Modeling Detailed Energy-Efficiency Technologies and Technology Policies within a CGE Framework

John A. "Skip" Laitner[*] *and Donald A. Hanson*[**]

Policy makers and analysts are raising questions about the adequacy of policy and technology representation in conventional energy and economic models. Most conventional models rely on a highly stylized and limited characterization of technology. In these models, any desired changes in energy demand are driven largely by pure price mechanisms such as energy taxes or carbon charges. In this paper, however, we explore the mapping of discrete technology characterizations and examine how cost-effective technologies and programs might prompt desirable increases in energy efficiency. Using the commercial health care sector as an example, we show how changes in energy efficiency and technology investments might be more properly represented in policy models.

1. INTRODUCTION

Policy makers and analysts increasingly are asking questions about the adequacy of technology and policy representation in conventional energy and economic models (Worrell et al. 2003, Laitner et al. 2003, Munson 2004, Hanson and Laitner 2005, and Sanstad et al. 2006). Most conventional models (so-called "top-down" models) rely on a highly stylized but limited characterization of technology that requires large price increases to reduce energy demand and their associated externalities. These various price mechanisms, including energy taxes or some form of a carbon charge, tend to show negative impacts on the economy as a result of those higher prices. Yet, transitioning from current business-as-usual growth patterns to sustainable development paths need not imply lower standards of living. Rather, it may imply an alternative combination of different and more

The Energy Journal, Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down.

[*] American Council for an Energy-Efficient Economy, Washington, DC, USA. E-Mail: jslaitner@aceee.org.

[**] Argonne National Laboratory, Argonne, IL, USA. E-Mail: dhanson@anl.gov.

efficient technologies and energy resources as well as a change in industrial and household practices. It can also reflect shifting consumer preferences and a different mix of sector growth rates (Hanson and Laitner 2004; and Laitner et al. 2005).

This article is intended to illustrate how investment decisions can be represented in the modeling of energy and climate policies. We use algorithms within the Argonne National Laboratory's AMIGA modeling system to illustrate this perspective (Hanson and Laitner 2006a). The problem addressed here is separated into three distinct parts: (1) An overview of the AMIGA Modeling System, a hybrid (i.e., technology-rich) computable general equilibrium (CGE) model of both the U.S. and world economies; (2) the appropriate representation of the set of technology choices in large energy models of the U.S. or other economies; and (3) the presentation and discussion of an exercise which illustrates the shift of investments and energy flows within a single sector of the economy as a response to both price and non-price policies and programs. We conclude with a discussion of the methodology as it preserves the essential character of energy end use technologies within a hierarchical CGE structure.

2. OVERVIEW OF THE AMIGA MODELING SYSTEM

The AMIGA (**A**ll **M**odular **I**ndustry **G**rowth **A**ssessment) modeling system is a computable general equilibrium (CGE) model that examines the impact of changes in approximately 180 individual sectors (measured in dollar value and where appropriate in physical units as well). The system, programmed in the structured "C" language, is developed and supported by the Argonne National Laboratory in cooperation with the US Environmental Protection Agency's Office of Atmospheric Programs and the US Department of Energy's National Energy Technology Laboratory. AMIGA integrates a detailed energy end-use and energy supply market and technology specification within an input-output (IO) framework. In the absence of perfect foresight, agents act on approximate intertemporal rules for consumption and savings. The model calculates prices and macroeconomic variables such as consumption, investment, government spending, gross domestic product (GDP), and employment (Hanson and Laitner 2005, Hanson and Laitner 2006a and 2006b; and also see http://amiga.dis.anl.gov).

AMIGA integrates eleven modules that describe the various economic interactions among twenty-one world regions. Each region's assets include existing capital stock, labor resources, and exhaustible resources. The model tracks a detailed accounting of major goods and services demanded by households and the various production sectors of the economy that lead to changes in energy use and production, greenhouse gas emissions, and temperature changes. In short, AMIGA combines a bottom-up, discrete technology representation of the demand for energy and the many other goods and services available with regional markets together with a detailed interaction among the sectors and among the regions of the world. Various choices within these sectors are modeled through nested constant elasticity of substitution (CES) production functions. This, in turn, determines how economic output is supported through inputs of capital, labor, materials, and electric and non-electric energy.

The model allows for autonomous improvements in technologies as well as both price and other policy-induced improvements which can lead to cost-effective reductions in both energy use and the full complement of greenhouse gas emissions. AMIGA also incorporates macroeconomic feedbacks. Higher energy and other resource costs lead to the substitution of capital and labor for energy.

2.1 Technology Structure and Decision Framework

The technological structure of a typical production sector within the AMIGA Modeling System is shown in Figure 1, which highlights the CES hierarchical structure of generic commercial or industrial output, *X*. Output *X* is produced by combining a vector of materials *M* with an aggregation denoted by Z that is a function of the vector of disaggregated capital stocks *K*, labor *L*, and various energy inputs *E*. That is, *Z* is the value added aggregate plus energy services. *Tilde K* is non-energy productive capital as part of the value-added aggregate, *Tilde V* is the main value added, and *M* is a (Leontief) vector of purchased materials and services from other sectors. The elasticities of substitution for the highest level aggregates used in AMIGA are also shown in Figure 1.

Figure 1. Generic Representation of Commercial/Industrial Production

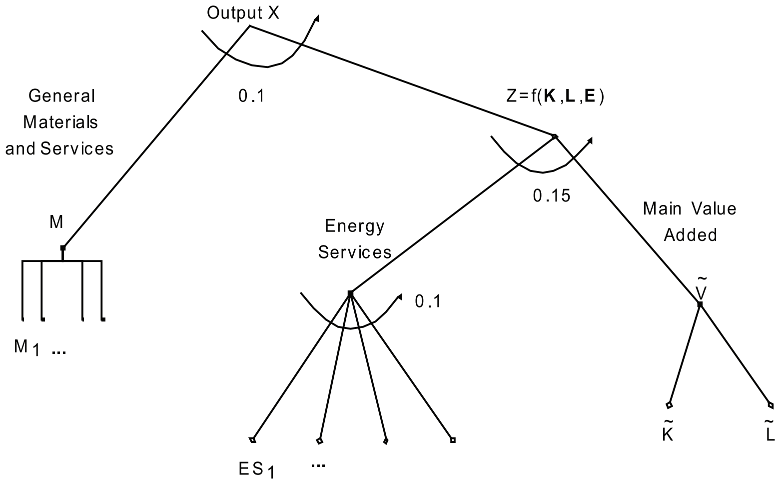


Figure 2 (on the following page) illustrates a more detailed arrangement of energy services for the commercial sectors within AMIGA. Notably, there is a clear trade-off of capital, *K*, and a variety of energy flows to meet different energy services, whether those energy flows are represented here by *Ele* for electricity or *Gas* for natural gas. Other fuels as coal and petroleum can also be included as appropriate to the region and end uses. A final level of detail is shown in Figure 3 which highlights, as an example, the more detailed representation of space comfort or space conditioning as it might be satisfied by electricity and natural gas technologies. Although not provided in this paper, AMIGA has additional detail to provide an evaluation of the mix of vehicles used to satisfy transportation service demands within the commercial or industrial sectors (as well as within the distribution of the six household consumer groups also included in the modeling system). The model further includes energy resource and energy conversion modules to represent conventional power generation, petroleum refining, combined heat and power (CHP) or cogeneration systems, other waste heat recovery and renewable energy technologies, and both current and future hydrogen production systems. The energy conversion modules calculate the operations and variable costs for existing capacity and optimal technology choice for capacity expansion. For example, the market shares for new base-load, shoulder-load, peaking, and intermittent renewable technologies need to be selected on a least cost basis. This yields marginal and average costs to produce a kilowatt-hour (kWh) of electricity; based on this, a rate schedule is provided to electricity customers.

As characterized in AMIGA, end-use energy consumption is driven by service demands and investment in energy efficient equipment and buildings. The service demands flow down the hierarchy as shown in Fig 1 and 2, starting with sector output, *X*, at the top of the tree. Sector output (from demands by households, other business sectors, government and export sectors) drives material demand, *M,* and demand for the aggregate *Z*. Material shares as they are distributed to goods and services purchases by input-output category, are based on the 2004 Annual IO Table (BEA 2004).

Figure 2. Generic Energy Services

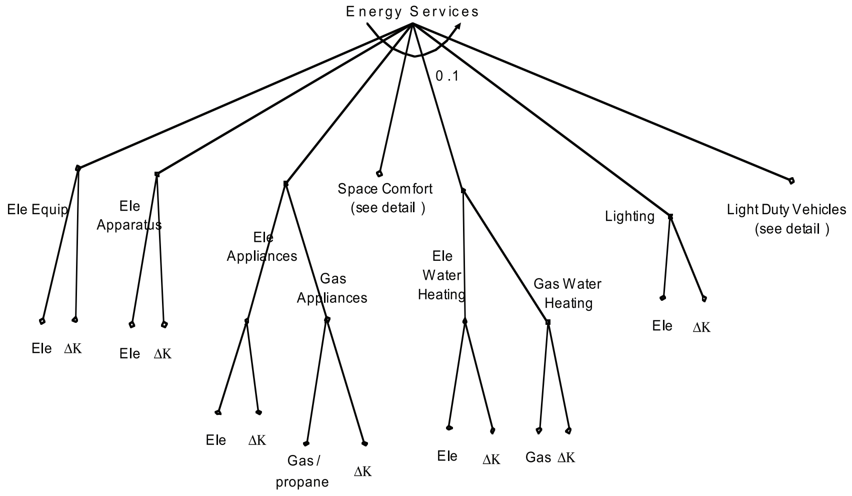
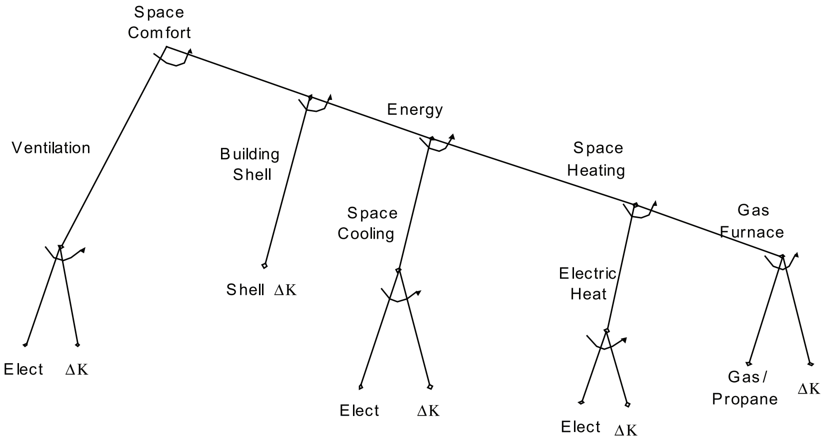


Figure 3. Hierarchical Representation of Space Conditioning



2.2 Substitution of Productive Capital for Energy in AMIGA

Throughout the world economy there is an on-going stream of investments in end-use sectors initiated by a variety of decision makers. The methodology that we describe here captures this diversity. Within the AMIGA Modeling System, the allocation of capital and energy resources involves six key dimensions: time, region, sector, service demand, energy form, and consumer or customer group. The AMIGA model evaluates the need for decisions in a given simulation year and the implications for energy demands and investment spending over all six of these dimensions.

Time. Each year households, public institutions, commercial businesses, and other industries choose among energy using technologies for new, replacement and retrofit demand. Although AMIGA generally reports out information over a 5 or 10-year period, the model calculates an annual set of impacts. The model generally solves through the year 2050 (Hanson and Laitner 2004) although it has the ability to extend through the year 2100 for special exercises such as the Energy Modeling Forum's Multigas, Multiregional Long-Term Emission Scenarios designated as EMF-21 (Hanson and Laitner 2006b).

Region. The AMIGA model of the U.S. economy is set up with a regional structure based on US Census regions. For international analysis, AMIGA now includes 21 distinct regions within world model (IEA 2004). This, of course, includes the United States as one of the distinct economies within the world model (Hanson and Laitner 2004). As documented elsewhere, there is a variety of data sources which provide base-year electricity and fuels consumption by region and end-use.

Sector. The deployment of end-use technologies is estimated for approximately 180 sectors in the U.S. region, and for approximately 30 sectors for the remaining 20 other regions within the model. The U.S. region is generally characterized by data from the U.S. Department's Bureau of Economic Analysis (BEA 2004) while the non-U.S. regions are generally characterized by Purdue University's Global Trade and Analysis Project (GTAP 2004). Different regions and sectors face different energy prices. These prices, drawn primarily from EIA (2005) and IEA (2004), are used in calibrating the factor demand equations and in long-term scenario analysis.

Service Demand. The deployment of end-use technologies attempts to satisfy different demands for energy services appropriate to the different end-use sectors. In residential and commercial buildings, for example, one set of technologies attempt to satisfy demands for heating, cooling, lighting, and other energy end uses. Industrial processes are generally aggregated into demand for electricity, steam and other thermal requirements. Service demands within the transportation sector, on the other hand, include miles traveled for both passengers and freight. The characterization of these energy service demands are drawn primarily from EIA (2005) and IEA (2004) as described more fully below.

Energy form. The AMIGA modeling system currently reflects six different energy forms for the delivery of end-use services. These include electricity, coals, natural gas, propane, petroleum-based fuels and solar energy resources. (Note that nuclear, wind, and hydropower resources are reflected within the electricity generation module.) On an end-use energy basis (whether expressed in Btus or joules), electricity costs several times the price of natural gas. Therefore, firms and households would presumably be willing to pay more to save a Btu of electricity than gas. This is an important aspect that is captured in the substitution analysis of capital and energy flows.

Consumer Decisions. Not all sectors, industries, or consumers which purchase energy apply the same decision criteria. The AMIGA Modeling system uses a distribution of capital recovery factors or hurdle rates to reflect differences among groups in their cost-of-capital, risk position, and decision criteria.

Energy-efficiency investment decisions often must overcome existing market failures and organizational barriers (Brown 2001; and Nadel and Geller 2001). With this in mind, a potential exists for well-defined energy efficiency programs to be lower in cost than supplying energy on the margin. Energy efficiency also lowers local pollution, global greenhouse gas emissions, and helps to conserve coal, natural gas, and crude oil resources, which are becoming economically more costly in a rapidly growing world economy.

The theoretical basis for our analysis of energy efficiency was presented 35 years ago by the economist Kevin Lancaster (1971). He pointed out that consumers and businesses don't consume fuels and electricity for their direct utility. Rather, they use energy as an input to a production function that combines capital, labor and energy to produce useful services such as transportation and refrigeration of perishable goods. (Note: as applied to consumers, the term household production function arose, emphasizing that there are services that can be produced by the household itself rather that necessarily purchased externally.)

The services to the household or business consumers are provided by the total existing end-use capital in place plus additions in the current period. Due to new demand growth, existing equipment failures, rising operating costs of older units, or other reasons, some new, replacement or retrofit investments are made in the current period. The choice process for the energy efficiency attribute of new purchases is described in the following sections.

2.3 From Technology Characterization to Production Isoquant

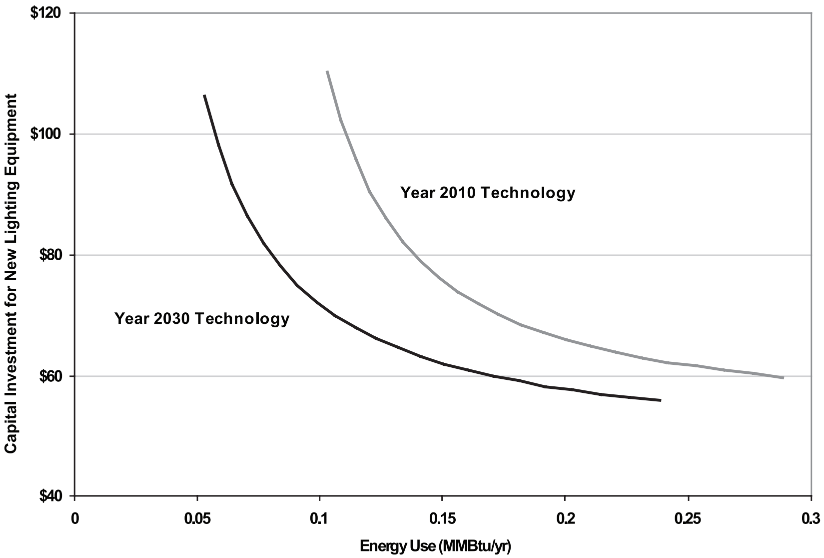
The business and household production functions, as presented more fully in the Appendix, are conveniently represented by a three parameter Constant Elasticity of Substitution (CES) production function (Varian 1992). The three parameters are denoted by *alpha* and *beta* which are scale parameters related to cost shares of the capital and energy factors, respectively, and *sigma* which is the elasticity of substitution that governs the ease of substituting capital for energy. Because of mathematical properties of the CES production function, *sigma* is often expressed as a function of another parameter denoted by *rho*. In addition to these first three parameters, we also have base capital costs and expected minimum efficiency parameters to describe actual technologies and their associated investment and energy costs.

Drawing from a series of data on commercial lighting, for example, we can use these five parameters to describe the array of lighting technologies with the CES function. Figure 4 shows illustrative technology "cost curves" for commercial lighting technologies (described more fully below) which have been adapted from technology data files provided by the Energy Information Administration (EIA 2005). Some regions or sub-sectors may have special circumstances that would suggest using separate curves to represent the special cases or special technology applications or niches. In effect, the isoquant represents the opportunity set facing the consumer or business for a particular demand for energy services. The decision-maker must select a point from this opportunity set. The point selected will reflect the relative weight that the decision maker places on "first costs" incurred when equipment is purchased or the project is being constructed compared to future operating costs.

For future years beyond (say) 2010, technical progress and learning from experience will increase the substitution possibilities between capital and energy. We model this as technological progress and cumulative learning having the effect of increasing the parameter sigma, the elasticity of substitution in the CES function prior to normalization. The other parameters alpha and beta are then adjusted accordingly to represent any expected change for the minimum efficiency of the equipment. Depending on the scenario being explored, AMIGA can accommodate changes as a simple function of time or as endogenously responsive to specific policy exercises.

The two curves in Figure 4 for the years 2010 and 2030 represent and contrast the potential for incremental energy-efficiency investment for a single

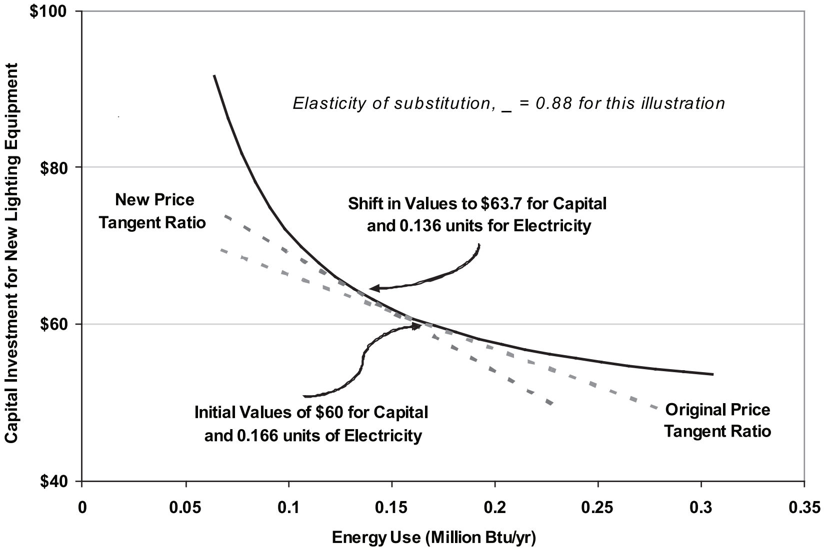
Figure 4. Illustration of an Isoquant for Commercial Lighting in 2010 and 2030



"lighting system" as an alternative to higher electricity consumption. In this example, both electricity and incremental capital are inputs to a production function intended to satisfy a demand for effective lighting of a commercial building. Holding the demand for energy services at a fixed level (in this case the providing of about 1000 lumens of light over the normal operating hours of an office building), the different technologies that might satisfy the demand for lighting can be represented as a production isoquant that describes the combinations of capital and energy which can produce the same level of the desired energy service.

In the year 2010 the technologies available at that time are shown both to cost more and to have less potential to reduce overall energy use compared to those which might be available in 2030. By 2030, however, some combination of technical progress, scale economies, and learning-by-doing (Wene 2000; McDonald and Schrattenholzer 2001; and Laitner and Sanstad 2004) are likely to shift the isoquant both lower and more to the left. This suggests that the technologies in 2030 year can be expected to generally cost less and achieve a slightly larger reduction in the amount of electricity needed to satisfy the service demand in that year. In AMIGA the actual decision to choose from a given set of technologies – each with its own cost and level of efficiency – is a function of both energy price, *Pe*, and the individual preferences of a consumer or firm as they might be reflected in a hurdle rate, *r*. This produces a price ratio, *Pe/r*, which influences the ultimate choice from among the available technologies. Given a specified mix of price and preferences, the rate at which capital is substituted for energy is governed by the production function's isoquant as shown in Figure 5 that follows.

Figure 5. The Increased Electricity Savings from Commercial Lighting in 2030



In this case, and drawing from an actual set of lighting technologies that might be available in 2030, we show how changes in consumer preferences might drive changes in the mix of capital and energy, assuming an elasticity of substitution of 0.88.[1] Assuming an electricity price of $24.29 per million Btu (~$0.083 per kilowatt-hour), a starting hurdle rate of 25 percent, and a *Pe/r* ratio of 97.2, a commercial building manager might have selected a lighting technology that costs $60 and consumes 0.166 million Btus (~49 kWh) per year. In some future policy case electricity prices might rise by some amount and preferences might shift as a result of promotional efforts mounted by the EPA Energy Star program (CPPD 2004).

In this case, we assume that electricity rates increase by 30 percent and the 25 percent hurdle rate is reduced to perhaps 20 percent as a result of some small set of programs. In this case the price ratio would increase by ~63 percent. Governed by a 0.88 elasticity of substitution, this change in preferences moves the optimal mix of capital and energy up the isoquant so that the new values are shown as $63.7 and 0.136 million Btus (~40 kWh). In other words, with the lower hurdle

---

[1] Some analysts may be used to seeing smaller elasticities. The reason is that when they use this functional form they apply an elasticity against total productive capital. In AMIGA, however, we estimate elasticities for a much smaller "energy-related" capital or mix of energy technologies. A smaller capital base against the same level of reduction, by definition, would generate larger elasticities. Readers should be cautioned in this regard not to apply the elasticities reported here to any other model since they were estimated directly for this purpose, using specific estimates of capital and energy.

rate, a commercial property manager is willing to increase capital expenditures by $3.7 per lighting unit to save 0.03 million Btus (9 kWh). With new electricity prices of $31.58 per million Btu ($0.108/kWh), the expected payback on this incremental investment is less than 4 years. With commercial lighting technologies (including fixtures and ballasts) having a 12-15 year average life (EIA 2005), a 4-year payback shown in this example suggests a cost-effective investment.

3. TECHNOLOGY CASE STUDY IN HEALTH CARE SECTOR

To pull all of these elements together in a way that illustrates how the larger set of technology decisions enter the model solution, we now highlight the results of an exercise for a single sector of the U.S. economy, in this case *health care*. In beginning this exercise, we combine data from the *hospitals and facilities*, *ambulatory care*, and *social assistance* sectors into a single *health care* sector using the 65-sector Annual Input Output Table (BEA 2004). The resulting base year data for 2004 are summarized in Table 1.

Table 1. Base Year 2004 Healthcare Expenditures (in billions of 2004 dollars)

Input-Output Account	Amount
Total Intermediate Inputs	493
Total Value Added	791
Total Industry Output	1284
Electricity Expenditures	7.85
Nat. Gas Expenditures	2.52

For each of the energy service CES functions in the production hierarchy, Table 2 shows the elasticities of substitutions that we used in the exercise. These are based on our current estimates provided in a variety of engineering data and studies (Hanson and Laitner 2006a).

Table 2. Substitution Elasticities for Hierarchy Functions

	Sigma		Sigma
Value Added	0.51	Space Heating Furnaces	0.39
Lighting Equipment	0.88	Space Heating Aggregate	0.41
Office Equipment	0.92	Space Cooling	0.67
Misc Apparatus	0.87	Space Energy Aggregate	0.20
Elec Water Heater	0.76	Temperature Control	0.65
Gas Water Heater	0.74	Ventilation	0.79
Water Heating Aggregate	0.45	Comfort Index	0.63
Electric Equipment	0.78	Aggregate Energy Services	0.10
Gas Equipment	0.73	KLE Aggregator Z	0.15
Equipment Aggregate	0.54	Materials	0.00
Electric Space Heating	0.43	Sector Output	0.10

Table 3. Year 2030 Scenario Price and Hurdle Rate Assumptions

	Reference Case	Price Only Case	Price and Program Case
Commercial Electricity Price (2004 $/Mbtu)	24.29	31.58	31.58
Commercial Nat. Gas Price (2004 $/Mbtu)	12.72	19.08	19.08
Building Shell Decision Criterion	18%	18%	14%
Ventilation System Decision Criterion	22%	22%	18%
Other Energy Investment Decision Criterion	25%	25%	20%

Table 3 above shows the scenario cases that we ran in terms of delivered electricity and gas prices and investment rates-of-return (i.e., hurdle rate) criteria. In the two policy cases, we increased the electricity price by 30 percent compared to the reference case and we increased the natural gas price by 50 percent, also compared to the reference case. Unspecified energy efficiency programs, which are included in our third case as a complement to the price increases, are represented by a 20 percent decrease in the investment screening criteria or hurdle rate. The building shell and ventilation system energy efficiencies have lower investment criteria since they tend to be integrated into the building construction. The other energy-related appliances and equipment are discrete from the building and are purchased separately. Purchasers tend to lower first costs by reducing non-essential incremental investments (e.g., energy efficiency improvements) when faced with high overall project costs.

In AMIGA the end-use energy consumption is driven by service demands and the amount of investment in energy efficient equipment and buildings. Table 4 shows the service demand drivers. As we described previously in Figures 1 and 2, the service demands flow down the hierarchy, starting with sector output, X, at the top of the tree (derived from demand by households for health care). Sector output, in turn, drives quantities demanded down the production hierarchy, ending at the lowest level to yield energy and capital investment demands.

Table 4, provides a detailed look at the change in service demands for the price only scenario as a means to illustrate key changes within the sector. The model results show that materials change very little in our scenarios; in effect, they are up a mere $0.2 billion as they substitute slightly for more expensive energy services. Our example here also focuses on the aggregator function, Z, which has two components: the main value added and associated energy services. Table 4 shows that Z is down $0.2 billion as it is offset by increased materials usage.

Within Z, value added is up $0.4 billion, but energy services are down $0.2 billion as the higher energy prices generate a downward push on the demand for energy. All the individual energy services are decreased only slightly: lighting; equipment, apparatus, and appliances; and heating and cooling. There is a slight shift away from gas applications toward electrical substitutes as the gas price increases by a greater percentage than the electricity price.

Table 4. Service Outputs for each CES Function in the Hierarchy (Year 2030 Results in billions of 2004 Dollars)

	Reference Case	Price Only Case	Change
Value Added	1275.6	1276.0	0.4
Lighting	6.9	6.8	-0.1
Office Equipment	2.4	2.3	-0.1
Miscellaneous Apparatus	8.4	8.2	-0.2
Elec Water Heater	0.5	0.5	0
Gas Water Heater	1.7	1.7	0
Water Heating Aggregate	2.3	2.3	0
Electric Equipment	1.4	1.4	0
Gas Equipment	0.8	0.7	-0.1
Equipment Aggregate	2.3	2.3	0
Electric Space Heating	1	1	0
Space Heating Furnaces	2.1	1.9	-0.2
Space Heating Aggregate	2.7	2.4	-0.3
Space Cooling	0.9	0.8	-0.1
Space Energy Aggregate	4	3.7	-0.3
Temperature Control	5.5	5.4	-0.1
Ventilation	2.3	2.3	0
Comfort Index	7.3	7.1	-0.2
Aggregate Energy Services	26	25.4	-0.6
KLE Aggregator Z	1297.1	1296.9	-0.2
Materials	729.7	729.9	0.2
Sector Output	2027.8	2027.8	0

Table 5 shows electricity and natural gas end-use demand under the three cases for the year 2030. Electricity consumption is down 73 trillion Btu (11.1%) in the Price-only Case and, for comparison, down 121 trillion Btu (18.4%) in the combined Price & Program Case. Natural gas consumption is down 43 trillion Btu (16.6%) in the Price-only Case and down 59 trillion Btu (22.7%) in the Price & Program Case.

Table 5. Energy Demand by End-Use Category for Three Cases, year 2030

	Ref Case	Price Only Case	Change from RefCase	Percent Change	Price and Programs Case	Change from RefCase	Percent Change
Electricity Use (Trillion Btu)							
Ventilation	52	46	-6	-11.5%	42	-10	-19.6%
Space Cooling	26	23	-3	-11.5%	20	-6	-22.3%
Elec Space Heat	33	30	-3	-9.1%	28	-5	-15.2%
Elec Appliances	26	23	-3	-11.5%	20	-6	-21.5%
Elec Water Heater	18	16	-2	-11.1%	15	-3	-17.8%
Misc Apparatus	230	205	-25	-10.9%	190	-41	-17.6%
Office Equipment	68	60	-8	-11.8%	54	-14	-20.0%
Lighting	203	180	-23	-11.3%	166	-37	-18.1%
Totals	656	583	-73	-11.1%	535	-121	-18.4%

Table 5. Energy Demand by End-Use Category for Three Cases, year 2030 (continued)

Natural Gas Use (Trillion Btu)							
Space Heat Furnace	137	117	-20	-14.6%	109	-28	-20.1%
Gas Appliances	39	31	-8	-20.5%	29	-10	-26.4%
Gas Water Heater	83	68	-15	-18.1%	62	-21	-25.1%
Totals	259	216	-43	-16.6%	200	-59	-22.7%

Table 6 shows the increase in energy-related capital stocks relative to the Reference Case. The Price-only Case induces an additional \$7.6 billion (2004 \$) energy-related end-use investment, whereas the Price & Program Case induces an additional \$16.2 billion energy-related end-use investment. The larger investment categories in order, starting with the largest, are misc. apparatus (e.g., motors and pumps), lighting, building shell, ventilation system, office equipment, and gas water heaters.

Table 6. Year 2030 Change in Energy-Related Capital (billion 2004 \$)

	Price Only Case	**Price and Programs Case**
Ventilation	0.8	1.6
Building Shell	1	2.4
Space Cooling	0.1	0.2
Gas Furnace	0	0
Elec Heating	0	0
Gas Appliances	0.3	0.5
Elec Appliances	0.3	0.7
Gas Water Heater	0.6	1.1
Elec Water Heater	0.2	0.4
Misc Apparatus	1.9	4.1
Office Equipment	0.7	1.5
Lighting	1.7	3.7
Totals	7.6	16.2

Most of the additional investment spending is on equipment, but the building shell improvements are investments in structures. Investment spending stimulates the economy and does not have the large external costs commonly associated with energy use.

4. CONCLUSION

In the illustrative scenarios explored in this paper we have proposed a methodology that preserves the essential character of a variety of energy using end-use technologies within a hierarchical CGE structure. In this hybrid modeling framework, we capture specific end-use technologies at the lowest level of the production tree. In this way we can more accurately represent the collection of opportunities to substitute specific capital investment measures (as well as labor operational changes) which reduce energy use. Although not explained in detail here, we also represent how investment decisions in energy efficiency are typically made and what specific policies and programs can cost-effectively reduce energy and its attendant and environmental damages and other external costs. See Hanson and Laitner (2006a) for more detail in this regard.

APPENDIX

A1. Lighting Technologies Which Define an Isoquant

To illustrate the transformation of actual technology characterizations into a production isoquant, Table A-1 provides a representative sample of commercial lighting technologies designed to provide comparable lighting services together with their annual energy consumption and capital costs. These are drawn from the list of technologies contained in the Energy Information Administration's National Energy Modeling System (EIA 2005).

Table A-1. Commercial Lighting Technologies

Lighting Technology	kWh/Yr	Million Btu	Capital Cost
Incandescent Lamp - 1150 lumens, 75 watts	90.0	0.307	$53.26
Fluor40 T12 - Standard Magnetic Ballast	28.0	0.095	$89.03
Fluor40T12 - Efficient Magnetic Ballast	23.3	0.080	$73.09
Fluor32T8 - Magnetic Ballast	21.0	0.072	$93.59
High Sulfur Lamp	13.8	0.047	$103.55

Several immediate observations are apparent from Table A-1. First, compared to commercial buildings that might now use incandescent lamps or lighting systems, the substituting of high sulfur lamps can reduce electricity consumption for lighting services by 85 percent. At the same time, however, the new technology (anticipated to be commercially available before 2010) is expected to cost about 90 percent more than the standard incandescent system. With commercial electricity prices at about $0.083 per kWh, the expected payback is about 8 years – too long for most businesses, especially since the lives of these technologies are generally on the order of 12 to 15 years. Second, there are some technologies which are both more energy-efficient and which cost less than others (e.g., the efficient magnetic ballasts for the T12 40-watt fluorescents compared to the standard magnetic ballasts for the same lamp). Third, a knowledgeable observer will immediately see that the array of technologies shown here is actually more limited than what is available in the market. Indeed, EIA lists about three dozen separate lighting systems in its database while a review of almost any manufacturer's catalog will suggest hundreds if not thousands of available technologies.

Moreover, there are also operating costs associated with lamp replacements and the associated labor costs to carry out those replacements. In fact, the EIA database suggests that the operating costs can vary by a factor of 30 with the higher costs attributable to incandescent lighting systems. Hence, there are a number of technologies for which non-energy operating costs as well as capital costs must be reflected in the production isoquants. In the highly structured C programming code, AMIGA can easily handle these technology attributes. For purposes of explaining the development of production isoquants, however, the discussion and examples are limited to the tradeoff between capital costs and anticipated gains in energy efficiency.

With the array of technologies shown in Table A-1, and drawing on the system of equations described further in this appendix, we can solve for the elasticity of substitution and other parameters that best characterize the set of technologies that potentially satisfy a given energy service demand such as the need or demand for commercial lighting. This requires a process of fitting a curve that minimizes the sum of squared differences between actual technology costs for each given energy use and the costs implied by a production function and its associated parameters. In the example here, and adjusting alpha, beta, and sigma parameters, the substitution elasticity which minimizes the differences between the capital energy tradeoff for the year 2030 is 0.88. This is, in fact, the value reflected in Table 2 and Figure 5 within the main text of this paper. The discussion following Figure 5 illustrates this point and suggests the kinds of decisions likely to be made given a change in electricity prices and consumer preferences (in this case, the commercial building manager is probably the decision-maker). With the technologies now reasonably defined, we turn our attention to the description of how this technology characterization is integrated into a methodology that captures the essential cost, performance, and impact of investments related to energy service demands.

A2. Functional Forms and Equations to Capture Technology Investment Decisions

In this next section of the appendix we describe the functional forms which relate investments and energy flows as they combine to satisfy given service demands. In other words, we describe the use of existing and emerging technology characterizations as they might be mapped into a wide variety of production isoquants. As we previously noted, technological progress in future time periods will shift the isoquant curve down and to the left to reflect performance improvements and cost reductions; hence all variables are subscripted with the vintage t. This technological change reflects learning from experience with energy efficient technologies, improved economies of scale in producing the technologies, or the penetration of more efficient products into the market for households and firms to select. In short, the isoquant is a reduced form representation of the technology options facing a specific firm or industry sector for a specific energy use. It is a useful analytical structure because it separates technology options from differences in decision criteria. Note that the slope of the isoquant gives the incremental investment necessary to reduce annual energy consumption by one unit. In many cases individual technologies can be identified along an isoquant.

Decision criteria will depend on factors internal and external to the firm. The firm's debt-equity ratio, corporate bond rating, and share price will affect the firm's cost-of-capital. Capital budgeting and decision authority channels within the firm will also affect decisions. Different firms could be distributed along an isoquant because they apply different decision criteria. Recognizing the range of decision criteria allows well-designed policy and programs to influence energy-efficiency investments for industrial equipment.

In analyzing and modeling industrial production systems and program effectiveness, a unit-isoquant is frequently used. By unit-isoquant we mean an isoquant normalized to unit service output, that is, $S_{jt}=1$. This assumption is equivalent to assuming that the production process is constant returns to scale, or what economists call *linear homogeneous*. This assumption is probably sufficiently accurate for most broad situations in which energy-efficiency is analyzed, and this assumption is commonly used in economic models of industry production and energy use. One can think of constant returns to scale as the case where each system or subsystem is ideally sized for new investments and these systems are added as modules. The slope of the isoquant is negative and captures the tradeoff between investing in energy-efficient equipment versus purchasing energy. Mathematically, the slope of the isoquant is given by

$$\left.\frac{dK}{dE}\right|_{\overline{S}} = -F'_E / F'_K \tag{1}$$

where output $\overline{S}$ is held fixed and the underlying production function is denoted by

$$S_{jt} = F_{jt}\,(K_{jt}, E_{jt}). \tag{2}$$

The decision criterion is that dollars should be invested in energy-efficient equipment as long as the capital cost of saving one unit of energy is less than the discounted present value of purchasing one unit of energy over the life of the equipment. The discounted present value formula is the inverse of the capital recovery factor (CRF), which we will denote by r. For a uniform series of annual energy flows, r is given by the formula

$$r = \frac{\varphi\,(1+\varphi)^n}{(1+\varphi)^n - 1} \tag{3}$$

which approaches for long-life equipment. The is the hurdle rate that the firm uses for incremental investments and includes the firm's marginal cost-of-capital and organizational barriers to optimal investment allocations within the firm. A high value for r implies that only energy-efficiency investments with a short payback will be undertaken. The energy-efficient investment decision is then determined by the condition

$$\left.\frac{dK}{dE}\right|_{\overline{S}} = -P_E / r \tag{4}$$

which is the point on the isoquant at which its slope and the factor price ratio are equal, i.e., the tangent point.

Modern computer simulation models (e.g., the AMIGA modeling system) can use a virtually unlimited number of separate isoquants to represent different industrial or commercial subsystems, variations in technology by firm or location, and technical progress. The production steps represented by isoquants can also be combined into hierarchies providing more detail internal to an industrial process. Internal shadow prices for each step in the hierarchy are calculated as unit costs. Based on the decision criteria applied, factor ratios can be calculated at each step in the production hierarchy. The most common functional form used for representing the production function and its associated isoquants is the Constant Elasticity of Substitution (CES) production function (Kemfert 1998; Varian 1992).

In AMIGA we use the CES production function to build the subsystems of major industrial processes as shown in Figures 2 and 3 of the main text. The CES production function is given by

$$S = A((K / \alpha)^{-\rho} + (E / \beta)^{-\rho})^{-1/\rho} \tag{5}$$

where A is a shift or productivity parameter, α and β are related to cost shares, and ρ captures the elasticity of substitution between factors K and E, given by

$$\sigma = \frac{1}{1+\rho}. \tag{6}$$

As a function of the factor price ratio and output S, we can write the energy and capital factor demands as follows:

$$D = \alpha^{1-\sigma} + \beta^{1-\sigma}\left(\frac{P_E}{r}\right)^{1-\sigma} \tag{7}$$

$$K^* = \alpha^{1-\sigma} D^{1/\rho} S / A \tag{8}$$

$$E^* = \beta^{1-\sigma}\left(\frac{P_E}{r}\right)^{-\sigma} D^{1/\rho} S / A \tag{9}$$

ACKNOWLEDGMENTS

This work has been supported by the U.S. Environmental Protection Agency's Office of Atmospheric Programs and the National Energy Technology Laboratory through separate interagency agreements with the U.S. Department of

Energy. The Energy Foundation has also contributed funds in support of this paper. However, none of the conclusions contained in this paper should be construed as the opinion of the Argonne National Laboratory, the US Government, or the Energy Foundation. The usual disclaimers apply.

REFERENCES

Brown, Marilyn, (2001). "Market Failures and Barriers as a Basis for Clean Energy Policies." *Energy Policy*, volume 29, pp. 1197–1207.

[BEA 2004] Bureau of Economic Analysis (2004). "Benchmark Input-Output Accounts for the U.S. Economy 2002," Washington, DC: U.S. Department of Commerce.

[CPPD 2004] Climate Protection Partnerships Division (2004). "Protecting The Environment—Together Energy Star and Other Voluntary Programs Climate Protection Partnerships Division (CPPD) 2003 Annual Report." US Environmental Protection Agency, Washington, DC.

[EIA 2005]. Energy Information Adminustration (2005). "AEO 2006 Reference Case Tables and Technology Files for Buildings Sector," Data file used as an input into the National Energy Modeling Systems, U.S. Department of Energy, Washington, DC, December 2005.

[GTAP 2004] Global Trade and Analysis Project (2004). College of Agriculture, Department of Agricultural Economics, Purdue University, West Lafayette, IN.

Hanson, Donald A. and John A. "Skip" Laitner (2004). "An Integrated Analysis of Policies That Increase Investments in Advanced Energy-Efficient/Low-Carbon Technologies." *Energy Economics*, 2004, *26*(4), pp. 739-755.

Hanson, Donald A., and John A. "Skip" Laitner (2005). "Tripling the Nation's Clean Energy Technologies: A Case Study in Evaluating the Performance of Energy Policy Models," 2005 ACEEE Summer Study on Energy Efficiency in Industry. Washington, DC: American Council for an Energy-Efficient Economy.

Hanson, Donald A., and John A. "Skip" Laitner (2006a). *The AMIGA Modeling System, Version 4.2: Disaggregated Capital and Physical Flows of Energy within a General Equilibrium Framework,* Argonne National Laboratory, Argonne, IL (draft).

Hanson, Donald A., and John A. "Skip" Laitner (2006b). "Technology Policy and World Greenhouse Gas Emissions in an Economy-Wide Model." *Energy Journal* (forthcoming).

[IEA 2004] International Energy Agency's, 2004 *World Energy Outlook 2004*. Paris, France.

Kemfert, Claudia (1998). "Estimated Substitution Elasticities of a Nested CES Production Function Approach for Germany," *Energy Economics,* 1998, 20, pp. 249-264.

Laitner, John A. "Skip", Donald A. Hanson, Irving Mintzer, and Amber J. Leonard (2006). "Adapting in Uncertain Times: A Scenario Analysis of U.S. Energy and Technology Futures." *Energy Studies Review,* 2005, 14(1), pp. 120-135.

Laitner, John A. "Skip", and Alan H. Sanstad (2004). "Learning-by-Doing on Both the Demand and the Supply Sides: Implications for Electric Utility Investments in a Heuristic Model," *International Journal of Energy Technology and Policy*, 2004, *2*(1/2), pp. 142-152.

Laitner, John A. "Skip", Stephen J. DeCanio, Jonathan G. Koomey, and Alan H. Sanstad (2003). "Room for Improvement: Increasing the Value of Energy Modeling for Policy Analysis," *Utilities Policy* 11 (2003), pp. 87-94.

Lancaster, Kelvin (1971). *Consumer Demand: A New Approach*, Columbia University Press, New York.

McDonald, Alan and Leo Schrattenholzer (2001). "Learning Rates for Energy Technologies." *Energy Policy*, *29*, pp. 255-261.

Munson, Richard (2004). "Improving Prediction of Energy Futures." *Issues in Science and Technology*, Spring, pp. 26-29.

Nadel, Stephen, and Howard Geller (2001). *Energy Efficiency Policies for a Strong America*, Washington, DC: American Council for an Energy Efficient Economy, September.

Sanstad, Alan H., John A. "Skip" Laitner, and Jonathan G. Koomey (2006). "Back to The Future: Long-Range U.S. Energy Price and Quantity Projections in Retrospect," *International Journal of*

Energy Technology and Policy (in review).

Varian, Hal R. (1992). *Microeconomic Analysis*, Third Edition, W.W. Norton & Co., New York.

Wene, Clas-Otto (2000). *Experience Curves for Energy Technology Policy*. Paris, France: International Energy Agency.

Worrell, Ernst, Stephan Ramesohl, and Gale A. Boyd (2003). “Towards Increasing Policy Relevance in Energy Modeling, *Proceedings of the 2003 ACEEE Summer Study on Energy Efficiency in Industry*, American Council for an Energy-Efficient Economy, Washington, DC.