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The AMIGA Modeling System, Version 4.2: Disaggregated Capital and Physical Flows of Energy within a General Equilibrium Framework

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This report provides documentation of the structure and assumptions that underpin version 4.2 of the Argonne National Laboratory's AMIGA modeling system. The first versions of the AMIGA model were supported by Phil Patterson, in the former Office of Transportation Technologies (OTT) within the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE). Eric Petersen, Brian Card, and David Patton of the DOE Office of Energy Efficiency and Renewable Energy also provided support for versions 1 and 2 of the model. In 1997 the U.S. Environmental Protection Agency's (EPA) Office of Atmospheric Programs (OAP) began an active support and development of versions 2, 3 and 4 of the modeling system. OAP and DOE's National Energy Technology Laboratory provided additional support for this current version of the model.

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ABSTRACT: AMIGA MODELING SYSTEM, VERSION 4.2

The **A**ll-**M**odular **I**nterindustry **G**rowth **A**ssessment (AMIGA) modeling system is a general equilibrium model that examines the impact of changes in 200 individual sectors in both dollar value and, where appropriate, in physical units. Programmed in the highly structured C language, AMIGA integrates a detailed energy end-use and energy supply market specification within a structural economic model. AMIGA calculates prices and macroeconomic variables such as consumption, investment, government spending, gross domestic product (GDP), and employment. The model provides annual equilibrium paths from the present through the year 2100.

AMIGA integrates eleven modules that describe the various economic interactions among twenty-one world regions, including the United States. Each of the region's assets includes 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 technology representation in the demand for energy and the many other goods and services sectors available with regional markets together with a detailed interaction among those sectors and among the regions of the world. Various choices within these sectors are modeled through nested constant elasticity of substitution (CES) production functions. The CES production functions determine how economic output is supported through inputs of capital, labor, electric and non-electric energy, and other materials, commodities, and services.

AMIGA tracks a number of greenhouse gas emissions which result from the production of goods and services within the economy and which have been identified as contributing to potential climate change impacts. In addition to the production of energy-related carbon dioxide (CO_2), the AMIGA emissions inventory includes non-energy CO_2 (e.g., cement and other industrial processes), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorcarbons (PFCs), and sulfur hexafluoride (SF_6). The atmospheric impacts from these gases are estimated using the MAGICC model; or more formally, the Model for the Assessment of Greenhouse–gas Induced Climate Change. AMIGA also tracks the so-called criteria air pollutants generated by electricity production. The model allows for autonomous improvements in technologies as well as improvements driven by price and non-price policies which can lead to reductions in energy consumption as well as greenhouse gas emissions and the so-called criteria air pollutants. Finally, AMIGA incorporates macroeconomic feedbacks as changing resource costs and household income all impact the demand for capital, labor, and energy.

1. INTRODUCTION

1.1 Perspectives on the AMIGA Modeling System

The **A**ll-**M**odular **I**nterindustry **G**rowth **A**ssessment (AMIGA) modeling system is a general equilibrium model of the United States and the world economy that introduces new capabilities into the modeling of economic, energy and environmental policies. Many of these capabilities pertain to the explicit representation of technologies and technology policies within the transportation, building, industry, and electric generation sectors. To that extent, AMIGA also includes the ability to reflect and evaluate both price and a variety of non-pricing energy and climate policies. The non-pricing policies, generally ones designed to promote efficiency improvements in the energy end-use and energy supply sectors, include research & development (R&D) programs, energy performance standards, tax and other fiscal incentives, and a wide array of voluntary programs.

The AMIGA modeling system has several major objectives. One is to provide policy makers with an equilibrium model and analytical tool to better understand market behavior and dynamics through the many interactions within the U.S. and the rest of the world. Another objective is to undertake economic impact studies, especially as they relate to energy and climate change policies. Sensitivity analyses and alternative scenarios also can be run. Although AMIGA applies default assumptions that characterize a reference or business-as-usual projection, any of the economic driver variables and technology characterizations can be changed so that we can observe the response patterns suggested by the model structure. As an example, the model can explore the impact of investing in new end-use energy efficiency technologies or advanced fossil fuel power plants which can reduce carbon dioxide emissions. The impacts range from changed investment and consumption patterns (the latter most affected by potential energy bill savings) to reduced pollution control expenditures and higher prices.

Packages of energy and environmental-related policies can be designed and then simulated within the AMIGA system — yielding economic assessments of their resulting impact across different sectors and world regions. In the area of climate policy analysis, for instance, analysts often use some form of a price signal as a general strategy to reduce greenhouse gas emissions. These Pigouvian prices[1] which are high enough to meet a desired environmental objective are likely to also result in other adverse economic consequences, including:

- significant transfers of income out of firms in some sectors,
- unintended competitive effects in an open economy, and

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[1] Named for English economist Arthur Cecil Pigou, the so-called Pigouvian prices refer to normal commodity prices plus a tax levied on the producer to reflect the social cost of an externality. In this case of the AMIGA modeling system, the externalities would generally reflect environmental costs associated with energy production and consumption.

- regressive impacts on the distribution of household income (Baumol and Oates 1988).

Relying only on higher prices to correct externalities may be ruled out on political grounds (e.g., the unpopular gasoline tax) and may be less preferred by society compared to a package of policies that include other programs and measures.[2] Many of these strategies target a variety of cost-effective actions which can generate additional benefits such as reducing other pollutants, reducing wastes, or increasing production throughput in an industrial facility.

The AMIGA model is intended to address several kinds of questions that involve real resource allocation, relative growth (or decline) in specific activities or economic sectors, shifts in relative prices and the resulting incentives for substitutions, and the role for technology related programs.[3] AMIGA can be used to examine "what if" questions regarding technology policy, such as potential economic effects of federal government R&D co-funding with business;[4] investment tax credits (ITCs) or other measures to promote adoption of improved technologies; and minimum performance standards for some technologies.[5]

The evidence suggests that markets and institutions do not operate perfectly with respect to the dynamic processes of innovation and technology adoption (Brown 2001, Goldberg 2003, Sanstad and Howath 1994, and DeCanio 1993). These imperfections result in underinvestment in innovation in the economy as a result of the difficulty faced by inventors in capturing the benefits by the inventors. The lock-in of inferior technologies and principal-agent costs within organizations also contribute to existing imperfections. Given these "real-world" circumstances, well-designed public policies could yield a more efficient allocation of resources with net social benefits and a higher rate of economic growth. The businesses and households that adopt measures encouraged by these policies may be better off. If the adopted cost-effective technologies are more energy efficient, generate less waste, and are less polluting, then there will be gains in environmental quality and protection as well.

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[2] Existing programs shown to be cost-effective include Energy Star, industrial energy audits and assessments, promotion energy efficient buildings, Motor Challenge, Steam Challenge and other and voluntary programs run by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE).

[3] An important policy strategy is the replacement of some of the current distorting taxes on incomes and payrolls with more efficient taxes on activities with attendant external damages, i.e., pollution taxes or tradable permit systems.

[4] For example, the DOE Industries of the Future, FutureGen, and Freedom Car programs.

[5] Other policies include building code revisions, energy efficient mortgages and other financing programs, incentives to purchase energy efficient capital goods (e.g., revenue neutral "feebates" on appliances, heating and air conditioning equipment, and light duty vehicles), flexible CAFE and equipment standards, use of cellulose derived biomass transportation fuels, and government procurement of energy efficient technologies.

The kinds of questions posed above are generally addressed in the context of maintaining a growing economy. This way of using the model is supported by large number of studies that provide detailed information on the costs and benefit of technology-based, market-oriented solutions which increase the productive use of energy both here in the United States and worldwide (see, for example, Energy Innovations 1997, Interlaboratory Working Group 2000, Nadel and Geller 2001, Barrett et al. 2002, and Krause et al. 2002).

1.2 History of the AMIGA Modeling System

This documentation supports version 4.2 of the AMIGA Modeling System and is the version being used in the current Energy Modeling Forum 22, the Long Term Emission Scenarios exercise. Version 1.0 was a strictly U.S.-based energy-economic framework developed for U.S. Department of Energy's Office of Transportation Technologies (OTT) in the Office of Energy Efficiency and Renewable Energy. At that time, the model had a 2020 time horizon and was used for preparing the OTT research and development report to Congress. Version 2.0 included carbon emissions and tracked the Energy Information Administration's (EIA) National Energy Modeling System (NEMS) technology characterization and reference case assumptions as they were used to prepare the Annual Energy Outlook (EIA 2005). Its first use as a policy evaluation tool was in support of the Clean Energy Future (CEF) analysis released in November 2000 (Interlaboratory Working Group 2000).

Version 3.0 incorporated the Argonne Unit Planning and Compliance model and incorporated sulfur dioxide (SO_2), nitrogen oxide (NO_X), and mercury (Hg) emissions. An emission trading capability was also introduced with version 3.0 and used for the so-called Jeffords-Lieberman analysis (EPA 2001) and the EMF-19 scenarios (Hanson and Laitner 2004). Version 3.1 increased the representation of the transportation sector with a 2050 time horizon and was used to produce analyses for the Pew Climate Center (Mintzer, Leonard, and Schwartz 2002), the Keystone Center (2002), and the EPA-Argonne Energy Future Scenarios (Laitner et al. 2006, forthcoming). Finally, version 4.0 added the other (Non-CO_2) greenhouse gases (Delhotal et al. 2004) and the other regions of the world with a time horizon out to 2100. This was the platform used to evaluate the International Energy Agency's World Energy Outlook 2004 (IEA 2004). Version 4.1 included the MAGICC atmospheric feedback model (Wigley 2003) while version 4.2 now includes the MARS module, or the Macro Analysis of Refinery Systems (Marano 2005).

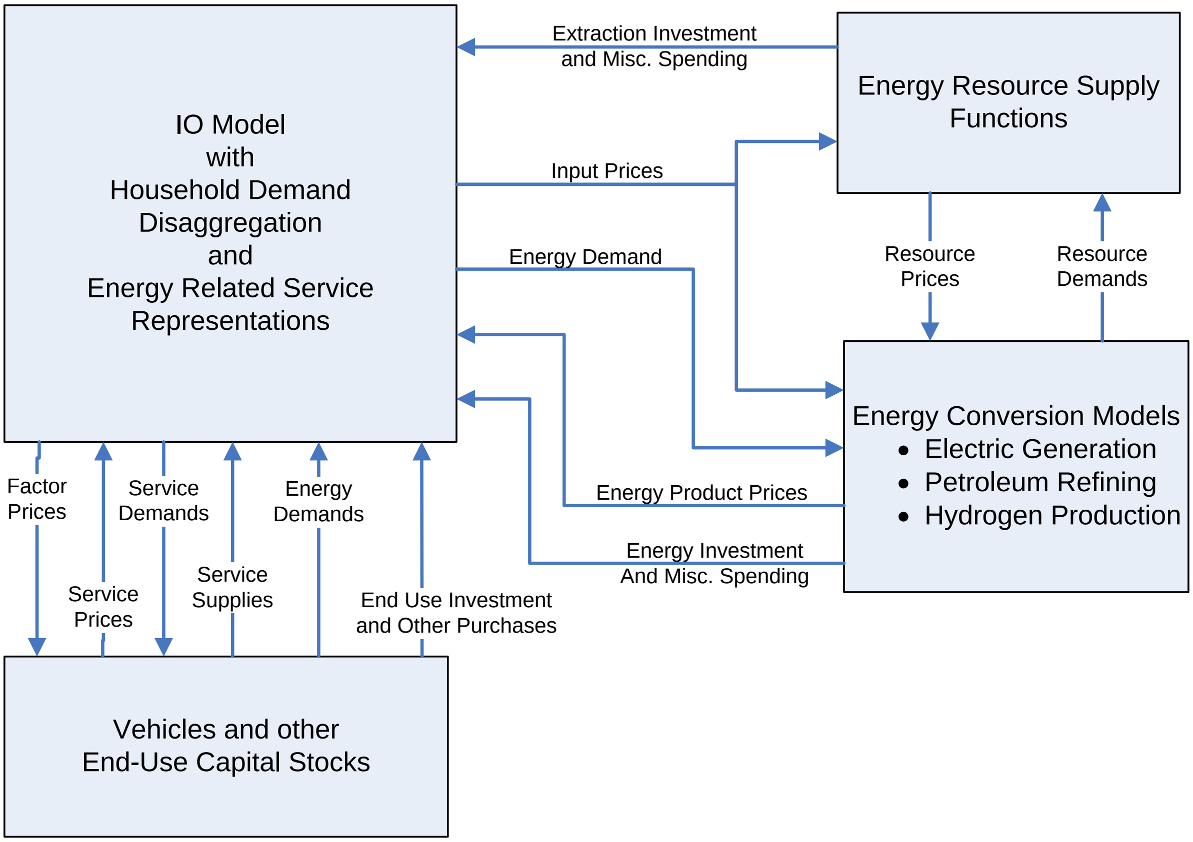
1.3 Overview of the Modeling System

In evaluating the various energy and climate policy scenarios, AMIGA integrates a number of modules that describe the various economic interactions among twenty-one world regions, including the United States. This modular approach facilitates a detailed accounting of the major goods, services, and technologies demanded by households and the various production sectors of the economy that lead to changes in energy production and consumption, greenhouse gas emissions, and resulting temperature changes. The modules include:

- Household Consumption
- Service Sectors and Government
- Buildings Capital Stock
- Process Transformations
- Product Manufacturing Activities
- Industrial Capital Stock
- Vehicle Stock and Transportation Services
- Electricity Supply Capacity and Generation
- Natural Gas Supply
- World Oil Pricing
- Non-carbon Greenhouse Gases

Figure 1-1 shows the linkages that form the core of the AMIGA modeling system.

Figure 1-1. Block Diagram of the AMIGA Modeling System



Household demand for goods and services is based on consumer preferences, the relative prices of delivered goods, and permanent income. Personal transportation and housing-related services are among the services that households demand.

The buildings capital stock module supplies both the housing and commercial building related services. In meeting the household demand, the module allows the average efficiency of household appliances, equipment, and residential structures to change with time. The module represents existing housing and appliance stocks, available new technologies, and near commercialized technologies soon to be available.[6] This view of households is consistent with the theory of Kelvin Lancaster (1971) who considered consumer preferences to be expressed in terms of the characteristics of, and services derived from, the durable and nondurable goods that households purchase and use. In a classic paper, Hausman (1979) characterized energy as a derived demand of providing common household services.[7]

The buildings capital stock module also supplies floorspace and capital equipment services to the service and government sectors module. These sectors include personal and business services, administrative offices, wholesale/retail trade, warehousing, financial services, schools and hospitals. Also in this module, the penetration of more efficient technologies can lower the cost of supplying energy-intensive building services. Both the residential and commercial buildings and appliances modules use a vintage approach with newer more energy-efficient capital entering the stock to meet expanded demands and to replace older buildings and equipment. Government purchases are assumed to be independent of the scenario, with exceptions such as energy purchases (which are based on the energy efficiency of the stock of equipment used by government agencies) and energy or climate-related Research and Development (R&D) or program expenditures.

The motor vehicle module uses a vehicle stock vintage approach to account for the distribution of characteristics of the fleet of operating vehicles. This module provides personal transportation services to households, business, and federal, state and local

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[6] Cost reductions for a new generation of technology often occur from learning (as a function of cumulative output) and scale economies in distribution. A market transformation may also occur as lower efficiency products are displaced, since scale economies impose an upper limit to the number of products in a particular market.

[7] Hausman writes that "[m]ost demand for energy at the household level is a derived demand of other activities: transportation, services of household appliances, and heating and cooling provide examples. Thus, energy demand may be viewed usefully as part of a 'household' production process in which the services of a long-lived consumer durable good are combined with energy inputs to produce household services. From this perspective, two important components of energy demand emerge. First, the technological design of the consumer durable determines required energy input per unit of household service output. Automobiles, home air conditioners, and home heating systems provide three examples where important differences exist across models in required energy inputs. The second aspect of energy demand is the utilization of the household capital stock. The number of automobile trips, summer and winter house temperatures, and utilization of other household appliances determine the demand for final services, and thus total household energy demand" (Hausman, 1979).

governments. If new vehicles have higher fuel economy, the average efficiency of the fleet will increase.

The electricity generation module includes the Argonne Unit Planning and Compliance model that captures a wide variety of technology characteristics within the electric generating sector. This includes a database with all electric generating units operated within the U.S. and a system dispatch routine that allows the retirement and the dispatch of units on the basis of traditional cost criteria as well as the impact of various permit prices on operating costs. It also includes non-utility generation sources such as industrial combined heat and power applications, renewable energy and other decentralized generation systems. The costs of sulfur dioxide, nitrogen oxide, and mercury emission allowances and any future greenhouse gas emission charge would be included in variable costs, which can change the loading order among units with different heat rates or different fuel types.[8] New capacity expansion decisions are based on life-cycle costing. The model can impose the Renewable Portfolio Standard (RPS) and public benefits programs that are part of the federal electricity deregulation act.

AMIGA is a technology-rich model that includes hundreds of supply and demand-side technologies. Production is structured as a hierarchy as illustrated in Figure 1-2. These include detailed residential and commercial building technologies, more than 200 vehicle and other transportation technologies, and more than two dozen new electric generation technologies (in addition to the 2000 existing power plants in the current database). All technology characterizations are drawn initially from the Energy Information Administration's National Energy Modeling System (NEMS) database for the building, transportation, and electricity generation sectors (EIA 2003).

The performance and cost characterization generally includes capital cost, energy consumption, and operating and maintenance costs (if any). However, NEMS does not provide investment characteristics of technologies within its industrial module. Here we turn to a variety of engineering assessments to estimate the incremental investments associated with different end-use efficiencies. These include detailed technology cost characterizations developed by New York State Energy Research and Development Authority (NYSERDA 2004), Lawrence Berkeley National Laboratory (Martin et al. 2000), University of Michigan (Ross et al. 1993), and Sachs (2004), among others. This is cross-checked with other studies that provide detailed characterization of industrial end-use technologies (e.g., STAPPA-ALAPCO 2000, and US EPA 2001b). Depending on the policy scenario, the technology characterizations can be modified in all sectors to reflect either new technologies which might emerge in later years or the improved performance of existing technologies as they might be affected by the specific set of price and non-pricing policies reflected in a given modeling exercise.

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[8] Tradable carbon permit programs or emission charges could be applied selectively (say, to fossil-fuel electric generation to encourage the dispatch of lower carbon generators before higher carbon generators).

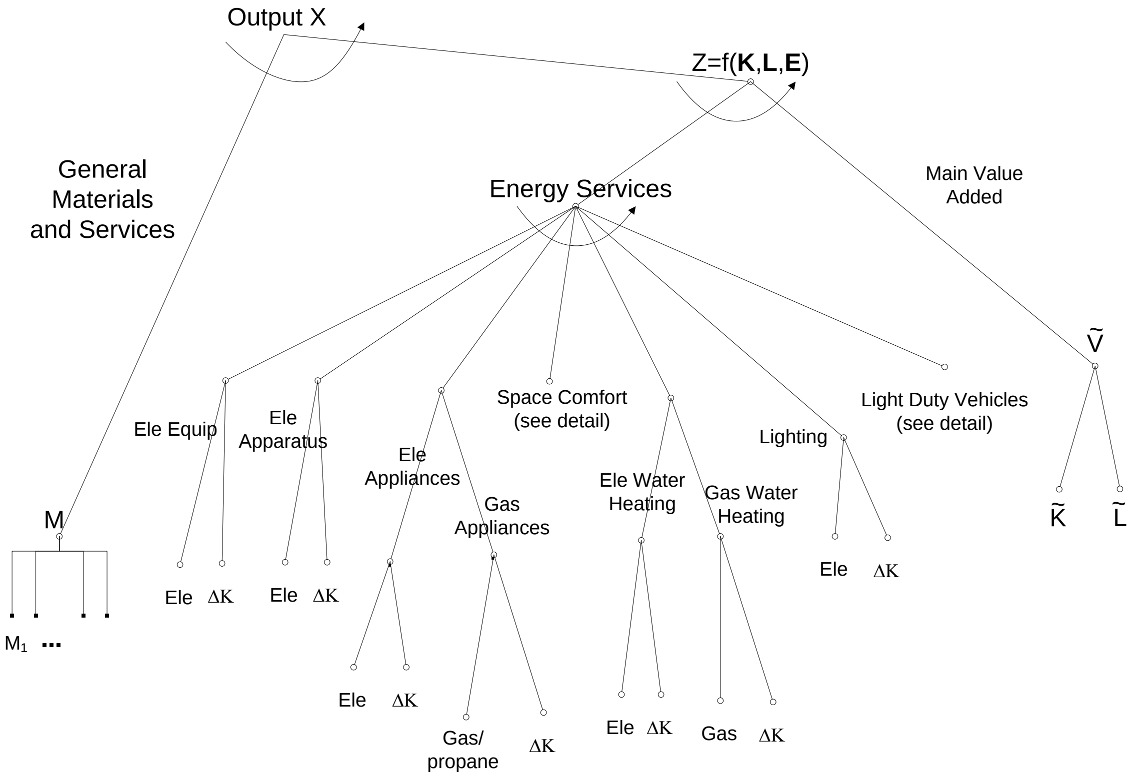

Figure 1-2. Hierarchical flow diagram of commercial/industrial production.

There are six household consumer groups in the model, as shown in Table 1-1.

Table 1-1. Distribution of Consumers, 2004

Consumer Group	Population 16 & up	Percent Population	Income Percent
Low income	57.3	25%	7.9%
Lower Middle	57.3	25%	16.5%
Middle income	57.3	25%	25.7%
Early Adopters	6.9	3%	5.2%
Upper Middle	27.5	12%	20.7%
Very High	22.9	10%	24.0%
Totals	229.1	100%	100%

The top quarter (upper middle group including early adopters, and very high income group) accounts for about half of consumption spending.

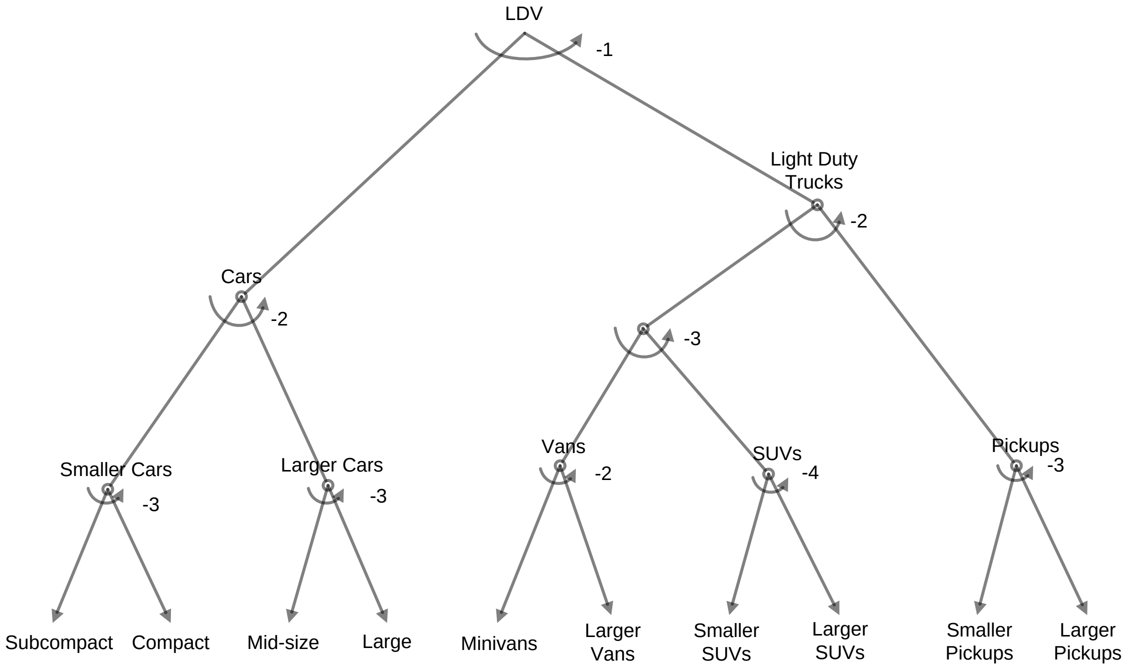

Figure 1-3. Hierarchy of household consumer vehicle demand by size-type.

As income has risen in past decades, and as it is expected to continue to rise, households have been spending more on larger more powerful vehicles. Hence vehicle choice is an important part of a climate policy model. The AMIGA model contains ten vehicle size types as shown in the choice hierarchy in Figure 1-3. It also provides these sizes for a variety of powertrains including HEVs, FCVs, and higher performance LDVs. Households with different incomes and different access to capital each make their own decisions. An interesting statistic is that new car buyers have an income 1.8 times the US average. So it is the higher income groups that are largely putting new vehicles on the road.

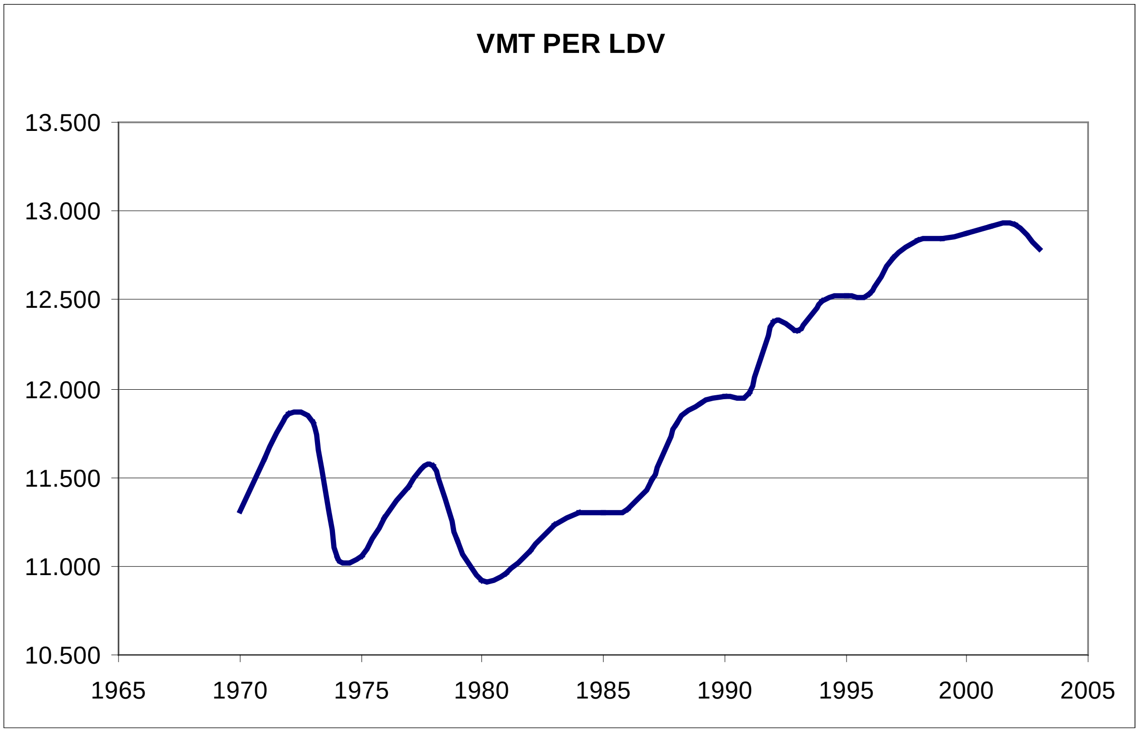

Figure 1-4. VMT per vehicle has shown price and income sensitivity historically.

It is important that a climate policy model can represent the effects of energy price changes and incomes on VMT and vehicle purchases. The AMIGA vehicle model does that. Historically fuel prices and income changes have effected the VMT per vehicle as shown in Figure 1-4.

1.4 Model Design Philosophy and Programming Code

We have devoted considerable effort into creating a well-structured design and implementation of the system. We follow the view of Press *et al*. (1992), "…that practical methods of numerical computation can be simultaneously efficient, clever, and – important – clear." As is often the case with large, integrated modeling systems, key components of the system are organized into separate modules. A module is made up of one or more data objects and several program routines which operate on the data objects. The individual modules are programmed in the highly structured C language. Outputs of modules may be inputs to other modules.

In addition, AMIGA has a main system control module (i.e., an operating shell also programmed in the C language) which executes the other modules in an orderly manner to insure overall convergence to a general equilibrium solution.
The program solves a system of equations, mostly linear but some nonlinear. An entire module is not executed at once. Rather, all the cost and price routines are called from

every module, and then later sector quantity routines are called from all the modules, and so on. After the model has converged, then one may write output reports. The AMIGA system has both detailed and summary report writers also programmed in C and which exports its results as an Excel Workbook.

The AMIGA system can handle hundreds of different sectors, subsector activities, and capital stocks. It reads in lists of activities and types of capital stocks exogenously so a user may easily change the model configuration to work with a more aggregated set of economic sectors or a more detailed breakdown of activities. Sectors of particular interest for study can be disaggregated as desired. For example, automobile manufactures and its suppliers can be studied in detail while embedding these sectors within a representation of the entire or balance of the economy. The effects of the level of aggregation can be explored. One may also examine the question of the importance of sectoral shift on aggregate behavior.

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2 STEPPING THROUGH THE MODEL EQUATIONS

2.1 Brief Statement of the Problem to be Solved

The problem is to solve market clearing equations simultaneously for all the goods and services represented in the model, where supplies and demands may depend on various prices, activity levels, incomes, and other endogenous and/or exogenous variables. The labor market plays a special role in that achieving full-employment is associated with maximizing economic output subject to constraints.

Where markets are competitive and in long-run equilibrium, prices equal long-run marginal costs. The sub-problem of solving for prices is a simultaneous equation specification because input cost to one sector or activity will depend on the price of that input which is produced in another sector. For natural resources like natural gas and water, prices will depend on supply and production rates, and sometimes rents due to limited capacity or opportunity costs.

Disaggregated, specific capital for producing energy-intensive services can be viewed as putty-clay where new investments are malleable, but existing stocks have fixed or predetermined factor ratios. Energy-intensities can sometimes be changed by retrofitting long-lived equipment or structures. Also facility or equipment operations can sometimes be changed in response to energy price changes. For example, existing vehicles are operated less on average than new vehicles. Existing building shells and lighting systems can be retrofitted to achieve higher energy-efficiency. Power-plants are operated according to their variable costs.

Below, we describe the model equations presented in the order in which they are solved as the model iterates to a general equilibrium solution. Price equations are solved first. Next we solve factor intensities which depend on prices. Finally, all the quantity levels are solved subject to full employment in the economy. Table 2-1 provides notation and definitions for model variables and parameters. Figure 2-1 shows the general structure of production applicable to most sectors of the model. Prices are solved up the hierarchy, factor intensities are solved on each branch, and quantities are solved down the hierarchy.

Table 2-1. Notation for Variables and Parameters

Value Added Function

i	Index for industry or commercial sector
$\tilde{K}_i$	Main capital stock, industry *i*.
$\tilde{L}_i$	Main labor input, industry *i*.
$\tilde{V}_i$	Main value added, industry *i*.
$\left\langle \frac{\tilde{K}}{\tilde{V}} \right\rangle_i$	Capital-intensity of main value added, industry *i*.
$\left\langle \frac{\tilde{L}}{\tilde{V}} \right\rangle_i$	Labor-intensity of main value added, industry *i*.
$\tilde{\sigma}_i$	Capital-labor elasticity of substitution in main value added, industry *i*.
$\tilde{\theta}_i$	Base-year capital calibration parameter, industry *i*.
$\tilde{\alpha}_i$	Parameter for units scaling and capital-augmenting technical change.
$\tilde{\phi}_i$	Base-year labor calibration parameter, industry *i*.
$\tilde{\beta}_i$	Parameter for units scaling and labor-augmenting technical change.
$\tilde{A}_i$	Parameter for value added output scaling and neutral technical change.
$\tilde{D}_i$	Common denominator for value added factor demands, industry *i*.
$CCAP_i$	Cost-of-capital, industry *i*.
$WAGE_i$	Wage rate, industry *i*.
PVA_i	Price index for value added, industry *i*.

Energy Service Functions in Industry i

b	index over decision-criteria used in industry *i*.
$ENERG_j^{bi}$	Energy (e.g., gas or electricity) used in service *j*.
ESK_j^{bi}	Specific capital for energy service *j*.
ESQ_j^{bi}	Energy service output *j*.
$\left\langle \frac{ENERG}{ESQ} \right\rangle_j^{bi}$	Energy-intensity of new service equipment *j*.
$\left\langle \frac{ESK}{ESQ} \right\rangle_j^{bi}$	Capital investment per unit of service *j*.
$sigma_{ji}$	Energy-capital elasticity of substitution for energy service *j*.
$Theta_{ji}$	Base-year technology capital calibration parameter for energy service *j*.

$Alpha_{ji}$	Parameter for units scaling and capital-augmenting technical change.
Phi_{ji}	Base-year technology energy calibration parameter for energy service *j*.
$Beta_{ji}$	Parameter for units scaling and energy-augmenting technical change.
ESA_{ji}	Parameter for energy service output scaling and neutral technical change.
ESD_j^{bi}	Common denominator for factor demands for energy service *j*.
$ACCAP_{bi}$	Average cost-of-capital for decision group *b*, industry *i*.
$MCCAP_{bi}$	Marginal cost-of-capital for decision group *b*, industry *i*.
PE_j^i	Price of energy for service *j*, industry *i*.
ESP_j^{bi}	Price index for energy service *j*, industry *i* with criteria *b*.

Energy Service Aggregator Functions in Industry i

j	index over energy services used in industry *i*.
ESQ_j^i	Energy service quantity *j*.
$ESQIndex_i$	Aggregate index of energy service output.
$\left\langle \frac{ESQ_j}{ESQIndex} \right\rangle_i$	Ratio of energy service *j* to the aggregate quantity.
σ_i''	Aggregator of energy services elasticity of substitution industry *i*.
θ_{ji}''	Base-year capital calibration parameter, industry *i*.
α_{ji}''	Parameter for units scaling and capital-augmenting technical change.
A_i''	Coefficient set to 1.0.
D_i''	Common denominator for energy service demands, industry *i*.
$ESPIndex_i$	Aggregate energy service price index, industry *i*.

Top Level Aggregators for Industry i

Z_i	The KLE aggregation, industry *i*.
$\vec{M}_i$	Materials and purchased services vector, industry *i*.
X_i	Activity or sector output, industry *i*.
$\left\langle \frac{ESQIndex}{Z} \right\rangle_i$	Energy services intensity, industry *i*.
$\left\langle \frac{\tilde{V}}{Z} \right\rangle_i$	Value added intensity, industry *i*.

$\left\langle \frac{Z}{X} \right\rangle_i$	KLE-intensity, industry *i*.
$\left\langle \frac{\vec{M}}{X} \right\rangle_i$	Purchased materials and services intensity, industry *i*.
$\hat{\sigma}_i$	Energy services vs. value added elasticity of substitution, industry *i*.
$\hat{\pi}_i$	Base-year energy service share parameter, industry *i*.
$\hat{\gamma}_i$	Parameter set to 1.0.
$\hat{\psi}_i$	Base-year value added share parameter, industry *i*.
$\hat{\upsilon}_i$	Parameter set to 1.0.
$\hat{A}_i$	Coefficient set to 1.0.
$\hat{D}_i$	Common denominator for Z's factor demands, industry *i*.
$\hat{\hat{\sigma}}_i$	Materials/services vs. KLE elasticity of substitution, industry *i*.
$\hat{\theta}_i$	Base-year KLE calibration parameter, industry *i*.
$\hat{\alpha}_i$	Parameter for KLE technical change.
$\hat{\phi}_i$	Base-year *M* calibration parameter, industry *i*.
$\hat{\beta}_i$	Parameter for industry de-materialization trends.
$\hat{\hat{A}}_i$	Parameter for sector output scaling and neutral technical change.
$\hat{\hat{D}}_i$	Common denominator for *X*'s factor demands, industry *i*.
PZ_i	Price index for aggregate *Z*.
PM_i	Price index for aggregate materials & purchased services, *M*.
PX_i	Price index for sector output.
M_{gi}	Quantity of good (or service) *g* purchased by industry *i*.
a_{gi}	Share of good (or service) *g* purchased by industry *i*.

Sector and Energy-Service Household Demands

$MakeShr_{ig}$	Share of good *g* made by industry *i*.
$Pprod_g$	Price of good (or service) *g* in producer prices
h	index over household income groups
PD_d^h	Household price of demand item *d*.
PD_{d0}^h	Base year household price of demand item *d*.

$Basedmd_d^h$	Base year market share for demand item *d*.
$\breve{\alpha}_d$	Elasticity related parameter in household demand functions.
B_h	Expenditure budget for household *h*.
B_{h0}	Base year expenditure budget for household *h*.
QD_d^h	Quantity demanded of item *d* by household *h*.
$Qpurch_g^h$	Quantity purchased of good *g* by household *h*.
$HHQpurch_g$	Quantity purchased of good *g* by all households.
$HHQprod_g$	Induced demand for producers' output, transportation, and markups.
m	Index for transportation, wholesale trade and retailing markup sectors.
$hmuwt_{gm}$	Transportation & retailing markup weight for household sales
$NORMB_{ht}$	Normalization deflator for household *h* demands.
$\left[\dfrac{B_{ht}}{NORMB_{ht}}\right]$	Normalized expenditure budget for household *h*.
PE_j	Household price of the energy type used in service technology *j*.
QE_j^h	Household energy use in service technology *j*.
$PDLD_{ZD,t}^h$	Level "D" vehicle services price for size-type *ZD* on the tree.
$PDLE_{ZE,t}^h$	Level "E" vehicle services price for size-type *ZE* on the tree.
$PDLE_{ZE+1,t}^h$	Level "E" vehicle services price for size-type *ZE+1* on the tree.
$BasePDLE_{ZE}^h$	Base year level "E" vehicle services price for size-type *ZE*.
$\vartheta_{E,ZE}^h$	Unit demand function for services from vehicle size-type *ZE*.
$\vartheta_{E,ZE+1}^h$	Unit demand function for services from vehicle size-type *ZE+1*.
$BasevdmdE_{ZE}^h$	Base year vehicle service demand for vehicle size-type *ZE*.
ε_{ZE}^{LD}	Service price elasticity at level "D" for vehicle of size-type *ZE*.
$QDLD_{ZD}^h$	Level "D" vehicle services quantity index for size-type *ZD*.
$QDLE_{ZE}^h$	Level "E" vehicle services quantity index for size-type *ZE*.
$QDLE_{ZE+1}^h$	Level "E" vehicle services quantity index for size-type *ZE+1*.

Light-duty Vehicle Notation

v	Vehicle vintage
y	Vehicle powertrain types
z	Vehicle size-types
h	Household population income group.
$Veh\,\mathrm{Pr}\,ice_{yz}$	New vehicle price.

$Vehpric_{yz}^{bas}$	Base price of new vehicle type.
$Vehpric_{yz}^{eeffc}$	Incremental vehicle cost for improved energy efficiency.
NV_{vyz}^{h}	Number of vehicles in the stock

$salesV_{t,yz}$	Vehicle sales
VSD_{z}^{h}	Vehicle service demand by household group and size
$VSPI_{vyz}^{h}$	Vehicle service price index
$\left\langle \frac{VMT}{NV} \right\rangle_{vyz}^{h}$	Optimal VMT per vehicle by type and vintage
$PVMT_{vyz,t}$	Imputed price of VMT.
$P_{E,t}$	Cost of fuel or electrical energy
$EUrate_{yz}$	Vehicle energy use rate (inverse MPG)
vc_{vyz}	Vehicle variable cost.
f_{yz}^{κ}	Tradeoff function between technology, fuel economy, and performance
$Pveffc_{yz}$	Price of vehicle efficiency

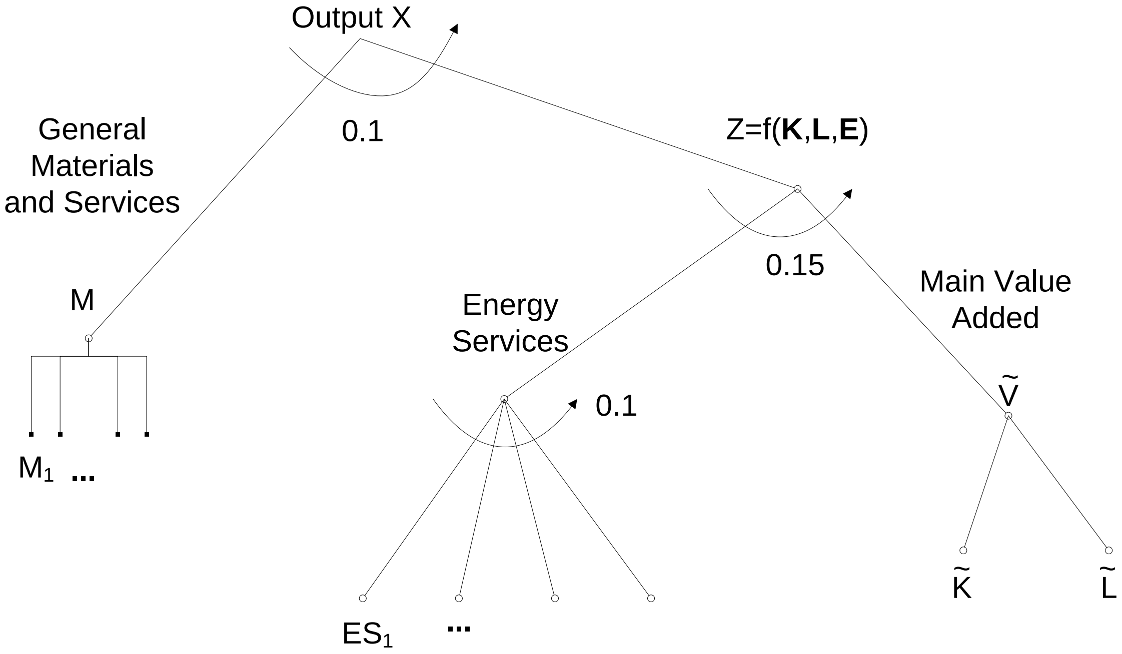

Figure 2-1. Generic representation of commercial/industrial production.

2.2 Price Equations in Commerce and Industry

For a given commercial or industrial sector *i*, factor prices are taken as given at the lowest level shown in Figure 2-1 and calculated up the diagram, ultimately leading to the output price of the sector.

Whereas some capital (and in some applications, labor) is specifically energy efficiency capital intended for the investment purpose of saving energy costs, most capital and labor are considered generic and combined to produce value added. Starting with value added, firms in the sector take wage rates and market interest rates as given and then calculate optimal capital-labor rations and the resulting price of supplying an incremental unit of value added. The value added factor intensities are given by

$$\left\langle \frac{\tilde{K}}{\tilde{V}} \right\rangle_i = \left(\frac{\tilde{\alpha}_i}{\tilde{A}_i} \right) \cdot \left(\frac{\tilde{\theta}_i}{\tilde{\alpha}_i \cdot CCAP_i} \right)^{\tilde{\sigma}_i} \cdot \left(\tilde{D}_i \right)^{\frac{1}{\tilde{\rho}_i}} \tag{2-1}$$

$$\left\langle \frac{\tilde{L}}{\tilde{V}} \right\rangle_i = \left(\frac{\tilde{\beta}_i}{\tilde{A}_i} \right) \cdot \left(\frac{\tilde{\phi}_i}{\tilde{\beta}_i \cdot WAGE_i} \right)^{\tilde{\sigma}_i} \cdot \left(\tilde{D}_i \right)^{\frac{1}{\tilde{\rho}_i}}, \tag{2-2}$$

where

$$\tilde{D}_i = \tilde{\theta}_i^{\tilde{\sigma}_i} \cdot \left(\tilde{\alpha}_i \cdot CCAP_i \right)^{1-\tilde{\sigma}_i} + \tilde{\phi}_i^{\tilde{\sigma}_i} \cdot \left(\tilde{\beta}_i \cdot WAGE_i \right)^{1-\tilde{\sigma}_i}. \tag{2-3}$$

These are the factor demand equations derived from the CES production function, taking factor prices as given. Appendix A provides a calculus derivation of these factor demand equations.

The $\tilde{A}_i$ parameter is a constant term which we generally set to 1.0. Following Acemoglu (2002), the alpha and beta parameters can represent technological change which is factor biased or factor augmenting. The theta and phi parameters are used for base year calibration. Base year calibration is discussed in Section 3.

The price index for value added is based on the wage and cost-of-capital times the intensities of these factors respectively:

$$PVA_i = CCAP_i \cdot \left\langle \frac{\tilde{K}}{\tilde{V}} \right\rangle_i + WAGE_i \cdot \left\langle \frac{\tilde{L}}{\tilde{V}} \right\rangle_i. \tag{2-4}$$

Since we are assuming constant returns to scale, the price index is equal to unit expenditures. As shown in Figure 2-1, the price index for value added becomes an input price at the next level up the hierarchy.

The various energy-related services are also at the bottom level of the hierarchy as shown in detail in Figures 2-2 and 2-3. The lowest level of the energy service tree branches shows individual technology opportunity surfaces for trading off capital for energy. Each different surface, i.e., electric water heating, is denoted by j. Common examples are lighting, office equipment, and electrical apparatus such as pumps and motors. The tradeoff surfaces are based on the CES production function. For the energy service application equations, we select a different notation style than used in the value added equations above. (Later we will use an even different notation for imputing personal vehicle services.) Let *ESQ* be energy service quantity output, *ESK* be the energy service capital factor, and *ENERG* be the energy variable such as electricity or natural gas.

The elasticity of substitution for most of these energy services, as derived from technology data, is on the order of 0.6 to 0.9. Representing the possibility to directly substitute capital for energy in specific end uses, rather than indirectly substituting an aggregate industry capital index for an aggregate industry energy index, makes a big difference in the ease of capital-energy substitution.

Again, following Acemoglu (2002), the alpha and beta parameters can represent technological change which is factor biased or factor augmenting. The theta and phi parameters are used for base year technology, which is discussed in Section 6.

The factor intensity equations (capital-output ratio and energy-output ratio) are functions of the factor prices, i.e., the energy price and the marginal cost-of-capital for business firm *b* in industrial sector *i*:

$$\left\langle \frac{ESK}{ESQ} \right\rangle_{j}^{bi} = \left(\frac{Alpha_{ji}}{ESA_{ji}} \right) \cdot \left(\frac{Theta_{ji}}{Alpha_{ji} \cdot MCCAP_{bi}} \right)^{sigma_{ji}} \cdot \left(ESD_{j}^{bi} \right)^{\frac{1}{rho_{ji}}}, \tag{2-5}$$

$$\left\langle \frac{ENERG}{ESQ} \right\rangle_{j}^{bi} = \left(\frac{Beta_{ji}}{ESA_{ji}} \right) \cdot \left(\frac{Phi_{ji}}{Beta_{ji} \cdot PE_{j}^{i}} \right)^{sigma_{ji}} \cdot \left(ESD_{j}^{bi} \right)^{\frac{1}{rho_{ji}}}, \tag{2-6}$$

where

$$ESD_{j}^{bi} = Theta_{ji}^{sigma_{ji}} \cdot \left(Alpha_{ji} \cdot MCCAP_{bi} \right)^{1-sigma_{ji}} + Phi_{ji}^{sigma_{ji}} \cdot \left(Beta_{ji} \cdot PE_{j}^{i} \right)^{1-sigma_{ji}}. \tag{2-7}$$

Here *ESA* is a constant term which we generally set to 1.0. The price of energy service, which is the cost of increasing energy service output by one unit, is given by:

$$ESP_{j}^{bi} = ACCAP_{bi} \cdot \left\langle \frac{ESK}{ESQ} \right\rangle_{j}^{bi} + PE_{j}^{i} \cdot \left\langle \frac{ENERG}{ESQ} \right\rangle_{j}^{bi}. \tag{2-8}$$

Energy used intensively in specific heavy manufacturing processes, such as process heat and high pressure, temperature steam, including large CHP, are discussed in Section 5 on energy conversion processes.

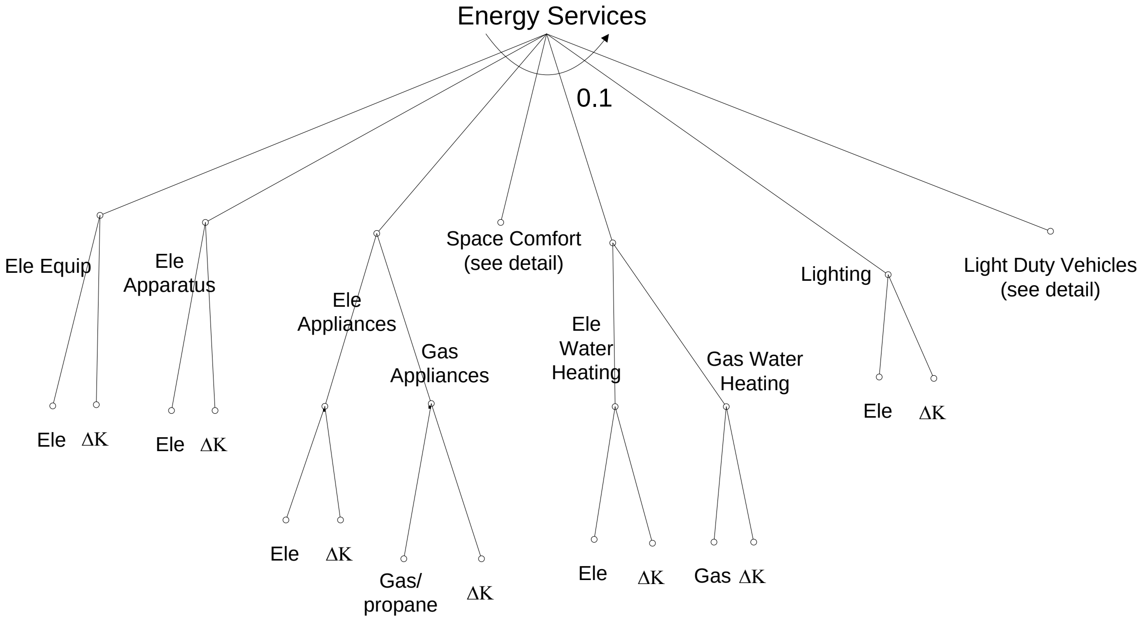

Figure 2-2. Generic energy services.

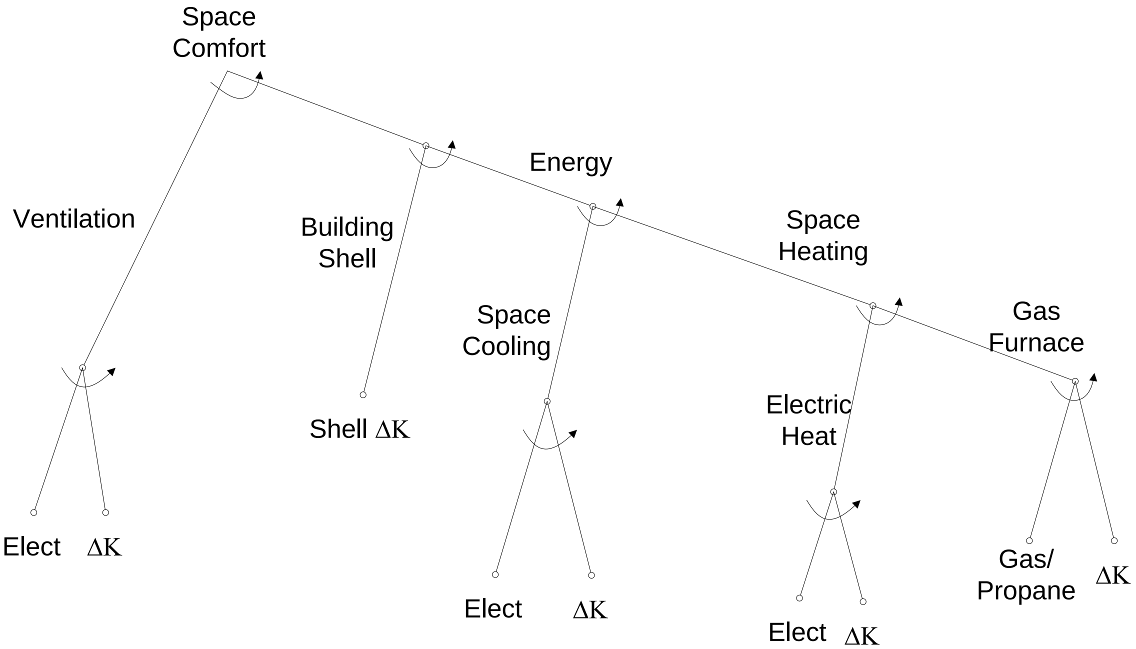

Figure 2-3. Hierarchical representation of space conditioning.

Next, we turn to the aggregation of energy services. Notice in Figures 2-2 and 2-3 that there are several hierarchy steps for processes such as gas and electric appliances (e.g., stoves) and gas and electric water heating. Space conditioning is the most complex since it involves ventilation of the building, the opportunity to substitute improved building shell for energy, the need for both heating and cooling, and the ability to substitute various energy carriers. These equations are solved in turn up the branches of the energy services production hierarchy shown in Figures 2-2 and 2-3.

Figure 2-2 also shows light duty vehicle services. Vehicle purchases are an investment item for business. Vehicle fuel purchases show up the input-output table as an expenditure. Both investment and fuel consumption depend on the energy efficiency of the vehicle purchased. Accounting for these vehicle considerations is discussed later in this section when we present vehicle purchase and services.

For the more complex situations with several steps in the hierarchy, the aggregation process up the hierarchy works the same at the various levels. Next we present the aggregation equations ultimately leading to where all the energy related services are combined into a total measure. In the equations below for the CES aggregator function, we allow for more than two branches coming together into an aggregate index.

The elasticity of substitution σ_i'' is taken to be only 0.1, since very little substitution is expected among the energy services that are aggregated together. The ESP_j^i is the price input to the aggregator function over *j*, yielding the intensity of each service demand:

$$\left\langle \frac{ESQ_j}{ESQIndex} \right\rangle_i = \left(\frac{\alpha_{ji}''}{A_i''} \right) \cdot \left(\frac{\theta_{ji}''}{\alpha_{ji}'' \cdot ESP_j^i} \right)^{\sigma_i''} \cdot \left(D_i'' \right)^{\frac{1}{\rho_i''}} \qquad (2\text{-}9)$$

where

$$D_i'' = \sum_j \left(\theta_{ji}'' \right)^{\sigma_i''} \cdot \left(\alpha_{ji}'' \cdot ESP_j^i \right)^{1-\sigma_i''} . \qquad (2\text{-}10)$$

The price index for aggregated services that is passed up the hierarchy is given by

$$ESPIndex_i = \sum_j ESP_j^i \cdot \left\langle \frac{ESQ_j}{ESQIndex} \right\rangle_i \qquad (2\text{-}11)$$

The aggregator function variables are denoted with a “ to indicate levels up the hierarchy from the individual energy services.

Technological progress in the energy services aggregator function may reflect industry trends toward less of a type of an energy service. Over the years about half of the savings in motor electricity use has been due to installing efficient motors and half due to manufacture systems improvements where fewer motors were needed. As another important example, industrial lighting energy use has been dramatically reduced partly due to more efficient lighting and partly due to segmenting lighting services into two niches, low level background lighting and optimized task lighting. These trends have been documented by the ACEEE.

Continuing to solve for prices as we move up the production structure hierarchy in Figure 2-1, we come to combining main value added with aggregate energy related services. Again at the aggregate level, energy services tend to be complementary with main value added rather than substitutes. Therefore we take a very small elasticity of substitution equal to 0.15.

The two aggregate factors are combined to form an index we call *Z(K,L,E)* which is a function of capital, labor, and energy. In contrast to much economic literature, however, capital, labor and energy are not pre-aggregated into factor totals. Instead, capital, labor and energy are left as disaggregated vectors, so that their unique roles in production are preserved. That is, specific opportunities for factor substitution for individual technologies are represented. In our view, this improves the meaningfulness of the model results.

The following equations yield the intensity of main value added and aggregate energy services and their resulting aggregate price index *PZ*:

$$\left\langle \frac{ESQIndex}{Z} \right\rangle_i = \left(\frac{\hat{\gamma}_i}{\hat{A}_i}\right)\cdot\left(\frac{\hat{\pi}_i}{\hat{\gamma}_i\cdot ESPIndex_i}\right)^{\hat{\sigma}_i}\cdot\left(\hat{D}_i\right)^{\frac{1}{\hat{\rho}_i}} \tag{2-12}$$

$$\left\langle \frac{\tilde{V}}{Z} \right\rangle_i = \left(\frac{\hat{\upsilon}_i}{\hat{A}_i}\right)\cdot\left(\frac{\hat{\psi}_i}{\hat{\upsilon}_i\cdot PVA_i}\right)^{\hat{\sigma}_i}\cdot\left(\hat{D}_i\right)^{\frac{1}{\hat{\rho}_i}} \tag{2-13}$$

where

$$\hat{D}_i = \hat{\pi}_i^{\hat{\sigma}_i}\cdot\left(\hat{\gamma}_i\cdot ESPIndex_i\right)^{1-\hat{\sigma}_i} + \hat{\psi}_i^{\hat{\sigma}_i}\cdot\left(\hat{\upsilon}_i\cdot PVA_i\right)^{1-\hat{\sigma}_i}\,. \tag{2-14}$$

and

$$PZ_i = PVA_i\cdot\left\langle \frac{\tilde{V}}{Z} \right\rangle_i + ESPIndex_i\cdot\left\langle \frac{ESQIndex}{Z} \right\rangle_i\,. \tag{2-15}$$

Finally, moving on to the top node for the price of sector output, *PX*, we combine *Z(K,L,E)* with total materials.

$$\left\langle \frac{Z}{X} \right\rangle_i = \left(\frac{\hat{\alpha}_i}{\hat{\hat{A}}_i} \right) \cdot \left(\frac{\hat{\theta}_i}{\hat{\alpha}_i \cdot PZ_i} \right)^{\hat{\hat{\sigma}}_i} \cdot \left(\hat{\hat{D}}_i \right)^{\frac{1}{\hat{\hat{\rho}}_i}} \tag{2-16}$$

$$\left\langle \frac{\vec{M}}{X} \right\rangle_i = \left(\frac{\hat{\beta}_i}{\hat{\hat{A}}_i} \right) \cdot \left(\frac{\hat{\phi}_i}{\hat{\beta}_i \cdot PM_i} \right)^{\hat{\hat{\sigma}}_i} \cdot \left(\hat{\hat{D}}_i \right)^{\frac{1}{\hat{\hat{\rho}}_i}} \tag{2-17}$$

where

$$\hat{\hat{D}}_i = \hat{\theta}_i^{\hat{\hat{\sigma}}_i} \cdot \left(\hat{\alpha}_i \cdot PZ_i \right)^{1-\hat{\hat{\sigma}}_i} + \hat{\phi}_i^{\hat{\hat{\sigma}}_i} \cdot \left(\hat{\beta}_i \cdot PM_i \right)^{1-\hat{\hat{\sigma}}_i} . \tag{2-18}$$

and

$$PX_i = PZ_i \cdot \left\langle \frac{Z}{X} \right\rangle_i + PM_i \cdot \left\langle \frac{\vec{M}}{X} \right\rangle_i . \tag{2-19}$$

We now come to an interesting situation. The price of input materials depends on the output prices of the sectors of the economy that produce those materials. The economy is further complicated because any given material is frequently made by more than one industry.

Let $MakeShr_{ig}$ be the share of commodity g made by industry *i*. Then the price of material *g* (in producer prices) is given by

$$Pprod_g = \sum_i PX_i \cdot MakeShr_{ig} \tag{2-20}$$

The aggregate price index for all materials and purchased services for industry *i* is given by

$$PM_i = \sum_g Pprod_g \cdot a_{gi} \tag{2-21}$$

where the a_{gi} are technical coefficients as a share of total materials, as derived from base year data.

2.3 Price Equations for Household Consumers

Households purchase in the market place most of the goods and services that they demand. The price index for the purchases that consumers make is a weighted average of the price of the item at the factory gate and the prices of transportation (trucking, air freight, water, rail, and pipeline), wholesale trade and warehousing, and retailing. The markup sectors in the model are denoted by *m*. Hence the price index takes the form.

$$HHPpurch_{gt} = \frac{Pprod_{gt} + \sum_{m} hmuwt_{gm} \cdot Pprod_{mt}}{1.0 + \sum_{m} hmuwt_{gm}} \tag{2-22}$$

where $hmuwt_{gm}$ is the household markup weight (as a share of the factory gate) based on historical data when purchasing good g .

However, following the consumer theory of Kevin Lancaster, consumers value items based on their attributes. Further, consumers need to produce some of these valued attributers themselves. Examples are personal transportation and home lighting and comfort. Households produce these services that they value using a household production function technology and factor inputs such as capital and purchased energy. For example, households do not get direct utility form consuming gasoline, rather they value the transportation that it helps to produce. The household production function can exhibit technical progress in which the same service output could potentially be produced at lower costs with less of some inputs such as gasoline. If a manufacturer produced a more efficient car that performed identically to an existing car but used less gasoline (due to say lower engine friction), the consumer would spend less for the same miles driven and same comfort. This cost reduction in the household production function would free up resources to spend on other goods and services.

So some of the items that consumers demand, we call energy-related services, are produced internally using some household production function technology. In the model households are assumed to demand the same set of energy related services shown in Figures 2-2 and 2-3. The consumer will demand a combination of goods and services that will maximize utility subject to an overall budget constraint. We write the budget constraint for consumer income group *h* as follows for cash outlays:

$$\begin{aligned} B_{ht} &= \sum HHPpurch_{gt} \cdot Qpurch_{gt}^{h} + \sum_{j} PE_{gt} \cdot QE_{jt}^{h} + \\ &\sum_{v}\sum_{y}\sum_{z}\left[Vehrental_{vyz}^{h} \cdot NumV_{vyz}^{h} + (P_{E,t} \cdot EUrate_{yz} + vc_{vyz}) \cdot VMT_{vyz}^{h}\right] \end{aligned} \tag{2-23}$$

The first term in the budget constraint is expenditures on purchased goods and services; the second term is expenditures on energy derived from energy service demands; the third term are vehicle rental expenditures by vintage, powertrain and size-type; and the fourth term is vehicle fuel and operating costs.

We assume that consumers have exponentially shaped demand functions for goods, services and attributes *d*. An exponentially shaped demand function fits between a linear demand function and a constant elasticity power function.

$$QD_{dt}^{h} = Basedmd_{d}^{h} \cdot \exp\left\{\breve{\alpha}_{d} \cdot \left(\frac{PD_{dt}^{h} \cdot B_{h0}}{B_{ht}} - PD_{d0}^{h}\right)\right\} \cdot \left[\frac{B_{ht}}{NORMB_{ht}}\right] \tag{2-24}$$

The demand functions are calibrated to base year demand shares. In the base year the exponent term is zero. Real prices are the ratio of demand prices relative to the budget constraint. This dependence on real prices is a necessary condition derived from consumer theory discussed in Section 4. The price elasticity of demand in the base year is proportional to the alpha parameter. Note that elasticity parameters are taken to be the same for all consumers; differences arise due to different incomes and, for household production functions, different prices.

Demands are proportional to the budget constraint, normalized with a common denominator which is s form of price deflator that converts the nominal budget into a “real” value. Also, because the common denominator will depend on all commodity prices, it is the channel through which cross price elasticities arise.

Where an demanded item is purchased in the market, its price is the market price, so that

$$PD^h_{dt} = HHPpurch_{gt}\,, \tag{2-25}$$

Where goods purchased are demanded directly, $g{=}d$ and the quantity purchased is given by the demand function

$$Qpurch^h_{gt} = QD^h_{dt}\,. \tag{2-26}$$

We can now re-write part of the first term (where $g{=}d$) in the budget constraint as follows:

$$\begin{aligned}&\sum_{g=d} HHPpurch_{gt}\cdot Qpurch^h_{gt} = \sum_{g=d} PD^h_{dt}\cdot QD^h_{dt} = \\ &\left[\frac{B_{ht}}{NORMB_{ht}}\right]\cdot\sum_{g=d} PD^h_{dt}\cdot Basedmd^h_d\cdot\exp\left\{\breve{\alpha}_d\cdot\left(\frac{PD^h_{dt}\cdot B_{h0}}{B_{ht}} - PD^h_{d0}\right)\right\}\,.\end{aligned} \tag{2-27}$$

Substituting (2-27) into (2-23) and re-writing yields an expression for the common term

$$\left[\frac{B_{ht}}{NORMB_{ht}}\right] = \left[\frac{\mathrm{Re}\,alBudgetNumerator}{\mathrm{Re}\,alBudgetDeno\,\mathrm{min}\,ator}\right] \tag{2-28}$$

where

$$\begin{aligned}&\mathrm{Re}\,alBudgetNumerator = B_{ht} - \sum_j PE_{gt}\cdot QE^h_{jt} - \sum_{g\neq d} HHPpurch_{gt}\cdot Qpurch^h_{gt} - \\ &\sum_v\sum_y\sum_z\left[Vehrental^h_{vyz}\cdot NumV^h_{vyz} + (P_{E,t}\cdot EUrate_{yz} + vc_{vyz})\cdot VMT^h_{vyz}\right]\end{aligned} \tag{2-29}$$

and

$$\mathrm{Re}\,alBudgetdeno\min ator =$$

$$\sum_{g=d} PD_{dt}^{h} \cdot Basedmd_{d}^{h} \cdot \exp\left\{ \breve{\alpha}_{d} \cdot \left(\frac{PD_{dt}^{h} \cdot B_{h0}}{B_{ht}} - PD_{d0}^{h} \right) \right\} \cdot \tag{2-30}$$

Note that without the energy service and vehicle related terms, *NORMB* would simply be *RealBudgetDenominator* and equation (2-29) would not be needed.

The energy expenditure term $\sum PE_{gt} \cdot QE_{jt}^{h}$ and other purchases of equipment

where $g \neq d$ arise as derived demands needed to meet the household demand for energy-related services j shown in Figures 2-2 and 2-3. We now turn to demand for light duty vehicles.

2.4 Demand for light duty vehicle services

Figure 2-4 shows the consumer demand hierarchy for vehicles by size types, of which there are ten, as shown in the figure. Note that the selections at the nodes are pair wise. There are levels "A" though "E", with A being the top. Household service demands for vehicle services at the top level A are calculated from the household demand function equation (2-24). Prices of vehicle services are calculated up the hierarchy and demand quantities are calculated down the hierarchy. The derivation of the methodology is provided in Appendix 2B. The resulting equations are as follows:

For prices we start at level "E" and work up to the next level "D". The unit demand functions are given below. Here *ZE* is a specific size-type on level "E" and *ZE+1* is the adjacent competing size-type

$$\vartheta_{E,ZE}^{h} = BasevdmdE_{ZE}^{h} \cdot \exp\left\{ \varepsilon_{ZE}^{LD} \cdot \frac{BasePDLE_{ZE}^{h} \cdot PDLE_{ZE+1,t}^{h}}{BasePDLE_{ZE+1}^{h} \cdot PDLE_{ZE,t}^{h}} \right\} \tag{2-31}$$

$$\vartheta_{E,ZE+1}^{h} = BasevdmdE_{ZE+1}^{h} \cdot \exp\left\{ -\varepsilon_{ZE}^{LD} \cdot \frac{BasePDLE_{ZE}^{h} \cdot PDLE_{ZE+1,t}^{h}}{BasePDLE_{ZE+1}^{h} \cdot PDLE_{ZE,t}^{h}} \right\} \tag{2-32}$$

The price elasticities by vehicle type, as shown in Figure 2-4, are based on Greene et. al. 2004. Based on these unit demand equations, the prices at the next level up can be obtained as:

$$PDLD_{ZD,t}^{h} = PDLE_{ZE,t}^{h} \cdot \vartheta_{E,ZE}^{h} + PDLE_{ZE+1,t}^{h} \cdot \vartheta_{E,ZE+1}^{h} \tag{2-33}$$

where *ZD* is the node up from a specific vehicle *ZE*.

Quantities work down the hierarchy starting with the level A demand from the consumer demand function (2-24). The equations for moving from level D to level E are

$$QDLE^{h}_{ZE} = \vartheta^{h}_{E,ZE} \cdot QDLD^{h}_{ZD}, \tag{2-34}$$

$$QDLE^{h}_{ZE+1} = \vartheta^{h}_{E,ZE+1} \cdot QDLD^{h}_{ZD}. \tag{2-35}$$

Given these vehicle service demands, we now need to show how vehicle services are produced from the stock of vehicle and their operation in terms of VMT.

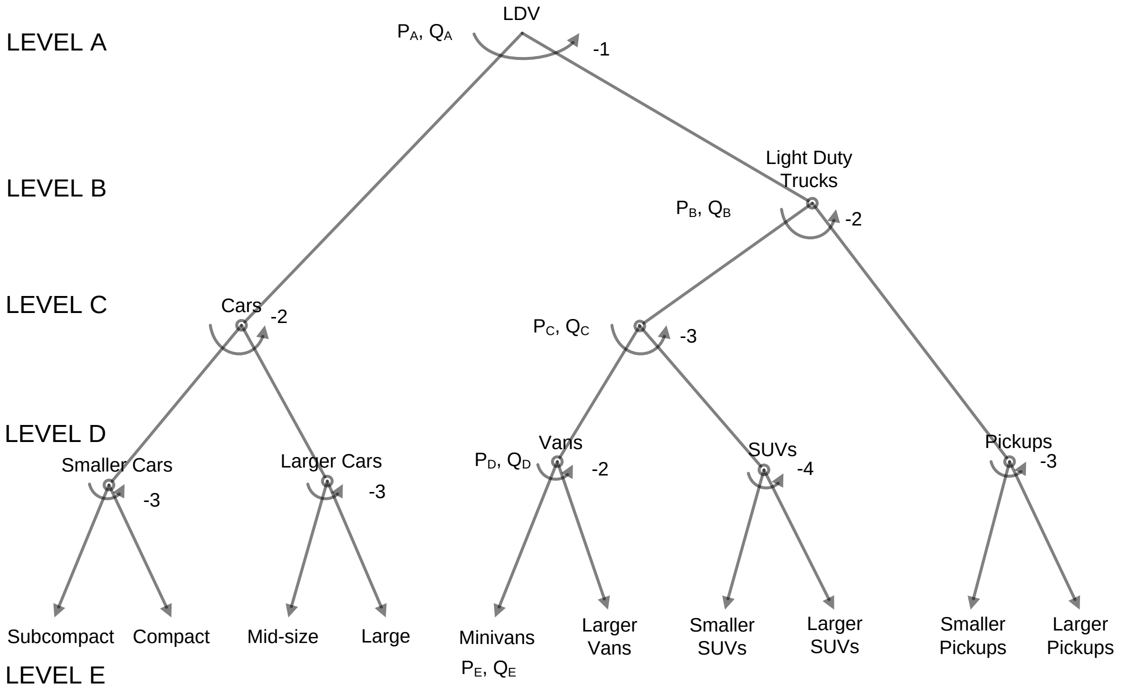

Figure 2-4. Calculation of vehicle service demand prices and quantities up and down the demand hierarchy.

There are ten size-types of vehicles z , three powertrain types (conventional IC engine, HEV, and FCV), and two performance levels fro each powertrain type. The performance level and powertrain type are merged into a single index y . There are a wide variety of similar vehicles that can be modeled as incremental cost and fuel economy variations on the basic categories provided here. The variations include diesel engines, E85 fuel modifications, plug in HEVs etc. These vehicles are treated as incremental cost and efficiency changes from base options. Since the computer model has the capacity to remember large amounts of data, once these variations are adopted as new sales that will remain in the fleet with their fuel type and efficiency over their lifetime. The vintage is denoterd by *v*.

The *h* is the index for consumer group. There are currently six household types in the model as show in Table 1-1. There are five income groups. The sixth group is a small percentage of the upper middle class which acts as early adopters of technology innovation. They are not risk averse to technological change. Research shows that the small group of early adopters plays an important role in getting new technology into the market.

One of the features of the vehicle model is its ability to transcend physical measures of cars, such as number of cars, with economic measures such as consumer budget expenditures on cars, which can differ significantly from number of cars purchased. The num of vehicles by size, powertrain, and vintage is denoted by (factor inputs are generally nonnegative),

$$NumV_{vyz}^{h} \geq 0 .$$

For existing vehicles, household demands plus business demands must sum to the total available of that type:

$$\sum_{h} NumV_{vyz}^{h} + NumV_{vyz}^{b} \leq NumV_{vyz}^{Tot}, \qquad \mu_{vyz} \geq 0, \qquad for\ v = 1,\ 2,\ or\ 3,\ and\ \ for\ all\ \ yz \tag{2-36}$$

Newer vehicle totals (vintage 0) by type and size are given by incremental demands which are summed to get total new sales.

$$NV_{0yz}^{Tot} = \sum_{h} NV_{0yz}^{h} + NV_{0yz}^{b}, \tag{2-37}$$

where the summations are over all households, *h*, and business groups, *b*. Business groups are commercial fleets, heavier industries, and other industries.

We represent the market price of a new car or light truck as the sum of its base price and the incremental full retail price of the incremental energy efficiency investment.

$$Veh\,\mathrm{Pr}\,ice_{yz} = Vehpric_{yz}^{bas} + Vehpric_{yz}^{eeffc} \tag{2-38}$$

The vehicle rental price is specific to the consumer or business. For these groups, the vehicle rental cost for new and used vintages respectively is given by

$$Vehrental_{0yz}^{h} = (r_{o}^{h} + \delta_{0yz}) \cdot Vehpric_{yz}^{bas} + (r_{e}^{h} + \delta_{oyz}) \cdot Vehpric_{yz}^{eeffc} + vfx_{vyz}, \tag{2-39}$$

$$Vehrental_{vyz}^{h} = (r_{o}^{h} + \delta_{vyz}) \cdot \mu_{vyz}^{bas} + (r_{e}^{h} + \delta_{vyz}) \cdot \mu_{vyz}^{eeffc} + vfx_{vyz} \quad for\ v = 1,\ 2,\ and\ 3 . \tag{2-40}$$

Vehicles are treated like a joint asset with hedonic prices for its attributes. The

$\mu_{vyz}^{bas}, \quad \mu_{vyz}^{eeffc} \ \ for\ v = 1, 2,\ and\ 3$ are the market prices for those existing assets.

The price of VMT is given by

$$P_{VMT,t} = P_{E,t} \cdot EUrate_{yz} + vc_{vyz} \tag{2-41}$$

where the rate of fuel consumption $EUrate_{yz}$ is the inverse of MPG.

The household production of vehicle services is given by a CES production function in number of vehicles, their operation through VMT, and a fixed factor. This implies a VMT to vehicle ratio given by:

$$\frac{VMT_{vyz}^{h}}{NumV_{vyz}^{h}} = \left(\frac{\alpha_{vyz}}{\beta_{vyz}}\right) \cdot \left(\frac{\theta_z \cdot \beta_{vyz} \cdot Vehrental_{vyz}^{h}}{\phi_z \cdot \alpha_{vyz} \cdot (P_{VMT,t})}\right)^{\sigma} \tag{2-42}$$

A fixed factor captures the lack of constant returns to scale in household vehicle services, i.e., a household’s mobility less than doubles if it were to own twice the number of cars.

In business there generally are constant returns to scale: Output doubles when all the capital stocks double including vehicles, and all the variable costs double such as gasoline consumption for twice the driving, and labor doubles. That is, business would have twice as many workers to use twice as many vehicles. But households do not have labor as a household production function factor input in the same way as business does. One can think intuitively of the fixed factor as being the number of household vehicle drivers (population age 16 & over).

Think of a mental exercise where household income doubles with the same population. The income effect should be less than 1.0; the nimber of vehicles per household should not double. This has been the case historically where vehicles per capita have grown slower than income as shown in Figure 2-7.

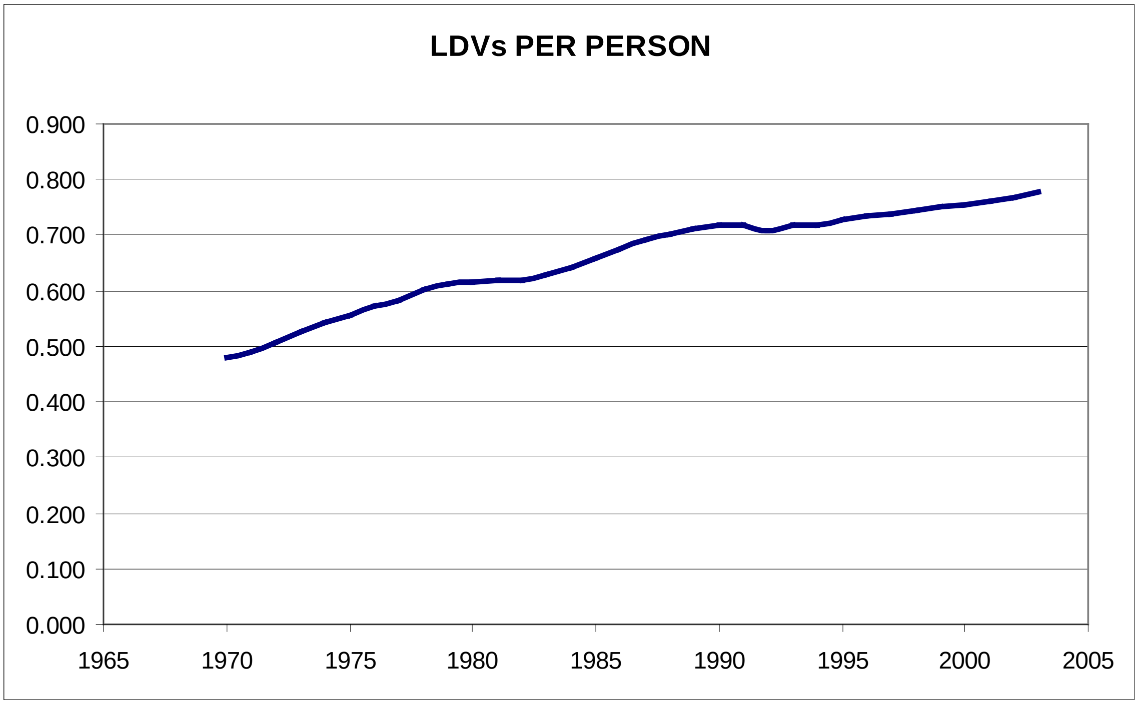

Figure 2-7. The stock of cars per capita has risen with income growth but with an elasticity less than one.

The households are assumed to exhibit optimizing behavior and allocate the fixed factor among vehicles at its disposal to maximize vehicle service. To do this, households append the fixed factor constrain and the CES production function that yields vehicle services to its budget constraint which is equation (2-23), with a lagrange multiplier lambda as follows

$$\eta^h \cdot (\sum_v \sum_y \sum_z OP^h_{vyz} - \overline{OP}^h) \; + \tag{2-43}$$

$$\lambda^h_z \cdot \left\{ VSD^h_z - \sum_v \sum_y \left[A_{vyz} \left(\theta_z \left(\frac{VMT^h_{vyz}}{\alpha_{vyz}} \right)^{-\rho} + \phi_z \left(\frac{NumV^h_{vyz}}{\beta_{vyz}} \right)^{-\rho} + \pi_z \left(\frac{OP^h_{vyz}}{\gamma_{vyz}} \right)^{-\rho} \right)^{\frac{-1}{\rho}} \right] \right\}$$

The proxy that we use to represent the fixed factor is driving age population in the income group *h* given by $\overline{OP}^h$.

The resulting necessary conditions allows us to calculate a vehicle-to-service ratio, which when multiplied by the number of vehicle must yield the given total service demand VSD_z^h where

$$VSD_z^h = QDLE_{ZE}^h \tag{2-44}$$

which comes from the vehicle service choice hierarchy tree shown in Figure 2-4. Hence, for all size-types z, we have the sum of vehicle services over vintage and powertrain-type must equal the consumer's vehicle service demand for that size class:

$$\sum_v \sum_y A_{vyz}{}^{1-\sigma} \left(\frac{\beta_{vyz} \cdot Vehrental_{vyz}^h}{\phi_z \cdot VSPI_{vyz}^h} \right)^{\sigma} \cdot NumV_{vyz}^h / \beta_{vyz} = VSD_z^h \tag{2-45}$$

where a price index for the service derived from the CES production function is given by:

$$VSPI_{vyz}^h =$$

$$\frac{1}{A_{vyz}} \left[\theta_z{}^{\sigma} (\alpha_{vyz} \cdot PVMT_{vyz})^{1-\sigma} + \phi_z{}^{\sigma} (\beta_{vyz} \cdot Vehrental_{vyz}^h)^{1-\sigma} + \pi_z{}^{\sigma} (\gamma_{vyz} \cdot \eta_h)^{1-\sigma} \right]^{\frac{1}{1-\sigma}} \tag{2-46}$$

The fixed factor constraint implies

$$\sum_v \sum_y \sum_z \left(\frac{\gamma_{vyz}}{\beta_{vyz}} \right) \cdot \left(\frac{\pi_z \cdot \beta_{vyz} \cdot \mu_{vyz}}{\phi_z \cdot \gamma_{vyz} \cdot \eta_h} \right)^{\sigma} \cdot NV_{vyz}^h \le \overline{OP}^h, \qquad \eta_h \ge 0, \qquad h = 1,\ NConsumers \tag{2-47}$$

Equation 2-47 follows from setting the ratios of marginal products of NV and OP to their price ratios, a necessary condition for determining the optimal factor ratios.

The benefits side of improved vehicle performance is modeled as a form of factor augmenting technical progress. It is represented by a change in the parameter α_{vyz} . Intuitively we model driving or VMT using a higher performing car as providing greater vehicle service to the consumer.

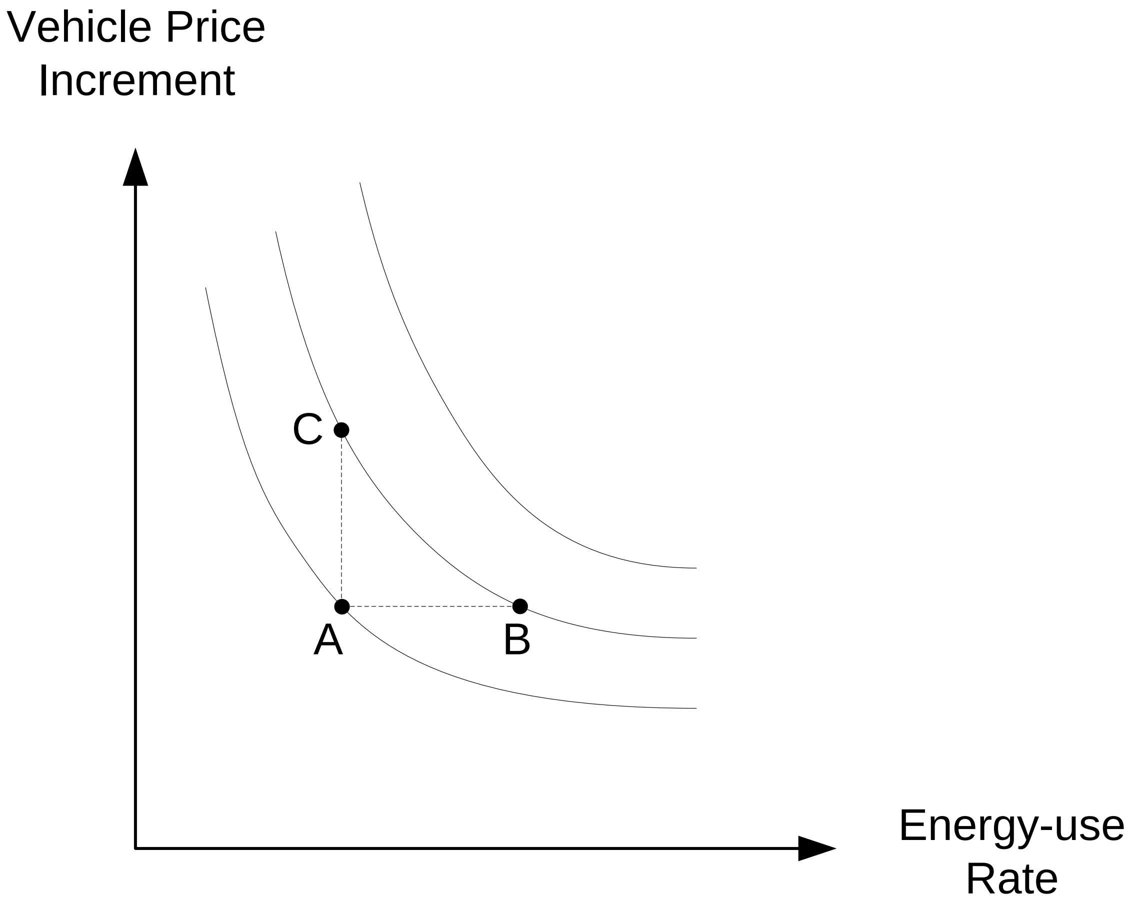

Figure 2-5. CES representation of incremental capital cost of vehicle efficiency gains at different levels of powertrain performance.

Incremental technology investment in vehicles (as reflected in the vehicle price) can be used to improve fuel economy or to increase performance. In recent decades car manufactures have chosen the later in response to consumer desires. Hence the opportunity cost of higher performance is the price of fuel which must be paid. Figure 2-5 illustrates incremental vehicle cost vs energy use rate (inverse of MPG) for difererent levels of vehicle performance. Mathematically, these curve can be derived from a fuction of the following form:

$$Perform_{0yz} = f_{yz}^{\kappa}(Vehpric_{yz}^{eeffc}, EUrate_{yz}) \tag{2-48}$$

This function is taken to be a homothetic transformation of CES function. The exponent κ in the function is less than one and reflects decreasing ability (or increasing cost) to raise performance even higher. The optimal point on these isoquants must satisfy

$$\left(\frac{f_E^{'}}{f_K^{'}}\right) = \left(\frac{P_{E,t}}{r_e^h}\right)\cdot\left(\frac{VMT_{0yz}^h}{NV_{0yz}^h}\right) \tag{2-49}$$

For the specific functional form

$$f_{yz} = \left[\Theta_{yz}\left(\frac{Vehpric_{yz}^{eeffc}}{\omega_{yz}}\right)^{-\zeta} + \Phi_{yz}\left(\frac{EUrate_{yz}}{\tau_{yz}}\right)^{-\zeta}\right]^{\frac{-1}{\zeta}}, \tag{2-50}$$

the necessary condition (2-49) becomes

$$\frac{f_E^{'}}{f_K^{'}} = \left(\frac{\Phi_{yz}}{\Theta_{yz}}\right)\cdot\left(\frac{\tau_{yz}}{\omega_{yz}}\right)^{\varsigma}\cdot\left(\frac{Vehpric_{yz}^{eeffc}}{EUrate}\right)^{1+\varsigma} \tag{2-51}$$

2.5 Sector Quantitites

Household demand for purchased inputs are mapping into the input-output sectors as follows:

$$HHQpurch_{gt} = \sum_h Qpurch_{gt}^h \tag{2-52}$$

$$\frac{HHQprod_{gt}}{HHQpurch_{gt}} = \frac{1.0}{1.0 + \sum_m hmuwt_{gm}} \tag{2-53}$$

$$\frac{HHQprod_{gmt}}{HHQpurch_{gt}} = \frac{hmuwt_{gm}}{1.0 + \sum_m hmuwt_{gm}} \tag{2-54}$$

The goods demands are mapped into demands for sector outputs using the MAKE matrix shares:

$$X_i = \sum_g MakeShr_{ig}\cdot QG_g \tag{2-55}$$

These sector outputs then drive all the other quantity variables in the production hierarchy. Intermediate demand for good g is given by

$$Intermed_g = \sum_i a_{gi}\cdot\left\langle\frac{\vec{M}}{X}\right\rangle_i\cdot X_i \tag{2-56}$$

Value added factor demands are given by:

$$\tilde{K}_i = \left\langle \frac{\tilde{K}}{\tilde{V}} \right\rangle_i \cdot \left\langle \frac{\tilde{V}}{Z} \right\rangle_i \cdot \left\langle \frac{Z}{X} \right\rangle_i \cdot X_i \tag{2-57}$$

$$\tilde{L}_i = \left\langle \frac{\tilde{L}}{\tilde{V}} \right\rangle_i \cdot \left\langle \frac{\tilde{V}}{Z} \right\rangle_i \cdot \left\langle \frac{Z}{X} \right\rangle_i \cdot X_i \tag{2-58}$$

Energy service demands are given by:

$$ESQ_j^i = \left\langle \frac{ESQ_j}{ESQIndex} \right\rangle_i \cdot \left\langle \frac{ESQIndex}{Z} \right\rangle_i \cdot \left\langle \frac{Z}{X} \right\rangle_i \cdot X_i \tag{2-59}$$

These energy service demands are satisfied by existing of new equipment. Existing stocks and their energy consumptions are pre-determined from earlier years in the forecast. Replacements and incremental loads are met by new equipment purchases:

$$ESK_j^{bi} = \left\langle \frac{ESK}{ESQ} \right\rangle_j^{bi} \cdot ESQ_j^i \tag{2-60}$$

with energy consumption given by:

$$ENERG_j^{bi} = \left\langle \frac{ENERG}{ESQ} \right\rangle_j^{bi} \cdot ESQ_j^i \tag{2-61}$$

2.6 Investment Dynamics

The AMIGA model allocates memory space for every year. However, when the investment paths are required every year to meet incremental changes in the demand for capital, considerable year-to-year fluctuations in investment arise. A smoother solution is obtained if the increment in investment for five years is calculated and then spread out linearly over the five year period. The methodology for doing this is laid out in this section, using vehicle sales as an example.

Let *t* be the current projection year. This is the year that the model is making a decision for how much vehicle service to supply to meet the demand. Since the model decides capacity additions on a five-year period step, *t-5* will be the year that capacity was last decided. Hence, sales of vehicle type *yz* in year *t-5* are known at time *t* and given by $salesV_{t-5,yz}$. Sales are taken to grow linearly over the five-year period between decision years, incremented each year by “sales_increm.”

That is, t fills in the years after the last decision time, t=-5. Then

$$salesV_{t,yz} = salesV_{t-1,yz} + sales\_increm_{yz}, \qquad (2\text{-}62)$$

where

$$sales\_increm_{yz} = (VS^{Tot}_{0yz} - 4.5 \cdot salesV_{t-5,yz}) / 12.5, \qquad (2\text{-}63)$$

where for the total stock of vintage 0 vehicles of type *yz* is the sum over households,

$$VS^{Tot}_{0yz} = \sum_h VS^{h}_{0yz} . \qquad (2\text{-}64)$$

This vintage 0 stock is the sum of the vehicles purchased over the previous four years plus half of the sales in the current year. The reason is that vehicle sales are assumed to be uniform throughout the year, so that vehicles purchased early in the year provide services for most of the year but vehicles purchased late in the year do nor contribute much to current year service. On average, half of the sales in the year add to the stock of in-service vehicles. Hence,

$$VS^{Tot}_{0yz} = \frac{1}{2} \cdot sales_{t,yz} + sales_{t-1,yz} + sales_{t-2,yz} + sales_{t-3,yz} + sales_{t-4,yz} \qquad (2\text{-}65)$$

Vintage 0 vehicles are those sold in the current year or in one of the previous four years. By simple algebra, we derive that the sales increment is given by

$$sales\_increm_{yz} = (VS_{0yz}^{Tot} - 4.5 \cdot salesV_{t-5,yz})/12.5\,. \tag{2-66}$$

As each year passes, each vehicle ages one year. Some survive and the remainder retire and are scrapped. The probability of survival is given be a gamma distribution similar to what is done in the NEMS model. Variables that enter this probability function are mean age and a variance parameter gamma. We take the mean vehicle age to be 14 years. The variance parameter gamma is taken to be 3.0.

Then the stocks of existing vehicles are added up. For vintages 1 and 2we have

$$\begin{aligned} VS_{1yz}^{Tot} = {} & surv\_sales_{t-5,yz} + surv\_sales_{t-6,yz} + surv\_sales_{t-7,yz} + \\ & surv\_sales_{t-8,yz} + surv\_sales_{t-9,yz} \end{aligned} \tag{2-67}$$

$$\begin{aligned} VS_{2yz}^{Tot} = {} & surv\_sales_{t-10,yz} + surv\_sales_{t-11,yz} + surv\_sales_{t-12,yz} + \\ & surv\_sales_{t-13,yz} + surv\_sales_{t-14,yz} \end{aligned} \tag{2-68}$$

Vintage 3 consists of all surviving vehicles 15 year and older.

Under a carbon charge of higher fuel prices, there would be an incentive to retire older, less fuel efficient vehicles earlier. This “economic retirement” can be modeled as a change in variable operating costs shifting the optimal expected retirement age. Including economic retirement is a future task that we intend to undertake.

2.7 Savings and Aggregate Consumption

Consumers typically save a portion of their income for future consumption and for bequests to their off spring. In the aggregate then,

$$C = (1 - S(Y, i)) * Y, \tag{2-69}$$

Where the savings rate S is an increasing function of income and of the interest rate. This aggregate consumption becomes the budget constraint described in Section 3.3 on consumption.

In the macroeconomy, savings must equal investment. Therefore, we have the equation

$$\text{Total savings} = \text{Sum} \{ I_j(i) \} \tag{2-70}$$

Where the summation is over all investment categories in the model. A rise in interest rate therefore all else equal will raise savings and reduce all the investments. This closes the model.

2.8 Solution to Three Connected Sets of Simultaneous Equations

In this subsection, we discuss the solution to the set of equations that define the general equilibrium in the economy at a given point in time. Most of these equations describe interindustry demand flows and corresponding production costs, but some describe the resource supply side. The latter equations include the coal, oil, natural gas supply functions.[9]

We suggest that a useful way to envision the general equilibrium is in the format of an input-output table which defines the structure of the economy at some desired point in time. Within that input-output framework, then, we can estimate the different sectors use labor, energy, capital, and materials to produce the appropriate vectors of final goods.[10] Finally we discuss briefly the notion of perturbation analysis in general equilibrium theory. Basically, we want to know what happens to the equilibrium solution if some key inputs or assumptions are changed.

This section presents the structure of the model in general terms; later sections describe details of individual modules. It also provides a context to help the reader understand where specific equations presented in later sections fit into the solution algorithm for the system as a whole. The figure below illustrates the basic “sub-problems” which are solved within the equilibrium framework – iterating until prices and quantities converge.

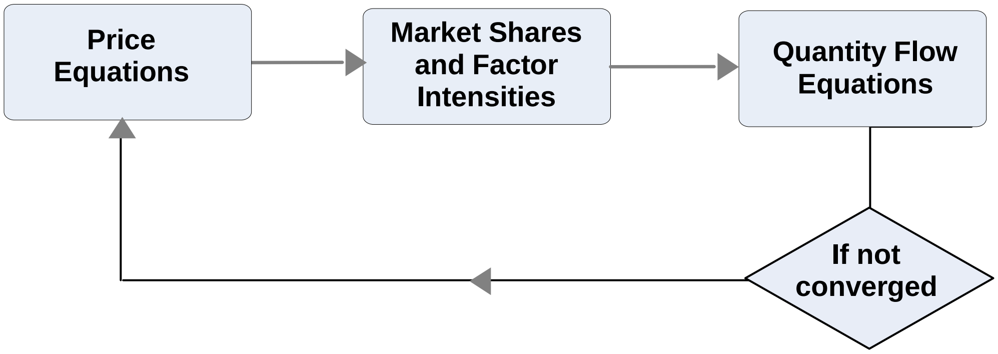

Figure 2-6. Flow Chart of the Convergence Method

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[9] Energy conversion and supply-side technologies are described more fully in section while energy end-use and energy efficiency technologies are described in section 7.

[10] For a more complete review of input-output modeling techniques, see Miller and Blair (1985). For a discussion of how an input-output structure might evolve over time within a general equilibrium framework, see Hanson and Laitner (2006).

The general method is the Gauss-Seidel method of converging systems of simultaneous equations by repeated solution of the equations. In the AMIGA model, we have three "sub-problems," two of which are essentially linear. These include: (i) microeconomic choices based on market chares and factor intensities, (ii) interactions among production quantities; and (iii) integration of prices into the model's solution. Each sub-problem is solved as a function of temporary values obtained from the other two sub-problems. As we suggest in the figure above, the flow of calculations continues until AMIGA reaches convergence to an equilibrium solution characterized by prices and production levels so that demand equals supply for all commodities.

In the literature on numerical methods, it is well known that the Gauss-Seidel algorithm is the fastest method of solving large scale problems. In the neighborhood of the solution, nonlinear functions can be approximated as being linear by using the Taylor series expansion. At this point as the global solution is approached, the entire problem looks like a large scale linear system, which the Gauss-Seidel algorithm solves very quickly (Press et al 1992).

When the algorithm starts, the initial values are possibly far away from the equilibrium solution. Significant nonlinearities must be accommodated through a partial adjustment in key variables between the previous temporary solution and the new iteration. These partial adjustments in nonlinear variables are made at the interface or boundaries between the three sub-problems.

The microeconomic choice decisions arising in the individual modules comprise the first sub-problem. In most cases, business and household decision makers are assumed to be price takers, without market power.[11] Then given a set of prices, business and consumers choose technologies (or market shares) and factor ratios (including labor and energy intensities). Also included among these choices are least-cost operational dispatch of power plants and the baskets of goods and services for various representative consumers. Most of these decisions are nonlinear functions of relative price ratios.

The second sub-problem specifies the simultaneous interaction among quantities of production. The equations reflect "supply equals demand" for all the goods and services. They also reflect demands for capital, for labor, for physical energy carriers, and material services. Broadly, then, this is a "KLEM" specification, but one in which disaggregation is preserved for the factors of production within each of these categories.

Our claim is that factor aggregation will result in lost information and, hence, will lead to specification errors. Moreover, with today's programming capabilities (using the C programming language in the case of the AMIGA modeling system), it is not necessary to combine the components of capital into some aggregate measure of the capital stock prior to calculating the various capital services. For example, why combine trucks and houses into an aggregate capital stock prior to calculating transportation and housing

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[11] This condition can be relaxed and varied, however, as different policy scenarios or alternative futures might be explored.

services (as many models now appear to do)? Similarly it is not necessary to collect labor, energy, and materials into aggregate measures. Rather than struggle with combining electricity and oil and gas into a meaningful measure of energy, current programming capabilities allow modelers a more accurate analytical result by preserving the unique characteristics of different energy forms and their interactions with other production sectors and other sectors.[12]

Production activities in firms, as well as internal household production yielding household services such as transportation, give rise to purchases of intermediate goods and services including purchased energy. Most goods and services are provided in the market place and purchased with arms-length transactions. The purchases of inputs are driven by outputs of goods and services.

The third sub-problem provides the price equations. In competitive markets, prices are driven toward a condition of zero profits, bidding away excess rents. Revenues received from all sales must equal expenditures on inputs, hence determining the output price as a function of input prices and factor intensities.

When the AMIGA model begins to solve the quantity sub-problem, the initial conditions for the quantities matter. The quantity equations are solved in a pre-selected order. In general one wants to solve the equation with the largest pre-determined component first. This generally means that the commodity equations for those goods mostly delivered as final goods are solved first. Then commodity equations that are largely for intermediate or semi-finished goods are solved next. Finally, the raw material demand equations are solved last. To rank the commodity equations in order of how much is pre-determined, a pre-processor sort is employed. This determines the solve order during an AMIGA model run. For example, the demand and production of new vehicles is solved before the production of tires is solved; and tire production is calculated before rubber production is calculated. The full employment condition effectively puts a constraint on output.

The price equations are solved in reverse order of the quantity equations, starting with the price of raw materials and working up toward the price of finished goods. Hence, the prices of purchased inputs tend to be calculated before sector output prices.

The initialization of the raw material prices is done from their supply functions. Natural gas is a good example. If the quantity equations show excess gas demand at current gas prices, then the price will need to rise in the next iteration, moving along the gas supply curve. This process connects the quantity equations with the price equations.

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[12] This is a critical issue for energy and climate modelers. Ross (1986) describes a distinction between core strategic capital and discretionary capital within firms. Casten (2005), an economic and developer of waste to energy facilities throughout the United States, notes in a recent discussion, for example, he “has never found an exception to the rule that they treat ‘core’ and discretionary ‘non-core’ capital budgeting and investments differently.” In a recent analysis, Laitner (2005) shows that if modelers parameterize a production function using aggregate capital, they are likely to get an entirely different result when they evaluate energy efficiency using total capital stock rather than technology-specific or “energy-related” capital stock.

The outcome at the end of the iteration of the third sub-problem is a revised set of temporary prices. The new price vector is compared with the previous price vector (at the beginning of the iteration) and price adjustments are made. Given these revised prices, the market share and factor intensity equations in the first sub-problem are solved again, and the next round begins. The iterations continue until the solution is within a very small prescribed distance of the full equilibrium, i.e., an arbitrarily small distance "epsilon

2.9 Resource Supply Functions

A general equilibrium model gives price and quantity changes to an exogenous shift such as a carbon emissions constraint. Pursuing this example, typically under a carbon constraint coal demand and coal prices are lower. AMIGA has a small price effect on coal through a reduced form supply function. This coal supply price elasticity was derived from other coal supply modeling done for EPA. Perhaps the most important supply consideration is for natural gas. One way to comply with a carbon constraint is to switch fossil fuels to one with a lower carbon emission factor, namely, switch to natural gas. However, moving up the gas supply curve will raise its price and crowd out some of the gas demand. If a carbon policy is balanced with end-use efficiency measures, gas consumption can be freed up in some uses. Total economy-wide gas demand will determine the price and quantity on the gas supply curve.

It is common to have separate resource supply function by supply basin or by supply country. In the case of gas, AMIGA has gas supply curves for the US and for Canadian imports. These two linear reduced-form gas supply curves were fit to multiple NEMS model runs (EIA 2005). The domestic price elasticity of supply for these fitted curves is about 0.37 and the Canadian import price elasticity is about 0.65. In other words, a 10 percent increase in natural gas prices will increase domestic supply and Canadian imports by 3.7% and 6.5%, respectively.

Total gas supply function is the horizontal summation of the two countries. The gas price is assumed to be the same on both curves. These runs and the resulting AMIGA supply functions show considerable technology improvement over time. Hence the curves shift to the right with time, making more gas available at a given price. We are currently reviewing the appropriateness of these gas supply curves.

Oil is a significantly different resource. It is a global market and most of the world's conventional crude oil resources are concentrated in the Middle East. (Note that there is a comparable quantity of heavy oil sands in Canada and Venezuela and oil shale in Montana and the surrounding region.) Energy economists who have studied OPEC pricing generally believe that lowering world demand for oil results in lower sustainable OPEC oil prices. This is the so-called monopsony effect. For the EMF climate change studies, and drawing from the literature, modest $2 to $3 dollar reductions in the world oil price were assumed to be associated with the large (circa 50%) reductions in world oil use under a climate stabilization policy. Oil supply functions for AMIGA are being reviewed for updating in the near future.

2.10 Analysis of Perturbations in the Equilibrium

With the input-output equilibrium structure of the AMIGA model established over some reasonable period of time, we can then introduce a set of perturbations that reflect some desired policy or scenario analysis that we might wish to explore. These “counterfactual” scenarios can then be compared to the business-as-usual accounts to more fully examine the impacts on the economy. For example, one area in which general equilibrium analysis can provide some useful insight is on the “bounce back” or so-called “rebound” effects of measures which reduce the cost of energy services. In the case of high oil prices and conventional vehicle technology, for instance, consumers will reduce their vehicle miles traveled (VMT) due to price, income, and information effects. However, with the introduction of more efficient vehicle technology that might be chosen by consumers and businesses, drivers will presumably be able to afford to drive somewhat more than they can otherwise afford without this advanced technology. An engineering analysis might suggest a 15 percent improvement in fuel economy over time, but in the counterfactual equilibrium analysis such as AMIGA provides, the analysis might suggest a 1 percent increase in travel as more efficient vehicles reduce the cost of driving. It might also suggest that less gasoline is demanded so that energy prices drop compared to a more static analysis. In effect, the equilibrium solution might actually indicate only a 14 percent improvement in fuel economy with slightly lower energy prices. When this effect is combined with a small increase in travel, the total energy savings might actually turn out to be only, say, 13 percent rather than 15 percent.

With its detailed technology and sector characterizations, AMIGA is able to handle a variety of detailed assessments. These might include the change in investment patterns resulting from either an alternative reference case or a change in policies compared to a given reference case. We can also examine changes in sector output and household consumption as well as changes in the mix of energy supply technologies under different policy scenarios. Section 7 provides a summary of perturbation impacts which examine the influence of similar energy and climate policies as they might impact a completely different set of base cases. As a complement to this current version of the AMIGA documentation, Hanson and Laitner (2006) provide a more in-depth review about the impacts of assumptions or perturbations might have on the equilibrium solution.

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Appendix. Derivation of the Vehicle Size Type Hierarchy Equations

Demands for vehicle types and sizes are based on price and quantity indexes for corresponding vehicle services. We model ten vehicle types and sizes (and we intend to add sport cars as well). It is easier to specify demand functions for the ten vehicle types and sized by structuring a hierarchy similar to multinomial logit functions using in Greene, et. al., 2004. As shown in Figure 1, the levels of the hierarchy are labeled from A to E with A being the upper most level and E being the lowest level.

At level E, the bottom level, quantities of vehicle services (for, say, a subcompact car) is calculated from CES production functions. The corresponding price index is given by the CES price aggregator function. Prices flow up the network from level E to A. Quantities demanded flow down the network from level A to E. Prices of close substitutes tend to have large price effects. However, prices of all goods and services will effect demand for every other good and service, at least in some small way. Below we describe the flow of prices up the network and quantities down the network.

Prices for each of the ten vehicle type-sizes are calculated from the CES function price index. The marginal cost of expanding quantity Q_D, i.e., increased costs associated with

$$\Delta Q_D = 1$$

so that

$$MC_D = p_{E1} \cdot \Delta Q_{E1} + p_{E2} \cdot \Delta Q_{E2}$$

where

ΔQ_{E1} is the change in level E first quantity associated with a unit increase in Q_D. We insist that our quantity indexes have the property of being linear homogenous. This means that there exists an aggregator function f such that

$$Q_D = f(Q_{E1}, Q_{E2}) \tag{A2.1}$$

with the property that Q_D will double if both Q_{E1} and Q_{E2} double. Given prices p_{E1} and p_{E2} it is necessary that Q_D is maximized for given expenditures. This occurs where the price ratio is tangent to the transformation curve. Holding Q_D constant, the slope of the transformation curve is given by

$$-\left.\frac{dQ_{E1}}{dQ_{E2}}\right|_{Q_D} = \frac{f_2^{'}}{f_1^{'}} = \frac{p_{E2}}{p_{E1}} \tag{A2.2}$$

The demand functions for Q_{E1} and Q_{E2} must satisfy equations (A2.1) and (A2.2), which implies they must be of the form:

$$Q_{E1} = \vartheta_1\left(\frac{p_{E2}}{p_{E1}}\right)\cdot Q_D$$

$$Q_{E2} = \vartheta_2\left(\frac{p_{E2}}{p_{E1}}\right)\cdot Q_D$$

It follows that the price index at level D, p_D, is given by the marginal cost of increasing Q_D which is

$$p_D = p_{E1}\cdot\vartheta_1 + p_{E2}\cdot\vartheta_2 .$$

The same formula applies moving up the hierarchy allowing all the prices in the hierarchy network to be calculated.

Moving down the hierarchy to calculate quantity indexes, again makes use of the demand functions. We prefer the exponential functional form for the demand functions since it has a curvature between a linear demand function and a constant elasticity of demand (i.e., a power function). Elasticities ε in the base year, as adopted from Greene, et.al., 2004 are shown in Figure 1. Then the demand functions at time t depend on the base period market shares, the base period elasticities, the base period prices at time 0, and the current time t price ratio.

$$\vartheta_1 = mrktparm_1\cdot\exp\left(\varepsilon\frac{p_{E1,0}\cdot p_{E2,t}}{p_{E2,0}\cdot p_{E1,t}}\right)$$

$$\vartheta_1 = mrktparm_2\cdot\exp\left(-\varepsilon\frac{p_{E1,0}\cdot p_{E2,t}}{p_{E2,0}\cdot p_{E1,t}}\right)$$

The market parameters are calibrated to correspond to base year market shares by vehicle type.

3. PRODUCTION

Paul Samuelson described the pattern of production in the economy as “round about” production (Samuelson 1967). That is, the outputs of some processes and industries are inputs to other processes and industries. This leads to a simultaneous equation specification for gross sector outputs and product prices. For example, the computer industry will typically out-source accounting services, and the accounting sector purchases computers to do its job.

This section elaborates on the CES production functions used in Section 2. We discuss the calibration of the main value added structure to the BEA input-output value added data. We also consider imperfect decision making, investment criteria, and incorporating risk and risk premiums in a CGE framework. We also describe various special cases of production and resource pricing. One example is dealing with different quanility grades of fossil energy feedstocks.

3.1 Demand for Materials, Goods and Services

Demand for materials and intermediate goods and services are driven by real industry output, or some measure of material flow or throughput. Let H_i^j be throughput for process *j* in industry *i*. Throughput could be a process input or output. For petroleum refining, as an example, the alkylation process (to make high-octane fuels), hydrogen production, and sulfur removal from hydrogen sulfide are output-based processes, whereas most other processes are based on input feed, e.g., tonnes per day of crude oil fed to distillation units. Co-production plants, generating electricity, steam, and other outputs such as hydrogen or syngas (for synthesis of chemicals or liquid fuels), are also based on input feed rates measured in short tonnes of coal or petcoke per day (Marano 2005).

However, those industries described by a single economic sector, are typically driven by a dollar measure of real industry output denoted by X_i. Then

$$H_i^j = X_i \,. \tag{3-1}$$

An industrial sector or process will use a wide range of material inputs and other intermediate goods and services. We denote these input goods by *g*. So X_{gi}^j is the demand for good *g* by process *j* in industry *i*. The coefficient relating derived demand for good *g* and throughput is denoted by a_{gi}^j. Hence,

$$X_{gi}^j = a_{gi}^j H_i^j \,. \tag{3-2}$$

One source of these technical coefficients is engineering process evaluation. This is our source of data for major energy conversion processes such as power generation and petroleum refining. Our petroleum refinery module, for example, has up to twenty-six process steps in one of its refineries (see Section 5). Each process step has technical coefficients for electricity, process fuel, high and low pressure steam, cooling water, process water, and waste water, and other variable material input costs.

The technical coefficients a_{gi}^{j} are generally determined for the economic sectors by benchmark year input-output tables. The Bureau of Labor Statistics provides forecasts of growth rates for sectors of the US economy. Sectors with disproportionate growth include high tech industries, professional and personal services, medical care, and construction. The traditional manufacturing industries such as textiles continue to lose employment. One convenient hypothesis which provides a baseline for policy analysis and long-term assessments is that sector growth rates continue to differ for some specified period of time, say to the year 2015, at which point in the future growth rates tend to converge and market shares tend to stabilize at new shares from the benchmark year. Using this method, we incorporate time trend into the technical coefficients up to some specified year. This provides a practical solution to capture medium term structural change in the US and world economies. Yet the really interesting policy changes for energy transitions and climate policy will likely fall in the post-2015 era.

Appendix 2-2 shows the aggregate structure of the US economy in 2004 based on the BEA annual input-output table (BEA 2004) as it has been updated from the most recent 1997 benchmark table (BEA 1997). The first summary table in Appendix 2-2 includes an aggregation of about 500 sectors in the US economy with goods and services represented in 15 rows and industry production represented in 11 columns. A second summary table in that same Appendix summarizes the final demand for goods and services which include consumption, investment, government purchases, and exports minus imports.

Value added components for industry production are shown in the bottom rows of the first summary table. In future forecasting years, value added is calculated as expenditure shares for capital and labor. This includes the value added from the "main" capital and labor and also the value added from energy-related and transportation-related capital stocks which are treated elsewhere in the report in Sector 6 on end-use representation.

The future state of the economy can be represented by constructing consistent input-output tables for specific years of interest. In Appendix 2-3 we present such a table for the year 2030.

Total demand for good *g* is given by the sum of intermediate demands by all the sectors in the economy plus final demands.

$$X_g = \sum_i \sum_j X_{gi}^{j} + FD_g \ . \tag{3-3}$$

By replacing X_{gi}^{j} with its technical coefficient times sector output, X_i, or throughput as in Eq. (3-2), we obtain one of the sets of market equilibrium equations. This set represents a block of equations to solve for the vector of gross sector outputs.

Final demand is given by

$$FD_g = C_g + I_g + G_g + EX_g - IM_g . \tag{3-4}$$

Consumption is discussed in the next section, Section 4. Total investment must equal total savings which is discussed in Section 4. The components of investment are related to energy supply, end-use technologies, and additions to the “main” capital stock described below. In our current configuration, government spending is specified as an exogenous trend except as it might be impacted by policy-induced changes in energy or transportation related variables. We consider only fixed investment (neglecting inventory changes).

Most imported goods are differentiated to a degree from domestically produced goods. This is the Armington assumption (Armington 1969). For this case, imports of good *g* are driven by total demand for good *g* and the domestic price of good *g*. Exports also depend on the domestic price of good *g*. Domestic cost of production, determined primarily by the wage rate, adjusts over time to reduce the trade deficit and gradually (over decades) bring down the US foreign debt to a sustainable ratio relative to US GDP.

Homogenous commodities have to be treated as special cases. They are often supplied in competitive, global markets. Domestic supply and Canadian imports of natural gas have been represented by dynamic supply curves in the AMIGA model. Similarly, domestic oil production (produced in mature oil fields and declining since 1970) is currently taken to be an exogenous trend. Imports and exports of petroleum products have been relatively small and designed in particular to exchange gasoline for US consumption for diesel fuel that is sold at a premium in Europe and Asia. Coal imports and exports are relatively small; the US is no longer the least cost producer for this critical resource. Electricity is produced domestically with only a few arranged cross-border power exchanges embedded in the model.

3.2 Competitive Conditions

In general, we consider industries to be competitive. That is, they are described by the “zero-profit” condition commonly imposed in general equilibrium modeling. The zero profit (or perhaps better said, the “zero excess profit”) condition is another way of saying that the market drives down price in an industry to average cost (AC) of production (including “normal returns” on investment). It is important to distinguish here that we need not assume ideal, perfect firms. To the contrary, firms are made up of imperfect agents in the Coasian sense.[13] That is, both the firms and their agents or representatives have imperfect knowledge; and they face a series of search and transaction costs that hamper or limit an effective decision process. Moreover, they face the constraints of real

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[13] Ronald Coase is a British-born economist who raised the question of how transaction and information costs might encourage the organization and production of goods and services in alternative ways so as to minimize such costs.

capital markets. Capturing these less than optimal market and institutional arrangements can be an important aspect of any modeling exercise. That is to say, although the price is driven to average costs, those same average costs may reflect market and organizational imperfections. The potential to arbitrage energy efficiency opportunities within imperfect markets is one of the focuses for this modeling effort.

Some industries in the AMIGA model produce multiple output goods. Where an industry produces multiple goods, the zero-profit condition becomes a condition that total revenue equals total costs, including payments to labor and capital. Expenditures on intermediate inputs are considered to be variable costs. To provide clarity, we denote goods produced (i.e., the outputs of an industry) by *g'* and inputs to the industry of materials and other goods and services by *g*, as shown below:

$$\sum_{g' \in i} P_{g'} X_i^{g'} = \sum_{j \in i} \sum_{g} P_g X_{gi}^{j} + VA_i . \qquad (3\text{-}5)$$

The traditional "make" table in input-output analysis gives the vector of product outputs from each industry sector.

For a number of reasons, industries may apply a risk premium or a higher hurdle rate to accepting an investment than its risk free cost of capital. This can shift the composition of capital in a the model and shift the allocation of resources relative to a static perfectly competitive economy.

3.3 Energy Resources as Part of Production

Basic resources such as crude oil and natural gas are critically important in applications of general equilibrium models used for energy security and climate policy assessments. To highlight this, we re-write the above equation to explicitly show resource inputs.

$$\sum_{g' \in i} P_{g'} X_i^{g'} = \sum_{j \in i} \sum_{g} P_g X_{gi}^{j} + \sum_{\mu} P_{\mu} R_{\mu} + VA_i \qquad (3\text{-}6)$$

Often industrial processes can use alternative feedstock inputs. For example, hydrogen can be produced from natural gas, naphtha, or methanol. This possibility for input substitution leads to a standard pricing equation in resource economics; that is, if multiple resource inputs are simultaneously economic to produce, then their price differential must equal the difference between their marginal yields and their marginal costs (including labor, capital, materials, and energy costs). Specifically this can be seen by maximizing the profit equation above with respect to use of two substitutable resource inputs, say high-sulfur crude oil, μ, and low-sulfur crude oil, v, yielding first-order necessary conditions as follows:

$$P_{\mu} - P_{\nu} = \sum_{g' \in i} P_{g'} (\partial X_i^{g'} / \partial R_{\mu} - \partial X_i^{g'} / \partial R_{\nu}) - \sum_{j \in i} \sum_{g} P_g (\partial X_{gi}^{j} / \partial R_{\mu} - \partial X_{gi}^{j} / \partial R_{\nu}) - (\partial VA_i / \partial R_{\mu} - \partial VA_i / \partial R_{\nu}) \qquad (3\text{-}7)$$

The above first-order conditions provide the basic pricing equations we use in AMIGA for standard goods and services as well as for raw energy resources. The latter includes a variety of conventional and unconventional crude oil resources with different physical properties including heating value, carbon emission factors, sulfur content, nitrogen content, heavy metals, density, and corrosiveness. For the next ten years, the Energy Information Administration forecasts adequate supplies of light sweet (low sulfur) crude oil production, with new production coming on-line in West Africa, South America, and other locations (EIA 2005).

In the longer term, relevant for energy security and climate assessment modeling, light sweet crude oils are expected to be relatively scarce; resources are limited and world demand for petroleum products is rising exponentially. Hence there will be a need to process huge quantities of very heavy oils and "tar" or "oil sands" and oil shales. The cost of upgrading these heavy resources is high including the energy requirements and resulting carbon emissions. Various experts have proposed natural gas, coal gasification, and nuclear heat sources to provide energy to upgrade very heavy oils. This, together with the challenge of maintaining and expanding the nation's energy infrastructure – including productive investments on both the supply and the demand side of the nation's energy balances – is one of the biggest issues facing future energy supplies and greenhouse gas emissions assessments (Hanson et al. 2004).

3.4 Capital and Technology Characterization

To better evaluate the economic consequences of energy security and climate policy scenarios, the AMIGA model contains detailed technology characterizations for both energy supply and energy end use. On the supply side, for example (see Section 5), AMIGA contains process step representations of the hydrocracking, coking, and gasification involved with very heavy oil upgrading. On the demand side (see Section 6) AMIGA contains a detailed characterization of end use technologies ranging from residential heating and commercial lighting to industrial output and transportation services. We describe the four-level hierarchy of the model below:

The main value-added is given as a CES function of the main capital, $\tilde{K}_i$ (excluding energy-related incremental capital) and labor. The main capital and main value added exclude certain energy-intensive equipment and transportation equipment (i.e., trucks) that are accounted for as providing separate energy-related and/or transportation-related services to the industry. The elasticities of substitution in the main value added equation is shown in Table 1 for major sector groups (Ballard, 1985).

Table 1. Elasticities of Substitution for Selected Sector Groups

Sector	Sigma	Rho	Labor α Parameter*	Capital β Parameter*
Agriculture	0.676	0.479	0.149	0.62
Mining	0.61	0.639	0.102	0.626

Utility Services	0.41	1.439	0.017	0.598
Construction	0.52	0.923	0.457	0.122
Food Processing	0.712	0.404	0.351	0.405
Clothing and Apparel	0.902	0.109	0.659	0.277
Paper Products	0.904	0.106	0.623	0.311
Petro Chemicals	0.833	0.2	0.383	0.488
Heavy Manufacturing	0.737	0.357	0.554	0.243
Light Manufacturing	0.912	0.096	0.717	0.23
Transportation Equipment	0.923	0.083	0.762	0.196
Transportation Services	0.77	0.299	0.487	0.329
Business Services	0.57	0.754	0.216	0.388
Personal Services	0.51	0.961	0.526	0.082
Government	0.42	1.381	0.692	0.01

*The labor and capital share parameters are defined as alpha or beta raised to the power of rho.

Base year 2004 sector calibration is shown below in Table 2. The theta and phi parameters in the main value added function can be fit explicitly to base year (2004) BEA industry value added data. These calibration equations are closed from and can be easily applied.

Table 2. Labor Input 2004 (thousand workers)

Sector	**Employment**
Agriculture	2,232
Mining	539
Utility Services	1,168
Construction	10,768
Food Processing	1,187
Clothing and Apparel	406
Paper Products	465
Petro Chemicals	748
Heavy Manufacturing	5,365
Light Manufacturing	3,348
Transportation Equipment	4,964
Tranportation Services	26,713
Business Services	27,540
Personal Services	47,442
Government	6,365
Total	139,250

3.5 Dual Prices

Some prices in the model are market prices for purchased goods, services, energy, labor, and emission permits. Other prices are internal to the firm as in a transfer price. In either case, however, the factor price represents an opportunity cost of using one more unit of the factor.

In cases where perfect markets are assumed to exist, duality theory may be employed to calculate output prices based on expenditure functions.

In the model, the interest rate is determined by the marginal product of capital. Sectors employ capital up to the point where the value marginal product equals the cost-of-capital. Sectors employ labor up to the point where the value marginal product of labor equals the wage. Wages and interest rates adjust in general equilibrium to clear the labor market and to equate the demand for capital to its supply.

Table 3 shows a typical sensitivity analysis on the response of the factor intensity functions to the factor price ratio. In this case we examine the effect of a 50 percent increase on the change in energy intensity for selected end use service demands. Although not shown, the average reduction in energy intensities shown in Table 3 is about 13 percent. Based on the substitution elasticities, the implied change in capital is about 20 percent.[14] In other words, a 50 percent increase in energy prices might drive a roughly 20 percent increase in capital which, in turn, reduces energy intensity by about 13 percent.

Table 3. Sensitivity to a 50% Increase in Relative Price Ratios with Current Technology*

End Use Demand	**Sigma Parameter**	**Percent Change in Energy Intensity***
Commercial electricity use		
Space Cooling	0.67	6.3
Lighting	0.88	15.9
Refrigeration	0.78	10.7
Other	0.94	19.3
Commercial gas use		
Space Heating	0.69	8.6
Other	0.66	7.5
Commercial building shell	0.87	15.6
Light industry electricity	0.93	18.7
Light industry gas	0.76	11.5

*Note that technological advance would increase the percentage reduction in energy intensity resulting from a given change in energy prices

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[14] For those who might want to estimate specific changes in capital for each of the technologies in Table 3, given the 50 percent increase in energy prices, the formula is $\{1.5^{Sigma} * (1\text{-PercentEnergySavings}/100)\text{-}1\} * 100$ percent. This relationship reflects the fact that the substitution elasticity is composed, in this case, of both a change in energy and a change in capital. To calculate the payback for each of these technologies we would also need to know the starting quantities of capital and energy as well as the base price of energy.

3.6. Non-Neutral Technological Progress

Most of the literature on non-neutral technological change has focused on factor biased or factor augmenting change, holding the elasticity of substitution (i.e., *sigma*) as fixed (Acemoglu, 2002). However, *sigma* may be an important parameter involved in technological change because it captures the curvature of the isoquants. Advanced technology may focus cost reduction on that end of the isoquant at which there is scarcity for an important factor of production such as energy. We use a form of the CES function, derived in Appendix 2-1, which accommodates several parameters frequently used to represent technological change.

3.7 General Equilibrium Economic Structure

To illustrate the evolution of the "equilibrium" of the U.S. economy from its base year representation to some point in time, we again turn to Appendix 2-2 and 2-3 which compares two different sets of input-output tables. The first set of tables (in Appendix 2-2) highlights an aggregate input-output summary representing the historical accounts for the base year economy within AMIGA. As we noted earlier, the two tables are based on the Bureau of Economic Analysis Annual Input-Output data as they have been updated for the year 2004 (BEA 2004).[15] The second set of tables (Appendix 2-3) highlights the expected input accounts after solving the three blocks of equations for the year 2030. What is important here is to note that the solution to the set of AMIGA equations can be represented in the format of a set of constructed future interindustry transactions tables which describes the structure of the US economy for that projected year. This construction includes the components of final demand and rows for payments to labor and capital by sector, as well as energy use and intermediate material purchases by sector.

3.8 Future Analysis

There are systematic market and organizational failures that affect the point at which firms substitute capital and labor to reduce the intensity of energy use. For example, energy service companies which obtain access to an industrial plant site can finance a series of energy efficiency measures to lower the energy bill of that industrial facility. The lower energy bill can then become a source of new revenue which can then be shared by the host firm and the energy service company. This creates a win-win result for both firms. In a similar way the U.S. Environmental Protection Agency's Energy Star© programs (CPPD 2004), the U.S. Department of Energy's Industrial Assessment programs (DOE 2004), and other voluntary and information programs (Howarth et al. 2000), can also result in lower costs to a firm. With the "zero-profit" condition, these cost savings would be passed on as lower product prices to households and to business customers. Hence, the savings from lower energy-related service costs in an industry propagate, in general equilibrium, throughout the economy and create net benefits. The

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[15] These BEA 2004 data are discussed more completely in Section 4.

AMIGA Modeling System can include these and other categories of program and policy initiatives within the equilibrium framework.

Improved BEA industry data provides a new opportunity to improve the underlying empirical estimates in AMIGA and similar models. The data has been improved in a number of ways including:

- A switch from Standard Industrial Classification (SIC) to the North American Industrial Classification System (NAICS). The latter provides disaggregations of industrial activities that differentiate the fast growing technology and service activities. Time series based on NAICS have been constructed by BEA as far back as 1947.
- Consistency between the Input-Output and Annual Industry Accounts. In the past these two measurement systems differed. Now the Annual time series data can provide output measures and value added from capital and labor consistent with the input-output benchmark years. This also helps BEA to prepare annual updates to 65 sector annual input-output tables.
- BEA is working on longer range projects towards reconciling the US National Income and Product Accounts (NIPA) and the United Nations System of International Accounts. This will aid in preparing economic analysis for climate policy assessments.

The improved data will allow construction of time series and sectoral cross-section data that can be used in improving estimates of sector specific production function parameters.

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Appendix 3-2. Derivation of CES Factor Demand Equations with Technological Progress Parameters

Define

$$\sigma = 1/(1+\rho)$$
$$\sigma + \sigma\rho = 1$$
$$\rho\sigma = 1 - \sigma$$

$$Q = A(\theta(K/\alpha)^{-\rho} + \phi(E/\beta)^{-\rho})^{-1/\rho}$$

$$(Q/A)^{\rho} = (\theta(K/\alpha)^{-\rho} + \phi(E/\beta)^{-\rho})^{-1}$$

$$K = \alpha((1/\theta)(Q/A)^{-\rho} - (\phi/\theta)(E/\beta)^{-\rho})^{-1/\rho}$$

$$(K/\alpha)^{\rho} = ((1/\theta)(Q/A)^{-\rho} - (\phi/\theta)(E/\beta)^{-\rho})^{-1}$$

Marginal product of K,

$$MP_K = \left(\frac{\theta}{\alpha}\right) A^{-\rho} \left[\frac{Q}{K/\alpha}\right]^{\rho+1}$$

$$MP_E = \left(\frac{\phi}{\beta}\right) A^{-\rho} \left[\frac{Q}{E/\beta}\right]^{\rho+1}$$

Minimize for a given Q

$$\text{J} = Criterion = p_K K + p_E E - \lambda Q$$

$$MP_K = p_K / \lambda$$

$$MP_E = p_E / \lambda$$

$$MP_E / MP_K = p_E / p_K$$

$$p_E / p_K = \left(\frac{\alpha\phi}{\beta\theta}\right)\left[\frac{K/\alpha}{E/\beta}\right]^{\rho+1}$$

Miss-leading to compare E with entire economy; we are not substituting the entire economy for energy!

Substitute K equation above into the criteria J to get:

$$J = p_K \alpha((1/\theta)(Q/A)^{-\rho} - (\phi/\theta)(E/\beta)^{-\rho})^{-1/\rho} + p_E E$$

Given Q, J is now a function only of E and can be minimized by calculating the derivative and setting it to zero, yielding

$$p_E = \left(\frac{\alpha p_K}{\rho}\right)(term)^{-1-1/\rho}\left(\frac{\rho\phi}{\beta\theta}\right)(E/\beta)^{-\rho-1}$$

where

$$term^{(1+\rho)/\rho} = \left(\frac{\alpha\phi p_K}{\beta\theta p_E}\right)(E/\beta)^{-\rho-1}$$

$$(1/\theta)(Q/A)^{-\rho} - (\phi/\theta)(E/\beta)^{-\rho} = \left(\frac{\alpha\phi p_K}{\beta\theta p_E}\right)^{\rho/(\rho+1)}(E/\beta)^{-\rho}$$

$$(1/\theta)(Q/A)^{-\rho} = \left(\frac{\alpha\phi p_K}{\beta\theta p_E}\right)^{\rho/(\rho+1)}(E/\beta)^{-\rho} + (\phi/\theta)(E/\beta)^{-\rho}$$

$$(Q/A)^{-\rho} = (\theta/\phi\left(\frac{\alpha\phi p_K}{\beta\theta p_E}\right)^{\rho/(\rho+1)} + 1)\phi(E/\beta)^{-\rho}$$

$$(\beta Q/EA)^{-\rho} = \theta\left(\frac{\alpha\phi p_K}{\beta\theta p_E}\right)^{1-\sigma} + \phi$$

$$(EA/\beta Q)^{\rho} = (\beta p_E/\phi)^{-(1-\sigma)}(\theta^{\sigma}\left(\frac{\alpha p_K}{1}\right)^{1-\sigma} + \phi\left(\frac{\beta p_E}{\phi}\right)^{1-\sigma})$$

$$EA/\beta Q = (\phi/\beta p_E)^{\sigma} D^{1/\rho}$$

$$D = \theta^{\sigma}(\alpha p_K)^{1-\sigma} + \phi^{\sigma}(\beta p_E)^{1-\sigma}$$

Yielding factor demand functions:

$$E = \beta^{1-\sigma}(\phi/p_E)^{\sigma} D^{1/\rho} Q/A$$

$$K = \alpha^{1-\sigma}(\theta/p_K)^{\sigma} D^{1/\rho} Q/A$$

Appendix 3-2. Table of BEA Annual 15x11 Sector Input-Output Interindustry Transactions Updated for Year 2004

Interindustry Transactions 2004 (in millions of 2004 dollars)

	Farms_etc	Mining	Utilities	Construc	Non-Dur	PetroChem	Heav_Mfg	Ligh_Mfg	Trans_Eqp	Services	Govt	TotIntMed
Farms_etc	73,411	0	1	1,377	155,428	3,521	14	16,849	2	18,406	2,487	271,496
Mining	516	42,192	90,399	7,134	1,575	213,721	12,707	439	1,328	5,226	10,551	385,788
Utilities	5,678	2,615	172	3,288	14,748	14,608	11,416	5,843	2,875	126,528	47,427	235,198
Construc	1,444	66	2,184	1,064	1,869	1,763	1,909	1,790	687	71,616	48,748	133,140
Food_etc	18,563	0	0	0	91,378	1,994	10	436	30	107,106	19,904	239,421
Apparel	502	12	2	2,286	28,193	3,140	554	6,313	7,271	8,755	5,445	62,473
Paper_etc	600	207	83	2,731	50,799	9,797	4,152	7,087	1,508	57,562	8,136	142,662
PetroChem	24,035	12,151	2,442	52,976	49,978	228,294	22,401	33,291	26,250	214,981	90,101	756,900
Heav_Mfg	5,632	13,828	1,755	136,186	19,698	17,807	214,023	55,769	101,333	82,031	25,260	673,322
Ligh_Mfg	1,202	681	1,208	99,680	8,992	9,452	23,916	147,222	37,433	144,720	41,289	515,795
Trans_Eqp	516	801	13	4,158	281	176	4,695	517	167,903	63,768	42,960	285,788
Tranport	19,023	11,685	24,504	126,084	88,246	86,203	87,120	78,996	54,108	399,746	70,934	1,046,649
Bus_Serv	21,417	46,845	7,300	128,345	117,856	101,839	77,322	125,704	57,756	3,031,832	381,931	4,098,147
Per_Serv	4,499	1,184	978	14,572	17,781	15,235	13,923	12,531	19,366	310,441	111,631	522,141
Govt	111	53	131	1,188	872	337	645	806	362	61,195	9,071	74,771
Labor VA	39,182	42,723	42,566	389,212	140,454	128,843	204,747	228,418	144,141	4,069,846	1,263,250	6,693,382
Capital VA	102,695	129,421	181,224	195,902	119,228	157,673	111,682	80,918	41,121	3,763,616	211,073	5,094,553
VA total	141,877	172,145	223,790	585,113	259,682	286,516	316,429	309,336	185,262	7,833,463	1,474,322	11,787,935
TIO	319,124	306,326	354,992	1,166,800	912,581	1,008,427	809,882	812,561	668,621	12,611,870	2,428,563	21,399,747

Final Demand 2004 (in millions of 2004 dollars)

	Consump	Invest	Govt	Exports	Imports	Total_FD	Tot_Dmd
Farms_etc	48,927	0	-1,830	28,202	28,013	48,483	319,981
Mining	113	56,493	1,204	5,896	166,451	-96,451	289,337
Utilities	205,236	0	0	1,054	1,438	207,728	442,926
Construc	0	806,138	227,452	69	0	1,033,659	1,166,800
Food_etc	415,419	0	1,232	29,028	51,005	399,901	639,322
Apparel	162,595	3,828	34	14,944	132,800	51,486	113,959
Paper_etc	19,072	0	0	13,290	22,144	12,755	155,418
PetroChem	340,468	1,680	172	117,316	199,871	278,722	1,035,620
Heav_Mfg	25,163	161,389	11,497	112,414	200,736	138,068	811,387
Ligh_Mfg	214,766	260,395	41,716	154,400	392,680	294,109	809,903
Trans_Eqp	248,638	192,231	44,220	123,223	238,511	375,487	661,276
Tranport	1,432,142	146,134	10,919	148,297	-10,101	1,763,156	2,809,806
Bus_Serv	2,334,386	323,116	33,090	191,767	48,033	2,836,944	6,935,091
Per_Serv	2,704,344	0	0	1,816	2,659	2,703,547	3,225,690
Govt	53,260	0	1,846,923	256	0	1,900,439	1,975,212
Labor VA	8,214,296	1,872,643	2,215,919	1,052,072	1,676,077	11,734,285	21,346,046

Appendix 2-3. Table of BEA Annual 15x11 Sector Input-Output Interindustry Transactions Updated for Year 2030

Interindustry Transactions 2030 (in millions of 2004 dollars)

	Farms_etc	Mining	Utilities	Construc	NonDur	PetroChem	Heav_Mfg	Ligh_Mfg	Trans_Eqp	Services	Govt	TotIntMed
Farms_etc	162,568	1	2	3,835	276,049	7,549	30	35,625	4	36,632	3,772	526,067
Mining	1,153	51,966	150,919	19,861	1,017	346,483	28,500	1,047	3,307	9,626	16,005	629,884
Utilities	9,001	3,244	183	6,356	12,039	19,824	19,156	9,744	5,085	180,686	49,747	315,065
Construc	3,214	204	3,317	2,961	2,523	3,692	4,966	4,280	1,791	148,278	73,947	249,173
Food_etc	41,425	0	0	0	160,091	4,194	24	921	82	187,431	30,194	424,362
Apparel	1,111	23	3	6,364	34,148	6,731	1,471	13,374	18,270	16,966	8,260	106,721
Paper_etc	1,339	415	126	7,602	31,067	20,701	10,722	16,280	3,790	113,999	12,342	218,383
PetroChem	47,678	21,846	2,747	128,499	56,526	444,659	55,537	77,510	65,599	359,442	111,688	1,371,731
Heav_Mfg	12,560	30,948	2,713	379,150	28,985	36,903	550,779	135,768	257,971	169,172	38,317	1,643,266
Ligh_Mfg	2,682	1,907	1,855	277,515	6,955	19,832	63,209	359,863	96,944	280,965	62,632	1,174,359
Trans_Eqp	1,148	1,628	21	11,576	428	340	12,798	1,257	422,961	135,911	65,167	653,235
Tranport	42,367	23,873	40,226	351,025	114,761	172,165	215,712	190,104	136,844	850,911	107,601	2,245,589
Bus_Serv	47,677	87,975	11,344	357,320	178,953	210,174	203,966	313,298	147,830	6,282,835	579,359	8,420,731
Per_Serv	10,010	3,010	1,505	40,570	23,939	31,109	35,378	30,560	48,585	619,581	169,336	1,013,583
Govt	247	156	206	3,307	1,281	693	1,684	1,900	925	117,734	13,760	141,893
Labor VA	86,524	84,223	66,258	1,083,591	178,744	268,719	530,896	556,443	370,919	8,143,811	1,916,248	13,286,376
Capital VA	228,520	179,013	278,774	545,402	174,818	325,034	282,543	184,183	104,807	8,128,080	320,180	10,751,354
VA total	315,044	263,236	345,032	1,628,993	353,561	593,752	813,439	740,627	475,726	16,271,891	2,236,429	24,037,730
TIO	708,944	501,170	561,332	3,248,444	1,279,684	1,983,750	2,070,879	1,961,932	1,701,832	26,088,690	3,683,935	43,790,592

Final Demand 2030 (in millions of 2004 dollars)

	Consump	Invest	Govt	Exports	Imports	Total_FD	Tot_Dmd
Farms_etc	150,043	0	-2,642	124,924	83,678	188,646	714,712
Mining	297	187,093	1,738	26,117	369,107	-153,863	478,112
Utilities	357,034	0	0	4,669	3,089	358,614	679,574
Construc	0	2,669,739	328,407	307	0	2,998,453	3,248,444
Food_etc	703,322	0	1,779	128,583	123,081	710,603	1,136,355
Apparel	326,495	9,689	50	66,194	362,152	40,275	149,974
Paper_etc	56,105	0	0	58,871	66,147	48,829	337,807
PetroChem	612,169	3,825	248	519,664	526,190	609,715	2,008,622
Heav_Mfg	72,358	591,654	16,600	497,951	751,133	427,429	2,077,148
Ligh_Mfg	585,576	964,463	60,232	683,931	1,511,445	782,756	1,966,883
Trans_Eqp	676,191	644,854	63,847	545,829	897,026	1,033,695	1,687,004
Tranport	2,679,560	386,420	15,766	656,895	-53,362	3,792,003	6,081,421
Bus_Serv	5,372,950	940,805	47,776	849,450	146,260	7,064,721	15,514,180
Per_Serv	4,059,994	0	0	8,046	7,356	4,060,684	5,082,331
Govt	153,866	0	2,666,680	1,136	0	2,821,682	2,963,806
Total	15,720,109	5,941,596	3,199,455	4,660,259	4,949,785	24,571,634	44,271,692

4 CONSUMPTION: DEMAND FOR GOODS AND SERVICES

4.1 Introduction to the Household Demand Module

Household demand, from basic preferences to final purchases, is usefully represented with a hierarchical structure.[16] We begin by discussing the highest level of the demand structure hierarchy focusing on the underlying theory of demand and functional forms.

The purpose of this section is to elaborate on some of the details and empirical estimates for household demand.

4.2 Applications of the Lancaster Approach

The energy-intensive services for households are produced following the Lancaster theory using inputs of energy and specific capital. Twenty years ago Kevin Lancaster (1971) rigorously developed the distinction between household consumption services that consumers demand and the purchased inputs needed to deliver the services. According to Lancaster, production not only takes place in the industrial sector but also in the household sector, in the sense that consumption services may have to be produced from purchased inputs. This viewpoint is important because it implies that household services could be provided more efficiently with technological improvements, similar to efficiency gains in manufacturing processes. Households may achieve reductions in purchased inputs without sacrificing, and perhaps increasing, their welfare, since welfare is based on services rather than purchased inputs. For example, households demand comfort from their heating, ventilating and air conditioning (HVAC) systems. They demand refrigeration, cooking, clothes washing, drying, and transportation services. Households produce these services using energy and the stock of durable goods (including the house or building structure).

When households produce the service more efficiently at lower cost, the price of the service is effectively reduced. With a lower effective price of the consumption service, the household’s feasible consumption set shifts outward so that all goods and services in the household’s consumption bundle can increase. The final demands for energy commodities, natural gas, electricity, gasoline, and home heating oil, are derived demands from the household demand for building HVAC services, appliance services and transportation vehicle miles traveled (VMT).

4.3 Demand Theory and Functional Forms

In the model we allow for multiple consumer groups, generally distinguished by income and associated attributes (e.g., cost-of-capital, housing type such as single family). We can get an important range of choices using just three income groups in the AMIGA model. Considering a distribution of income, rather than having just one average

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[16] A hierarchical structure is consistent with the theory of consumer choice (Varian, 1992).

consumer for the entire economy is important for a number of reasons. Lower income consumers tend to have a balance sheet with fewer assets and typically have a higher cost of capital. Savings rates are higher in higher income groups. The mix of consumer goods depends on income. For example, new cars are typically purchased by higher and middle income groups. In fact, the average new car purchaser has an average income 1.8 times the average income in the population as a whole (Ross 2006).

Each consumer is described by a system of demand functions depending on prices of all goods and services and a budget or total expenditures for that consumer. Suppose that there are *G* goods and service categories from which the consumer can choose. Let q_{it} be the demand for the i^{th} good or service category by some consumer at time *t*. Demand functions have the following general form:

$$q_{it} = D_i\left(p_{1t},\dots, p_{Gt}, B_t\right), \quad i = 1, G \tag{4-1}$$

where,

p_{it} = consumer price of good category *i* at time *t*, and
B_t = consumer budget.

The budget constraint for the consumer is given by:

$$\sum_i p_{it} * q_{it} = B_t, \quad \text{for each } t. \tag{4-2}$$

Price and income elasticities are defined as follows:

$$\varepsilon_i = p_{it} * \left(\partial D_i / \partial p_{it}\right) / q_{it} \tag{4-3}$$

$$\varepsilon_{ij} = p_{jt} * \left(\partial D_i / \partial p_{jt}\right) / q_{it} \tag{4-4}$$

$$\eta_i = B_t * \left(\partial D_i / \partial B_t\right) / q_{it} \tag{4-5}$$

where

ε_i = (own) price elasticity of demand for good *i*,
ε_{ij} = cross price elasticity of demand for good $i, j \neq i$,
η_i = income (i.e., budget) elasticity of demand for good i.

Price changes, both own and cross (holding the consumption budget, B_t, constant) will have both substitution and real income effects as described by the Slutsky equation.[17] So the usual price elasticities as defined above are not pure substitution effects.

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[17] Named after the Russian economist Eugen Slutsky, best known for his work on consumer demand theory, the so-called Slutsky equation is most simply defined as *Price effect = Income effect + Substitution effect*.

Demand functions derived from economic principles are homogeneous of degree zero, meaning that multiplying all arguments in the function by the same scalar, say *m*, will leave the quantities demanded unchanged (since the consumption bundle would still be both feasible and optimal). Thus,

$$q_{it} = D_i\left(m\, p_{1t}, \ldots, m\, p_{Gt}, m\, B_t\right). \tag{4-6}$$

Now differentiate Equation (4-6) with respect to *m*, yielding

$$\partial\, q_{it} / \partial\, m = 0 = \sum_j \; p_{jt}\; \partial D_i / \partial\, p_{jt} + B_t\, \partial D_i / \partial B_t, \tag{4-7a}$$

which can be written in terms of elasticity notation as:

$$\varepsilon_i + \sum_{j \neq i} \varepsilon_{ij} + \eta_i = 0, \tag{4-7b}$$

showing that the price and income elasticities must be related. In order to provide an interpretation, we will write equation (4-7b) as follows:

$$-\varepsilon_i = \eta_i + \sum_{j \neq i} \varepsilon_{ij} \tag{4-8}$$

The left hand side of equation (4-8) is the magnitude of the own price elasticity of demand. Suppose for the sake of discussion that the sum of the cross price elasticities was near zero, so that the magnitude of own price elasticity would be approximately equal to the income elasticity. We might find that some goods, such as nondurable food and clothing, are relatively inelastic with lower than average percentage sensitivity to both per capita income and price changes. Whereas other items, notably personal services, may be quite sensitive to income changes due to, e.g. economic growth, and to price changes due to, e.g. changing labor costs. Now consider the cross price elasticity effects for the two examples below:

Example 1. Consider two goods which are close substitutes with cross price elasticity equal to 1.3. Let good *i* have an income elasticity equal to 1. Then by equation (4-8), the magnitude of the own price elasticity of good *i* must be 1.0 + 1.3 equals 2.3. Consider the following intuition for this result: The substitution effect will depend on relative prices, say p_{jt} / p_{it}, where *j* is the other good; hence a change in P_{it} should be just as effective at changing the demand for good *i* through the substitution effect as would be a change in p_{jt}. But the own price elasticity has another effect besides substituting for the other good. The general sensitivity of good *i* to income changes implies also a general sensitivity to its own price. Now consider the income effect and suppose (just for interpretive purposes), that there were no substitution effects and that budgeted expenditure shares, S_{it}, were fixed among goods. Then $q_{it} = S_{it} * B_t / p_{it}$ and the percentage effect of a decrease in own price would be the same as a percentage increase in income, B_t.

Example 2. In macroeconomic analysis, the vector of consumption goods is often relatively small in number (compared with the full variety of goods and services an actual household would face) and with each good having a significant expenditure share of the consumption budget. Then we find that the cross elasticities are relatively small in magnitude (either positive or negative). When the price of some other good *j* rises, there is a substitution effect and an income effect that must be considered. Suppose, for example, that there were two goods, nondurables, like food and clothing, and personal services. Suppose that the price of nondurables rose. The income effect would be large, since nondurables is a large share of the consumption budget, i.e., the household would be faced with less real income to spend on other items so the cross elasticity on personal services is likely to be negative, dominating the substitution effect of trading off services for food and clothing, due to relative price changes. A negative cross price elasticity would imply from equation (3-8) that the magnitude of the own price elasticity for nondurable goods would be less than their income elasticity.

Using the homogeneity property, the demand functions can be written in terms of relative prices by scaling by the inverse of one of the prices, as follows:

$$q_{it} = D_i\left(p_{1t} / p_{Gt}, \ldots, 1, B_t / p_{Gt}\right) \tag{4-9}$$

The reference price, taken here to be p_{Gt}, is called the numeraire. Alternatively, the demand functions can be written equivalently in terms of normalized prices, $\hat{p}_{it}$, where

$$\hat{p}_{it} = p_{it} / \left[B_t / B_0\right], \tag{4-10}$$

which are prices relative to the consumption budget, normalized to one in year $t = 0$. That is, the arguments in the demand function are all scaled by B_o/B_t, where B_0 is a known base year value, yielding

$$q_{it} = D_i\left(\hat{p}_{1t}, \ldots, \hat{p}_{Gt}, B_0\right). \tag{4-11}$$

Note that in the base year, $\hat{p}_{i0} = p_{i0}$, that is, the normalized prices and the ordinary prices are the same. For other years, normalized prices differ from ordinary prices by the growth factor in the per capita consumption expenditures. Hence, the income effect of B_t increasing by some percentage must be equivalent to the total price effect from all prices decreasing by that percentage.

The expenditure budget, equation (4-2), implies another restriction on the income elasticities for the various goods and services. Let S_{it} be the expenditure share for good *i* given by

$$S_{it} = p_{it} * q_{it} / B_t. \tag{4-12}$$

Then differentiating equation (3-2) by B_t yields:

$$\sum_{i} S_{it} * \eta_{i} = 1, \tag{4-13}$$

that is, the weighted average of the income elasticities, η_i, must equal one. In this sense, the "average" income elasticity must be one.

Varian (1992) discusses three common functional forms for the own price relationship to demand: linear, exponential, and constant elasticity power functions. The exponential function has a price curvature somewhere between that of a linear demand function and a power function. This middle degree of curvature in the exponential function seems most sensible; whereas with the linear demand function, price elasticities become unrealistically large (unbounded) at low levels of demand, and with the power function, price elasticities are not allowed to increase at all when quantities demanded are low due to high prices. Following Varian, the demand functions estimated in the AMIGA model are based on the exponential functional form.

The demand for good *i* depends on changes in the normalized prices from the base year and is proportional to expenditures, B_t, as shown below:

$$q_{it} \;=\; h_i \,*\, \exp\{-\,a_i \,*\, (p_{it} \,/\, [B_t/B_0] - p_{i0})\} \,*\, B_t \,/\, Z(), \tag{4-14}$$

with denominator, *Z*( ), being the function:

$$Z(p_{1t}\,, \ldots, p_{Gt}\,, B_t) \;=\; \sum_{j} \{p_{jt} \,*\, h_j \,*\, \exp\{-\,a_j \,*\, (p_{jt} \,/\, [B_t/B_0] - p_{jo}\,)\}\} \tag{4-15}$$

which guarantees that the homogeneity property and the budget constraint are satisfied. Here, a_j and h_j, refer to elasticity-related parameters (as explained more fully below). At the same time, Varian interprets the function *Z*( ) as an aggregate price index which converts the budget, B_t, into "real" dollars, $B_t / Z(\,)$.

It can be shown that the additional properties necessary in order to be consistent with consumer choice under utility maximization are also satisfied by the demand function above. Hence, concepts that depend on underlying utility maximization, such as equivalent variation measuring changes in household welfare, can be used. The equivalent variation provides a solid foundation on economic principles for changes in household welfare and can be compared with traditional macroeconomic indices.
The demand function above can be written explicitly in the form of equation (4-11) as follows:

$$q_{it} \;=\; B_0 \,*\, h_i \,*\, \exp\{-\,a_i \,*\, (\hat{p}_{it} - \hat{p}_{i0})\} \,/$$

$$\sum_{j} \{\hat{p}_{jt} \,*\, h_j \,*\, \exp\{-\,a_j \,*\, (\hat{p}_{jt} - \hat{p}_{j0}\,)\}\}, \tag{4-16}$$

and expenditure shares can be expressed as

$$S_{it} \;=\; \hat{p}_{it} \;*h_i \;*\; \exp\{-\,a_i \;*(\hat{p}_{it} \;-\hat{p}_{i0})\}\;/ \\ \sum_j \;\; \{\hat{p}_{jt} * h_j * \exp\{-a_j * (\hat{p}_{jt} - \hat{p}_{j0})\}\} \qquad (4\text{-}17)$$

The h_i will be equal to base year consumption expenditure shares provided that we reqiure the condition that $\sum_j h_j = 1$. With $p_{i0} = \hat{p}_{i0} = 1$ for all i in the base year, the demand functions above yield the values $q_{i0} = h_i * B_0$, and Z in equation (4-15) at time 0 is one.

The parameter a_i is the magnitude of the price elasticity evaluated under base year conditions, provided that expenditures on good i are sufficiently small as a share of total expenditures so that the aggregate price index, Z, can be taken to be constant. With Z constant, note that $\partial\, q_{it} / \partial\, p_{it} = -a_i\, q_{it} * B_0 / B_t$, which is $-a_i\, q_{it}$ at $t = 0$, which implies that $\varepsilon_i = -a_i$ under base year conditions where prices are indexed to one. (If prices are not indexed to one in the base year, then a_i is equal to the magnitude of the elasticity scaled by the price.) We will refer to a_i as the elasticity parameter.

The general formula for the own price elasticities is

$$-\,\varepsilon_i \;=\; (1 - S_{it}) * a_i\, p_{it} * B_0/B_t \;+\; S_{it}. \qquad (4\text{-}18)$$

The special case discussed above is for $S_{it} = 0$. For $S_{it} > 0$, the price elasticity is shifted towards the value -1 (and would become -1 for $S_{it} = 1$, if some good i were to take the entire budget).

The general formula for the income elasticities is

$$\eta_i = 1 + a_i\, p_i * B_0 / B_t - \text{weighted average over } j \text{ of } \{a_j\, p_{jt} * B_0 / B_t\} \qquad (4\text{-}19)$$

Hence, income elasticities are greater than (less than) one depending on whether "$a_i\, p_{it}$" is greater than (less than) "the weighted average over all goods of $a_j\, P_{jt}$", where the weights are the expenditure shares.

Goods with a higher than average value for the elasticity parameter a_i, will tend to have both a higher price elasticity and an income elasticity greater than one. These sectors tend to be sensitive to both prices and income. Service sectors are leading examples of those sectors that tend to be sensitive to both prices and income. Some other sectors, such as food, tend to be less elastic to price changes and have an income elasticity less than one.

In summary, the economic theory of consumer choice imposes certain restrictions on the specification of the demand functions (see Varian, 1992):

- The demand functions must be linear homogeneous of degree zero in prices and the consumer budget expenditures;

- The sum of the expenditures on individual goods and services must equal the consumer budget expenditure; and
- The price derivatives of the Hicksian demand functions must be symmetric.

The first condition states that the demand for real goods and services must be invariant to arbitrary scaling of all prices and the dollar expenditure budget. The third condition places a restriction on the cross price elasticities of demand. Further, the household demand module meets the separability conditions needed to represent sectoral demand in two stages of a hierarchy (Varian, 1992).

4.4 Estimation of Elasticity Parameters

Historical consumption expenditure shares shift over time. These changing sectoral shares provide the basis for estimating the sector elasticities and the intercepts of the demand functions. We estimate the elasticities using the NIPA product time-series data obtained from the DOC/BEA STAT-USA (www.stat-usa.org). This site provides historical expenditure series by product type in both nominal dollars and real dollars. The ratios of nominal to real expenditures by product type yields a time-series for prices.

Household price and income elasticities are estimated with restrictions from the theory of the consumer as presented in Section 4.3. One restriction is that the weighted average income elasticity over all goods and services must be 1.0. Recall that restrictions derivable from utility maximization imply that certain relationships must hold between price and income elasticities.

Sectors tend to be either more elastic or more inelastic with respect to both price and income changes. For example, food and clothing tend to be inelastic both with respect to price and income. Services tend to have high elasticities both with respect to prices and income.

Table 4.1. Table of Key Elasticities for Consumer Goods

Consumer Good	Own Price	Income
Motor vehicle services	0.64	0.66
Other durable goods	0.63	0.66
Nondurable goods, excl. energy	0.51	0.36
Housing Services	0.67	0.66
Other Services	1.51	1.83

The demand functions specified in Section 4.3 satisfy the additional properties that are necessary to be consistent with consumer choice under utility maximization (Varian, 1992). Hence, concepts that depend on underlying utility maximization, such as the equivalent variation as a measure of changes in household welfare, can be used. Then changes in consumption patterns, comparing a policy impact simulation relative to a reference scenario, can be associated with economic welfare effects. The AMIGA system can calculate real dollar benefits or losses using the equivalent variation measure.

The equivalent variation can be compared with traditional macroeconomic consumption indices.

4.5 Choice of Domestic or Imported Goods

If the consumer can distinguish imported goods from domestically produced goods, then the consumer's preferences will extend to his/her ranking foreign vs. domestic goods. Here we represent this choice between two goods classified within the same category as the second-level in the demand function hierarchy, whereas at the top level the consumer makes choices among the major categories.[18] This two-stage hierarchical demand structure can be shown to be consistent with consumer's basic preferences (Varian, 1992). Further, the mechanics of the demand functions work as one would expect. Namely, the dual of the functional form at the second level provides a price aggregator function which combines the delivered prices of domestic goods and imported goods into a price measure for the category as a whole. These category price measures are used in the top-level demand functions described in Section 3.3 to determine the demand vector for the categories. Then these category demands are multiplied by the factor intensities (based on the second-level aggregator function) yielding derived demands for domestic and imported goods.[19]

For the second-level demand functional form, we use a constant elasticity of substitution function. The elasticities of substitution in this aggregator function for international trade categories are taken from the M.I.T. model (Yang , 1996).

3.6. Personal Vehicle Choice

A new study by the Oak Ridge National Laboratory Greene et al. (2004) estimated the demand functions for light duty vehicles (LDV) including demand by size category, vehicle type, drive train (including hybrid and diesel vehicles), fuel economy (MPG), performance, luxury, and other characteristics. The functional form that they used, the nested Multinomial logit model, is similar to the one that we use within AMIGA. This model is exponential in vehicle price and other attributes and is normalized to base year market share data. Hence, these estimates have the same exponential functional form as is described in this Section and are consistently integrated into the household demand structure.

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[18] The major household energy services such as personal transportation are not imported. In fact they are produced by the household itself. For energy services, second level demands are those derived demands that are used in the household production function such as durable goods (e.g., vehicles) and gasoline. These second-level demands differ from the case of import and domestic shares in that the household preferences pertain only to the top-level demand for the energy service and not to the derived demands (e.g., the gasoline purchased).

[19] The import and domestic intensities are close to adding to one so loosely speaking they can be thought of as import and domestic shares of demand for Armington goods.

Vehicles have so many different attributes (choice dimensions), including design features focusing on attracting sales, that manufactures could not possible supply enough models of vehicles to span the full set of possible attribute combinations. This limitation is aggravated by the existence of significant scale economies in producing any give model, which effectively sets a minimum market size for each vehicle offering, or it will not be produced. But even with a limited discrete set of options, the number of offerings available is quite large. So the consumer choice problem is to pick the most preferred vehicles among the offerings, giving rise to market shares. For example, instead of a continuum of vehicles with ranges of performance, fuel economy, and cost, a selected set of these combinations are offered for each vehicle type category and drive train.

Consider the example of fuel economy. The Oak Ridge National Laboratory study surveys the weights or level of importance that consumers tend to place on the fuel economy (MPG) attribute. The analysis suggests a 3-year payback as a midpoint of available estimates. When the price of fuel rises (either due to market forces, a fuel tax, or a carbon charge), the fuel economy attribute gets more weight and vehicles that score better in fuel economy will raise their market share.

4.7 Accounting for Distribution Costs

Distribution costs are important to include on both the price and demand sides of the model. They are important cost components and as a result also important sector activities. Sectoral shifts in the economy will cause shifts in demand for distribution activities.

Delivered prices drive the demand functions. Delivered prices to the consumer include transportation from the factory or, in the case of imported goods, from the international border transshipment point, referred to here as the “dock”. Also included are wholesale and retail trade markups. Goods transportation and wholesale/retail trade are assumed to be competitive businesses. Let *d* be the index over the following six generic distribution activities:

1. rail shipping,
2. truck shipping and warehousing,
3. water shipping,
4. air freight,
5. wholesale trade, and
6. retail trade.

The delivered domestic goods price is the weighted average of the factory-gate FOB[20] price index and the price index for distribution. The delivered imported goods price is the weighted average of the dock price for imported goods and the price index for distribution.

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[20] FOB is the “Free-on-Board” value of a good calculated based on its production cost, not including the cost of transporting the good to the consumer.

The producer prices (at the factory gate) are the solution to the simultaneous set of price equations (see Section 2). Foreign prices are exogenous when running only the US model. The distribution markup data are available from the BEA for benchmark input-output years. We calibrate the distribution cost fractions to the most recent 1997 benchmark IO data (BEA 1997). The size of the markups varies from 20% for automobiles to 30-55% for other manufactured goods. By far the largest markup sector is retailing. These markups are shown in Appendix 3-1 to this section for the 1997 benchmark AMIGA sector list. Notice that the retail markups are large in many sectors, with some examples over 200%. The average markup on marketing petroleum products is about 100%.

Table 4.2. Production and Distribution Fractions for Selected Product Groups

	factory share	railroad share	trucking share	water transport	air freight share	wholesale share	retail share
Totals	84.4%	0.1%	0.5%	0.0%	0.1%	3.8%	11.2%
lumber&furniture	51.6%	0.1%	0.3%	0.0%	0.0%	3.8%	44.1%
Stone,glass,clay	45.2%	0.3%	1.3%	0.1%	0.2%	6.0%	46.9%
fabricated equipment	49.4%	0.0%	1.1%	0.0%	0.1%	7.9%	41.5%
transport equipment	80.8%	0.8%	1.2%	0.0%	0.0%	3.2%	14.0%
elect equipment	57.1%	0.1%	1.3%	0.0%	0.2%	9.3%	32.0%
instruments	45.3%	0.0%	0.1%	0.0%	0.2%	10.6%	43.8%
misc mfg	45.1%	0.0%	0.8%	0.0%	0.1%	13.1%	40.9%
food mfg	63.9%	0.2%	1.2%	0.0%	0.1%	11.2%	23.3%
textiles	48.6%	0.0%	0.3%	0.0%	0.2%	6.4%	44.5%
pulp&paper	65.8%	0.0%	1.6%	0.0%	0.0%	6.9%	25.6%
printing	58.3%	0.0%	2.0%	0.0%	0.8%	8.1%	30.8%
synthetic materials	61.8%	0.0%	1.0%	0.0%	0.2%	9.6%	27.4%
other nondurables	44.5%	0.0%	3.9%	0.0%	0.1%	8.8%	42.7%
agriculture	53.3%	0.3%	5.6%	0.0%	1.3%	9.0%	30.4%
chemicals	52.6%	1.1%	4.8%	0.1%	0.1%	9.4%	31.8%
oil refining	46.2%	0.3%	0.9%	1.0%	0.0%	30.9%	20.7%

4.8 References

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Appendix 4-1. AMIGA Benchmark 1997 Sector List, Consumption in Producer Prices, and Retail Markups

	Description	AMIGA Code	Retail Markup	Consumption in Producer Prices	Markup Ratio(%)
1	Crop production	1110	16720	26967	62.0
2	Animal production	1120	1461	4474	32.7
3	Forestry, logging, fishing and hunting	1131	783	4232	18.5
4	Agriculture and forestry support activities	1150	0	459	0.0
5	Oil and gas extraction	2110	0	0	
6	Coal mining	2120	66	57	115.5
7	Iron, copper, nickel, lead, zinc mining	2150	0	0	
8	Gold, silver, and other metal ore mining	2155	0	0	
9	Mineral mining and quarrying	2160	29	40	73.7
10	Drilling oil and gas wells	2170	0	0	
11	Oil and gas operations support	2180	0	0	
12	Support activities for mining	2190	0	0	
13	Power generation and supply	2210	0	94516	0.0
14	Natural gas distribution	2250	0	36832	0.0
15	Water, sewage and other systems	2290	0	21428	0.0
16	New residential construction	2301	0	0	
17	New nonresidential construction	2302	0	0	
18	Residential maintenance and repair	2304	0	0	
19	Maintenance and repair construction	2305	0	0	
20	Food mfg	3110	93953	222517	42.2
21	Wet corn milling	3112	210	546	38.5
22	Beverage mfg	3121	24104	57168	42.2
23	Tobacco mfg	3122	10212	32257	31.7
24	Textile and product mills	3135	17053	22023	77.4
25	Apparel mfg	3150	78958	99875	79.1
26	Leather product mfg	3160	21040	23704	88.8
27	Mobile home mfg	3202	0	0	
28	Wood product mfg	3210	1439	1556	92.5
29	Pulp mills	3223	0	0	
30	Paper and paperboard mills	3230	2862	6503	44.0
31	Converted paper product mfg	3235	4796	8600	55.8
32	Printing and related activities	3240	1977	2739	72.2
33	Petroleum refineries	3410	31624	56716	55.8
34	Asphalt blocks, shingles, coatings	3422	0	0	
35	Petroleum and coal product mfg	3425	826	1920	43.0
36	Petrochemical mfg	3430	0	0	
37	Industrial gas mfg	3441	70	157	44.2
38	Synthetic dye and pigment mfg	3442	0	0	
39	Other basic inorganic chemical mfg	3450	8	21	38.5
40	Other basic organic chemical mfg	3460	387	539	71.7
41	Plastics material and synthetic rubber	3251	0	0	
42	Organic fiber mfg	3252	0	0	
43	Nitrogenous fertilizer	3471	26	63	40.7
44	Phosphatic fertilizer and mixing	3475	31	80	38.4
45	Pesticide and other agricultural chemicals	3480	518	1152	45.0
46	Pharmaceuticals and medicine	3254	28696	60783	47.2
47	Paints, coatings, and adhesives	3255	946	1059	89.3
48	Soaps, cleaning compounds, toiletries	3256	21747	36657	59.3
49	Other chemical products	3259	1518	2394	63.4

	Description	AMIGA Code	Retail Markup	Consumption in Producer Prices	Markup Ratio(%)
50	Plastics product mfg	3261	5292	7364	71.9
51	Tires and rubber products	3262	9123	7865	116.0
52	China and ceramics	3271	2469	2903	85.0
53	Glass and products	3272	1445	1726	83.7
54	Cement mfg	3275	0	0	
55	Concrete products	3276	15	15	96.7
56	Lime and gypsum mfg	3274	0	0	
57	Other mineral products	3279	704	979	71.9
58	Iron and steel mills & mfg	3311	55	75	73.0
59	Steel wire and ferroalloy mfg	3312	489	664	73.7
60	Alumina refining	3321	0	0	
61	Primary & secondary aluminum production	3322	0	0	
62	Aluminum sheet, plate, foil, etc. mfg	3327	0	0	
63	Primary & secondary copper production	3331	0	0	
64	Other primary & secondary nonferrous metal	3332	0	0	
65	Copper rolling, drawing, extruding, and wire	3334	0	0	
66	Other nonferrous metal shaping	3337	23	57	40.6
67	Ferrous metal foundries	3341	0	0	
68	Aluminum and other foundries	3343	13	6	213.3
69	Iron and steel forging	3346	0	0	
70	Other forging, stamping, and rolling	3349	217	256	84.8
71	Cutlery and hand tool mfg	3350	4836	4910	98.5
72	Architectural and structural metals mfg	3360	59	74	79.9
73	Boiler, tank, and shipping container mfg	3370	98	123	80.0
74	Other fabricated metal product mfg	3380	1681	2296	73.2
75	Ordnance and accessories mfg	3390	1104	1459	75.7
76	Farm machinery and equipment mfg	3511	0	0	
77	Lawn and garden equipment mfg	3512	647	619	104.4
78	Construction machinery mfg	3513	0	0	
79	Mining machinery and equipment mfg	3514	0	0	
80	Oil and gas field machinery and equipment	3515	0	0	
81	Traditional industrial machinery mfg	3520	279	273	102.2
82	Semiconductor and other machinery mfg	3525	120	284	42.1
83	Commercial and service industry machinery	3530	1411	1995	70.7
84	HVAC equipment, commercial refrigeration	3540	700	1601	43.7
85	Metalworking machinery mfg	3550	61	62	97.7
86	Turbine and turbine generator set units mfg	3560	0	0	
87	Other engine equipment mfg	3565	181	521	34.7
88	Mechanical power transmission equipment	3569	0	0	
89	Other general purpose machinery mfg	3570	1236	1170	105.6
90	Computer and peripheral equipment mfg	3610	6146	16207	37.9
91	Audio, video, communications equipment	3620	10922	22607	48.3
92	Semiconductor and electronic components	3630	169	433	39.2
93	Electronic instrument mfg	3640	3750	3609	103.9
94	Magnetic media mfg and reproducing	3646	207	415	49.9
95	Electric lamp bulb and part mfg	3661	1212	1184	102.4
96	Lighting fixture mfg	3666	2026	2224	91.1
97	Electric house wares and household fan mfg	3671	1584	3653	43.4
98	Household vacuum cleaner mfg	3672	850	1996	42.6
99	Household cooking appliance mfg	3673	1349	3148	42.8
100	Household refrigerator and freezer mfg	3674	1172	2782	42.1
101	Household laundry equipment mfg	3675	1185	2819	42.0
102	Other household appliance mfg	3679	534	1065	50.1

	Description	**AMIGA Code**	**Retail Markup**	**Consumption in Producer Prices**	**Markup Ratio(%)**
103	Electrical equipment mfg	3680	208	224	92.9
104	Batteries	3692	3358	4084	82.2
105	Other electrical component mfg	3696	468	717	65.3
106	Automobile and light truck mfg	3710	23208	129191	18.0
107	Motor vehicle body mfg	3721	2	9	18.7
108	Motor vehicle parts mfg	3726	7216	8370	86.2
109	Heavy duty truck mfg	3731	0	0	
110	Truck trailer mfg	3737	0	0	
111	Motor home and travel trailer mfg	3740	2054	6271	32.8
112	Railroad car, boat, and ship mfg	3750	1433	4181	34.3
113	Aerospace product and parts mfg	3764	129	695	18.5
114	Motorcycle, bicycle, and parts mfg	3770	2776	3378	82.2
115	Military armored vehicles and tank parts	3780	0	0	
116	Other transportation equipment mfg	3790	955	1684	56.7
117	Furniture and related product mfg	3810	26859	29943	89.7
118	Medical equipment and supplies mfg	3830	10018	7617	131.5
119	Other miscellaneous manufacturing	3890	46537	52037	89.4
120	Wholesale trade	4200	0	222467	0.0
121	Truck transportation	4840	0	34462	0.0
122	Air transportation	4810	0	53765	0.0
123	Rail transportation	4820	0	4584	0.0
124	Water transportation	4830	0	5941	0.0
125	Pipeline transportation	4860	0	713	0.0
126	Transit, ground passenger transportation	4850	0	16807	0.0
127	Sightseeing, transportation support activity	4870	0	3122	0.0
128	Couriers and messengers	4920	0	0	
129	Warehousing and storage	4930	0	452	0.0
130	Newspaper, book, and directory publishers	5111	18233	39520	46.1
131	Software publishers	5112	1636	5591	29.3
132	Motion pictures, videos, sound recording	5120	6838	18398	37.2
133	Radio, TV and cable	5130	0	32385	0.0
134	Telecommunications	5133	0	105376	0.0
135	Information and data processing services	5143	0	6123	0.0
136	Monetary authorities, credit intermediation	5211	0	207204	0.0
137	Securities, commodities, funds, trusts	5235	0	126237	0.0
138	Insurance carriers	5240	0	162551	0.0
139	Real estate	5310	0	190399	0.0
140	Owner-occupied dwellings	5318	0	592862	0.0
141	Automotive equipment rental and leasing	5321	0	40507	0.0
142	Machinery and equipment rental and leasing	5324	0	91	0.0
143	General rental centers	5326	0	8496	0.0
144	Video and CD rentals	5328	0	8193	0.0
145	Lessors of nonfinancial intangible assets	5330	0	0	
146	Legal services and accounting	5401	0	58710	0.0
147	Architecture, engineering, and design	5403	0	2523	0.0
148	Computer systems design and services	5415	0	0	
149	Management and technical consulting	5416	0	1045	0.0
150	Scientific research and development	5417	0	8649	0.0
151	Advertising and related services	5418	0	714	0.0
152	Other professional and technical services	5419	0	14725	0.0
153	Management of companies and enterprises	5500	0	0	
154	General administrative and support services	5610	0	14279	0.0
155	Employment services	5613	0	784	0.0

	Description	**AMIGA Code**	**Retail Markup**	**Consumption in Producer Prices**	**Markup Ratio(%)**
156	Travel arrangement and reservation services	5615	0	6961	0.0
157	Waste management and remediation	5620	0	8732	0.0
158	Educational services	6100	0	121013	0.0
159	Ambulatory health care services	6210	0	389518	0.0
160	Hospitals	6220	0	337821	0.0
161	Nursing and residential care facilities	6230	0	92577	0.0
162	Social assistance	6240	0	64556	0.0
163	Performing arts, sports, museums, parks	7110	0	23293	0.0
164	Amusements and recreation	7130	0	79451	0.0
165	Accommodation	7210	0	53423	0.0
166	Food services and drinking places	7220	0	291088	0.0
167	Automotive repair and maintenance	7300	0	105396	0.0
168	Electronic and other repair services	7400	0	14507	0.0
169	Retail trade	4400	0	617895	0.0
170	Personal services	7510	0	71803	0.0
171	Laundry services	7520	0	12178	0.0
172	Civic, social, professional, religious orgs	7600	0	78928	0.0
173	Postal service	7810	0	7046	0.0
174	Other Federal Government enterprises	7830	0	0	
175	Other State and local govt enterprises	7930	0	29053	0.0
176	Private households	7700	0	12035	0.0
177	Noncomparable imports	8000	0	45260	0.0
178	Scrap	8110	0	-3585	0.0
179	Used and secondhand goods	8160	40506	39106	103.6
180	General government industry	8200	0	0	
181	Rest of the world adjustment	8300	0	-90012	0.0
182	Inventory valuation adjustment	8500	0	0	
	Totals		617852	5571584	11.1

5. ENERGY SUPPLY AND GREENHOUSE GAS EMISSIONS

5.1 Electric Generation

In any production sector, there is always the distinction between current production using the existing capital stock and investments which augment the capital stock for future use. That is, there are operating decisions based on short run marginal costs and investment decisions based on maximizing the present worth of the firm. These two problems are linked because the future return on making an investment is the integral over short run outcomes over the life of the investment. In a static world in which the short run never changes, long run and short run marginal costs will be equal, providing the correct market signal to efficiently operate current production and to create an adequate incentive to make further investments.

This distinction is particularly important for modeling the electric power sector. In the short run, on a daily, or even hourly, basis available generating units are dispatched to meet current loads. The short run marginal cost will be the variable cost of bringing the last unit on line. The last unit may have an operating cost much higher than the average operating unit. For example, a peaking turbine will have a much higher operating cost than a base load unit. For efficient use of electricity, customers must see the marginal cost of generating power through its price in real time, say hourly. If demand is high (relative to existing generation capacity) and if real time prices are high when demand is high, then investors will see an opportunity to add capacity at a profit. If spot and futures prices for electricity are allowed to move freely, eventually investors will be forthcoming. An alternative to this framework is to have separate markets for electrical energy and for providing capacity reserves for reliability. We could model either market configuration. Here we model the first case since it represents pure and ideal market conditions with no efficiency loss. The second configuration, to use an analogy, would be like paying two bills to your local car wash, first a price based on water consumption and second a reliability rent to cover capital costs of the facility. In most markets the latter is embedded in the product or service price.

Figure 5.1 (on the following page) illustrates how the load curve (LC) facing dispatchable generating technologies is constructed and how the generating units are ordered on the LC. The LC shows expected power demand and generation for each hour of a given year. To obtain the LC, it is necessary to subtract non-dispatchable generation from total load. Non-dispatchable sources include intermittent renewable generators, cogenerators, and small distributed generators. This result yields net generation by hour facing centrally dispatched power plants: coal, nuclear, NGCC, and peaking turbines. The above figure labels the switch point at which the last coal unit is loaded, H_{Base}, and the first peaker turbine is loaded, H_{Peak}. These switch points effectively divide the LC into three segments: base, shoulder, and peak.

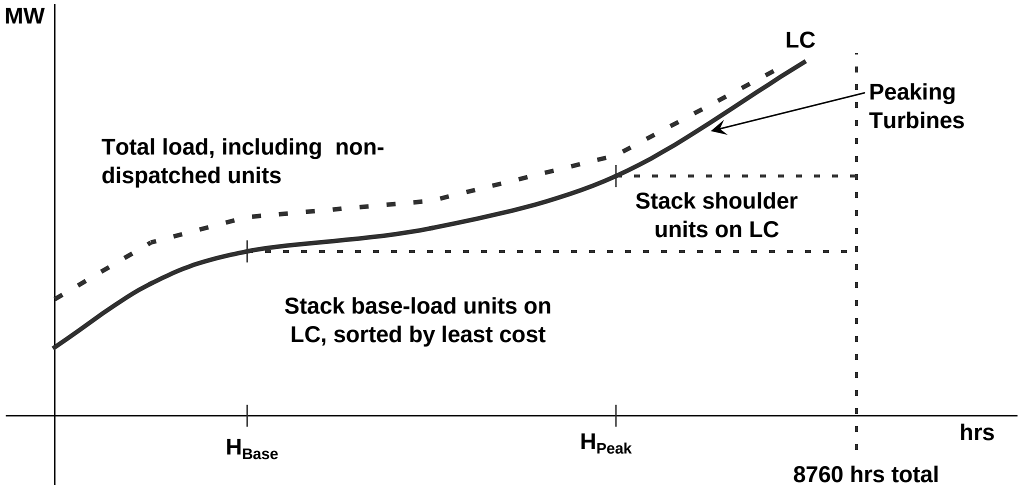

Fig. 5.1. Load Curve (LC) Diagram

Available generating units are “stacked” to compose the LC in the order of least variable cost as shown in Figure 5.1. Normally, nuclear units have the lowest variable cost, then newer coal units, then older existing coal units, then NGCC, then old gas and residual oil boiler units (where they still exist), and finally gas and distillate oil peaking turbines. The variable cost, i.e., marginal cost, for these units can be plotted as a function of the point on the hour axis of the LC at which a unit just becomes economic to run. This marginal cost function is illustrated in Figure 5.2. Marginal cost will be an increasing function along the hour axis because units are dispatched in order of marginal cost. Within a plant category (e.g., existing coal units), the graph showing marginal costs may appear to be almost continuous, since marginal cost may increase only slightly from one unit to the next in the loading order.

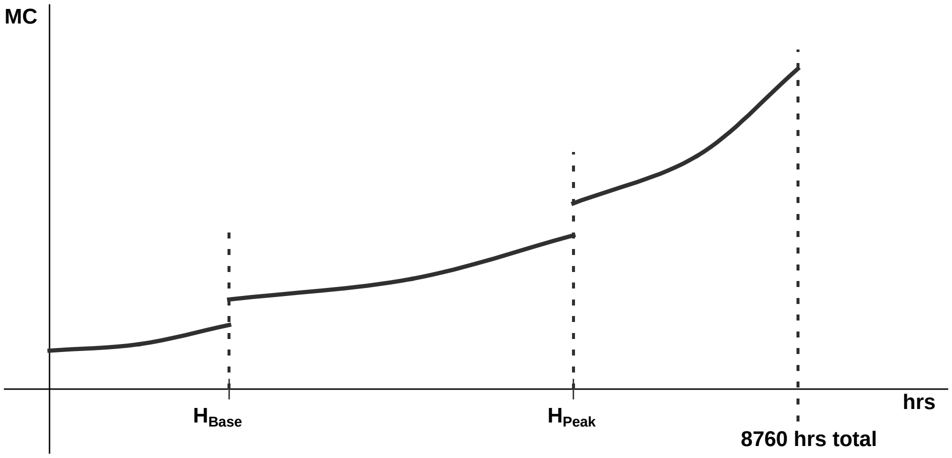

Fig. 5.2. Marginal Cost Diagram

However, there are substantial discrete jumps in marginal cost at the switch points, at which all of one type of generating unit has been loaded and the next lowest marginal cost unit is a new generating category (e.g., the marginal cost of running an NGCC unit will be much greater than that of a coal unit). It is the dispatchable units, mostly fossil fuel units, that are on the margin and, hence, they determine marginal costs. Because existing power plant units have variation in their heat rates (i.e., a power plant's efficiency varies inversely with its heat rate), changes in fuel prices and/or emission charges can change the marginal cost of running a unit and impact the loading order of generating units. For example, a carbon charge will tend to increase the capacity factor of more efficient units and decrease the capacity factor of less efficient units.

Key questions are how much base load capacity should be built and how much peaking capacity should be available. The economic criteria for building a power plant are much like the conditions for market entry. Firms have an incentive to enter a market as long as there are rents to be earned, where average price is greater than long-run marginal costs (LRMC). For a power plant, the LRMC for increasing output by one kWh is the full levelized cost. Hence, the present value of total revenues must cover full present value costs in order to provide an incentive for new investment.

In the reference case, AMIGA takes nuclear power and the share of new coal capacity that is IGCC to be exogenous. IGCC is more expensive than a new state-of-the-art pulverized coal unit, so if IGCC captures some market share, it does so for reasons other than cost. For example, electric power companies that are currently considering building IGCC units say they want to gain experience with a technology that some day may need to be deployed in order to capture and store CO_2.

In short, coal and natural gas do not compete for the same market segments; instead the substitution of natural gas capacity for coal capacity (or vice versa) takes place on the margin between market segments. If it is profitable to add new coal capacity (say, because of higher gas prices), then more coal capacity stacked on the LC will increase the switch point H_{Base}, expanding the base-load segment until coal just breaks even again.

If it becomes unprofitable to build new coal units (say, because of a new carbon charge), then H_{Base} will decrease resulting in a larger shoulder segment, more NGCC investment, and a higher electricity price that returns coal investment again to break even status, albeit at a lower level of coal investment. Further, a higher electricity price will raise the eventual market share of renewable energy and, hence, increase the rate at which it penetrates the market given by the logistic equation.

The return on investing in a new coal plant is based on the integral over the entire load curve (scaled by plant outage rate or down time) of hourly revenue, where hourly revenue is given by hourly sales time the current spot price. In principle, a new base load unit would be first in the loading order and so would be able to sell electricity whenever it is available. The present value of this annual revenue projected into the future must be greater than or equal to the cost of building a new coal power plant.

The return on investing in an NGCC unit is based on the integral over the shoulder and peak periods of the load curve (scaled by plant availability) of hourly revenue, where again hourly revenue is given by hourly sales time the current spot price. The present value of this annual revenue projected into the future must be greater than or equal to the cost of building a new NGCC power plant.

The return on investing in a gas peaking turbine is based on the integral only over the peak period of the load curve (scaled by plant availability) of hourly revenue, where again hourly revenue is given by hourly sales time the high peak spot prices. The present value of this annual revenue projected into the future must be greater than or equal to the cost of building a new combustion turbine. Note that the peaking turbine has a lower capital cost than the other technologies but it also has a lower utilization rate, a few hours per year during which the spot price is really high.

AMIGA calculates carbon emissions from power generation based on the e-GRID data base. AMIGA also calculates sulfur dioxide, nitrogen oxides and mercury emissions from power plants.

5.2 Renewable Energy

The fossil fuel technologies analyzed in the previous sub-section are widely available, mature technologies: base load coal plants, NGCC, and peaking turbines. They benefit from extensive experience, learning, and have a market large enough to exploit scale economies. Developing technologies lack all these cost reduction advantages and also carry with them uncertainties associated with the lack of experience and learning. Hence, investments in developing technologies will be slower than what they should eventually achieve in the long run.

The very low carbon technologies such as wind, photovoltaic, solar thermal power, geothermal, biomass, and even new nuclear designs and IGCC, are developing, not yet mature, technologies. Of these technologies, the renewable technologies are represented in the electricity sector model as gradually gaining market share, x_t, from an initial small market share according to the logistic function that has been used widely in the economic literature on technology adoption. The logistic function can be expressed in a recursive, dynamic form:

$$x_{t+1} = x_t \cdot \left(1 + b \cdot \left(y(p) - x_t\right)\right) \tag{5.1}$$

where y is a forecast of the eventual market share and b is related to the growth rate occurring at low market shares. Since these developing renewable technologies sell available output at the price of electricity, p, the eventual market share is endogenously determined within the model and depends on p.

Table 5-1. Reference Case Electricity Cost and Performance Assumptions

Technology	**2005**				**2035**			
	Capital Costs ***(2000$ per kW)***	**Heat Rate** ***(Btu per kWh)***	**Fixed O&M** ***(2000 $/kW)***	**Variable Cost** *(mills/kWh)*	**Capital Costs** ***(2000$ per kW)***	**Heat Rate** ***(Btu per kWh)***	**Fixed O&M** ***(2000 $/kW)***	**Variable Cost (mills/kWh)**
Waste Combustion	1,531	13,300	44	5	1,441	12,525	44	5
Nuclear Genrn	1,568	0	76	2	1,477	0	76	2
Hydro Genrn	1,820	0	43	0	1,714	0	43	0
Wind Class 6 & up	1,049	0	23	1	930	0	23	1
Wind Class 5	1,017	0	23	1	902	0	23	1
Wind Class 4	963	0	23	1	854	0	23	1
Wind Local DG	1,070	0	23	1	949	0	23	1
Central Solar	1,177	0	43	1	1,044	0	43	1
Photovoltaic	2,034	0	75	0	1,803	0	75	0
Geothermal	2,141	0	96	1	2,016	0	96	1
NGCC	632	7,600	14	1	595	7,157	14	1
Peaker Turbines	415	8,665	8	1	391	10,359	8	1
Pulverized Coal New	1,147	10,000	21	4	1,260	9,417	21	4
IGCC Coal	1,491	8,759	34	2	1,404	8,248	34	2
IGCC Pet Coke	1,527	9,973	43	5	1,438	9,392	43	5
IGCC Biomass	1,595	10,382	48	6	1,502	9,777	48	6
CCS Coal IGCC	1,880	12,356	42	3	1,770	11,636	42	3
CCS Pet Coke IGCC	2,007	12,675	50	5	1,890	11,936	50	5
CHP Coal	1,456	15,000	27	4	1,371	14,126	27	4
CHP Gas Oil	728	14,000	16	1	685	13,184	16	1
CHP Renewable	1,070	0	32	6	1,008	0	32	6
Small Generators	321	13,000	8	1	302	12,242	8	1
Bldg PV	2,034	0	54	0.1	1,803	0	54	0.1

In particular, the long run return on investing in a solar or wind unit is based on the integral over the entire load curve of hourly revenue times the probability of availability, since these are intermittent technologies. The present value of this annual revenue projected into the future must be greater than or equal to the cost of building a new renewable power plant.

Wind turbines in particular suffer from lack of availability during peak load when electricity is most valuable. On average wind operates with only about a 20% capacity factor (relative to rated turbine output) during peak hours. This is because wind speeds tend not to be high when electricity demand is high.

A solution to the intermittency problem of renewable energy, particularly wind power, is plug-in vehicles. The battery pack in vehicles can charge when electricity is in surplus and its price is low. This requires electricity pricing consistent with the availability and cost of power. A small wireless connected computer in the vehicle can make buy and no-buy decisions to charge its batteries based on market prices and the energy needs of the vehicle. If there were enough such vehicles connected to the grid, the load curve would be affected and much more renewable energy capacity would be economic. NREL has a detailed least cost energy model count by county and showed the about three times the renewable energy would be economic if vehicle battery packs were grid connected (Short 2005).

5.3 Petroleum Refining and Hydrogen Production

The petroleum refining industry is second only to the electric power generation sector in energy use and carbon emissions. It is also closely connected with the choice of transportation fuels and the efficiency of transportation technologies.

Over the last 18 months, we have added a new "MARS" petroleum refining module to the AMIGA modeling system.[21] Most energy-related CGE models treat the conversion of crude oil resources into petroleum products as a static "black box" conversion. However, there are dramatic changes occurring in this market requiring changes in refining, so we think that it is important to represent the various energy-intensive steps used to refine petroleum. These have implication for carbon emissions, since the carbon content of fuels may change and refinery carbon emissions may increase.

One reason to model petroleum refining in detail are changes in the composition of feedstocks. EIA keeps extensive, detailed records on crude oil imports. These EIA data

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[21] In the process of developing the refinery module we added a new member to our AMIGA modeling team of experts — Dr. John Marano, refinery technology consultant at Argonne and Adjunct Professor of Chemical Engineering, University of Pittsburgh. He also consults for the EIA on the NEMS Petroleum Market Model (PMM). We have named the new module "MARS," for Macro Analysis of Refining Systems. For this effort Argonne is funded by the DOE Office of Fossil Energy and the National Energy Technology Laboratory. The funds support oil and gas market analysis, including analysis of energy security and climate policy scenarios.

shown in Figure 5.3 (source: Joann Shore, EIA) show imports of light sweet (low sulfur) crude oil decreasing as a share over the last fifteen years. In the current supply situation, the marginal sources of additional supplies tend to be the heavy sour crude oils.

The need for US refiners to process heavy sour crude oils has spurred a large investment in heavy oil processing equipment. Light sweet crude feedstock may only need atmospheric distillation and a catalytic cracker to convert medium heavy oils into gasoline. The process units that have been added to refineries to process the heavier oils are vacuum distillation, thermal cokers (which produces petroleum coke as a by-product), residual oil desulfurization, gas oil hydrotreating, and distillate hydrocrackers. In addition, the ultra low sulfur diesel rules applied to fuel production require one or two stages of high severity distillate hydrotreating.

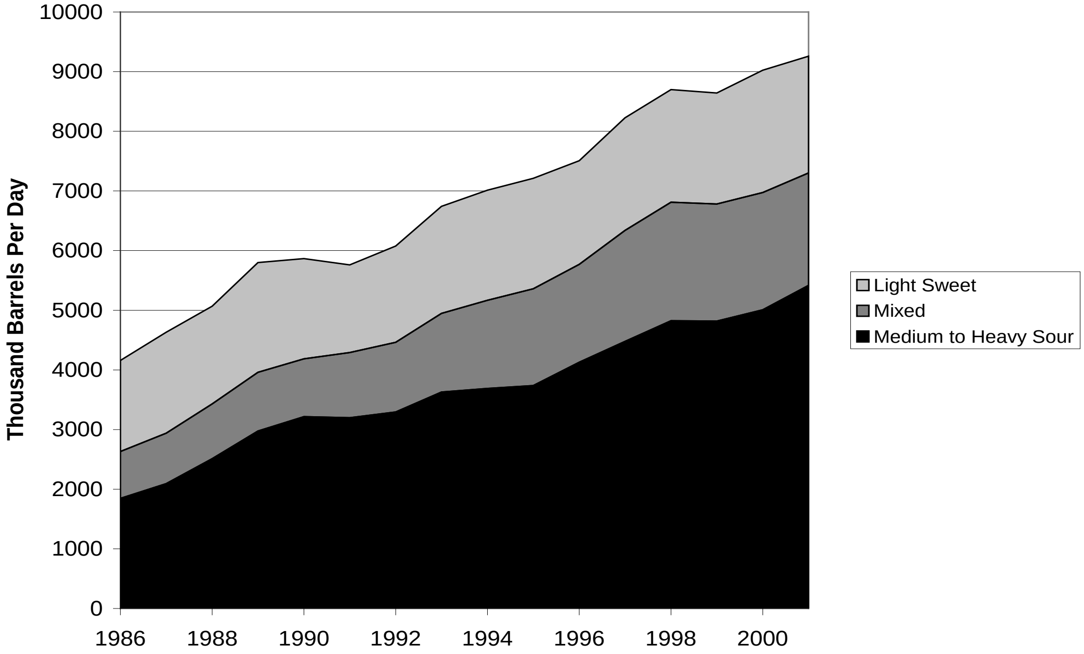


Fig. 5.3. Trends in Quality of Crude Oil Imports

Marano (2005) has collected the compositions (assays) for seven representation crude oils and he is adding others. The ones currently used as representative crude oils are:

- North Sea Light Sweet Crude,
- Alaskan North Slope Medium Sulfur, Heavy Crude,
- Arab High Sulfur Light Crude
- Arab High Sulfur Heavy Crude
- Venezuela Very Heavy Crude
- Synthetic Crude from Canadian Oil Sands that has been upgraded before importing to the US (by cutting off the heaviest ends).

Crude oils are characterized by their response to atmospheric and vacuum distillation, i.e., their boiling points and the properties of the various fractions based on these boiling point range. We can think of this as the composition of the crude oil. During distillation, a crude oil is fractionated into the following broad ranges:

- gases such as propane and butane,
- light straight run naphtha which is isomerized into gasoline blending components,
- medium and heavy naphthas which is hydrotreated and catalytically reformed,
- kerosene, used mainly for jet fuel,
- distillate fuel oils which are hydrotreated and used for diesel and home hating oil,
- heavier gas oils which are cracked to make more gasoline and diesel fuel,
- residual oils.

The properties of the crude oil aggregate are based on the individual properties of its components. These properties include density (specific gravity), sulfur content by weight fraction, nitrogen content, heavy metals content, heating value, and carbon content. The MARS refinery model is mass balanced so that mass coming in must equal mass leaving for all processes. These properties of the components of crude oils are tracked throughout the refining process steps, yielding characteristics for intermediate streams and final streams that are blended into products such as gasoline, jet fuel, and diesel fuel. In particular, the MARS model calculates the heating value in Btus of these products and their carbon contents which result in CO_2 emissions when the fuels are combusted in their end use. Figure 5.4 gives an overview of the kinds of refining process streams and products.

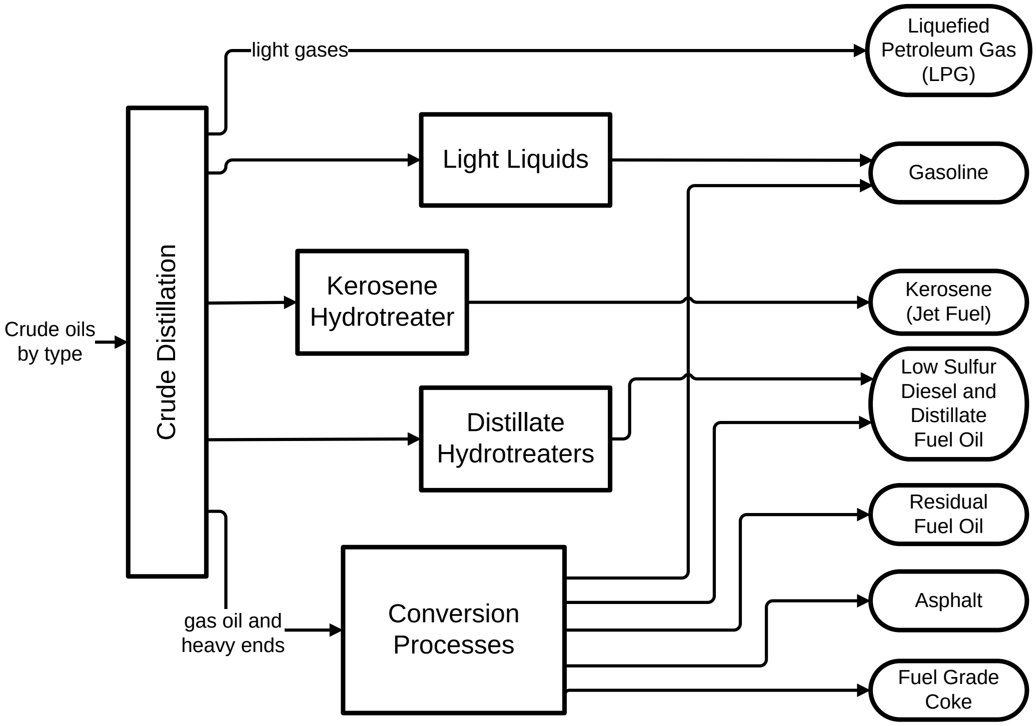


Fig. 5.4. Overview of Petroleum Refining and the Major Products

Gasoline is the largest refinery product by a factor of two over diesel. Its manufacture is depicted in Figure 5.5.

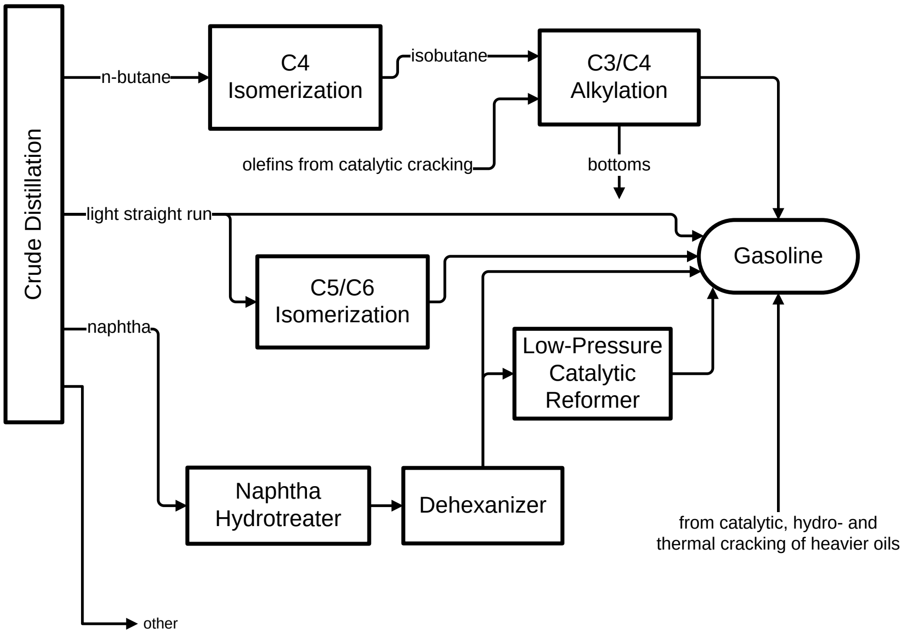


Fig 5.5. The Manufacture of Gasoline, the largest Petroleum Product

The processes included to upgrade the heavy oil bottoms into useable transportation fuels are shown in Figure 5.6. The basic equations in the refinery model are yield equations from the process steps. A process generally will have multiple yields of various types of oils. These yields and the consumption of hydrogen in the process steps are functions of the input feed characteristics to the process such as the feed density and sulfur content (see, Marano 2005).

Eight of the processes in the MARS model consume hydrogen to increase the hydrogen-carbon ratio in gasoline and diesel fuel and to remove heteroatom impurities such as sulfur. Of the eight, hydrocracking and gas oil hydrotreating are massive consumers of hydrogen. Much of this hydrogen is currently produced from natural gas (note another major source of natural gas demand and CO_2 emissions). Additional hydrogen is needed for distillate oil hydrotreating to purify intermediate streams to meet ultra low sulfur requirements for diesel transportation fuel. An additional future source of hydrogen is to install gasification plants at refinery sites to gasify petcoke to produce hydrogen and cogenerate electricity and steam. The MARS model also includes characterization of the Fischer-Tropsch coal-to-liquids process, with and without carbon capture and sequestration.

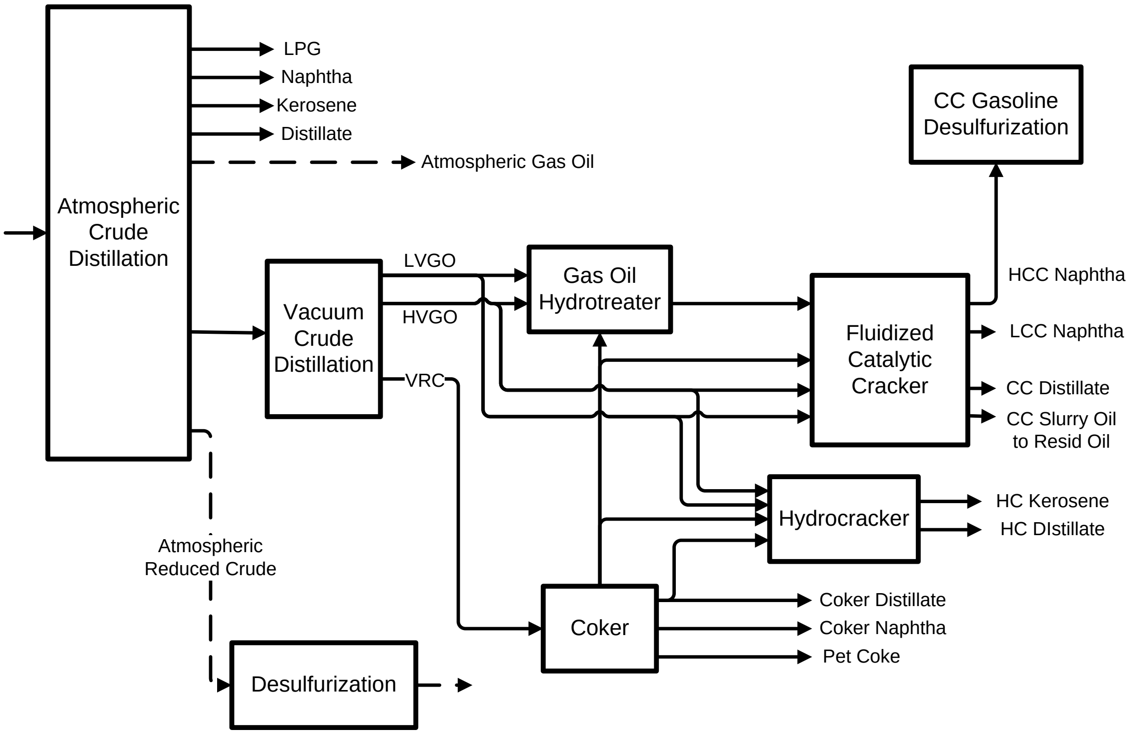


Fig. 5.6. Added Refinery Process Steps to Upgrade Residual Oils into Gasoline and Diesel

Table 5.1 shows the paths of inputs, i.e., totals for US refineries, in our reference case. These are US economy-wide numbers in thousand barrels per day. In addition to the six representative crude oil types that feed the distillation units, other inputs include natural gas liquids (light liquids from natural gas production), unfinished oils (mostly imported), oxygenates like MTBE and ethanol, purchased fuels such as natural gas, and purchased hydrogen from merchant hydrogen plants.

Although Table 5.1 is shown for the US as a whole, the MARS model has the capability to include any number of separate refineries with different configurations and feedstocks. It is currently set up to operate for the five Petroleum Administration Defense Districts (PADDs) which are major regions in the US.

Table 5.1. Reference Case Refinery Inputs for the US Projected to 2040, MBPCD

US Refineries Total	2005	2010	2020	2030	2040
LS Light	5594	5492	4945	4328	3712
MS Heavy	2840	2749	2663	2481	2241
HS Light	1997	2145	2294	2368	2294
HS Heavy	2956	3799	4853	5696	6118
HS Very Heavy	1925	2178	3189	3947	4200
Syncrude	500	1000	1600	1840	2080
Crude subtotal	15812	17363	19544	20661	20645
NGL	422	429	429	422	422
Unfinished Oils	510	608	878	976	976
Oxygenates	335	335	335	335	335
Total Inputs	17079	18735	21185	22394	22378

Table 5.2 shows the feed rates in thousand barrels per calendar day for major refinery processing steps. US refineries are currently operating at or near full capacity utilization. Existing capacity data is collected on EIA surveys by individual refinery and its existing processes. We have entered these current capacity data by PADD and process into the model. So, growth in process throughput results in the capacity of those processes being expanded (likely expanded on existing refinery sites). Marano (2005) provides the capital costs to expand the various refinery processes. The resulting capital investment is used in AMIGA. Clearly, more efficient transportation equipment will reduce the investment requirements for US refiners.

The operating costs for each refinery process are also provided in MARS. These are broken into nine components:

- Electricity usage,
- Fuel for process heat,
- Low pressure steam,
- High pressure steam,
- Cooling water,
- Process water,
- Waste water,
- Labor input,
- Other variable costs.

Changing crude oil type by some increment will have implications for refinery investment, energy use, carbon emissions, variable costs, and product yield slate. The process cost impacts as well as product yield impacts as a function of crude oil feedstock characteristics are used in the equations given in Section 3, Eqs. 3.6 and 3.7, to obtain the relative value, i.e., market price, for the different crude types that are modeled.

Table 5.2. Major Refinery Process Throughputs as Projected, MBPCD

	2005	2010	2020	2030	2040
Atmospheric Distillation	15903.7	17464.2	19657.2	20781	20764.8
Vacuum Distillation	6895	7742.2	9207.4	10119.6	10334.5
Residual Oil Desulfurization	150.6	149	136.6	121.9	106.3
Resid Hydrocracker	147.7	163.9	196.4	219	224.1
Thermal Coker	2105	2297.4	2680.8	2948.3	3008.7
Gas Oil Hydrotreater	2064.6	2342	2919	3206.9	3250.1
Fluid Catalytic Cracker	4959.4	5584.4	6682.3	7247.6	7339
Gasoline Desulfurization	1597.2	1800	2155.9	2340.4	2371.5
Gas Oil Hydrocracker	1481.3	1644	1926.9	2104.6	2139.6
Low Severity Distillate Hydrotreater	3595	2137.2	326.4	350.6	353.8
High Severity Distillate Hydrotreater	414.2	2312.9	4765.8	5051.2	5067.6
Kerosene Hydrotreater	577.4	631.9	698.5	727.2	721.3
Naphtha Hydrotreater	3471.6	3674.5	3840.4	3856.1	3717.8
Dehexanizer	3642.8	3904.3	4216.8	4345.3	4260.7
Gasoline Reformer	3541.4	3801.8	4124.4	4264.8	4190.8
Isomerization	1204.3	1292.8	1375.5	1398.8	1363.8

Additional important technologies contained in the model are combined heat and power (CHP), hydrogen production from natural gas (steam methane reforming), other hydrogen technologies, hydrogen purity upgrading, saturated and unsaturated gas cleaning, hydrogen sulfide removal, alkylation, isobutene production, and waste heat capture. Those processes which combust fuels and emit CO_2 have carbon emission factors. A large source of CO_2 emissions in refineries is the burning off of carbon coke that forms on the catalyst in the fluid cat cracking unit.

5.4 Combined Heat and Power (CHP)

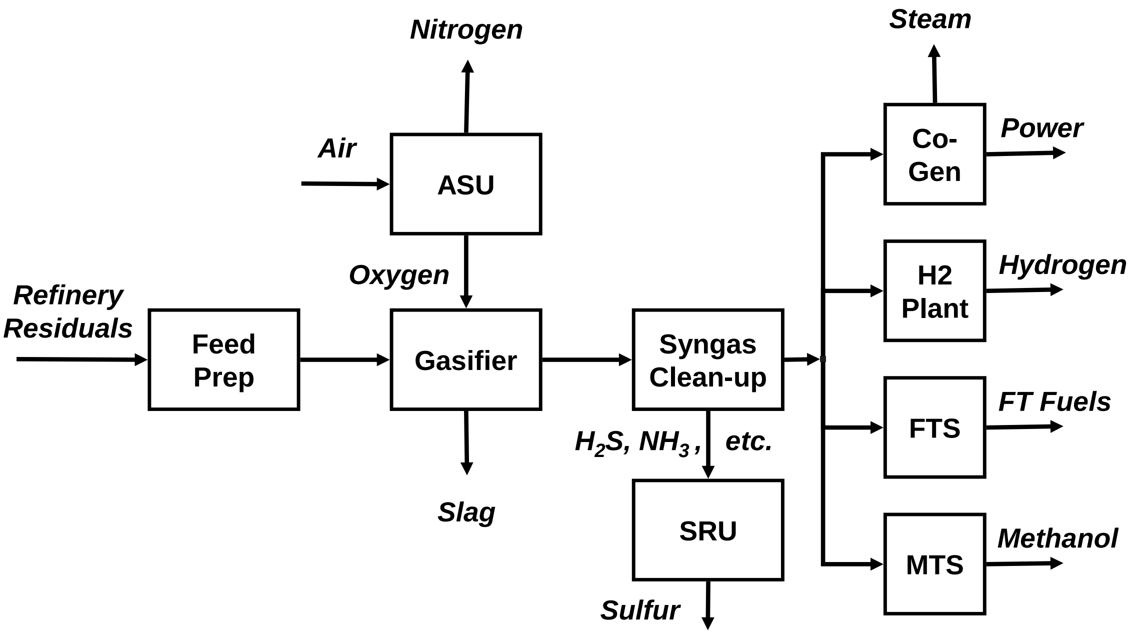
CHP units vary from small units designed for commercial buildings to very large units used in refineries, petrochemical plants, and pulping mills. There are significant scale economies in CHP units. In AMIGA, we do the economics based on the levelized cost of supplying steam demands and take a credit for the value of electricity generated. This self generation either displaces purchases from the grid or is sold back to the grid. Most pricing arrangements make the former more attractive than the latter.

Our petroleum refinery model as described in the section below has a full characterization of the performance and costs of CHP on refinery locations. Refineries can be very attractive facilities for CHP because they are large users of both electric power and steam and produce residual by-products that can be burned to produce this power and steam.

In general in medium sized industries, CHP is a substitute for gas-fired steam boilers, which are very inefficient. With very high current gas prices and forecasts, many analysts believe that it is only a matter of time before industrial boilers are replaced with more efficient CHP units.

In AMIGA again we model this technology penetration with a logistic market penetration process.

Figure 5-7. Example of Co-Generation Process in a Refinery including CHP



Syngas generated by the gasification of refinery residuals can be to co-generate a variety of products. Currently, there are two refineries in the US producing Power and steam from gasification derived syngas, and two refineries producing hydrogen, power and steam. In Europe, there are five refineries employing gasification with others planned. In the future, the syngas may also be used to produce clean-burning Fischer-Tropsch diesel or other high-valued products such as methanol derived petrochemicals.

There are many opportunities for CHP within the refinery. Many refinery processes operate at high temperatures and fired-heaters are used to produce the necessary heating of the process feed. The waste heat can be recovered from the fired-heater exhaust and used to produce steam and/or power. A very large opportunity for this type of integration exists with atmospheric distillation, which processes all of the crude oil fed to the refinery.

5.5 Non-CO2 Greenhouse Gas Emissions

In addition to carbon emissions, AMIGA tracks a number of non-CO_2 greenhouse gas emissions in the agriculture, manufacturing, energy, and transportation sectors. The non-CO_2 greenhouse gases represented in AMIGA are methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorcarbons (PFCs), and sulfur hexafluoride (SF_6).

Forecasts of non-CO_2 gases are driven by corresponding sector activities variables, where available and appropriate, or a broad population or income measure. For example, agricultural livestock emissions are driven by the NAICS livestock sector output. However, the adoption of mitigation or abatement technology can reduce the emissions per unit sector output.

The theory underlying abatement cost functions is as follows: Total abatement cost (TAC) is a rising, generally convex function of emission reductions, given a sector activity level Q. Hence,

$TAC = f(Em, Q)$.

Marginal abatement cost is defined as the slope of total costs, or,

$MAC = -dTAC/dEm = g(Em, Q)$.

It helps for computational reasons to fit mathematical functional forms to the cost curves derived from actual abatement technologies and measures. Although a variety of functional forms for cost curves may be used, cost functions based on the CES function are particularly convenient and flexible. Interpreting the CES function in terms of a TAC function, the sector activity level is Q, total cost is the factor K, and the second factor is emissions (similar to energy).

The use of these cost functions in a CGE model such as AMIGA is to find least cost allocations of greenhouse gas emissions over sectors and emission species. For each greenhouse gas, the CGE model converges to a shadow price that supports the least cost solution. Least cost emission reductions must satisfy the condition

$P = MAC = g(Em, Q)$.

Using the CES functional form, there exists a closed form solution for the least cost emission reduction Em* given sector activity Q and shadow price P. We call Q the economic driver variable, since optimal emissions tend to rise proportionately with Q.

Notice that our cost functions, both TAC and MAC, are in terms of upfront, present value abatement expenditures. Then, the general method works for various given interest rates and tax rates associated with specific sectors or firms. It also makes clear the role of adoption of these abatement technologies, since adopting the abatement technology requires an up front commitment and capital expenditure. However, this method may be generalized for cases where there are also variable operating costs (or credits such as methane capture and sale from landfills). Operating costs shift the MAC up and credits shift it down.

Figure 5.7 shows a typical MAC curve and two choice points for different cost-of-capital values associated with different degrees of adoption. The price ratio on the vertical axis is the greenhouse gas shadow price divided by the relevant cost-of-capital. The MAC function is constructed with incremental capital costs on the vertical axis and the percent emission reduction on the horizontal axis.

The area under the MAC curve is the total abatement cost (TAC) function. The TAC that corresponds to Figure 5.7 is shown in Figure 5.8. The TAC curve is normalized to the level of economic activity. That is, if sector output were twice as large, then at the same percent reduction, remaining emissions would be twice as large. The TAC curve shows investment requirements on the vertical axis. This investment is a real resource expenditure which must be accounted for in the economy.

Since there are many small emitting sources, adoption of long run least cost abatement measures is not expected to be instantaneous. We use the market penetration equation (5.1) above to establish a penetration path which eventually approaches its long run value, given by the MAC curve and the shadow price on emissions.

However, along this path firms can discover improvements in the abatement technologies and there could be other learning from experience. This is represented in the AMIGA model as a downward shift in the TAC curve, as shown in Figure 5.9. Again, the CES functional from can accommodate various modes of technological progress.

The data for the MAC curves is from the EMF-21 Web Site, Non-CO_2 Gases Study. Methane reductions are particularly cost effective. About 90% of methane emissions in the US come from five source categories: Landfills, coal mining, natural gas systems, manure management, and enteric fermentation. For these source categories, EPA has developed capital, operating costs, and credits for individual technologies that comprise the abatement cost curves. These options are sorted by least cost to assemble MAC curves. The resulting MAC curves are smooth and fit nicely to the CES functional form.

Although these data are commonly expressed as functions of the price of carbon equivalent using global warming factors for conversion, we prefer to express costs in terms of dollars per metric tonne of the non-CO2 greenhouse gas. This allows shadow prices, or emission reduction values, for the various greenhouse gases to diverge from fixed ratio relationships.

The atmospheric impacts from these gases are estimated using the MAGICC model (Model for the Assessment of Greenhouse–gas Induced Climate Change). The MAGICC model has a simple input template with the various gases identifies as columns and years as rows. The MAGICC model generated plots over time of concentrations for each gas, radiative forcing, and temperature (Wigley 2003).

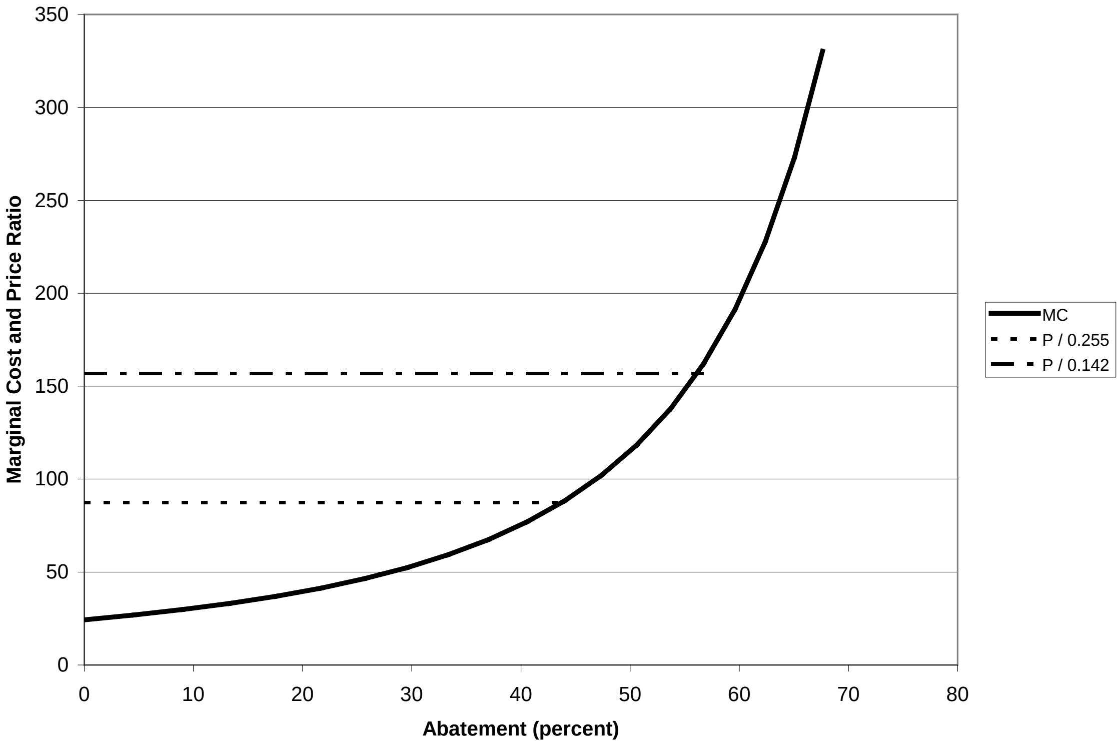


Fig. 5.7. Typical Marginal Abatement Cost Function for Non-CO_2 Gases

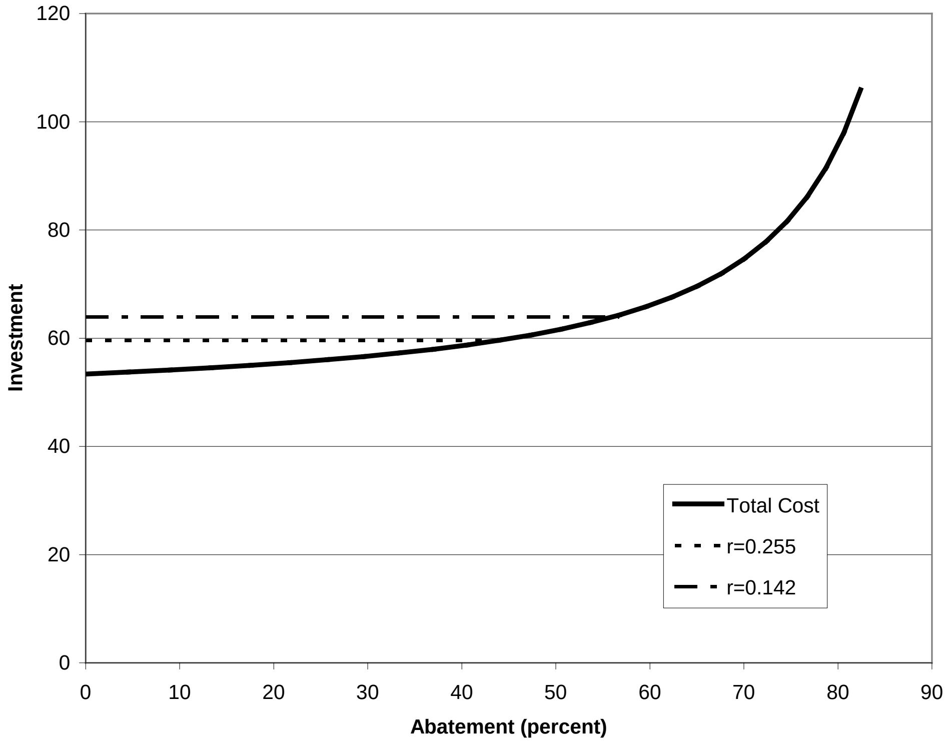


Fig. 5.8. Total Abatement Cost Function for Non-CO_2 Gases

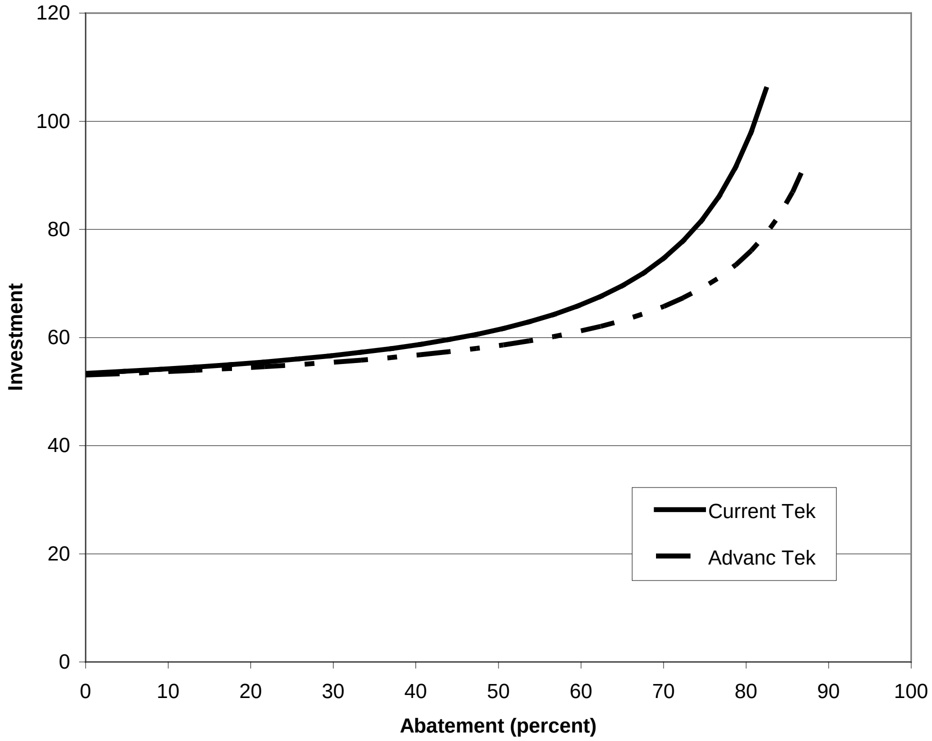


Fig. 5.9. Technological Shift in Total Abatement Cost Function for Non-CO_2 Gases

5.6 References

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6. END USE TECHNOLOGIES

6.1 Introduction

In the previous chapter we discussed how AMIGA represents technologies that produce energy carriers: electricity, pipeline-quality natural gas, petroleum products (gasoline, diesel, heating oil, jet fuel, LNG), steam, and hydrogen. Energy carriers have the property that they can move energy, often over long distances, and they can function as a factor input for the production of the goods and services demanded by consumers. However, households and business firms do not consume energy for its own sake; rather they demand what might be called energy-related services (Lancaster 1971). Such services range from the powering of industrial processes and providing heating and lighting in our homes, schools, and offices to transporting both people and freight to their destinations.

As with other goods and services, the production of energy-related services can also be represented by a production function with the usual capital, labor, energy, and material inputs. At the same time, however, it is important to specify: (i) the capital as equipment devoted to the provision of energy services, (ii) the quality of trained labor, (iii) the type of energy flows, and (iv) the type of materials (non-energy variable costs) which meet the demand for those energy services.

To provide a more complete context for the description of energy end-use technologies, this chapter opens with an overview of the methodology. This is followed by a characterization of the different end-use technologies that are now mapped into the AMIGA modeling system. The technology characterization is then followed by a discussion to illustrate how AMIGA actually represents the technology characterization within the modeling system. This last discussion is supported by a number of examples to highlight the technology mapping. Finally, the section concludes with several appendices which contain key data that describes the characterization and performance of the end-use technologies. One note in this last regard, the default technology data now mapped into AMIGA can be easily modified or expanded to accommodate different scenarios or modeling evaluations. This is a key aspect of almost any simulation models used for economic policy analysis.

6.2. Substitution of Productive Capital for Energy: The AMIGA Methodology

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 2005).

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 200 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 (2004). Different regions and sectors face different energy prices. These data, drawn primarily from EIA (2004) and IEA (2004), are used in calibrating the factor demand equations and in long-term scenario analysis.

Service Demand. The deployment of end-uses 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 (2004) 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 cost 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 to reflect differences among groups in their cost-of-capital, risk position, and decision criteria.

Energy-efficiency investment decisions are often required to 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 natural gas and crude oil resources, which are becoming scarce in a rapidly growing world economy.

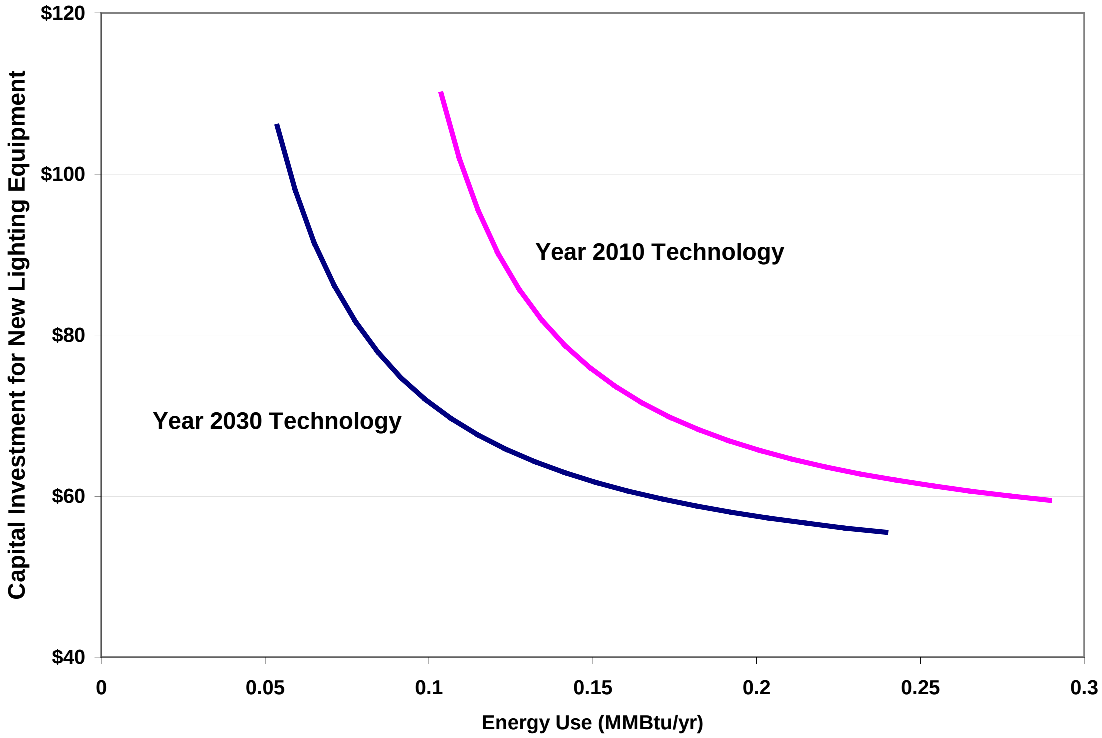
The theoretical basis for our analysis of energy efficiency was presented 30 years ago by the economist Kevin Lancaster (1971). He pointed out that consumers and businesses don’t consume fuels and electricity for their direct utility but rather energy is an input to a production function that combines capital, labor and energy to produce useful services, such as transportation and refrigeration of perishable goods. Hence, 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.

6.2 Overview of the Method

The business or household production function is like the standard production function. Output services are a function of the factors of production as well as technical progress which shifts the production function toward a lesser cost or a more productive level of production. For a specific category of durable goods or productive capital, such as a motor vehicle, an industrial boiler, or a commercial building lighting system, there is typically an opportunity to make an incremental investment that lowers operating costs in the future (see, for example, Martin et al 2001, Sachs et al 2004, NYSERDA 2004). The investment opportunity is often least-cost when there is a demand for new capital, but sometimes good retrofit opportunities also exist, such as with lighting and heating or cooling systems.

Figure 6-1 shows illustrative technology “cost curves” for commercial lighting technologies which have been adapted from technology data files provided by the Energy Information Administration (EIA 2005). These two curves for the years 2010 and 2030 represent and contrast the potential for incremental energy-efficiency investment for a single “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 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.

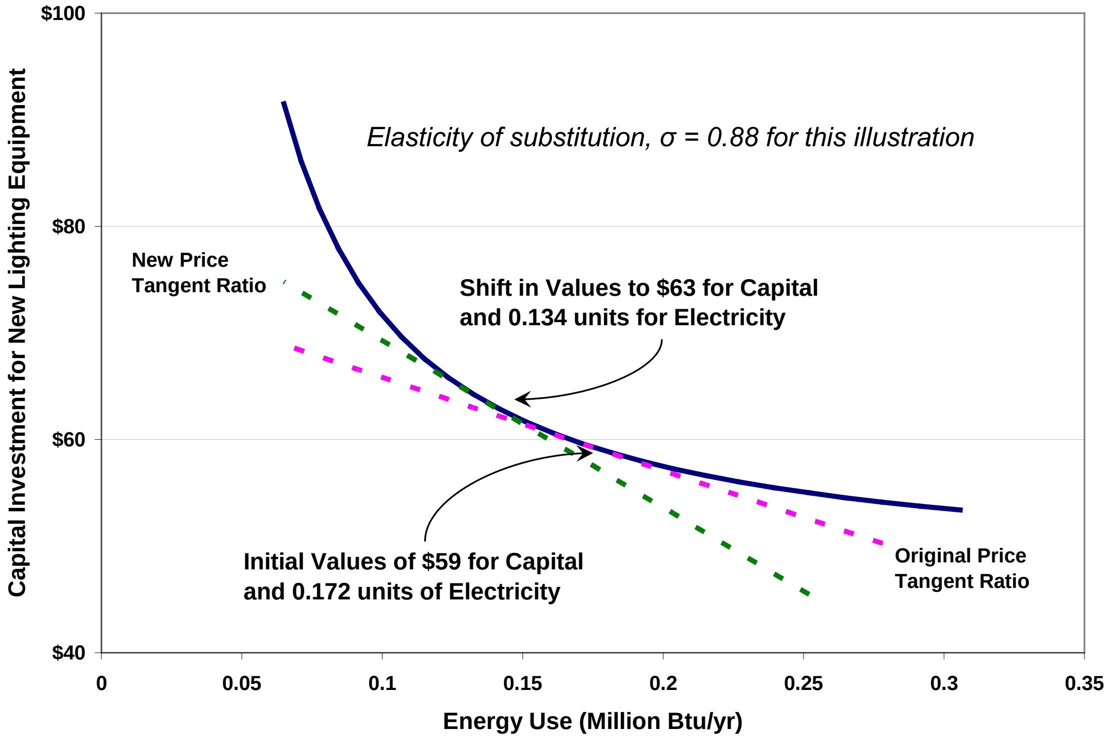
Figure 6-1. Illustration of an Isoquant for Commercial Lighting in 2010 and 2030



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 6-2, below.

Figure 6-2. 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.[22] Assuming an electricity price of $22.27 per million Btu (~$0.076 per kilowatt-hour), a hurdle rate of 25 percent starting, and a *Pe/r* ratio of 87.5, a commercial building manager might have selected a lighting technology that costs $59 and consumes 0.172 million Btus (~50 kWh) per year. Even when energy prices remain at anticipated levels, preferences might shift as a result of promotional efforts mounted by the EPA Energy Star program (Climate Protection Partnership Division 2004).

In this case, we assume that a 25 percent hurdle rate is reduced by half which increases the price ratio by 79 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 and 0.134 million Btus (~39 kWh). In other words, with the lower hurdle rate the commercial property manager is willing to increase capital expenditures by $4 per lighting unit to save 0.038 million Btus (11 kWh). At expected energy prices of $22.27 per million Btu ($0.076/kWh), the expected payback on this incremental investment is less than 5 years.

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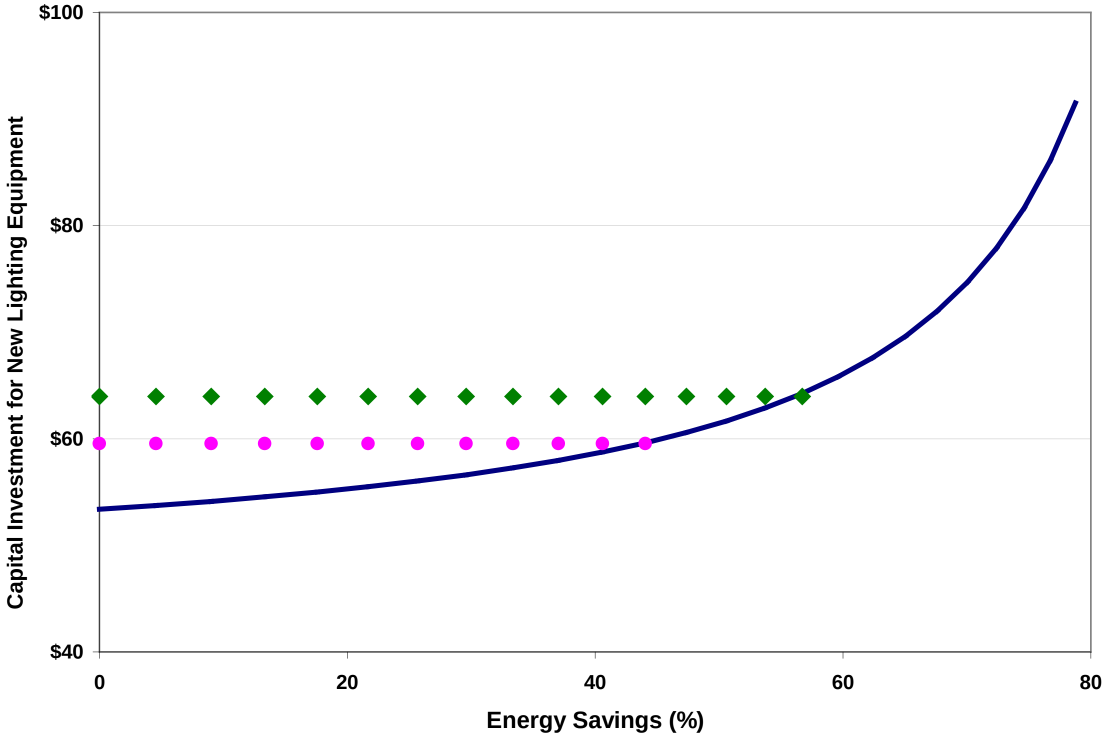
[22] Some analysts may be used to seeing smaller elasticities. The reason is that when they use this functional form they apply an elasticity against total productive capital. In AMIGA, however, we estimate elasticities for a much smaller "energy-related" capital or mix of energy technologies. A smaller 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 specifically for this purpose, using specific estimates of capital and energy.

To more conveniently describe the opportunities for additional energy efficiency investments, we often normalize and generalize the production isoquant by showing the capital costs as a function of the rising level of energy savings (expressed as a percent improvement). This is shown in Figure 6-3.

Figure 6-3. Increase in Investment Spending Shown with the Reversed Isoquant



Although perhaps not immediately obvious, the technology cost curve in Figure 6-3 is based on the same electricity isoquant for the year 2030 shown in Figure 6-1. In this case we have only reversed the energy axis to represent energy savings rather than index of energy use. The origin of the graph, i.e., the assumed point of zero energy saving, is some reference point reflecting the minimum amount of energy efficiency likely to be encountered in practice. This may be represented by the "bottom-of-the-line" product efficiency for a series of products that are available to businesses or consumers. We then calculate the energy savings axis in percentage terms relative to the minimum efficiency.

But there are two more degrees of freedom in applying these curves in practice. One is calibrating the base level of capital embedded in the equipment or structure. For example, what would a minimally efficient lighting system cost as a durable good purchase in commercial buildings? Once some estimate for this minimum efficiency is given, the curve is then shifted up by this base capital cost. So in the AMIGA model, as demand for energy services rises (more buildings with more lighting requirements) the model can calculate total durable goods spending on lighting systems. As we discuss below, Figure 6-3 shows a base capital of 45 added to the incremental capital derived from the CES function.

To further explain the example in Figure 6-3, let us again assume that the technology reflects costs associated with a single lighting system in a commercial building. The building management might discount future operating costs at (to pick a number) 25% against an expected (i.e., current) price of electricity of $22.27 per million Btu ($0.076 per kWh). Let us further suppose that current electricity use for a single lighting unit is 272 kWh per year. Given that circumstance it might be decided that it would be cost-effective to reduce electricity use another 30 kWh or 11% by increasing the capital expenditure from $50 to $57. The model suggests that the simple payback is about 3.1 years for this incremental investment, or an expected return of 32%.

However, if some energy-efficiency program such as Energy Star (CPPD 2004) is successful in lowering the hurdle rate applied to say 28%, the new cost effective investment might rise from $50 to $65. That would increase the savings to 57 kWh for a total savings of 21% below current lighting requirements. Assuming there is no expected change in electricity prices, the average payback is now just under 3.6 years which just meets our expected but lower return of 28%. Comparing a base case scenario with an alternative more efficient scenario (by taking differences) we see that there is an incremental 10% energy savings with an incremental investment of about $8. This incremental investment is incurred as a first cost. It adds to total energy efficiency investment spending in the year 2010. In summary, Figure 6-3 shows how the model calculates the investment spending is changed in an alternative future through either higher energy prices or greater effort expended through energy efficiency policies and programs, or through some combination of both.

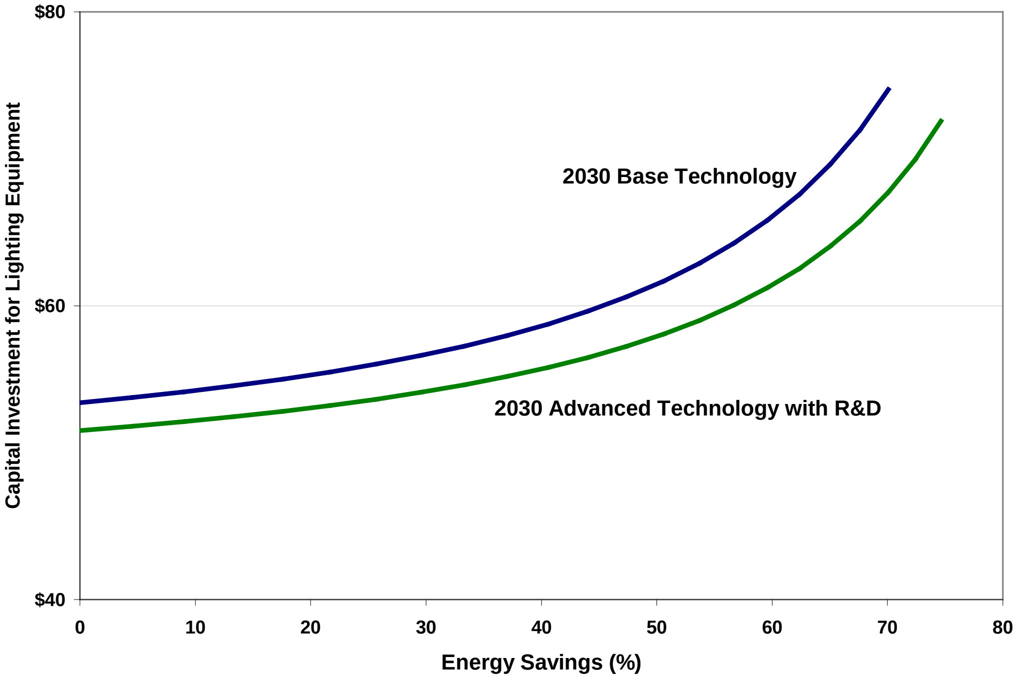
6.3 From Technology Characterization to Production Isoquant

As presented more fully below, the isoquant is 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 summary, we have five available parameters to describe actual technologies and their associated investment costs as a function of their energy efficiency characteristics. These include alpha, beta, sigma (or rho), base capital costs, and expected minimum efficiencies. Drawing from a series of data on commercial lighting, for example, we can describe the array of lighting technologies with the CES functional form by using these five parameters. 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 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. In Figure 6-4, we show how policies and further research and development might shift a “business as usual” technology curve downward and to the right as a result of a somewhat higher elasticity of substitution.

Figure 6-4. Representing Induced Technical Change in Commercial Lighting



Because the amount of R&D and learning (based on cumulative production experience) are both scenario dependent, the year 2030 curve will also be scenario dependent. In Figure 6-4 the commercial light technology curves is shown to be a bit lower in the alternative case because there is more cumulative experience with energy efficient products and measures than in the base case by year 2030. In this example, the elasticity of substitution parameters, *sigma*, for the standard reference case projection might be 0.88 as previously suggested. But in a policy dependent exercise in which it is assumed there will be a somewhat greater emphasis on R&D and accelerated production experience, the curve becomes “more elastic” so that *sigma* increases to 0.92.

6.4 Background and Formulas

In this next section 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

$$\left.\frac{dK}{dE}\right|_{\bar{S}} = -F_E^{'} / F_K^{'} \tag{6.1}$$

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

$$S_{jt} = F_{jt}(K_{jt}, E_{jt})\,. \tag{6.2}$$

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

$$r = \frac{\varphi(1+\varphi)^n}{(1+\varphi)^n - 1} \tag{6.3}$$

which approaches φ for long-life equipment. The φ 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

$$\left.\frac{dK}{dE}\right|_{\bar{S}} = -P_E / r \tag{6.4}$$

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 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).

The CES production function is a functional form that can be used to build up much of the subsystems of major industrial processes. It can be transformed in various ways to model an industrial process and technical change. The CES production function is given by

$$S = A((K/\alpha)^{-\rho} + (E/\beta)^{-\rho})^{-1/\rho} \tag{6.5}$$

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

$$\sigma = \frac{1}{1+\rho}. \tag{6.6}$$

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

$$D = \alpha^{1-\sigma} + \beta^{1-\sigma}\left(\frac{P_E}{r}\right)^{1-\sigma} \tag{6.7}$$

$$K^* = \alpha^{1-\sigma} D^{1/\rho} S / A \tag{6.8}$$

$$E^* = \beta^{1-\sigma}\left(\frac{P_E}{r}\right)^{-\sigma} D^{1/\rho} S / A \tag{6.9}$$

To illustrate the transformation of actual technology characterizations into a production isoquant, Table 6-1 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 6-1. Commercial Lighting Technologies

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 6-1. First, compared to those commercial buildings that might now be using incandescent lamps or lighting systems, by moving to a high sulfur lamp it is possible to reduce electricity consumption by 85 percent. At the same time, however, the new technology (anticipated to be commercially before 2010) is expected to cost about 90 percent more than the standard incandescent system. With commercial electricity prices at about $0.076 per kWh, the expected payback is about 9 years – too long for most businesses, especially since the lives of these technologies are generally on the order of 12 to 14 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 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, 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 structure 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 6-1, and drawing on the system of 10 equations described above, 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 for commercial lighting. It turns out that the substitution elasticity which best describes the capital energy tradeoff for our technology assumptions in the year 2030 is 0.88. The discussion following Figure 6-2 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 treated as a consumer rather than a producer in that he or she “consumes” lighting technologies as the building and its occupants in turn “produces” a given level of goods and services). With the technologies now reasonably defined, we turn our attention to the description of the many energy services that shape the demand for particular technologies.

6.5 Service Demands

AMIGA is designed to satisfy a set of specified service demands within each major end-use sector by allocating or deploying the mix of least-cost technologies given prevailing energy prices, decision variables, market barriers, and technology characteristics. This sector provides a detailed overview of the service demand now configured within the modeling system.

6.5.1 Buildings

In AMIGA we represent the total energy use that might be required by residential single family and multifamily buildings. In the commercial sector there is only single average building. Buildings and building sizes grow in patterns consistent with projections published by EIA. This includes both the slow retirement of the existing stock of buildings and the increase in total building space as overall economic activity supports their growth. Generally speaking, the buildings and building shells affect amount of heating and cooling required to support a given level of thermal comfort (i.e., warmth in the winter seasons and cooling throughout the summers), and to some extent lighting. As dictated by the existing stock of buildings, as well as the new buildings added to that stock, the design and operation of buildings include a large number of energy services ranging from heating and cooling to lighting, refrigeration, hot water, and a wide variety of services provided by appliances and commercial office equipment. Tables 1 through 4 show the general categories of end-use services and technologies that can be selected to provide these services in all three categories of building sectors within AMIGA.

6.5.2 Residential Energy Services

In 2002 there were an estimated 110.5 million households using an average energy service demand of 187.9 million per household as shown in Table 6-2 below.

Table 6-2. Residential Energy Service Demand Key Indicators

	2002	2005	2010	2030	AAGR
Households (millions)					
Single-Family	74.9	79.0	84.9	105.2	1.22%
Multifamily	29.2	30.1	31.5	36.8	0.83%
Mobile Homes	6.4	6.3	6.5	7.8	0.72%
Total	110.5	115.4	122.9	149.8	1.09%
Average House Square Footage	1,716	1,754	1,812	1,977	0.51%
Energy Intensity (mmBtu per household)					
Delivered Energy Consumption	101.5	101.3	99.6	93.7	-0.29%
Delivered Electricity Consumption	39.1	39.7	40.6	43.2	0.35%
Total Energy Consumption	187.9	187.3	187.0	177.8	-0.20%
Energy Intensity (kBtu per square foot)					
Delivered Energy Consumption	59.1	57.7	55.0	47.4	-0.79%
Electricity Consumption	22.8	22.6	22.4	21.8	-0.15%
Total Energy Consumption	109.5	106.8	103.2	89.9	-0.70%
Energy Consumption Total (quads)					
Delivered Energy Consumption	11.2	11.7	12.2	14.0	0.81%
Electricity Consumption	4.3	4.6	5.0	6.5	1.45%
Total Energy Consumption	20.8	21.6	23.0	26.6	0.89%
Energy Prices (2004 $/MBtu)					
Petroleum Products	10.35	15.95	14.77	18.42	2.08%
Natural Gas	8.03	12.30	10.33	11.32	1.24%
Electricity	25.95	28.74	24.78	25.02	-0.13%

Although the average size and number of households are expected to grow over the next three decades by an average annual rate of 0.51% and 1.09%, respectively, the introduction of new technologies are expected to decrease overall energy intensity per household. Hence, total residential energy use is expected grow more slowly – increasing by only 0.89% annually. These and other key indicators for residential energy service demand, including the major energy prices, as shown for benchmark years through 2030 in Table 6-2 below.

The data shown in Table 6-2 is taken from the EIA Annual Energy Outlook (EIA 2005). They form the basis for the AMIGA reference case scenario through 2030 with trends extended to 2050 or longer depending on assumptions associated with longer time horizons and the precise mix of policies and trends that model users would like to see evaluated.

In a given policy scenario (sometimes referred to as a "counterfactual"), any combination of changes in prices, policies, and/or preferences will impact the choice of technologies made by households. Given a new combination of prices, policies, and/or preferences the resulting efficiency investments are governed by the economic relationships found in equations (4) through (10), described earlier. For example, a carbon charge of $100 per ton may increase typical residential energy prices by 8-10 percent or more (depending on the fuel and period of time in question).

The rising prices together with a changed hurdle rate or consumer preference may prompt investments in technologies with an average 4-year payback that reduces energy intensity by, say, 6 percent compared to the baseline forecast in 2030. Hence, total energy consumption might be only 25 quads in 2030 compared to the 26.6 quad forecast. In AMIGA, the increased efficiency in this example, might have spurred an incremental investment (i.e., increased level of durable goods that is purchased by households) on the order of $115 billion between now and 2030 (or depending when the policy or price signal actually took effect). Consumers or households would then be expected to save about $30 billion per year but still satisfying the same level of demand for energy services.[23]

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[23] There are two other significant impacts evaluated in AMIGA that are not immediately obvious from this example. First, the reduced demand is likely to have a downward pressure on energy costs – both for consumers who take steps to become more energy efficient and for all other consumers and businesses are well. In the larger economy, therefore, energy prices as well as energy quantities will change compared to this isolated example. Second, investment in energy-efficient technologies such as commercial lighting will tend to reduce the need for capital in conventional energy supply technologies and infrastructure. Our experience suggests that if the energy savings is cheaper than energy supply (when compared on a dollar of investment per unit of energy consumed or saved), total direct capital may actually be reduced.

Table 6-3. Detailed Residential Energy Service Demands

Category of Service Demand	Description	Energy Form	Substitution Elasticity
1	New Single-family Bldg Shell		TBD
1	Retrofit Single-family Shell		
1	Gas furnace - single	Gas, Propane	
1	Electric Heating - single	Electricity	
1	Central AC - single	Electricity	
1	Ventilation Fan - single	Electricity	
1	Heat pump 1 - single	Electricity	
1	Heat pump 2 - single	Electricity	
2	New Multi-family Bldg Shell		
2	Retrofit Multi-family Shell		
2	Gas furnace - multifam	Gas, Propane	
2	Electric Heating - multifam	Electricity	
2	Central AC - multifam	Electricity	
2	Ventilation Fan - multifam	Electricity	
2	Heat pump 1 - multifam	Electricity	
2	Heat pump 2 - multifam	Electricity	
3	Hvy Elec RmAC	Electricity	
4	Water Heater	Gas, Propane	
4	Electric Water Heater	Electricity	
4	Solar Water Heater		
5	Lighting	Electricity	
5	Advanced Lighting	Electricity	
6	Refrigerators	Electricity	
7	Freezers	Electricity	
8	N. Gas St	Gas	
8	Electric Stoves	Electricity	
9	Dryers	Electricity	
9	Gas Dryers	Gas	
10	Clothes & dish washers	Electricity	
11	Electric apparatus	Electricity	

6.5.3 Commercial Energy Services

The basic units of service tracking demand energy use in the commercial building is the total floorspace and the various energy intensities per square foot of building. In 2002, for example, there were an estimated 72.2 billion square feed of commercial building in service within the U.S. Total primary energy consumption was estimates to be 241.3 thousand Btus per square feet in that same year. Total building space is expected to grow at an average annual rate of 1.58% through 2030. Greater reliance on electricity end uses are expected to increase by 0.46% per square foot annually while non electricity demands are forecast to decline to such an extent that overall energy intensities will decrease at a very small 0.04% per year. The end result is that total primary energy use is anticipated to grow 1.54% in commercial buildings over the forecast horizon. These and other key indicators for commercial energy service demand, including the major energy prices, as shown for benchmark years through 2030 in Table 6-4 below. Again, this data is taken from the EIA Annual Energy Outlook (EIA 2005) and forms the basis for the AMIGA reference case scenario through 2030 with trends extended to 2050 or longer depending on assumptions associated with longer time horizons and the precise mix of policies and trends that model users would like to see evaluated.

Table 6-4. Commercial Energy Service Demands, Consumption, and Prices

	2002	2005	2010	2030	AAGR
Total Floorspace (billion square feet)					
Surviving	69.9	74.4	80.4	109.4	1.61%
New Additions	2.3	1.8	2.0	2.6	0.48%
Total	72.2	76.2	82.3	112.0	1.58%
Energy Consumption Intensity					
(thousand Btu per square foot)					
Delivered Energy Consumption	114.2	110.7	109.3	111.0	-0.10%
Electricity Consumption	57.6	57.3	59.3	65.5	0.46%
Total Energy Consumption	241.3	234.8	237.0	238.6	-0.04%
Energy Consumption Total (quads)					
Delivered Energy Consumption	8.24	8.43	9.00	12.44	1.48%
Electricity Consumption	4.16	4.37	4.88	7.34	2.05%
Total Energy Consumption	17.42	17.89	19.51	26.73	1.54%
Commercial Energy Prices (2004 $/MBtu)					
Petroleum Products	7.22	11.77	10.56	12.28	1.91%
Natural Gas	6.79	10.65	8.76	9.29	1.13%
Electricity	24.03	25.49	22.31	22.90	-0.17%
Commercial Lighting					
Lighting demand (kBtu/sq ft)	14.95	14.37	14.26	13.60	-0.34%
Efficacy (lumens per watt)	49.30	50.89	52.36	55.17	0.40%
Total Electricity (quads)	1.08	1.10	1.17	1.52	1.24%

As with the residential sector, a counterfactual policy scenario may show any combination of changes in prices, policies, and/or preferences. Like the residential sector, this will impact the mix of commercial building technologies although the cost and performance of the commercial energy technologies are different than those faced by households. Given a similar combination of new prices, policies as in the residential sector, and with a change in preferences, that same carbon charge of $100 per ton may increase typical residential energy prices by 12-14 percent or more (depending on the fuel and period of time in question).

The rising prices together with a changed hurdle rate or consumer preference may prompt investments in technologies with an average 3.5-year payback that reduces energy intensity by, say, 8 percent compared to the baseline forecast in 2030. Hence, total energy consumption might be only 26.7 quads in 2030 compared to the 24.5 quad forecast. In AMIGA, the increased efficiency in this example, might have spurred an incremental investment by about $100 billion between now and 2030 (again, depending when the policy or price signal actually took effect). Commercial buildings would then be expected to save about $28 billion per year but still satisfying the same level of demand for energy services.

Table 6-5. Detailed Commercial Energy Service Demands

Category	Description	Energy	Substitution Elasticity
1	New Commercial Bldg Shell		
1	Retrofit Commercial Shell		TBD
1	Gas furnace - com	Gas	
1	Electric Heating - com	Electricity	
1	Central AC - com	Electricity	
1	Ventilation Fan - com	Electricity	
1	Heat pump 1 - com	Electricity	
1	Heat pump 2 - com	Electricity	
2	Water Heater - com	Gas, Propane	
2	Electric Water Heater - com	Electricity	
2	Solar Water Heater - com		
3	Lighting - com	Electricity	
3	Advanced Lighting - com	Electricity	
4	Refrigerators - com	Electricity	
5	Gas Cooking - com	Gas	
5	Electric cooking - com	Electricity	
6	Electric apparatus - com	Electricity	

6.5.4 Industry

Within the industrial sectors the basic unit of energy services is the number of Btus per dollar of output (or value of shipments). In 2002, industrial output was estimates at $5,340 billion (measured in 2000 dollars). For that benchmark year, total primary energy consumption was estimates to be 6.07 thousand Btus per dollar of shipment or output. Total industrial output is expected to grow at an average annual rate of 2.11% through 2030. A combination of shifts to non-energy intensive manufacturing (e.g., fabrication and assembly compared to, say pulp and paper or iron and steel manufacturing), together with greater use of more energy efficient process technologies are expected to decrease overall industrial energy intensities by 1.28% per year. The end result is that total primary energy use in the industrial sector is anticipated to grow 0.81% annually over the forecast horizon. These and other key indicators for industrial energy service demand, including the major energy prices, as shown for benchmark years through 2030 in Table 6-6 below (EIA 2005). Again, this data forms the basis for the AMIGA reference case scenario through 2030 with trends extended to 2050 or longer depending on assumptions associated with longer time horizons and the precise mix of policies and trends that model users would like to see evaluated.

Table 6-6. Industrial Energy Service Demands, Consumption, and Prices

	2002	**2005**	**2010**	**2030**	**AAGR**
Value of Shipments (billion 2000 dollars)					
Total Industrial	5,340	5,765	6,355	9,578	2.11%
Non-Manufacturing	1,372	1,486	1,572	2,069	1.48%
Manufacturing	3,968	4,279	4,783	7,509	2.30%
Energy Intensive	1,130	1,161	1,265	1,627	1.31%
Non-Energy Intensive	2,837	3,118	3,518	5,882	2.64%
Energy Consumption Intensity (kBtu/$)					
Delivered Energy Consumption	4.70	4.36	4.20	3.36	-1.19%
Electricity Consumption	0.62	0.61	0.57	0.45	-1.15%
Total Energy Consumption	6.07	5.68	5.42	4.24	-1.28%
Energy Consumption Total (quads)					
Delivered Energy Consumption	25.09	25.15	26.67	32.19	0.89%
Electricity Consumption	3.32	3.51	3.62	4.31	0.94%
Total Energy Consumption	32.41	32.75	34.46	40.58	0.81%
Industrial Energy Prices (2004 $/MBtu)					
Petroleum Products	6.78	11.57	9.46	11.36	1.86%
Natural Gas	4.00	8.41	5.69	6.45	1.72%
Electricity	15.18	17.57	15.65	15.95	0.18%

The industrial sector is more complex with some major service demand categories that are cross cutting over many industries and also some important technologies that are specific to an industry. Electric motors are a major cross-cutting technology, and are used in pumps, fans and blowers, air compressors, material handling and processing, refrigerators, dryers and washers, etc. Also building heating, ventilation, air conditioning and lighting are universal needs. Natural gas has become the pervasive choice for boiler and furnace fuel. Material heat treating, melting, casting, paper pulping, petrochemical manufacturing are examples of intensive uses of energy in specific industrial activities. These technologies and others are described in a number of useful references (see, for example, Interlaboratory Working Group 2000, NYSEDA 2004, and Martin et al 2001). As one specific example of technology characterization and opportunities within the industrial sector, Table 6-7 highlights 15 categories of electricity use within 22 industrial sectors as summarized by the American Council for an Energy Efficient Economy (NYSERDA 2004). The NYSERDA study further examined the current potential electricity savings that are deemed to be economic – assuming a 10% return on investment for each of the technology categories. The resulting percent electricity savings by industry are shown in Table 6-8.

Based on this type of technology characterization within AMIGA, a counterfactual policy scenario, with some assumed combination of changes in prices, policies, and/or preferences, will prompt a different mix of industrial technologies. Assuming the same carbon charge of $100 per ton as it impacted the residential and commercial end use sectors, typical industrial energy prices might increase about 14 percent or more. The rising prices together with a lower hurdle rate might encourage investments in technologies with an average 3.3-year payback. Compared to the reference case assumption, this would reduce energy intensity by about 9 percent compared to the baseline forecast in 2030. Hence, total energy consumption might be only 37 quads in 2030 compared to the 40.6 quad forecast. In AMIGA, the increased efficiency in this example, might have spurred an incremental investment by about $130 billion between now and 2030 (again, depending when the policy or price signal actually took effect). Industrial firms would then be expected to save about $40 billion per year but still satisfying the same level of industrial output.

Table 6-7. Distribution of Electricity Use by Industry

Industry	**Pumps and Air Handling**	**Material Handling**	**Refrig-eration**	**Process Heating**	**HVAC**	**Other**
Food mfg	25%	23%	25%	3%	6%	18%
Textile mills	12%	40%	9%	4%	14%	21%
Paper products	53%	24%	2%	3%	3%	15%
Chemicals	45%	17%	7%	3%	6%	22%
Plastic & rubber products	16%	36%	8%	16%	9%	15%
Nonmetallic mineral products	15%	46%	0%	23%	5%	10%
Primary metals	10%	15%	0%	29%	3%	41%
Fabricated metal products	10%	40%	2%	16%	9%	24%
Machinery equipment	10%	35%	3%	9%	18%	24%
Computers & electronics	10%	15%	10%	15%	26%	24%
Transportation equipment	16%	30%	4%	9%	15%	23%
Agriculture	50%	15%	10%	10%	0%	15%
Mining	32%	58%	0%	0%	0%	10%

Table 6-8. Cost-Effective Industry Electricity Savings at Current Prices

NAICS Code	Industry	Savings
311	Food mfg	33.2%
313	Textile mills	35.6%
322	Paper mfg	27.3%
325	Chemical mfg	25.8%
3254	Pharmaceutical & medicine mfg	28.1%
3259	Other chemical product mfg	27.4%
326	Plastics & rubber products mfg	21.0%
3261	Plastics product mfg	28.7%
327	Nonmetallic mineral product mfg	17.8%
3271	Clay product & refractory mfg	22.1%
3272	Glass & glass product mfg	17.4%
3273	Cement & concrete product mfg	18.6%
3279	Other nonmetallic mineral product mfg	15.8%
331	Primary metal mfg	14.5%
3313	Alumina & aluminum production & processing	23.5%
3314	Nonferrous metal (except aluminum) production & processing	12.4%
332	Fabricated metal product mfg	27.0%
333	Machinery mfg	32.4%
334	Computer & electronic product mfg	34.7%
336	Transportation equipment mfg	32.4%
11	Agriculture	36.7%
21	Mining	26.2%
	TOTAL	25.2%

6.5.5 Transportation

In the transportation sector there are a variety of service demands reflecting the many different modes and services provided. Light duty vehicles meet the demand for vehicle miles traveled. Trucks and trains support ton miles while aircraft provide passenger seat miles. Table 6-9 provides the key indicators for the major service demands within the transportation section. In 2002, for example, the very large mix of light duty vehicles supported 2,561 billion vehicle miles traveled (VMT) within the U.S. Growth in VMT is expected to increase at a rate 1.74% annually through 2030. However, average fuel economy is projected to improve, albeit slowly, rising from 20.39 miles per gallon in 2002 to 22.48 MPG by 2030. The small improvement in vehicle fuel economy means that total energy consumption will grow somewhat more slowly than VMT, increasing at an average annual rate of 1.37% through 2030. Similar details for freight and air travel are also highlighted in Table 6-9. As with the other sectors, this data forms the basis for the AMIGA reference case scenario through 2030 with trends extended to 2050 or longer depending on assumptions associated with longer time horizons and the precise mix of policies and trends that model users would like to see evaluated.

Table 6-9. Transportation Energy Service Demands, Consumption, and Prices

	2002	2005	2010	2030	AAGR
Level of Travel					
Billion Vehicle Miles Traveled					
Light-Duty Vehicles < 8500 lbs	2,561	2,619	2,890	4,132	1.74%
Commercial Light Trucks 1/	65	70	77	115	2.08%
Freight Trucks > 10000 lbs.	206	230	261	413	2.42%
Billion Seat Miles Available					
Air	908	990	1,192	1,567	1.99%
Billion Ton Miles Traveled					
Rail	1,507	1,552	1,721	2,403	1.79%
Domestic Shipping	612	649	683	824	1.20%
Implied Energy Efficiency					
Light-Duty Vehicle Stock (mpg)	20.39	20.11	20.40	22.48	0.36%
Stock Commercial Light Truck (mpg)	13.97	14.16	14.60	16.58	0.64%
Freight Truck (mpg)	6.00	6.02	6.02	6.82	0.48%
Aircraft (seat miles per gallon)	55.59	58.65	59.91	62.98	0.46%
Rail (ton miles/kBtu)	2.90	2.91	2.92	2.99	0.11%
Domestic Shipping (ton miles/kBtu)	2.13	2.14	2.15	2.25	0.20%
Energy Use by Mode (quads)					
Light-Duty Vehicles	15.7	16.3	17.7	23.0	1.37%
Commercial Light Trucks 1/	0.6	0.6	0.7	0.9	1.43%
Bus Transportation	0.3	0.3	0.3	0.3	0.45%
Freight Trucks	4.3	4.8	5.4	7.6	1.94%
Rail, Freight	0.5	0.5	0.6	0.8	1.68%
Shipping, Domestic	0.3	0.3	0.3	0.4	0.99%
Air	2.9	2.8	3.3	4.1	1.52%
All Other Transportation Uses	2.6	2.5	2.4	2.7	0.58%
Total	27.1	28.1	30.7	39.7	1.42%
Energy Prices (2004 $/MBtu)					
Distillate Fuel	9.83	16.99	14.29	15.65	1.67%
Jet Fuel	6.23	12.64	9.67	11.53	2.22%
Motor Gasoline	11.58	18.60	16.52	17.92	1.57%

Despite this different set of service demands, we treat transportation equipment in a similar way to the other sector technologies. That is, there exists opportunities to develop and invest in technologies that will reduce the energy intensity associated with providing the requisite transportation services. There is also great opportunity to adopt existing technology to improve the fuel economy of conventional personal vehicles. However, there is also great opportunity for hybrid electric vehicles and breakthrough technologies in advanced engines, fuel cells, and materials (see, for example, DeCicco et al 2001, Greene and Shafer 2003, Burke and Abeles 2004, and Santini and Vyas 2005). The personal vehicle representation and modeling is more complex than many business and household investment decisions because of the multi-dimensionality of the vehicle choice, as shown in Table 6-9.

AMIGA maintains a large amount of technological detail on light duty vehicles. Table 6-10 summarizes the many attributes associated with the array of vehicles represented in the modeling database while Table 6-11 highlights the cost and fuel economy associated with the different mix of medium size cars now represented in AMIGA.

Table 6-10. Dimensions of Vehicle Choice

Vehicle Type	**Drive Train**	**Materials**
car	conventional	conventional
SUV	hybrid electric	mix
wagon	HEV plug-in	advanced
van	electric urban	
pickup truck	advanced	**Luxury**
delivery truck		base
bus	**Engine**	middle
	spark	high
Size	compression	
small	fuel cell	**Performance**
compact		base
midsize		mid-range
large		high

Vehicle choice must fit in consistently with the Lancaster consumer demand theory and equations developed in Section 3. To do this a hierarchy structure is created starting with overall demand for real expenditures on the top, and then the disaggregation of those expenditures into discrete vehicles with different sizes and types. The size and type distributions are based on the market share logistic equations derived from the random utility choice model. The price elasticities (or willingness to pay) for substitute vehicle types and sizes have been recently described in a report by Greene, Duleep and McManus (ORNL/TM-2004/181).

We view hybrid electric vehicles (HEV) as a new emerging technology that is on a logistic market penetration path over time, with long run market share depending on ultimate performance and cost. Fell cell vehicles (FCV) at some future point may also become an emerging technology. The future role of FCVs are currently an exogenous scenario specification. Following Greene et al. preferences for other vehicle attributes are converted to dollar values using a weighing preference function. Greene reviews the literature and selects a 3-year payback for the average observed weight that new car buyers place on the present value dollars that they are willing to pay for fuel economy. On the supply-side, manufactures must choose how to employ improved technology, either to improve fuel economy with a fixed performance, or to improve performance with a fixed fuel economy (currently set by CAFÉ standards). Industry experts seem to unanimously believe that historically the later has happened. The opportunity cost of improved power and acceleration is the additional cost of fuel.

Table 6-11. Cost and Performance Characteristics of Medium-Sized Cars[24]

Vehicle Category	2000		2010		2030	
	Cost	MPG	Cost	MPG	Cost	MPG
Conventional	$24,833	22.0	$26,286	31.6	$26,977	31.7
Dedicated CNG			27,401	31.6	28,092	31.7
Advanced ICE/Diesel			27,677	44.1	28,368	44.3
Hybrid Electrics			31,899	46.9	28,343	61.2
Fuel Cell w/Reformer					32,549	61.9

To again illustrate how AMIGA might evaluate this level of technology detail within the model, let us again assume that a carbon charge of $100 per ton has been imposed on the U.S. economy. This might increase gasoline prices might increase about 11 percent by the year 2030. The rising prices together with a lower hurdle rate might encourage investments in more fuel efficiency cars with an average 4-year payback. Compared to the reference case assumption, this would improve fuel economy in the stock of light duty vehicles by about 9 percent compared to the baseline forecast in 2030. Hence, total energy consumption from light duty vehicles might be only 21.2 quads in 2030 compared to the baseline forecast of 22.4 quads in that same year. As with the other sectors, the increased fuel economy might have spurred an incremental investment of about $128 billion between now and 2030 (again, depending when the policy or price signal actually took effect). Both households and businesses which buy the more efficient cars would then be expected to save about $32 billion per year but still satisfying the same level of transportation services.

6.6 Additional Perspectives

Measuring the amount of capital embodied in a given subsystem can have important implications for energy price impacts and energy and climate policy impacts. If factor prices change enough, some older, existing systems can be shut down (i.e., early economic retirement). Then the resulting services that had been produced from the retired facility will have to be replaced with new spending that can crowd out a small increment of GDP growth. At the same time, if that new capital proves to be more productive than the newly retired capital, through increased energy savings for example, it can increase personal consumption or even reduce oil imports. Both of these effects, in turn, can positively impact GDP. Just as the Bureau of Economic Analysis totals up the components of GDP on quarterly or annual basis, AMIGA also tracks the ebbs and flows of the different contributions to GDP and employment by tracking the contributions of productive investment – including investment in energy efficiency.

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[24] Table 6-11 is in the process of being updated using reports by Greene, EPRI HEV study, M.I.T. vehicle study, and other recent literature.

One aspect of capital that AMIGA can also evaluate is how its performance and characterization change over time. Such changes are often referred to as technical change which can be driven by a number of factors including:

- Learning from experience which can reduce the cost of energy-efficient investments over the period of a policy scenario;
- Research and development (R&D which can both increase the performance of existing energy-efficient technologies as well as encourage the development and introduction of new technologies (often represented as so-called backstop technologies; and
- Introduction of new products and services that either save energy or lower costs (or both), thereby shifting the isoquant down at the high-cost end.

But capital must be deployed in order to stimulate these positive impacts to GDP. Efforts beyond the change in relative prices can contribute to the deployment and diffusion of productive capital through the implementation of cost-effective standards, financial incentives and through information and voluntary programs such as Energy Star which is a set of EPA and DOE programs designed to bring more efficient products into the marketplace (CPPD 2004). As a result of penetration of Energy Star products, the customer will face a new, more-desirable (i.e., shifted down) isoquant when choosing energy-efficient investments. Technical change can be captured in new isoquant slopes through recalibrating the underlying production function using a larger elasticity of substitution.

6.7 Model Dynamics and Investment

New additions to stocks of capital and durable goods (i.e., investment) are determined by the condition that related service demands are met by available capital stocks.

We take a stock-flow approach to end-use energy demand modeling. Flows are additions of equipment to meet growing service demands. Additions must also account for replacements due to retirements. Energy-related services are provided from the existing stocks of equipment, vehicles, and structures. This stock-flow approach is best expressed symbolically, as follows.

Let j be an index over the set of capital stocks in some sector such as vehicles or buildings. Let s be an index over the end-use services represented, such as building shell, heating, cooling, ventilation, lighting, office equipment. There are multiple equipment options, j, available to supply each service, s.

Let y be the current year and let τ denote previous vintages. Let d denote the decision-maker that chooses factor-intensities, since different decision makers have different incomes and may apply difference choice criteria or different weights on the attributes of the durable good. Let $Q_{j,d,y}$ be the quantity of additions selected by d in year y;

Let the intensities for service output, energy use of type e , and investment be denoted by $as_{j,d,y}$, $en_{j,d,y}$ and $invt_{j,d,y}$, respectively. The use fraction of equipment j, $use_{j,y-t}$, may deteriorate with age. The survival probability is also a function of age, $surv_{j,y-t}$.

The resulting service provision is a summation over all new and existing equipment vintages. Half of the new equipment put in place in the current year is assumed to be available for use in that year.

$$Serv_{s,d,y}^{Bldg} = \sum_{j} \left\{ 0.5 * as_{j,d,y}^{Bldg} * Q_{j,d,y}^{Bldg} + \sum_{\tau}^{y-1} surv_{j,y-\tau}^{Bldg} * use_{j,y-\tau}^{Bldg} * as_{j,d,\tau}^{Bldg} * Q_{j,d,\tau}^{Bldg} \right\}$$

Durable good expenditure (or investment expenditure) is given by:

$$Invest_{s,y}^{Bldg} = \sum_{d} \sum_{j} \left\{ invt_{j,d,y}^{Bldg} * Q_{j,d,y}^{Bldg} \right\}$$

Energy use for each type of energy is given by:

$$Energy_{s,y}^{e,Bldg} = \sum_{d} \sum_{j} \left\{ 0.5 * en_{j,d,y}^{e,Bldg} * Q_{j,d,y}^{Bldg} + \sum_{\tau}^{y-1} surv_{j,y-\tau}^{Bldg} * use_{j,y-\tau}^{Bldg} * en_{j,d,\tau}^{e,Bldg} * Q_{j,d,\tau}^{Bldg} \right\}$$

Mathematically (when represented in continuous time) the above equations are known as convolution integrals, because they sum over all historical equipment vintages.

The energy intensity, capital investment intensity, and service level are all functions of the energy price, cost-of-capital, and other prices and incomes. We can represent effective price elasticities by explicit formulas as functions of prices. These formulas for energy and capital factor demands (associated with new additions to meet a given service demand) are derived from fitting the technology options data to constant elasticity of substitution (CES) functional forms, as described earlier in this section. These functions provide the incremental capital needed to reduce energy consumption of an appliance, piece of equipment, process, or facility.

Empirical research by US DOE and others has found abundant evidence that durable good purchases and other investments must pass an investment criteria having a discount rate above the market interest rate for the purpose of evaluating the energy-efficiency of a product or facility. Therefore, we use a distribution of effective hurdle rates that apply to portions of the population making energy efficiency investment decisions.

The time step in the model is one year. Retirements and equipment additions are estimated each year. Investment each year is calculated from the expenditure on equipment additions. These investment flows represent one of society's uses of real resources. However, real resources allocated to energy savings may be more than offset by the savings of real resources from not having to produce domestically or import as much energy. When aggregated, investments of various types are included in the macroeconomic growth model to consistently capture endogenous investment spending.

6.8 Conclusion

Currently we employ production function isoquants by energy type (electricity, natural gas) to represent estimates of economically recoverable energy savings fractions in these sectors. We are in the process of fitting technology characterization data by end-use category for residential, commercial, and industrial energy use. We are using the residential and commercial EIA/NEMS database files. For industrial, we are using ACEEE studies. For personal vehicles, we use published estimates of vehicle incremental costs for fuel economy, performance measures, and other dimensions such as vehicle size.

In this section we present the methodology employed to derive energy efficiency choices and associated investments. There are many opportunities to substitute labor for capital. Commercial and large residential buildings employ professional HVAC operators. There objective is to dispatch heating, cooling, and ventilation services to tenants, not to save energy. Training courses on energy efficient operations for these professionals have been highly successful and resulted in large savings. Here we present our methodology in the context of substituting capital for energy. We certainly will not be suggesting that energy savings is obtained for free. However, we think that it is important that the investment measures must be taken in the near term prior to achieving a stream of energy savings. This timing mismatch is often related to the empirical evidence of underinvestment in energy efficiency, particularly from a societal, economy-wide perspective.

The methodology described here has been employed in studies for the Stanford University Energy Modeling Forum (EMF) and for the International Energy Agency's publication *World Energy Outlook 2004*.

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7. USE OF AMIGA IN A SCENARIO ANALYSIS

With the AMIGA modeling system now reasonably described, we can explore ways that it might actually generate some hopefully useful insights for decision makers. More specifically we describe an example of how the model structure and technology characterization might evaluate a set of programs and policies as they might impact the U.S. economy at some point in the future. In this way we set up a heuristic inquiry so that readers can determine whether the reference scenarios and complementary policy responses provide a set of results consistent with both economic theory and real world expectations.

In the discussion that follows we provide some necessary background discussion of a problem that might be of interest. Next we outline a set of scenarios which might provide some useful insights; and finally, we then describe the set of results AMIGA provides. In this way we can evaluate how the model actually performs in the context of a scenario exercise.

Based on a number of recent inquiries it appears that the U.S. will face complex multidimensional challenges as we confront potential supply shortfalls, infrastructure constraints, and environmental limitations in the years ahead. Using a technique known as scenario analysis, this section investigates key energy issues and decisions that could improve or reduce the ability of the United States to deal with the uncertainties that may challenge the U.S. economy during the next fifty years. The outcomes can then be used to evaluate overall effectiveness of the modeling system.[25]

7.1 Background

A growing number of researchers and scholars have warned that global shortfalls in the availability of conventional energy resources could occur as early as 2030 (Abt 2002; Hoffert et al., 2002; and Metz et al., 2001). The major concern is not that the world is running out of all energy resources, but rather that the major non-renewable supplies of oil, gas, and arable lands are being rapidly and irreversibly depleted. It is very likely a huge investment in both Research and Development (R&D) and infrastructure will be needed over the next several decades to ensure adequate energy availability and to commercialize the technologies that will replace cheap fossil fuels. Technologies likely to receive the most attention include unconventional fossil fuels, hydrogen, renewable resources, advanced nuclear power systems, and more energy-efficient machinery, equipment, and appliances.

Even with the promise of these new technologies and resources, the question has not been asked: “What is the mix of resource investments that make the most sense for the United States — given the need for balanced economic growth, enhanced environmental quality, and improved international security?” These are the kind of questions that Wirth et al.

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[25] This section of the model documentation is adapted from a forthcoming journal article by Laitner and Hanson (2006).

(2003) try to answer, and that we attempt to explore through the use of scenario analysis (Schwartz 2003).

7.2 Scenarios of Four Future Worlds

To fully explore the future of U.S. energy markets and their impact on the economy for the next fifty years, four scenarios have been developed representing a diverse range of future worlds. We use the AMIGA modeling system to evaluate the economic interactions and impacts of these four scenarios. AMIGA is a 200-sector computable general equilibrium model of the international economy with a detailed representation of both energy efficiency and energy supply technologies (Hanson 1999; and Hanson and Laitner 2004). These technologies include all of the ones most likely to be evaluated and promoted in the next 30 to 50 years. Described in a report released last year by the Argonne National Laboratory (Hanson et al 2004), the four scenario narratives discussed here include:

- *The Official Future;*
- *Cheap Energy Reigns Supreme;*
- *Big Problems Ahead; and*
- *Technology Drives the Market.*

Table 1, on the following page, provides key energy and economic indicators for comparison among the scenarios and to a set of linked policy cases (referred to as the "challenge and response cases"). We next describe the context or story logic that drives each of the scenarios.

7.2.1 The Official Future

The Official Future is a reference scenario that we benchmarked to the Annual Energy Outlook 2002 (Energy Information Administration 2002). The Annual Energy Outlook (AEO) forecast reflects conventional wisdom about the future patterns of U.S. energy supply and demand through 2020. For The Official Future, we assumed that existing U.S. policies, trends in market structure, and the market shares of various technologies generally follow a similar pattern in the years 2020 to 2050. Like each of the scenarios that follow, The Official Future is not a prediction or a forecast. It simply represents an internally consistent view of the way in which U.S. energy markets could evolve over time if current policies remain unchanged for the next fifty years. The Official Future is used as a reference case for purposes of comparison with the other scenarios described below.

Table 1. Summary Indicators for Historical Year 2000 and Study Scenarios Year 2050

Energy or Economic Indictor	Year 2000 Historical	The Official Future	Cheap Energy Reigns		Big Problems Ahead		Technology Drives Market	
			Base	Policy	Base	Policy	Base	Policy
Gross Domestic Product (Trillion Dollars)	$9.9	$36.9	$39.8	$39.3	$32.3	$32.0	$39.8	$39.7
Primary Energy Demand (Quadrillion Btus)	100.3	157.5	165.0	106.3	124.5	105.6	127.5	102.2
Carbon Emissions (Million Metric Tons)	1,559	2,471	2,584	914	1,879	859	1,741	839
Oil and Gas Imports (Billion Dollars)	$133	$313	$338	$58	$215	$94	$137	$53
World Oil Price (Dollars per Barrel)	$27.72	$26.74	$22.94	$15.13	$40.46	37.76	$21.26	$18.74
Average Wellhead Natural Gas Price (Dollars per Thousand Cubic Feet)	$2.76	$5.38	$6.13	$2.42	$6.25	$4.87	$4.82	$3.19
Average Electricity Price (Dollars per Megawatt-hour)	$67	$79	$76	$120	$91	$109	$82	$107
Light Duty Vehicle Travel (Billions Miles per Year)	2,400	4,588	5,436	3,879	3,738	3,407	3,990	3,753
New Car Fuel Economy (Average Miles per Gallon)	22.8	25.5	25.5	67.4	56.1	74.3	49.4	77.7
Average Fossil Fuel Heat Rate (Btus per Kilowatt-hour)	10,730	7,036	6,894	7,899	7,565	9,232	7,546	8,553

Notes: (1) All dollar values are constant 2000 dollars; and (2) The conversion of nuclear and renewable electricity production into primary energy is based upon average fossil fuel heat rates rather than the standard conversion units assumed in other models. For more detailed results over the full 50-year time horizon of these scenarios and their respective policy cases, see Hanson et al. (2004), available going to the publications section of the AMIGA website. The URL is: http://amiga.dis.anl.gov.

There are no major conflicts in The Official Future. Federal policies on energy and economic development achieve their goals. New technologies enter the market gracefully, with incumbent technologies readily adjusting to all new challenges. Foreign governments seek to cooperate with U.S. policy in the interest of stimulating global economic growth. Patterns of housing, urban development and agriculture all continue to follow recent trends. U.S. energy demand increases at a slow and gradual rate of about 0.9 percent per year for the entire 50-year period. Total U.S. primary energy demand rises from approximately 100 Quads in 2000 to 157 Quads in 2050. During the same period, the U.S. economy grows at an average rate of about 2.7 percent per year, experiencing few shocks and no significant disruptions. At this annual rate of growth, U.S. Gross Domestic Product (GDP) increases from just under $10 trillion in 2000 to about $37 trillion in 2050 (measured in constant year 2000 dollars).

Improvements in the energy intensity of the economy notwithstanding, the overall effect of economic growth, and the resulting use of fossil fuels, is to increase air pollutant emissions. Emissions of local air pollutants (including oxides of sulfur and nitrogen plus particulates) grow steadily with the rising demand for energy in general and for fossil fuels in particular. Fossil-fuel related emissions of carbon dioxide (CO2) increase from 1561 million metric tons of carbon equivalent (MMTC) in 2000 to 2,471 MMTC in 2050. In short, The Official Future is an optimistic, surprise-free scenario, a world of “more of the same,” with no major discontinuities or disruptive technologies.

7.2.2 Cheap Energy Reigns Supreme

Cheap Energy Reigns Supreme is a more extreme version of the world foreseen in The Official Future. This is a scenario in which abundant and inexpensive supplies of oil and gas continue to fuel the engines of economic growth in United States. American foreign policy is designed to provide continued access to low-cost supplies of oil and gas, placing great emphasis on stability in oil-producing regions. American consumers sustain their historical dependence on cheap fuels and disregard the occasional breakdown of energy supply and delivery systems. Environmental impacts of energy supply and use are considered to be the unavoidable consequences of economic growth.

As this scenario unfolds, OPEC leaders determine that their interests align closely with those of the United States and other industrialized, oil-importing countries. Thus, producers seek to maximize output while keeping prices low enough to promote sustained economic growth in developing countries. Confident of continuing increases in world oil demand, OPEC manages the world oil market so as to discourage R&D on new or alternative technologies that could lower future oil demand and, in so doing, to delay the commercialization of potentially competitive technologies.

Driven primarily by low prices, United States imports of petroleum and petroleum products grow even more rapidly in this scenario than they do in The Official Future. Total imports of petroleum and petroleum products reach almost 50 Quads in 2050, compared to 24 Quads in 2000.

Still more dramatic changes occur in the natural gas market. Gas demand triples in Cheap Energy Reigns Supreme, rising from 23 Quads in 2000 to 70 Quads in 2050. Two-thirds of the increase is achieved through expansion of domestic production, with rapid advances in exploration and production technology allowing U.S. energy companies to open up unconventional resources in tight formations, off-shore fields, unmineable coal seams, and Arctic basins. Substantial private investments in new pipeline and distribution infrastructure, begun in the 1990s and continued throughout this scenario, allow these new resources to be delivered to end-users in the Lower 48 states.

With seemingly unlimited supplies of cheap oil and gas steadily available, travel increases significantly. Fuel economy remains largely unchanged relative to The Official Future. U.S. total primary energy demand grows at an average rate of about one percent per year in Cheap Energy Reigns Supreme, reaching 165 Quads per year in 2050. Fueled by cheap energy, the U.S. economy grows at an annual average rate of approximately 2.8 percent during the same period. At this rate, the U.S. economy expands by a factor of four, from about $10 trillion in 2000 to nearly $40 trillion in 2050. In this world of cheap energy and domestic tranquility, the federal government makes no effort to promote energy efficiency or low-emissions technologies.

With increasing use of all types of fossil fuels, it is not surprising that air pollutant emissions increase in Cheap Energy Reigns Supreme. Emissions of particulates, oxides of nitrogen, and oxides of sulfur increase by hundreds of millions of tons per year. Carbon dioxide emissions from fossil fuel combustion grow from 1,559 MMTC in 2000 to an estimated 2,584 MMTC in 2050. In sum, Cheap Energy Reigns Supreme is a scenario characterized by inexpensive and seemingly limitless supplies of oil and gas. This surprise-free scenario exposes the United States to no major discontinuities or disruptive technologies.

7.2.3 Big Problems Ahead

Big Problems Ahead is a chaotic, event-driven scenario. Domestic policy is disjointed and episodic, buffeted by forces beyond U.S. shores. Similar to Cheap Energy Reigns Supreme, principal actors in this scenario include U.S. policy-makers, U.S. business leaders as well as leaders of foreign governments. But in addition, sub-national groups also play a role.

In contrast to Cheap Energy Reigns Supreme, foreign governments do not support U.S. policy goals or cooperate with U.S. leaders in Big Problems Ahead. They envision their interests strongly in conflict with the U.S. regime and see U.S. policies as designed to promote the imperial ambitions of the United States. They have no interest in preserving a tranquil environment to support U.S. economic growth. As a consequence of these conflicting visions, many foreign actors (including terrorist groups) take steps to limit U.S. access to resources and to disrupt international trade in energy resources. Chronic instability among Gulf regimes leads to a roller-coaster ride of rapid oil price surges, stressing the U.S. energy sector. Intermittent cutoffs of oil supply from the Gulf cause discontinuities in the path of economic development for both industrialized and developing countries. Efforts to develop new energy resources in the Lower 48 also encounter unexpected setbacks. For example, the federal government's attempt to reinvigorate the 1980's era synfuels program fails.

Reeling in another direction, the federal government decides to expand a small "Freedom Fuel" research effort into a national "crash" program to advance the technology of hydrogen production and use. This multi-billion dollar effort – one of the few successful federal energy initiatives -- funds R&D on producing hydrogen from coal and accelerates commercialization of new fuel-cell technologies by U.S. companies.

But, overall, new technologies falter. Unexpected engineering challenges prove insurmountable. Environmental impacts of the new systems generate significant public resistance to their widespread use. Institutional failures in managing the commercialization process ensure a lack of success in the marketplace.

U.S. oil imports continue to grow, increasing more than 100 percent from 2000 to 2050, and putting severe pressure on other oil-importing countries. A worldwide economic slowdown reduces world oil demand, allowing oil prices to remain largely flat in constant dollar terms over the scenario period. The market share of imports in U.S. oil consumption increases in this scenario from about 55 percent in 2000 to 73 percent in 2050. To reduce the pressure on oil imports, federal policy promotes the introduction of fuel cell vehicles after 2020. By 2050, fuel cell vehicles capture almost two-thirds of new light-duty vehicle sales. Both natural gas demand and wellhead gas prices double during the scenario period. Imports of natural gas increase from about 7 percent to 25 percent of total demand.

In this environment, the federal government abandons any pretense of a cohesive national energy strategy, and retreats into crisis management. The volume of both public and private investment in R&D declines steadily and the prospect of deflation looms over the economy. The incessant string of severe stresses and periodic shocks slows the rate of economic growth in Big Problems Ahead. GDP grows at an average rate of 2.4 percent per year, from about $10 trillion in 2000 to $32 trillion in 2050. During the same period, energy demand increases at a rate of about 0.5 percent per year, from 100 Quads in 2000 to just 124 Quads in 2050.

In short, Big Problems Ahead is a chaotic future beset with shocks, stresses, and discontinuities. Economic growth is slowed worldwide. U.S. energy policy is disjointed. Concerns about energy security keep everyone on edge. Rising U.S. oil imports increase U.S. dependence on unstable world regions. And U.S. responses to these challenges make it appear that the United States has become an arrogant and imperial player on the world stage, reducing the inclination toward international cooperation in many countries.

7.2.4 Technology Drives the Market

Technology Drives the Market is a scenario in which a variety of forces converge to reshape the market architecture of the U.S. energy sector. The promise of commercial and environmental benefits from new technologies motivates state officials to reform regulatory policy and eliminate barriers that hinder commercialization of new technologies. Implementation of institutional and regulatory reform sets the new and improved technologies on a level playing field alongside mature technologies in U.S. energy markets, allowing incumbent companies in these markets to embrace the new technologies. Engineering advances in the design and development of efficient, low-emissions technologies capture the imagination of business leaders, state officials, and individual consumers. Private investment by U.S. energy companies combines with rapid technical progress and value shifts by U.S. consumers to drive the new technologies to rapid market acceptance and widespread commercial applications.

In Technology Drives the Market, state regulators overcome historical tendencies and work together. Early in this scenario, state leaders establish an integrated set of tariff policies for energy efficiency systems, renewable energy technologies, and distributed electricity generation schemes. State governments work together to implement standardized equipment requirements for connecting the new technologies to local utility grids. Net metering programs (currently implemented in more than a dozen states) spread across the country and facilitate arrangements in which on-site generators sell electricity back to the grid through simplified accounting transactions. Improved techniques for real-time load-flow analysis facilitate time shifting of local loads and the introduction of regional sub-networks of micro-grids. These local micro-grids lower the stress on aging transmission systems and increase the reliability of utility generating networks. Strict environmental permitting standards are applied to both new and traditional technologies, limiting the energy sector's impact on the regional and global environments.

Engineering advances play a key role in this scenario, improving the technical performance and reducing the effective costs of small, distributed, energy-producing technologies. In this scenario, we assume a large number of technologies achieve commercial success, including building-integrated photovoltaic power systems, medium to large wind machines (i.e., machines with rated capacity of 5 kW to 5 MW), small methane-reforming appliances (located at local fueling stations that produce hydrogen for fuel cells from natural gas), fuel cells for mobile and stationary applications, and biomass energy systems to produce both heat and electricity.

In the transportation sector, the most dramatic improvements emerge in the light-duty vehicle arena. Shifting consumer values place increasing importance on reducing the environmental footprint of each consumer, making hybrid gasoline-electric or diesel-electric cars appear much more "cool" to the average consumer than would a large, heavy inefficient, sport-utility vehicle. As this scenario progresses, the growing success of methane-reforming appliances coupled with the increasing reliability and durability of fuel cells in mobile applications leads to a growing market share for efficient, low-emissions vehicles.

As consumer purchasing preferences shift to small and efficient vehicles, oil demand in the U.S. transportation sector plummets while personal mobility is maintained. New hybrid vehicles use much less gasoline (or diesel) for the same amount of driving, while the new fuel cell vehicles derive their power from domestic natural gas. This has significant positive implications for energy security as the demand for imported fuel begins to decline steadily.

Imports of petroleum and petroleum products actually decline by almost 15 percent in Technology Drives the Market, from 24 Quads in 2000 to just 21 Quads in 2050. Imports of natural gas increase over the same period, but less than in any other scenario, reaching only 12 Quads in 2050. Driven by massive public and private investment in new technologies, the U.S. economy grows more rapidly in Technology Drives the Market than in Big Problems Ahead, a scenario in which continuing uncertainty depresses investment. Similar to Cheap Energy Reigns Supreme, GDP in Technology Drives the Market increases from $10 trillion in 2000 to almost $40 trillion in 2050. However, the effect of investment in efficient technology combines with shifts in consumer values and behavior to slow the rate of growth in energy consumption in Technology Drives the Market. Thus, the energy intensity of the U.S. economy improves significantly. Hence, this scenario is one in which a variety of forces converge to bring a host of advanced, efficient, low-emissions technologies to commercial readiness.

The introduction of these technologies is made possible by a sustained commitment to Research & Development among private investors and a dedicated effort on the part of state officials to lower the barriers to commercialization of new technologies. In addition, consumers recognize added value in technologies perceived to be clean, safe, reliable, and convenient. As a consequence, although the general economy grows rapidly and steadily in this scenario, primary energy use grows much more slowly than does the overall economy, reducing energy intensity over time as well as aggregate expenditures on energy.

7.3 Concerns about a Sudden Surprise Could Change the Game

Each of the four scenarios described above is one among many possible U.S energy futures. Though not inclusive of all possible outcomes, these four scenarios, taken together, represent much of the range of future possibilities. But more can be learned from these scenarios if a strategic challenge sufficient to motivate major change in the behavior of key actors is introduced. The response to this challenge can then be simulated and tracked in three additional scenarios (referred to in this study as “challenge and response” policy cases), allowing analysis of the impacts on the general economy and on key energy-related sectors.

7.3.1 Introducing a Strategic Challenge and Response

The risk of abrupt climate change could plausibly represent one such challenge. Concerns about this low probability, high consequence event are not unreasonable in the face of recent scientific research. For the last several years, oceanographers and geophysicists have observed a change in the salinity of the North Atlantic Ocean and an associated slowing of the thermohaline circulation that is centered in an area west of the Norwegian Sea. These scientists warn that if the associated process called North Atlantic

Deep Water (NADW) formation slows further or comes to a halt, human societies may face a period of abrupt climate change, with rapid cooling experienced in the New England and Mid-Atlantic regions of the United States, as well as in Northwest Europe. They suggest that the continued buildup of greenhouse gases due to the combustion of fossil fuels increases the risk, not just of global warming, but also of the extreme regional cooling that would be associated with a shutdown of the thermohaline circulation in the North Atlantic. Many scientists believe that an abrupt climate change could occur during the next several decades and merits attention from policymakers.

The basecase scenarios (Cheap Energy Reigns Supreme, Big Problems Ahead, and Technology Drives the Market) contain no explicit consideration of the risks of climate change or of controls on emissions of greenhouse gases. However, in the "challenge and response" policy cases, the potential for abrupt climate change is introduced as a major stressor or challenge. This study postulates that consideration of the possibility of abrupt climate change causes national policymakers to accelerate the implementation of substantial steps to slow the buildup of greenhouse gases (Baranzini, Chesney, and Morisset, 2003). In each of the challenge and response scenarios, U.S. policy-makers implement a portfolio of energy policies designed to promote diversity in energy supply, decrease U.S. dependence on foreign oil, improve U.S. energy security, increase efficiency in all energy-intensive sectors of the economy through the introduction of conservation measures and advanced technologies, accelerate capital stock turnover particularly in the electricity and transportation sectors, sustain economic growth, and decrease CO2 emissions resulting from energy supply and use.

Similar policies and measures are introduced in all three basecase scenarios (Cheap Energy Reigns Supreme, Technology Drives the Market, and Big Problems Ahead), but are applied with differing degrees of stringency to produce the three "challenge and response" policy cases. This set of policies was not applied to The Official Future, which is used solely as a benchmark or reference case in this study. None of these challenge and response scenarios are intended to reflect likely outcomes, nor should the postulated response be seen as a policy recommendation. The scenario descriptions should be taken for their heuristic value only. In other words, they are intended to highlight the spread of possible outcomes and responses in ways that help policy makers better understand future interactions and outcomes. The response of key actors to these initiatives depends upon the fundamental dynamics and underlying logic of each scenario as well as on the conditions that are present when the policies are introduced. Hanson et al (2004) outlines the specific policies and measures implemented to achieve the emissions reduction targets of the challenge and response cases. As described above, the AMIGA model again was used to quantify the impact of the selected policies on key energy-related sectors of the economy in each "challenge and response" policy case. Table 1 above summarizes the key economic and energy indicators for each "challenge and response" policy case compared to its basecase scenario.

7.4. Implications and Conclusions: Lessons Learned

Several implications and conclusions can be drawn from a comparison of the basecase scenarios, the challenge and response policy scenarios, and the reference case.

7.4.1 Scenario Analysis an Important Tool

The pattern of future evolution for U.S. energy markets is highly uncertain at this time. Critical uncertainties include future rates of technological advance, levels of private investment in new technologies, strategies of foreign actors (especially oil suppliers), and directions of state and federal policy. A range of unexpected events or surprises may affect the ways that these uncertainties play out. Scenario analysis allows explicit consideration of these critical uncertainties and the dynamics of their interaction with the key driving forces affecting the evolution of U.S. energy markets. Quantification of the resulting scenarios allows direct comparison of the consequences that may arise as these scenarios unfold.

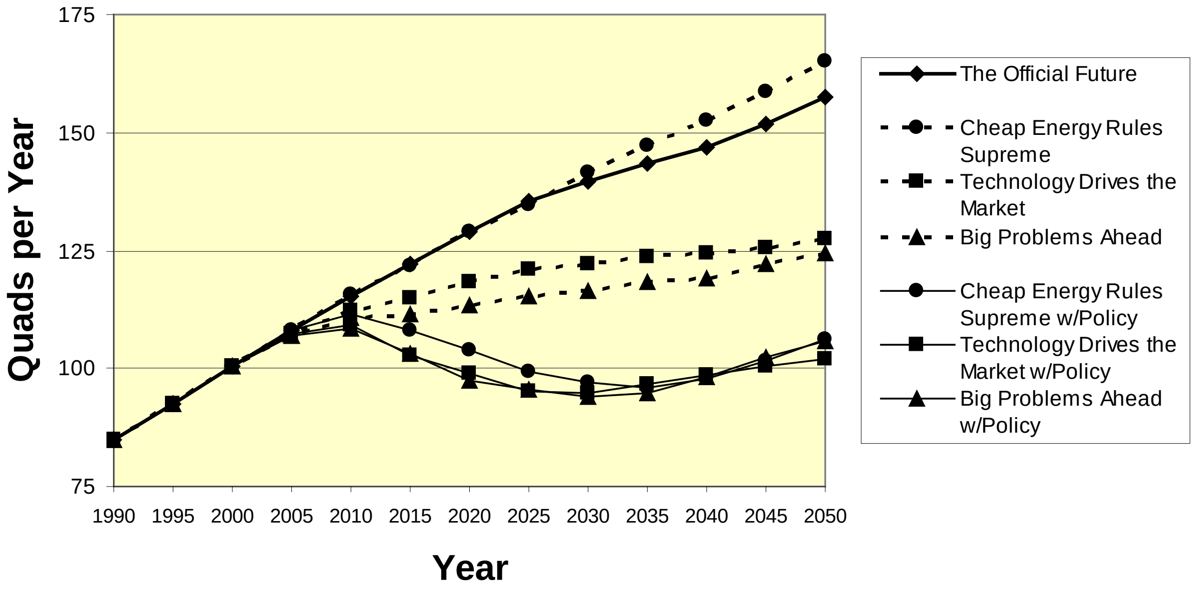
7.4.2 A Range of Feasible US Energy Futures

Interactions among the forces driving evolution of U.S. energy markets may lead to many different paths of technology development, market architecture, and consumer demand. Uncertainties persist concerning the interactions of these forces. Nonetheless, analysis of all three basecase scenarios, which span a broad range of possible paths, indicates that U.S. economic activity and energy demand will continue to increase in the period from 2000 to 2050 in the absence of specific energy policies to accelerate capital stock turnover and the commercialization of low-emissions technologies.

7.4.3 Policies to Encourage Capital Stock Turnover

Policies accelerating introduction of more efficient technologies and demand-reducing measures applied in the three challenge and response scenarios slow growth in primary energy demand. By 2050, primary energy demand remains close to the year 2000 level in all three policy cases. The corresponding increase in the three basecase scenarios and in The Official Future ranged from 25 to 60 percent. Figure 1 illustrates the trajectories of primary energy use in the challenge and response cases, and compares them to the higher trajectories of energy growth in the basecase scenarios.

Figure 1
Primary Energy Use in the Basecase and Policy Scenarios



7.4.4 Low Energy Prices Versus a Smart Investment Path

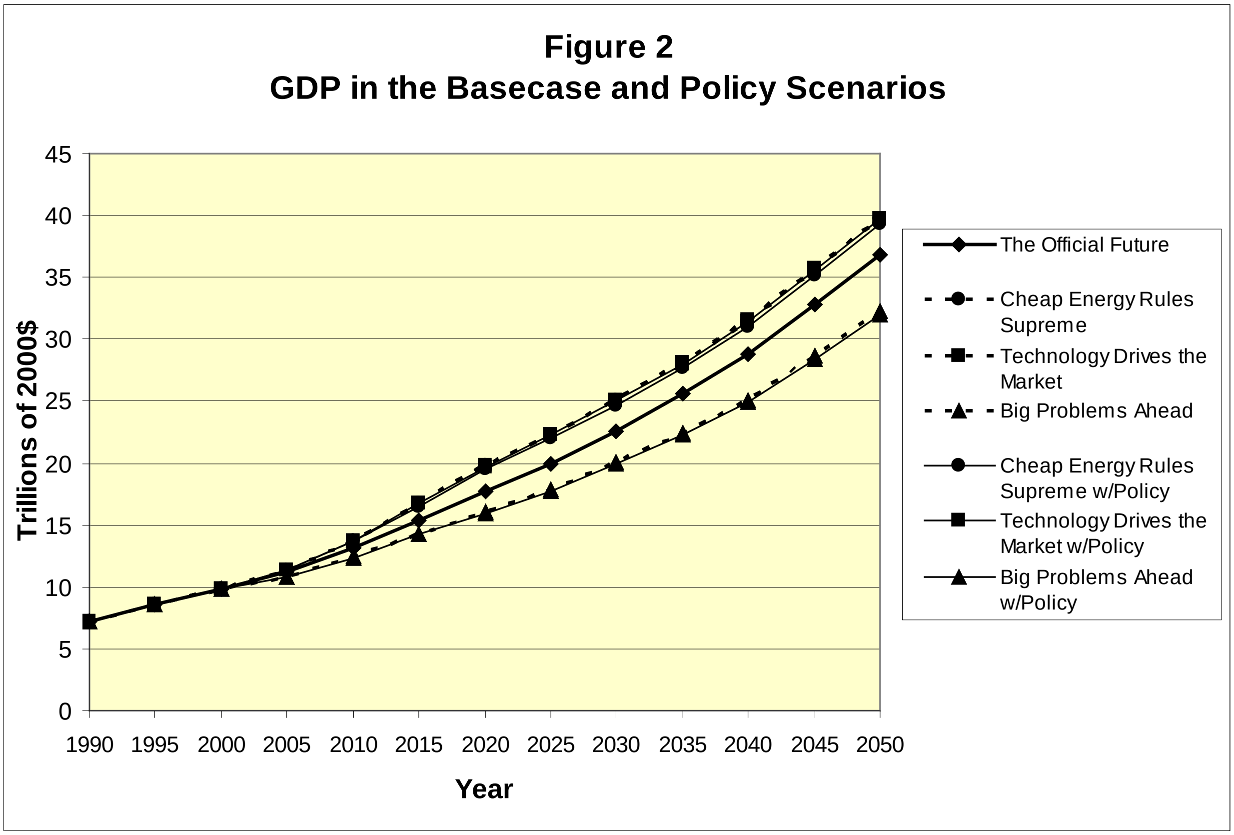
Each of the basecase scenarios investigated in this study involves continued and sustained economic growth — U.S. GDP grows at 2.4 – 2.8 percent per year from 2000 to 2050. In both the Cheap Energy Reigns Supreme and Technology Drives the Market basecase scenarios, GDP growth is at the high end of the range for the entire scenario, reaching approximately $40 trillion in 2050. The Official Future attains just $37 trillion, and GDP grows the least in Big Problems Ahead, to $32 trillion. This demonstrates that in scenarios without substantial policy intervention, strong GDP growth can be sustained either by low energy prices or by continuing investment in advanced technology.

7.4.5 Energy Efficiency Technologies Improve Prospects for Economic Growth

Surprisingly, despite the introduction of policies to promote capital stock turnover and to limit CO2 emissions, GDP in the challenge and response cases reaches approximately the same levels in 2050 as is achieved in the respective basecase scenarios. The projected differences are only 0.3 to 1.3 percent after 50 years (see Figure 2 on the following page).

Smart policy and investment choices made today will accelerate the turnover of fully amortized capital stock and can stimulate substantial economic growth. A balanced portfolio of market-oriented policies would likely include a combination of efficiency or performance standards for vehicles, appliances, and industrial equipment; a cap-and-trade program for large stationary sources; and a series of information initiatives and barrier-busting policies to level the playing field for commercialization of new technologies.

Investments made today in critical energy technologies are likely to remain robust across a diverse set of possible futures and strengthen the prospects for economic growth.



7.4.6 Public and Private Choices Affect Cost of Future Surprises

One thing is certain: The United States will face surprises in the future, just as it has in the past. Some of those surprises may be unfortunate or even catastrophic. One such "game-changing" surprise is represented by the risk of abrupt climate change. Another such surprise might result from a complete cutoff of Middle East oil exports to the OECD, something that could be precipitated by a series of successful Islamic revolutions in the region.

Low fossil fuel prices will discourage investments in energy efficiency or new technologies and can make the task of responding to future surprises both harder and more expensive. Should a major, disruptive surprise occur, large investments in adaptive responses and a rapid transition to new energy technologies could very well become necessary. Such a rapid transition would be both more expensive and more disruptive if steps are not taken soon to decrease U.S. oil import dependence and to invest in advanced energy technologies and energy efficiency measures. In sum, this study shows that early expenditures can significantly reduce the costs of responding to unexpected problems in the future.

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