for most technologies. Hence, we believe the total overlap in energy savings is limited.

We generated the conservation supply curve using two primary data points. The first is the amount of total manufacturing energy that the technology is likely to save in 2015 in a business-as-usual scenario. This is shown in the third column of Table 1 (Total Energy Savings). The second item is the amortized cost of conserved energy. For readability, however, we show in the fourth column the simple payback period in years as the metric of cost-effectiveness in this report. As an additional point of information about each technology, we also provide a qualitative estimate of the environmental benefits. To the extent that future policies create markets to cap emissions or environmental impacts, those technologies with additional environmental attributes may become even more cost-effective.

Using the detailed data that underpin the information in Table 1, we develop a supply curve for technologies assumed commercially available by 2015 and able to achieve some market penetration by that year. The Energy Information Administration forecasts industrial primary energy use at 41.96 Quads based on the Annual Energy Outlook 2002 (AEO 2002) (EIA, 2001).

The technical potential for primary energy savings of the 54 identified technologies is equal to 3.54 Quads (or 8.4% of the assumed 2015 industrial energy consumption). Based on the supply curve in Figure 2, for a discount rate of 15% and with 2015 energy prices as forecasted in AEO 2002, we estimate the economic potential to be 2.66 Quads (or 6.3%). The economic potential increases to 3.07 Quads (7.3%) for a discount rate of 8%, and declines to 1.64 Quads (3.9%) for a discount rate of 30%.

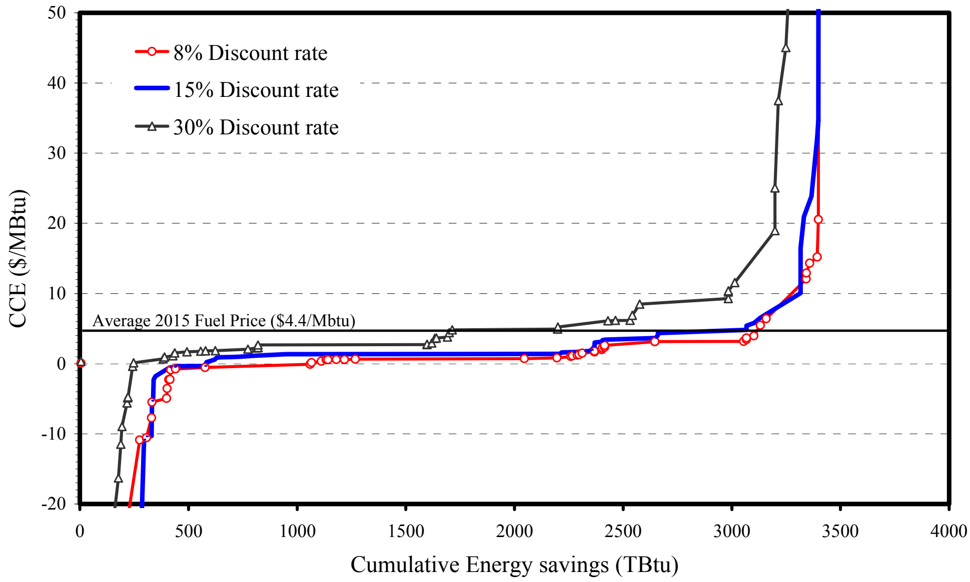
There are a number of critical issues related to the inclusion of emerging technologies in supply curves, which we discuss next.

Table 1. Summary of Emerging Energy-Efficient Industrial Technologies

Technology	Sector	Total Energy Savings (Tbtu)	Simple Payback (Years)	Environ. Benefits
Advanced forming/near net shape technology	aluminum	2.3	Immediate	None
Improved recycling technologies	aluminum	2.2	4.5	Significant
Efficient cell retrofit designs	aluminum	45.6	2.7	Somewhat
Inert anodes/wetted cathodes	aluminum	33.5	4.0	Significant
Roller kiln	ceramics	5.8	1.9	Significant
Heat recovery technologies - chemicals	chemicals	8.1	2.4	None
New catalysts	chemicals	13.6	7.9	Somewhat
Liquid membrane technologies-chemicals	chemicals	0.8	11.2	Significant
Gas membrane technologies-chemicals	chemicals	0.1	10.2	Significant
Levulinic acid from biomass (biofine)	chemicals	0.1	1.5	Significant
Autothermal reforming-Ammonia	chemicals	37.8	3.7	Significant
Clean fractionation - cellulose pulp	chemicals	0.3	1.9	Significant
Motor diagnostics	cross-cutting	0.0	Immediate	None
Anaerobic waste water treatment	cross-cutting	11.5	0.8	Significant
Advanced CHP turbine systems	cross-cutting	483.8	6.9	Significant
Sensors and controls	cross-cutting	136.5	2.0	Somewhat
Motor system optimization	cross-cutting	150.2	1.5	Somewhat
Advanced reciprocating engines	cross-cutting	777.3	8.3	Limited
Microturbines	cross-cutting	67.3	Never	Somewhat
Pump efficiency improvement	cross-cutting	50.2	3.0	None
Advance ASD designs	cross-cutting	2.5	1.1	None
Advanced lubricants	cross-cutting	1.6	0.05	Significant
Advanced compressor controls	cross-cutting	0.3	0.04	None
Compressed air system management	cross-cutting	56.3	0.4	None
Membrane technology wastewater	cross-cutting	117.8	4.7	Somewhat
Process Integration (pinch analysis)	cross-cutting	38.0	2.3	Somewhat
High efficiency/low NOx burners	cross-cutting	21.4	3.1	Significant
Switched reluctance motor	cross-cutting	0.2	7.4	None
Fuel cells	cross-cutting	184.7	58.6	Significant
Advanced lighting technologies	cross-cutting	230.6	1.3	None
Advanced lighting design	cross-cutting	407.7	3.0	None
Hi-tech facilities HVAC	cross-cutting	13.9	4.0	None
Continuous melt silicon crystal growth	Electronics	5.6	Immediate	Somewhat
Cooling and storage	food processing	7.5	2.6	Somewhat
Electron Beam Sterilization	food processing	34.0	19.2	None
Membrane technology - food	food processing	26.6	2.2	Somewhat
Heat recovery food industry - low temperature	food processing	9.4	4.8	None
100% recycled glass cullet for container glass	glass	4.3	2.0	Significant
Oxy-fuel combustion in reheat furnace	iron and steel	21.2	1.2	Significant
New EAF furnace processes	iron and steel	23.9	0.3	Somewhat
Near net shape casting/strip casting	iron and steel	137.6	Immediate	Somewhat
BOF gas and sensible heat recovery	iron and steel	10.8	14.7	Significant
Smelting reduction processes	iron and steel	31.6	Immediate	Significant
Variable wall mining machine	mining	0.1	10.6	None
Biodesulfurization	pet. refining	18.9	1.8	None

Technology	Sector	Total Energy Savings (Tbtu)	Simple Payback (Years)	Environ. Benefits
Fouling minimization	pet. refining	122.8	N/A	None
Plastics recovery	plastics	9.0	2.8	Compelling
Direct electrolytic causticizing	pulp and paper	-0.3	N/A	Somewhat
Dry sheet forming	pulp and paper	15.5	48.3	Somewhat
High Consistency forming	pulp and paper	5.2	Immediate	Somewhat
Impulse drying	pulp and paper	29.5	20.3	None
Condebelt drying	pulp and paper	34.1	65.2	None
Black liquor gasification	pulp and paper	63.7	1.5	Somewhat
Heat recovery – paper	pulp and paper	21.6	3.9	Somewhat
Ultrasonic dying	textile	5.1	0.3	Compelling

Figure 2. Year 2015 Supply Curve of 54 Emerging Industrial Energy Efficient Technologies



- **Completeness.** A disadvantage of using a supply curve for economic policy modeling is that many technologies may not be included. The study of emerging technologies (Martin et al., 2000b) started with a list of 180 technologies, of which 54 were discussed and analyzed in more detail. It is difficult to estimate the energy savings of the technologies not analyzed in detail. However, we tried to make a preliminary estimate based on a not yet published appendix of the report. Additional technologies identified in the study would add at least another 3 Quads in energy savings from technologies available by 2015. Hence, the technical potential might approach a total of 6.5 Quads. Although no economic evaluation of these additional technologies was possible at this time, if we assume a similar pattern of cost-effectiveness as shown in the smaller set of technologies (based on a 15% discount rate), the full set of 180 technologies might reduce energy use by almost 5 Quads in the year 2015. In analyzing emerging technologies, we necessarily focused on individual technologies. However, important synergies exist that may lead to additional energy savings if technologies were integrated, leading to underestimate the savings potential by focusing on individual technologies.

- **Penetration Rates.** The potential energy savings are limited by the assumed penetration rates for the technologies. In the study by Martin and his colleagues, the penetration rates were based on 'normal' stock turnover rates under business-as-usual conditions. This excludes increased savings from higher penetration rates due to strengthened policies or other factors. This means that the potential identified in Figure 1 is in fact not a "pure" estimate of the technical potential. Competition between technologies has been taken into account by the authors in their estimates. Nevertheless, competition with other technologies may result in lower technology penetrations by 2015, and lower savings.
- **Data Uncertainties**. In any assessment, there are uncertainties in assumed savings and costs. The uncertainty is likely to increase the longer the timeframe of the analysis. Emerging technology data is very difficult to estimate accurately, as often no or only a few have been implemented, the cost and energy data are based on a few demonstrations that usually have higher costs. In the future, the costs are likely to come down due to the effects of technical learning or economies of scale. However, such studies are scarce, making it difficult to develop reliable estimates of the likely costs by 2015.
- **Non-Energy Benefits.** Recent analyses focus on including the non-energy benefits in the analysis of energy efficient technologies. Traditionally, non-energy benefits (such as productivity increases, or lower emissions) have not been systematically included in the monetary analysis and construction of supply curves (Laitner et al., 2001; Finman and Laitner 2001). The authors of the emerging technologies study tried to include non-energy benefits where possible. However, for many technologies the authors were not able to quantify all benefits (e.g. value of reduction of criteria air pollutant emissions, productivity increases). Rather, the authors identified those technologies for which non-energy benefits were so important or compelling that they would likely drive implementation of these technologies in periods of low energy prices as forecast in the AEO 2002.
- **Discount Rate.** In the emerging technologies study, a discount rate of 15% was used to evaluate the cost-effectiveness of the energy efficiency measures. There is a debate about the choice of the appropriate discount rate to evaluate energy efficiency measures, given that it may vary based on the perspective (e.g. investor vs. society) and the time frame discussed (e.g. long-term discount rates are assumed to be lower than short-term) (Markandya and Halsnaes, 2001). In this analysis we have chosen a discount rate in between that of the social perspective (equal to 6-8% real discount rate) and the private investor perspective (often 30 – 50%). As discussed earlier, increasing the discount rate to 30% would limit the cost-effective potential to approximately 3.9%. Decreasing the discount rate to 8% would increase the cost-effective potential to approximately 7.3%. Note that many of the technologies included in the supply curve have a strategic character and are not a retrofit of an existing plant, and hence would most likely be evaluated against a lower discount rate.

- **Forms of Energy.** While primary energy savings are an important indicator for a technology, fuel and electricity may react to different dynamics. Due to fuel switching effects it is difficult to represent the electricity and fuel savings independently. Still, electricity is a unique energy source, with significant emissions and a large infrastructure supporting its generation and delivery. The share of electricity in the industry fuelmix is forecast to grow. The major electricity-saving measures are crosscutting technologies concerning motor systems, lighting, and utilities along with selected sector-specific technologies. The potential for electricity savings of the 54 technologies is estimated at 880 terawatt-hours (TWh), including Combined Heat and Power (CHP) technologies. Excluding CHP the total electricity savings potential is 643 TWh. In contrast, most fuel savings are found in emerging process-specific technologies, and selected cross-cutting technologies. Excluding additional fuel use for CHP the fuel savings of the 54 technologies are estimated at just over 1 Quad.
- **Implications for Reference Case Estimation.** Many of the emerging technologies may be expected to penetrate as a result of normal investment patterns. The question, although perhaps more speculative at this point, is how much of the potential energy savings might be captured in the reference case versus the full technical potential described in the emerging technologies study? Ross (1986) suggests that for discretionary spending, industries use a hurdle rate of about 30% to guide their decision-making process. If we assume, therefore, that any technology will be adopted if it is shown to be cost-effective above that hurdle rate, then we have a working estimate of what might already be adopted as part of normal technological progress.

  By the same token, if we evaluate what might be adopted should the hurdle rate be reduced to something closer to the cost of capital, say 8% for purposes of this analysis, then we have an estimate of what might be adopted in the event that future policies drive a more aggressive reduction. By these standards, then, a normal reference case adoption of the 3.54 Quad technical potential would be on the order of 1.64 Quads (based on the assumption of a 30% discount rate). Should policies continually drive the rate down to 8%, the adoption might be as high as 3.07 Quads. Hence, about 1.43 Quads of additional cost-effective industrial savings might emerge in policy scenarios that are not typically captured in the reference case assumptions. If we extend this estimate to include the savings of the full 180 technologies, the full policy level gain might roughly double this amount.

Reflecting Changes in Production Isoquants

In Figure 2 we presented the conservation supply curve as a combined representation of increasingly cost-effective opportunities to reduce energy consumption across manufacturing sectors. This combined curve easily shows the potential for energy savings and can be used to show the effects of changes in the discount rate applied to economic evaluations. At the individual industry and firm level, the conservation supply curve concept is also applicable for the subset of technologies that are relevant to that industry or firm. At this microeconomic level, the conservation supply curve corresponds to production isoquants that represent the choices between energy and capital that we previously described.

For forecasting and policy impact evaluation, energy-economic models are required. For economic models with disaggregated representations of industry outputs and energy demands it may be necessary to disaggregate the conservation supply data to match the categories represented in the model. The model would then be used to capture the additional effects of industrial output growth and investment, capital vintaging and retirements, and the choice of energy-intensity for new capital installed in each period. Energy-intensity choices are determined by the energy-efficiency opportunity set represented by isoquants and the criterion for making energy-efficiency investments.

Within production isoquants, the elasticity of substitution determines the ease or flexibility of replacing energy with capital. Generally referred to as sigma (σ) in the economic literature, it is generally a value of less than 1.0, with long-run substitutions ranging from 0.3 to 0.7. The smaller the elasticity, the more difficult it is to substitute capital for energy. Figure 3 illustrates two important aspects of production isoquants for a hypothetical industry — especially as they might be modified to reflect the information from conservation supply curves. First, an isoquant might shift inward toward the origin as a result of normal technological progress over time. This means that less capital and less energy are needed to support a given level of energy services necessary for the industry to meet demand for its products. Second, there is the possibility that the current elasticity may actually increase as it becomes easier to replace energy with capital. In this case, a tighter, more L-shaped curve evolves into a flatter curve indicating that, as energy prices rise or as other policy signals are strengthened, an industry has a greater capacity to substitute capital for energy.[2]

Examining Figure 3 more closely, the units of energy are shown on the x-axis while units of capital are shown on the y-axis. Although it might vary from industry to industry, if a model initializes the elasticity of substitution, or sigma, as 0.30, it might mean that energy use will decline by about 7 percent and capital will increase by about 15 percent for a doubling of energy prices. Simple payback on the technology might be on the order of 10-12 years. On the other hand, if sigma is assumed to be about 0.70, then energy use will decline by about 25 percent while capital spending will increase about 23 percent for a doubling of energy prices. Payback on the investment might decline to about 5-7 years (or perhaps 3-4 years or less depending on the relative change in prices and/or hurdles rates).[3] Hence, the higher the elasticity, the cheaper it is to implement changes in energy use patterns.

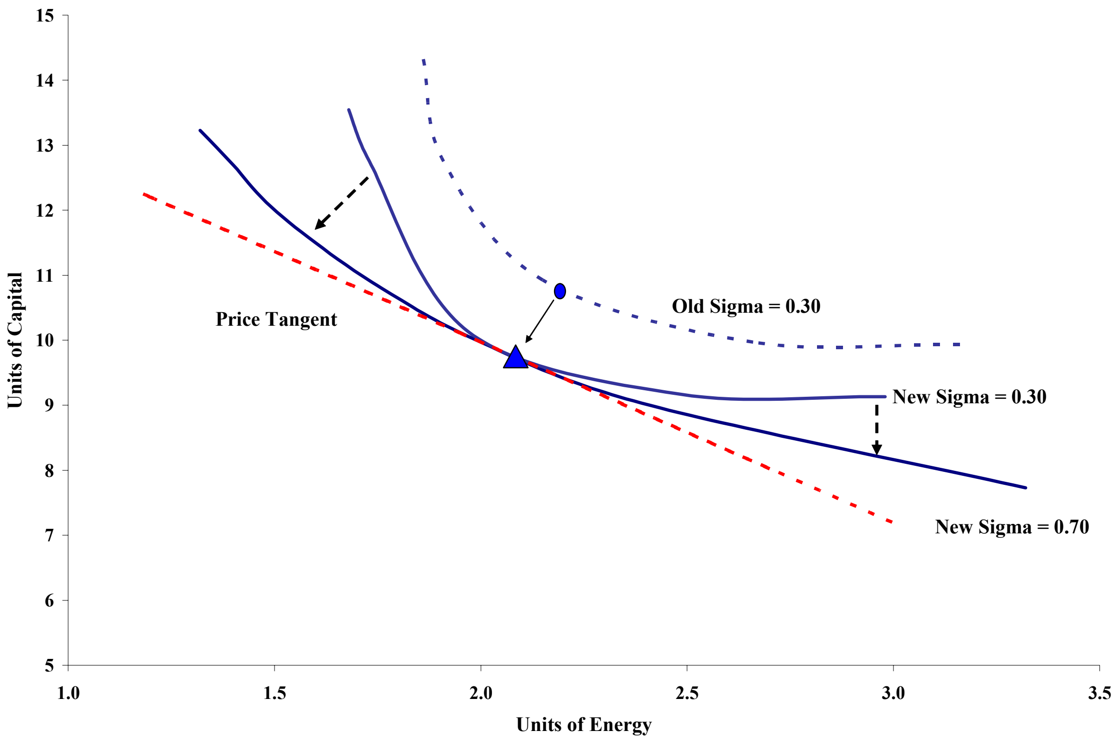
By way of example, we can explore just how the conservation supply curve approach might affect the production isoquant for the hypothetical industry shown in Figure 3. We begin with the topmost, dashed blue line, which reflects what might be called the year 2000 isoquant. This has an "old sigma" of 0.30. The heavy blue dot on the old isoquant might suggest that, at today's energy prices and cost of capital, the industry uses 2.15 units of energy and 10.8 units of capital. But with the availability of new technologies, the isoquant might actually shift inward to the origin. In the year 2015, energy use in the reference case might decline to 2.0 units while capital falls to 10.0 units. This point is shown on a blue

[2] For a more extended discussion of this concept, see Hanson et al (2003).

[3] The changes in energy and capital discussed in the text are indicative only. The precise relationship will vary from industry to industry and plant to plant depending on a variety of other economic assumptions. These include the overall level of capital and energy intensity and the existing cost of energy compared to the cost of capital. In addition, other factors of production, notably labor, must be included in a more complete review of production. Readers interested in exploring these details further should contact the lead author in this regard.

triangle sitting on a solid line at the end of the middle arrow and touching the price tangent line (in dotted red). At the same time, however, the influence of new technologies may also flatten the tails of the new isoquant, reflecting an easier path of substituting capital for energy. In this case, the illustration shows the value of sigma increasing to 0.70. As suggested above, if price levels double, the production technologies will be more easily shifted such that payback for new investment is cut in half.

Figure 3. Illustrating Industry Capital and Energy Tradeoffs with Different Substitution Elasticities



At this point, the question might be asked about the implications of this potentially linking of conservation supply curves and production isoquants. First, many of the existing models tend to have small elasticities for industrial sectors, suggesting a more difficult and more costly substitution of capital for energy. The Second Generation Model (SGM), for example, assumes a value of 0.30 and this is invariant over time (Sands 2002). On the other hand, Argonne's AMIGA modeling system assumes industrial sector elasticities of about 0.65, but this is also invariant over time (Mintzer et al 2003). Although the work to actually transfer the discrete technology representations of Martin et al. (2000b) to given sectors for specific energy categories has yet to begin (as discussed below), the emerging technologies study appears to suggest that these new technologies may provide a greater level of efficiency gains, closer to those used by the AMIGA model. Second, the study also suggests that overall energy intensity may either decrease more quickly than reference case assumptions, or that some industries may have a stronger capacity to substitute capital and knowledge for energy use in the event that policies require greater reductions in energy use sometime in the future. The effort needed to validate these points is not trivial, but the complementary relationship between conservation supply curves and production isoquants provides an encouraging opportunity to begin such assessments.

Conclusion

An appropriate characterization of technology performance is critical to future assessments of industrial efficiency gains and to future evaluation of proposed energy policies. To date, however, many of the standard models have assumed more restrictive assumptions about the ability of industrial firms to substitute capital for energy. At the same time, the emerging industrial technologies study appears to suggest a greater availability of energy efficient technologies that can both save energy and reduce operating costs for many firms. The study indicates, for example, a cost-effective energy savings potential that ranges from 2.7 to almost 5.0 Quads by the year 2015. To the extent that these potential savings are not already embedded in the standard reference case assumptions, it appears there may be a greater capacity to respond to future price and other policy signals than most models usually recognize. Unfortunately, the detailed technology representations provided by Martin et al. (2000b) have yet to be translated into information that might inform the modeling community of potential changes in sector- and fuel-specific production isoquants. Until that task is undertaken, the discussion in this paper remains more heuristic than predictive. But it is equally clear that further exploration is merited. It is hoped the complementary link between supply curves and production isoquants will provide a useful starting point for discussion with developers of energy-economic models.

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