An Electricity-focused Economic Input-output Model: Life-cycle Assessment and Policy Implications of Future Electricity Generation Scenarios

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Abstract

The electricity industry is extremely important to both our economy and our environment: we would like to examine the economic, environmental and policy implications of both future electricity technologies and the interaction of this industry with the rest of the economy. However, the tools which currently exist to analyze the potential impacts are either too complex or too aggregated to provide this type of information.

Because of its importance, and the surprising lack of associated detail in the input-output model of the U.S. economy, the power generation sector is an excellent candidate for disaggregation. This work builds upon an existing economic input-output tool, by adding detail about the electricity industry, specifically by differentiating among the various functions of the sector, and the different means of generating power.

We build a flexible framework for creating new industry sectors, supply chains and emission factors for the generation, transmission and distribution portions of the electricity industry. In addition, a systematic method for creating updated state level and sector generation mixes is developed.

The results of the analysis show that the generation assets in a region have a large impact on the environmental impacts associated with electricity consumption, and that interstate trading tends to make the differences smaller. The results also show that most sector mixes are very close to the U.S. average due to geographic dispersion of industries, but that some sectors are different, and they tend to be important raw material extraction or primary manufacturing industries.

Further, in scenarios of the present and future, for electricity and for particular products, results show environmental impacts split up by generation type, and with full supply chain detail. For analyses of the current electricity system and products,

economic and environmental results match well with external verification sources, but for analyses of the future, there is significant uncertainty. Future work in this area must address the inherent uncertainty of using an economic model to generate emissions values, although the framework of the model allows for infinite expansion and adjustment of assumptions.

Table of Contents

List of Tables

List of Figures

Introduction

It is difficult to overstate the importance of electricity to modern societies around the world. The generation and delivery of this power is an enormous industry – about $300 billion in operating revenue and $40 billion in net profits in the United States.[1] And, while Figure 1 shows that electric utility revenue has been dropping as a percentage of GDP, from almost 4% in 1992 to around 2% in 2005, 2% is still an enormous chunk of the economy of the United States.[2]

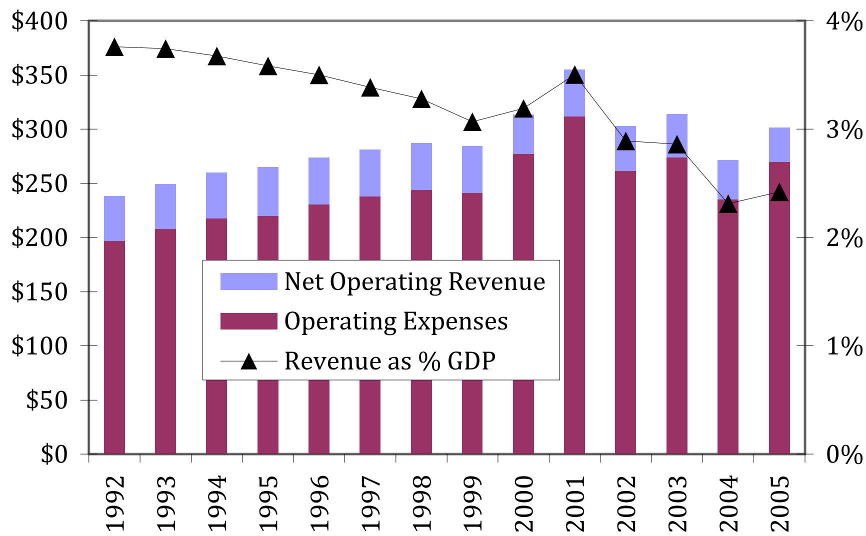

Figure 1: Reported US electric utility O&M revenues and expenses, in $Billions[1,2]

And, to support the production of this electricity, the utilities have enormous supply chains which reach throughout the entire economy of the United States and across the world. In 1997, nearly $30 billion was spent on the procurement of coal, petroleum and natural gas to fuel the generation of power. An additional $12 billion was spent on transportation to get the fuels from their extraction points to the power plants, and $40 billion more was spent in over 150 service, manufacturing and maintenance sectors.[3]

But these macroeconomic numbers don't really get at the real monetary value of electricity. Consider the blackout which hit the eastern United States in August of

2003. This outage affected 8 states – about 40 million people – for a period of less than 24 hours, yet is estimated to have caused between $4 and $10 billion in damages and lost productivity, or nearly a quarter of the annual profit of the entire industry.[4]

And yet, these economic numbers pale in comparison to the large role that generation and consumption of electricity plays in the environment. The raw tonnage of a myriad of pollutants that the burning of fossil fuels expels into the atmosphere is large, but difficult to comprehend. More easily grasped is how inordinately large the environmental impact of power generation is compared to its economic impact. In the coal mining industry in the United States, for instance, a little over 1% of supply chain dollars go towards the purchase of electricity, yet this purchase accounts for over 6% of the global warming potential (GWP) measured in tons of CO_2 equivalents associated with the operation of the mine and all suppliers.[5] This effect, where the total national environmental impacts are six or more times the economic impact, holds true for other types of emissions and pollution, and, as seen in Table 1, for other types of industries as well. Indeed, for aircraft manufacturers, the environmental impact as measured by global warming potential is nearly 50 times that of the economic impacts of the electricity purchased, and over 50 times for wineries.

Table 1: Economic and global warming potential (GWP) contribution of power generation to major industrial sectors[5]

	$	*GWP*
Coal mining	1.3%	6.3%
Aircraft manufacturing	0.6%	27.7%
Semiconductor manufacturing	0.8%	29.1%
Wineries	0.7%	37.7%
Primary aluminum	6.1%	48.2%

These emissions have world-wide reach and impacts. Electricity generation accounts for nearly a third of the carbon in the atmosphere, as levels have risen from 275ppm to 380ppm.[6] And use of electricity, and the continued accumulation of its associated environmental impacts, is expected to increase in the United States and around the world. Figure 2 shows historic and projected electricity sales in the United States in trillions of kilowatt-hours (kWh). Even with a modest 1.5% per year increase used by the Department of Energy, electricity use will nearly double in the United States by 2050.[7] Increasing the growth rate to 3% means three and a half times current usage, or 14 trillion kWhs.

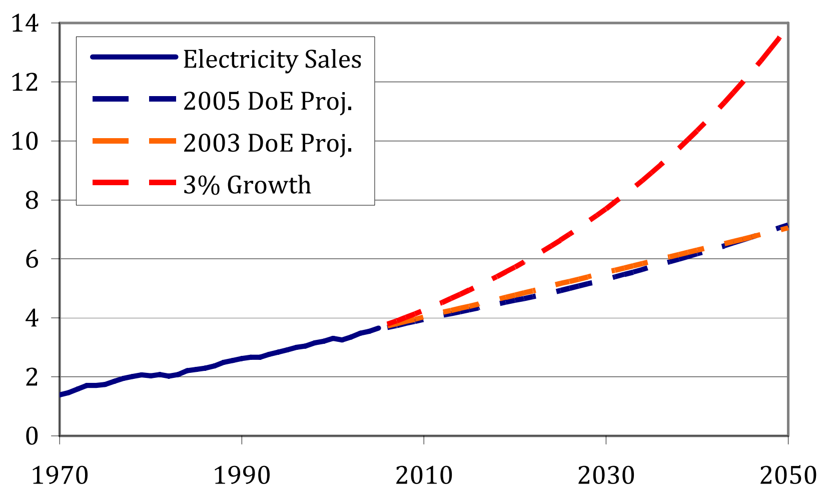

Figure 2: Electricity sales to all sectors with projections to 2050(PWh)[7,8]

Despite the importance of electricity to the economy and the environment, it is often seen as a homogenous commodity and treated casually, as if all kilowatt-hours were equal. Both consumers and scientists can fall into this trap, often using the US average mix, shown in Figure 3, or an average emission factor per kilowatt-hour to simplify this very complex system. However, while electrons may be equal when they are consumed, the means by which they were created are certainly not. Electrons have very different costs and impacts depending on how and where they are generated.

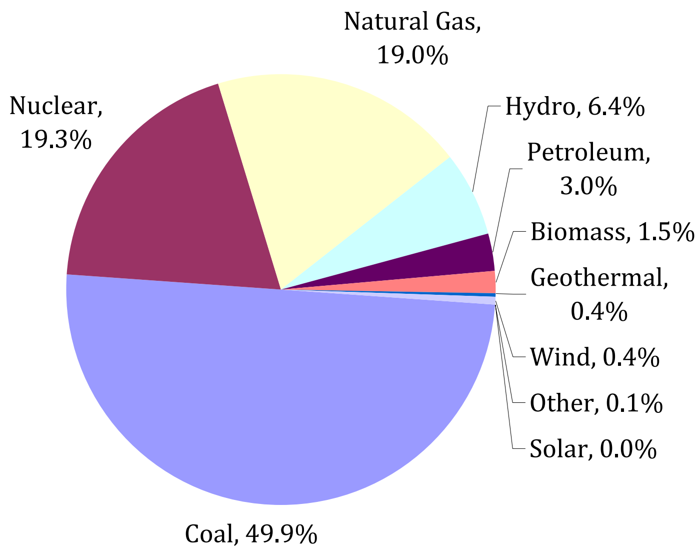

Figure 3: 2005 U.S. electricity generation mix, in % of generated kWh[1]

Because of electricity's critical role in the economy, and less positive, but equally potent role in affecting the environment, decision and policy makers at all levels are interested in what's currently happening and what's going to happen with the power generation industry, and just as importantly, how the rest of the economy will respond to changes in the power generation sector. Both day-to-day and future decisions regarding energy policy require the most complete information possible – analyses which take into account supply chains and the connectedness of the electricity sector to other areas of the economy.

There are quite a few examples in the electricity sector alone of "hidden" life-cycle and supply chain environmental costs. The large amount of methane released by flooded biomass behind conventional hydroelectric dams,[9] the thousands of miles of transmission lines and backup storage needed with large-scale wind generation[10,11] or the large amount of toxic releases associated with the production of photovoltaic solar cells are just a few of these examples.[12]

In her 2005 thesis, Bergerson showed that in certain potential high electricity demand futures, such as those shown in Figure 2, even with 90% point-source carbon capture on fossil power plants, the upstream, indirect, supply chain carbon emissions like those associated with coal mining and rail transportation approached current direct emissions from power plants and were greater than emissions from other sectors of the economy such as transportation.[13] The policy implications of this are enormous – we stand little chance of ever approaching Kyoto Protocol-like carbon levels if the supply chains of power generation produce that much carbon. This is a major, unexpected supply-chain result. In the future, we'd like to be able to make decisions about capital investment in generation methods and transmission and distribution assets as well as operations choices – confident that we haven't overlooked major contributions from the supply chains of those choices.

In addition, as decisions are made in other industrial and commercial sectors about the use of electricity – the purchase of power as part of the supply chain or life cycle – it is important not to view it as a homogeneous quantity. The tools available to policy makers to look at the complex problem of economics and emissions from electricity generation and use in the future are varied.[14,15] Unfortunately, these tools, such as the Environmental Protection Agency's MARKAL (Market Allocation) model or the Department of Energy's NEMS (National Energy Modeling System), tend to be either complex and data intensive – requiring extensive expertise to use, or are overly simplified, with data about electric utilities aggregated at too high a level to be useful. [16-19]

In the 500 sector input-output model of the US economy built by the Bureau of Economic Analysis, power generation and supply are aggregated into a single sector. By contrast, so are the impacts associated with tortilla manufacturing. A very diverse set of technologies and supply chains are represented in this single electricity sector. Comparing a kWh of electricity generated with hydro power to a kWh generated using coal power is difficult when the economics and emissions involved are so different – this difference is exacerbated when the supply chains are taken into account as well.

The model and results described in the following chapters provides a new level of economic and environmental detail to decision makers, tied to the very simple metric of dollars.

1 Background

This chapter covers the background information which is helpful in understanding the work that follows in subsequent chapters. It includes sections on the power industry, and generation in particular; and life-cycle inventory and assessment.

1.1 Power Generation & Supply

As was discussed in the Introduction, the electricity sector is a very important one. It is also very complex, made up of hundreds of public and privately owned utilities, ranging in size from a few hundred to hundreds of thousands of customers. Its primary roles are the generation, transmission and distribution of electricity, and in some cases, steam heat.

Because of the industry's importance, it is the subject of intense scrutiny and research, by government, private and academic institutions. The body of work looking at the myriad of issues is large, and expanding in both depth and breadth. The background provided here is intended to briefly describe some of the major issues associated with the major generation types and with transmission and distribution. It is not intended to be either definitive or ground-breaking.

As delivering electricity was becoming economically viable in the waning decades of the 19th century, it also became clear that there would be natural monopolies because of the large infrastructure cost of producing and distributing the power. For nearly one hundred years, the industry operated as a government-regulated monopoly, and during this period the industry saw incredible growth, and the United States saw nearly 100% electrification, even in far-flung rural areas. As sprawling and interconnected as that system was, in the past 15 years, the industry has been deregulated, and the complexity has increased accordingly.[20]

Coal-fired generators produced 50% of the electricity used in the United States in 2005.[1] Coal is cheap, abundant, and available domestically, and so is expected to continue to play a large role in providing base-load capacity. It is, however, a non-renewable resource, and the burning of coal causes damage to the environment in the mining, transportation and, most significantly, combustion phases. Although there are many regulations focused on cleaning up the output from this form of generation, there is still a large amount of NO_x, SO_x, particulate matter (PM) and volatile organic compounds (VOCs) emitted along with carbon and the less abundant, but more toxic lead and mercury.[21]

Nearly all of the coal-fired plants in the US are pulverized coal, or PC, plants. The coal is ground into a powder which is blown into a boiler to produce heat for producing steam. These plants have become more reliable over time, with average capacity factors around 60%[22], but the process is very inefficient, extracting between 30 and 35% of the input energy into usable electricity. Increased "tailpipe" environmental controls such as flue gas desulphurization (FGD) or selective catalytic reduction (SCR) further reduce this number.[23]

A newer technology with the potential for significant reduction in environmental impacts is IGCC, or integrated coal gasification combined cycle. In these plants, the pulverized coal – low sulfur coal is preferred in most gasifiers – is mixed with oxygen under high temperatures to produce a mixture of hydrogen, carbon monoxide, and methane,[24] which is then burned in a combined-cycle turbine, where the hot gases are used to spin one turbine, and the excess heat is used to create steam to spin a second turbine, thereby extracting more useful energy.[25] It is possible to remove sulfur and other pollutants from the fuel stream prior to combustion, making IGCC a cleaner use of a dirty fuel.[26,27] IGCC plants are more versatile as well; they can be used as either base load or load following plants, and the gasified coal can be used as a fuel or feedstock for other industrial processes.[28]

Natural gas-fired power plants, either as single-cycle (gas turbine only) or combined-cycle (gas and steam turbines) produced 19% of the electricity in the

United States in 2005, although natural gas power plants made up almost 40% of the installed capacity that same year.[1] This results in a lower average capacity factor, although this is tied more to the economics of producing power with high priced natural gas than the reliability of the combined cycle plants. Natural gas power plants produce electricity at a higher efficiency – between 50 and 60% for combined-cycle plants – than their sub-critical coal-fired counterparts, and do so with fewer emissions of NO_x, SO_x, carbon dioxide and particulate matter.

However, since the early 1990s, when low natural gas prices caused a rush of natural gas plant construction, the price of natural gas has been volatile in the short term, and increasing steadily in the long term, as shown in Figure 4. Because of the doubling and then tripling of the price that generators need to pay to purchase gas to run their plants, this large stock of plants is used mostly to meet short term peak demands, when retail electricity prices are high enough to justify paying the high gas prices. And while natural gas is considered a cleaner fuel than coal, it is still a non-renewable fossil fuel, with significant direct and supply chain emissions.[21]

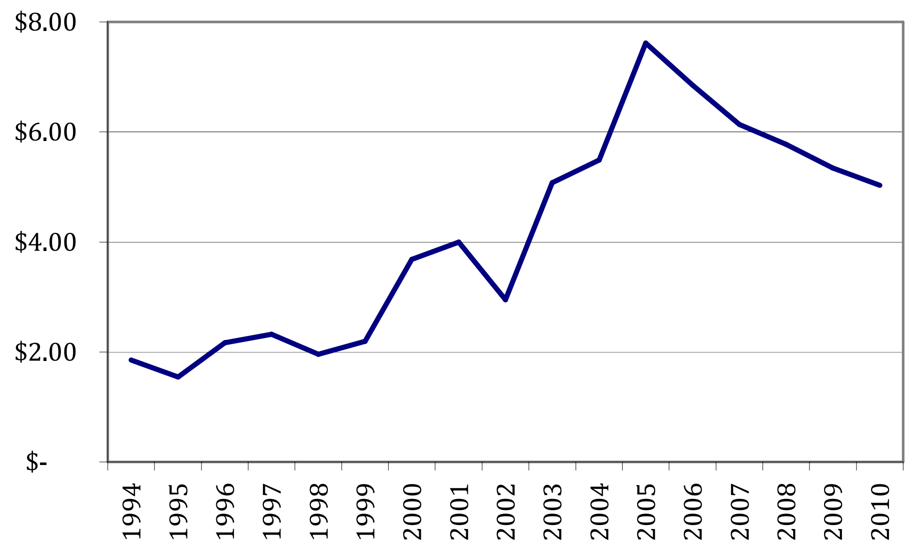

Figure 4: Natural Gas Price (Wellhead, 1994 $/tcf)

In 2005, 19.3% of US power was generated with nuclear steam plants. Running at capacity factors of over 90% in many cases, these power plants make up a significant portion of the base load capacity. Nuclear electricity has very few local emissions, although uranium and other heavy metals are present in small amount from effluent streams.[29] The nuclear life-cycle is important. Uranium, while generally abundant in the earth's crust and energy intense when concentrated, is usually available in dilute amounts, and the enrichment of the fuel takes significant amounts of energy. And, when the fuel is spent, it is thermally and radioactively hot, and is currently stored at the plant site, with some sites holding nearly 50 years of radioactive material.[30] Until a national nuclear fuel repository like Yucca Mountain is opened, the future of nuclear power in the United States will be uncertain, although several utilities are beginning the long licensing process necessary to install new, passively safe nuclear reactors.[31] These plants are expensive, even compared to the massive capital costs of other central generation projects.[32]

Although it is considered renewable, there are many environmental and social implications of the 6.4% of electricity generated with hydropower. In hydropower, water under high pressure (from gravity and water weight) spins turbines which spin generators. There are other benefits as well – in addition to the electricity, dams and the lakes behind them provide flood control, space for recreation, and a reliable water supply (to some) for municipal, industrial and agricultural needs. But hydroelectric dams, especially large scale canyon dams like those in the western US, dramatically alter the ecosystem wherever they are built as well as incurring a large impact during the construction and from biomass decay in the reservoir.[9] In addition, water "controlled" and held upriver is unavailable for use – for power, drinking or irrigation – to those downstream. The water that is available is fast moving, cold and devoid of nutrients and sediments which a river picks up along its course. No new large-scale hydropower is planned in the United States, although the potential exists for small "run-of-river" micro-turbines that would provide a small amount of power, but have little ecological impacts.

Although it is providing less than 1% of electricity in the United States, wind power is seen as a technology with a huge potential, with over $7 billion in new investment in 2005[33]. There are problems, however, both environmental and technical. Siting the turbines and the transmission lines is difficult because of political NIMBY issues. Long distance transmission capacity, which in turn increases resistive losses, is necessary because, as can be seen in Figure 5, areas with high winds are not necessary close to demand centers. This type of resource-demand disparity is true with other types of renewable generation as well. In addition, without energy storage, backup generation – usually fossil fuel – is needed for times when the wind isn't blowing.[11,34]

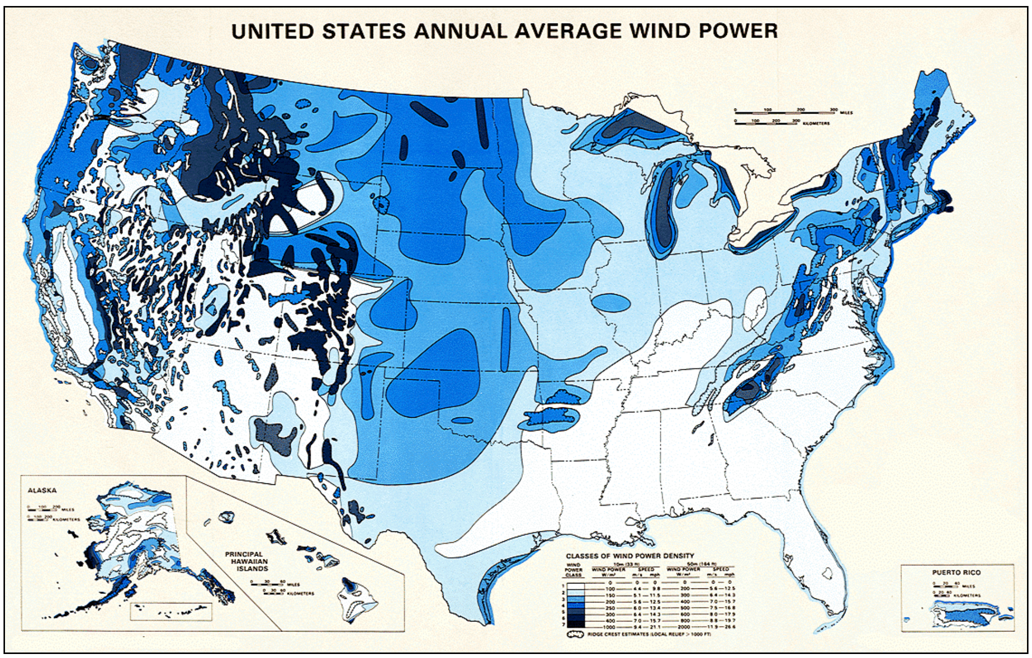

Figure 5: Average Annual Wind Power in the United States[35]

It is important to remember that no power generation method is completely benign from an environmental standpoint. The fossil fuel generation types - coal, petroleum, and natural gas - all emit large amounts of carbon to the atmosphere as they are burned, but there are significant variations in the amounts and makeup of their other emissions. About 1.5% of the U. S. generation mix is biomass burning, which is generally considered carbon neutral.[36] There is a small but growing amount of wind and solar power – although expensive[37] – used in the United States.

A major stumbling block is investors understanding of the future regulatory and policy environment – technical aspects are not the issue[38]. Geothermal, waste-to-energy plants, and "other fossil fuels" such as used tires are growing as well.[39] The impacts of these types are diverse, and certainly none is perfect.[21,40-42]

1.2 Life-cycle Inventory & Assessment

Life-cycle assessment, or life-cycle analysis, is a framework which captures the effects of all phases of the life of a product, service or sector: production, transportation, use and maintenance, and disposal (Figure 6). This is sometimes referred to as a cradle-to-grave analysis. LCA has been embraced by the environmental community, but it is not limited to that type of analysis. Similar assessments could be done to calculate the number of deaths caused by a product over its lifetime, or the number of sheets of paper consumed by an industrial sector. We are primarily concerned with LCAs done for environmental analysis here.[43-45] Life-cycle inventory, or LCI, encompasses all of the data gathering steps associated with LCA, but stops short of doing analysis of what that data means, either to the environment or the economy. These steps are shown in Figure 7.

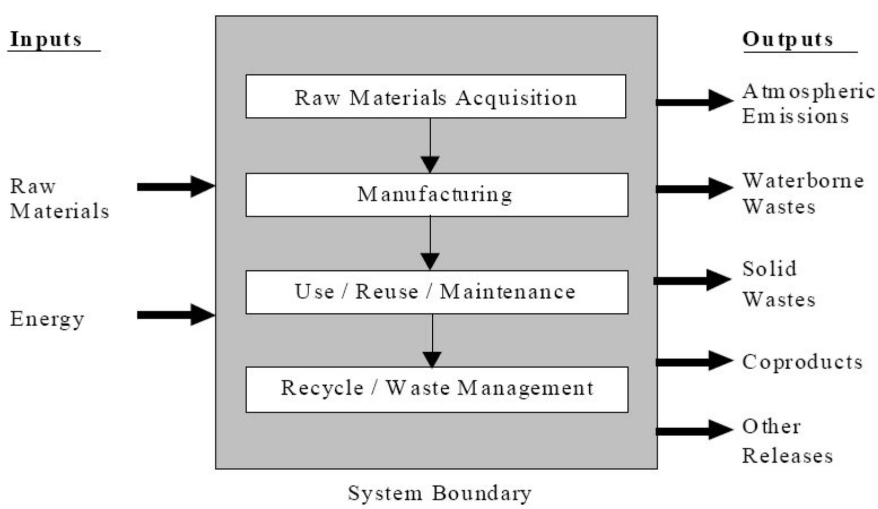

Figure 6: Life Cycle Stages[43]

In an attempt to formalize a very open and general framework, several organizations have developed standards for LCA, including the Society for Environmental Toxicology and Chemistry (SETAC), the Environmental Protection Agency and the International Standards Organization, as part of the ISO 14040 Environmental Management Systems standards.[46,47]

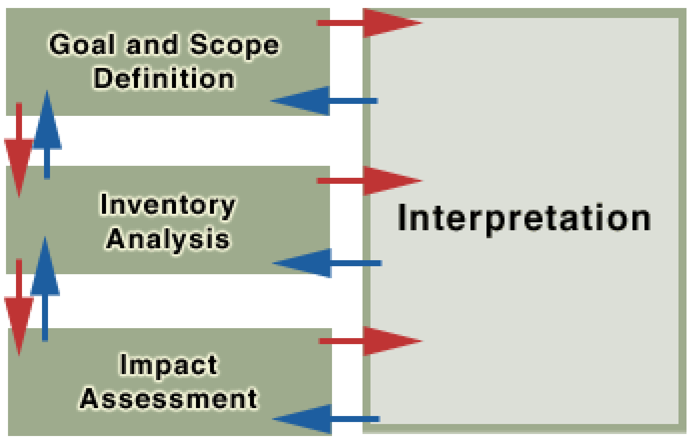

Figure 7: Phases of a life-cycle assesment[48]

Here we are concerned with three basic types of LCA: process LCA, Economic Input-output LCA, and hybrid LCAs, which are described below.

1.2.1 Process LCA

A process LCA is concerned with unit processes, such as a the production of 1 ton of copier paper, or 10,000 automobiles. Mass and energy balances are then done for each phase in the life-cycle of that unit. A critical step in this process is the identification of the boundaries and scope of the problem. For instance, you would include the energy required to run the assembly line for the automobile, but would you include energy required to produce the raw steel and aluminum, or the production of the robots doing the work?

Process LCA is a bottom-up method, and because of the large effort required to gather input and output data for each step in the process, it is necessary to draw an (arbitrary) boundary to reduce the complexity of the assessment. Significant portions of the supply chain and many upstream uses are neglected, leading to incomplete assessments or high costs.[43] It is difficult and controversial to choose between completeness and practicality. Varying boundaries for similar products lead to problems with comparisons and lead to an overall impression that LCA is more of an art than a science.

In addition, most process LCAs today are done using proprietary software and data, meaning that assumptions and boundary choices are not transparent to those who view the results.

1.2.2 EIO–LCA

In a reaction to the inherent complexity of process-based LCA, and also to compensate for the issue of drawing the analysis boundary, a top-down economic input-output method for doing environmental assessment was set forth by Wassily Leontief, based on methods originally developed for macroeconomic analysis.[49-51] The Economic Input-Output Life-cycle Analysis, or EIO-LCA, model , a workable and publicly-available web-based tool developed by the Green Design Institute at Carnegie Mellon University is a implementation of this method.[52-55]

EIO-LCA uses an 491-sector input-output model of the entire US economy, a model which is made up of US Bureau of Economic Analysis 1997 survey data which recorded what industries produced and what they purchased to produce it. The main piece of the model is the $\mathbf{(I\text{-}A)^{-1}}$ matrix, or total requirements matrix, a 491x491 table of transactions, where each entry *i,j* is fraction of $1 spent on output from industry *i* to produce $1 of output for industry *j*. The driving equation is:

$$E = X \cdot (I - A)^{-1} \cdot F$$

where **F** is a vector of final demand in dollar terms, for instance, $5000 of copier paper, or $200 million of cars, **R** is a vector of environmental stressors by sector and **E** is the total environmental output, and the underlined piece is total demand, including the supply chain.

The **A** matrix, as was said above, is made up of input and output data from industries, but the survey information is processed through several steps first. To build the **A**, a normalized "make" and a normalized "use" table are multiplied together. The normalized make table is a representation of each commodity an industry makes (outputs) as a fraction of total outputs created in a year. Likewise, the normalized use table can be thought of as a supply chain – each industry another industry purchases from (inputs) to produce its output as fraction of total inputs for a year.[56,57] These supply chains generally do not include construction or equipment replacement because they are thought of as a capital investment outside of the normal operation. However, a fraction of all capital investment is included as the assets are manufactured inside the economy. Labor is included as value added, rather than as a specific commodity.

The input-output tables are relatively easy to understand. Think of economy split into about 500 industries and 500 commodities, so that the aircraft manufacturing industry would make the commodity aircraft, etc. The make table shows which commodities are made by which industries, and is generally pretty sparse. Because there are mostly 1-to-1 relationships between industries and commodities (as with aircraft manufacturing above), the diagonal of the make table is the only entry in some columns and rows. There are exceptions, of course: an industry classified as "auto parts manufacturing" might produce the commodity auto parts, but also farm machinery parts.

The use table has many more values, and can be thought of as a series of supply chains – the commodities which industries purchase to produce their output. Most sectors in the use table use hundreds of commodities and their output is in turn used by dozens or hundreds of industries. There are circularities as well – a car manufacturer might purchases a certain number of automobiles as part of the operation.

The output from input-output models like EIO-LCA can be given in both direct and indirect economic and environmental results. Direct results are the economic activities and associated environmental outputs from the operation of the sector of interest and its suppliers. Indirect results are the economic and environmental activities associated with the operation of those supplier's suppliers. Total output is the sum of the direct and indirect outputs.

1.2.3 Hybrid LCA

One of the problems with using the current version of EIO-LCA as an analysis tool for future electricity scenarios is the level of aggregation in the electricity sector. Power generation of all types, construction, transmission and distribution are all modeled as a single sector. As was said earlier, in this model, tortilla manufacturing has the same sector representation as power generation and supply. The radically different environmental impacts of fossil-fuel, nuclear and hydro generation are all lumped together, or ignored. It is important to realize that this is a limit of the data available from the BEA, and not of the framework or method.

Significant attention has been paid to input-output tables and their use in macroeconomic analysis, which was the original purpose of input-output models. There are many sources of uncertainty – the use of survey data as a basis, the aggregation of millions of products and services into industrial sectors, changes to the structure of the economy over time, marginal changes in demands which can change the allocation of dollars in the model, etc.[58,59] Making changes to the structure of the a model with known uncertainty, and using it to model events 20 or more years in the future, is in itself an uncertain undertaking. Current literature shows us that if careful assumptions are made, the model is not particularly sensitive to small changes in structure or over time, although post-analysis should be done to attempt to quantify the uncertainty.[60]

Even at the 500 sector level, there is significant aggregation that happens in input-output analysis. A reaction to, and compromise for, this is hybrid LCA.

Hybrid LCA, as the name implies, is a combination of other forms of LCA. It is a newly developed idea which seeks, in our case, to combine the comprehensive, but high level, data of EIO-LCA with the detailed, low level information from a process LCA. In an automobile LCA, you might use EIO-LCA to estimate economy-wide discharges from the manufacturing phase and do a process LCA on the use phase of the car.[61-65]

In our case, we are using the existing supply chains for 490 sectors, and adding process-like detail to the Power Generation and Supply sector, so it could be considered a hybrid LCA. The top-down EIO-LCA model has broad, highly aggregated generalizations, and that is being combined with a bottom-up, or technology rich, data with a detailed representation of changes in the electricity sector. Combined, we can calculate broader effects throughout the economy with regionally and/or functional disaggregated details

2 Disaggregating Power Generation & Supply

In order to create the information decision makers might need about the electricity sector, and to accurately represent the vast differences among various methods of generating electricity, economic and environmental information must be disaggregated. This chapter will go through an analysis which shows why disaggregating power generation and supply is important. A portion of this work is previously published.[66]

As was said in the introduction , the emissions and other environmental stressors from energy use, or, more specifically, from electricity generation, are significant contributors to the total inventory in the life cycle assessments of many products, processes or industry sectors. The environmental burden from this use occurs in the form of air and water pollution, fuel and land consumption, and global warming emissions. It is important to have good measures of these stressors in order to quantify the possible implications for health, environment, and economy.

Many current product and process analyses that include the impacts of electricity generation and consumption use aggregate, or average, data for the electricity generation mix; all sectors consuming electricity are assumed to use the US average generation mix, which is largely fossil-fuel based – over 50% coal and 70% fossil fuels including natural gas and petroleum. These analyses might not do this explicitly, but, as in the case of thousands of users of the Economic Input-Output Life-Cycle Analysis tool developed at Carnegie Mellon[5], they might just treat electricity generation and consumption casually, without considering where the facility being analyzed is located. A great deal of detail is lost at the state or facility level since certain sectors – based on geographic location or purchasing choices – buy and consume electricity with a very different generation profile than the more aggregate, and fossil fuel-dominated, average mix. Perhaps the best example of this would be the aluminum manufacturing sector, an industry which uses a lot of electricity in its processes. While there are aluminum plants throughout the United

States, a significant percentage, if not the majority, are located in the Northwest US, particularly Oregon and Washington, where they take advantage of relatively low-cost (and low emission) hydroelectric power. These states generated 94% and 88% of their power with hydro, respectively, in 1997.[39] So one would expect, if a generation mix could be assigned on a sector by sector basis, that there would be significant changes in the LCA output – the impacts associated with this industry, such as lowering CO_2 emissions estimates. Global warming, ecosystem disruption, hazardous waste, and security – both energy and homeland – are elements that must be considered. The cost to the environment and to human health from electricity generation is large.

Disaggregating electricity generation, or splitting it up by primary energy source, would allow assignment of a specific mix of generation types – and therefore a specific mix of environmental effects – to each product or process. This is called a consumption mix. In this chapter, we look at the results of one method of disaggregation, and create an optimization model for interstate electricity trading to improve its accuracy. The analysis highlights the overall importance of disaggregating this sector and some unexpected results and the implications that these results have for environmental impact assessment of electricity consumption.

2.1 Creating Consumption Profiles

Ideally, to disaggregate and move away from using the US average mix for environmental analysis, we would have, broken down by fuel type, the amount of electricity that every industrial and commercial facility in the United States used. An automobile manufacturing plant near Detroit, for instance, might have a published "consumption mix" which would show that the electricity they consumed was generated with 75% coal and 25% nuclear. Comprehensive consumption mix data like this at the plant level would require synthesis of millions of power transactions from thousands of firms. It would be necessary to collect the amount of electricity each facility purchased from each supplier, and the type of generation method those suppliers were using or purchasing themselves. Models would match supply and demand and allocate electrons via the various grid-connected entities of different generation types based on values changing daily, if not more often. But these numbers are not readily available; in general, contracts between utility companies and their customers are confidential, even if the grid were metered at that level. It is apparent that some level of geographic aggregation is necessary, since the data needed to achieve complete disaggregation is not available.

We can make educated guesses about facility-level consumption mixes, based on the idea that electrons flow from the closest available source. Carnegie Mellon University in Pittsburgh, for instance, consumes power produced just down the Ohio River at one of several large coal plants, and some from a nuclear plant from 30 miles away in Beaver Valley. We can make this statement because we know two important things: 1) where Carnegie Mellon is located geographically, and 2) the generation assets in that region. Similarly, if we can identify the location of manufacturing facilities and combine that information with accurate regional generation profiles, we can systematically produce consumption mixes for all manufacturing sectors across the country.

Both pieces of information are readily available from public sources. Both the US Department of Energy and the US Environmental Protection Agency provide yearly state generation mixes (e.g., the percent of each generation type – coal, gas, nuclear, etc. – generated in the state in a given year).[39] The Bureau of Economic Analysis collects census data for every industry sector in the US.[67] We use the median number of employees for each sector in a state as an indicator of presence in the state, then divide by the total number of employees in that sector country-wide to produce a percentage in that state.[68] Other metrics of industry presence were checked, including number of facilities and value of products shipped. Number of employees correlated highly with value of products shipped and this type of data was available for more sectors.

Each industry sector then has a specific set of six percentage values assigned to it (for coal, petroleum, gas, nuclear, hydro and other), which is a combination of fractions of the generation mixes for each state that the sector has facilities in. In some cases, sectors will have locations in all 50 states; in other cases, there will only be a few states with facilities from a specific sector. For example, if we know that 60% of all widgets are manufactured in Idaho, and 40% are produced in Kentucky, the generation mix of Idaho – expressed as a 6 element array where each element is a percentage of a particular generation type – shown in Figure 8, is multiplied by 0.6 and the generation mix of Kentucky is multiplied by 0.4. This produces two new arrays, which are added to produce a single array. This is the new sector consumption mix for widgets.

	Coal	**Pet**	**Gas**	**Nuc**	**Hyd**	**Oth**
Idaho:	[0.6%	0.1%	8.5%	0.0%	86.5%	4.5%]
						x 60%
	[0.3%	0.0%	5.1%	0.0%	51.9%	2.7%]
Kentucky:	[96.8%	0.2%	0.5%	0.0%	2.5%	0.0%]
						x 40%
	[38.7%	0.1%	0.2%	0.0%	1.0%	0.0%]
Sum:	[39.1%	0.1%	5.3%	0.0%	52.9%	2.7%]

Figure 8: Calculating a consumption mix for the "Widget" manufacturing

One of the major assumptions that this method uses is the choice of states as the basic unit to capture regional differences in generation type. Although it is not difficult to think of cases where states have different generation profiles within the different regions of the state, many regional variations and state policies are captured by the state profile. County, ZIP code, or Power Control Area data might capture much more of this variation, but are unavailable for the whole United States.

In Figure 9, the differences between the US average generation mix and the generation mixes of states in different regions of the country, such as California, Idaho and West Virginia are apparent. Environmentally progressive policies in

California have created a generation mix that uses extremely small amounts of coal-fired electricity, and large amounts of cleaner burning natural gas and low-emission hydroelectric power. Or, as we'll see later, these policies simply push coal generation across the state's eastern borders. California also has significant amounts of geothermal, biomass and wind power, which is reflected in the "Other" category. West Virginia, like several other states in the region, has large amounts of coal available for mining, and this is apparent in its mix. Idaho, on the other hand, has been able to generate nearly all of its power with hydroelectric dams.

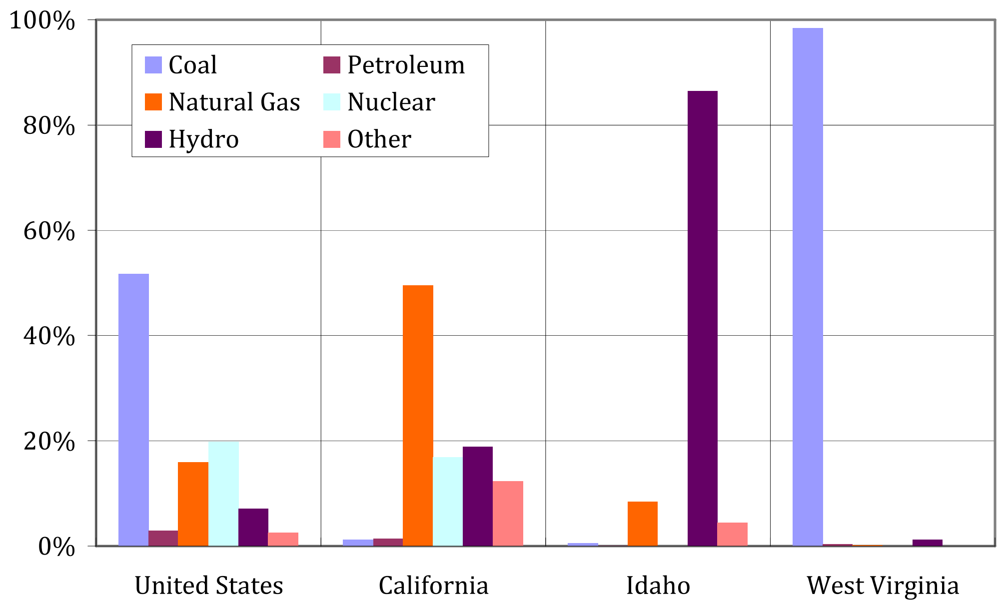

Figure 9: State Electricity Generation Mixes versus US Average Mix for 2000[39]

Another simplifying assumption made so far in this method is that it does not take into account interstate power sales. Not including interstate trading might have been a valid assumption prior to large scale deregulation of the electricity industry, enacted in 1994 and implemented first in 1998, but deregulation brings the additional complication of states being able to purchase electricity not only from a different state, but in fact from a particular company with a particular generation type. For example, Carnegie Mellon University purchases 6% of its total electricity as wind power from 75 miles away in Somerset County. While not in a different state, it illustrates the ability of consumers to choose their generation type, regardless of state or regulatory borders[69]. In 2000, interstate net exports totaled nearly 10% of the total electricity consumed in the United States[39].

So, although regional variation in generation types are accounted for by the state mixes, large power surpluses or deficits of electricity are not. Large amounts of power moves across state borders from states with excess capacity to those with a lack of electricity. California, the country's largest consumer and importer, brought in 26% of its power in 2000 – 67 terawatt-hours (TWh) worth. West Virginia exported nearly 70% of the power generated in-state[39]. It appears that the inclusion of import and export data has significant effects on the electricity consumed within the state. California, for example, generates a little over 1% of its electricity with coal, but it imports nearly 30% of the electricity it consumes, much of which is probably generated in nearby coal-heavy states such as Arizona and Wyoming.

Surprisingly, data on which states shipped power and to whom is not readily available. The National Energy Board in Canada publishes information about gross inter-provincial electricity transfers[70], but in the United States the only data consistently available is the net generation number published by the EPA. Basically, it is the state's gross consumption for a particular year subtracted from its gross generation. A negative number means the state is a net importer for the year; a positive number indicates a net exporter. This does not mean that a net importer exported no power. It is in fact quite likely that power was shipped out one border and in another, but this is not indicated by the net values available. We don't attempt to "fix" this, since assumptions about gross imports and exports would likely lead to a large amount of uncertainty and unverifiable results given the data gaps described above.

Modeling all electricity flow across the grid in North America is not an easy task. It is an incredibly complicated system with millions of components, constantly fluctuating supplies and demands, and hundreds of players attempting to maximize their own benefit. Again, as with disaggregation itself, assumptions and simplifications need to be made in order to make the problem tractable given the data available.

In lieu of creating a perfect representation of the entire North American grid, a model was made that approximated the grid's high-level physical behavior rather than a model based on the economic transactions that drive it. Consider again the example of Carnegie Mellon University purchasing wind power: while the university's purchase drives demand for the wind generation plants, due to the distance involved and the proximity of other local generation it is quite unlikely that any of the power generated there is actually used by the university without a direct link (a transmission line) between them. Power will flow over the grid to the closest demand, or, more accurately, along the paths of least resistance, which, all other things being equal, will be the shortest path. And the closest demand for Somerset's wind power is not 75 miles away in Pittsburgh, but likely in Somerset County itself.

Given this reasonable physical assumption that electricity will flow to the closest demand, the first model we considered was one which used adjacent states as the sources of imports. However, the data available does not make this a feasible model to use; as shown in Figure 10, a state such as California with a 67 TWh electricity deficit must import electricity from more than the three states immediately adjacent to it since, even when summed together, they do not produce enough to cover California's deficit. As a result, it is likely that California imports electricity from as far away as Montana, Wyoming and Canada.

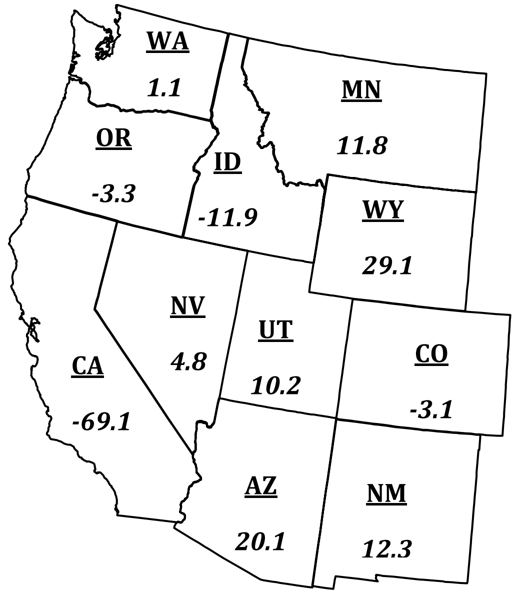

Figure 10: California & Western US Net Electricity Exports (TWh) [39]

Given the limitation of the data, a simple transportation linear programming model provides an estimate that makes intuitive sense. Traditional transportation optimization models are used to minimize distance traveled (and the associated cost of that travel) given a set of supply and demand constraints[71,72]. In this case, the model output will be a matrix, called an import-export matrix, which will show where each state with a deficit imported from, and how much was imported from that state.

The data needed to develop this model was available primarily from the Environmental Protection Agency's eGRID program, and from the Department of Energy's Energy Information Administration. From these two sources we gathered the state generation mixes for the year 2000 (the latest year for which complete data is available), along with gross generation and gross consumption amounts. A net import-export value was calculated by subtracting consumption from adjusted gross generation. Adjusted gross generation is the state's gross generation value multiplied by an average grid loss factor, which, according to EPA data, averages 9.5%[39]. This is to account for power that it lost as is travels across transmission lines (before it can be consumed). A positive net import-export means the state had an electricity surplus and a negative net import-export means that the state had a deficit in 2000. In 2000, there were 27 importers and 27 exporters. The 54 total entities included the 48 contiguous states, as well as the District of Columbia, Canada, and Mexico; California, Mexico and Canada were counted as both importers and exporters since gross data was available[39].

This data provided the first part of the model, which was the suppliers (exporters), customers (importers) and constraints (supplies and demands for each state). The second portion of the data for the model was the distance between each importer and exporter – a straightforward great circle distance between the entity's geographic centroids[73]. The full distance matrix is included in Appendix A.

In addition to this basic data, there were some additional elements of the power grid we modeled, one of which was the presence of three (Western, Eastern and Texas) managed interconnect regions in the United States and Canada. The borders for these regions are complicated, but can be approximated with state boundaries. The Texas interconnect region is basically the state of Texas, and the border between the Western and Easter interconnect falls along the eastern border of the states shown in Figure 10. There are few connections between interconnects, and in fact the regions are asynchronous – the AC power is phased differently, making direct transfer impossible. A DC tie line is needed to move power from one interconnect to another. It would be unrealistic if the model moved large amounts of power between the interconnect regions.

In order to reduce the amount of cross-interconnect transfer happening, but not prevent it entirely, we reduce the distances between states within the same interconnect by multiplying the distance by a certain factor, making it unlikely that the model would move power between states not in the same interconnect. The factor we used was 0.1, or a 90% reduction. A series of factors between 0 and 1 were tested, and a lower factor proved more effective at preventing transfer.

In general, high voltage direct current, or HVDC, lines are put in place to facilitate the movement of excess power from the generator to a place without enough generation, and provide known electricity transfer "routes" which can be modeled. But the linear optimization performs this task already, without the need to artificially modify the distances to make it more likely that power will travel along certain routes. And with the creation of ever larger AC transmission lines, it would be necessary to create these lines in the model as well as DC lines. A decision was made to keep the model simple rather than attempt to recreate the entire grid.

Finally, in order to modify the optimization to adhere to some limitations of the data, certain adjustments were made. Canada is not allowed to ship power to Mexico or vice versa, since the export data for Canada explicitly goes to the United States. Further, all of Mexico's imported power in 2000 came from California, so this transfer is made a constraint in the optimization. California then has its total electricity import increased by 2.1 TWh – the amount it transfers to Mexico. This modified distance matrix is included in Appendix B.

When run, the optimization minimizes the sum product of the weighted distance matrix and the import-export matrix, both described above, by modifying the values in the import-export matrix. This minimized value is the total "cost" of moving electricity from the exporters to the importers. It is subject to two main sets of constraints: each row sum in the import-export matrix must be exactly equal to the amount of excess power available in that state, and the column sums must be exactly equal to the power deficit of that state.

The final results of the optimization for all states are included in Appendix C, although the results for California are shown in Figure 11. This is a linear programming problem, so the result is the minimum cost that can be achieved with the given constraints. But the results seem to make intuitive sense as well: California imports from Arizona (29%), New Mexico (13%), Nevada (7%), Utah (15%) and Wyoming (36%). All had large electricity surpluses, and are within the Western interconnect.

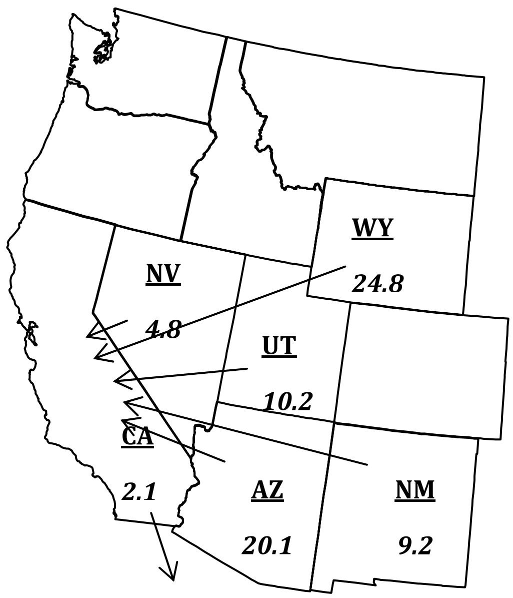

Figure 11: California Transfers from Optimization Model (TWh)

With the values from the optimized import-export matrix, and knowing the amount of electricity generated in the importing states, we can calculate a new electricity mix, which we refer to as a consumption mix, for each state. It is found by multiplying the percentage of imports received from each state by the generation mix from that state (assuming that the electricity they export will follow the generation mix for electricity used in-state) and multiplying that by the importing state's current generation mix.

In the example shown in Figure 12, the consumption mix for California is calculated based on the results shown in Figure 11. We know the percentage of power imported to the state, and this is broken out as percentages of the states which exported power to California. We therefore know the percentage of total consumption that each import makes up. And since we know the original EPA generation mixes for all the states in question, we can multiply each mix array by the respective state's percentage of consumption. By adding each generation type, we can get a final consumption mix for California which includes all the imports provided by the optimization.

California In-state Production	73.9%	
California Imported Power	26.1%	
California Imports	AZ	29.0%
As percent of imports, results from optimization	NM	13.3%
	NV	7.0%
	UT	14.8%
	WY	35.9%
		100.0%
As percent of CA consumption (.290 x .261 = .076, etc.)	AZ	7.6%
	NM	3.5%
	NV	1.8%
	UT	3.9%
	WY	9.4%
		26.1%
	CA	73.9%
		100.0%

In-State Generation Mixes
From EPA eGrid data

	Coal	*Oil*	*Gas*	*Nuc*	*Hyd*	*Oth*
CA	1.1%	1.4%	49.5%	16.9%	18.8%	12.3%
AZ	46.1%	0.2%	9.8%	34.1%	9.7%	0.0%
NM	85.4%	0.3%	13.6%	0.0%	0.6%	0.0%
NV	53.5%	0.1%	35.9%	0.0%	6.8%	3.7%
UT	94.8%	0.2%	2.4%	0.0%	2.0%	0.6%
WY	95.9%	0.1%	1.0%	0.0%	2.2%	0.7%

CA Consumption
As percent of consumption, by state and by gen. type

	Coal	*Oil*	*Gas*	*Nuc*	*Hyd*	*Oth*
CA	0.8%	1.0%	36.6%	12.5%	13.9%	9.1%
AZ	3.5%	0.0%	0.7%	2.6%	0.7%	0.0%
NM	3.0%	0.0%	0.5%	0.0%	0.0%	0.0%
NV	1.0%	0.0%	0.7%	0.0%	0.1%	0.1%
UT	3.7%	0.0%	0.1%	0.0%	0.1%	0.0%
WY	9.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CA Consumption Mix	20.9%	1.0%	38.6%	15.1%	14.9%	9.2%

Figure 12: Creating a State Mix – Example

The new generation mix for California is shown in Figure 13. The impact of the large amount of coal imports from Wyoming, Utah and Arizona is obvious. Despite the published generation mix for California's which seems to promote clean air, the results here suggest that California consumes almost 20% of its electricity overall from coal-fired power plants. This would lead to an increase of over 30% in tons of CO_2 emitted from the burning of fossil fuels to generate electricity for California, from 850,000 tons to almost 1.3 million tons[39]. And due to the general flow of air and pollutants from west to east in the western United States, California doesn't see all the emissions resulting from this consumption.

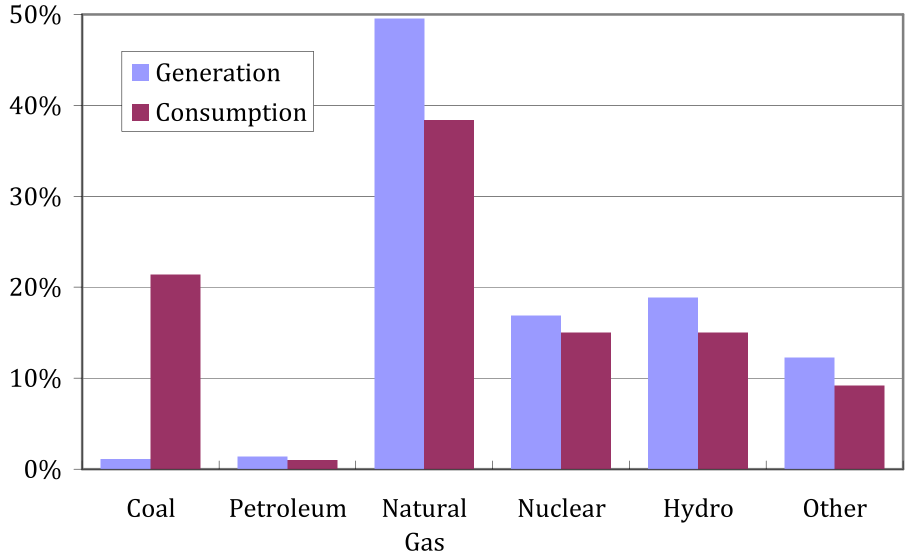

Figure 13: New Consumption Mix versus Old Generation Mix for California

Verification of the model results are difficult: the model was built because little data about interstate trading were available. However, there is some high-level aggregate information about where states get their power. Each year the California Energy Commission (CEC) estimates its electricity imports and which region they were was imported from. It separates the importers into three regions: Pacific Southwest, Pacific Northwest, and Other[74,75], and creates a Net System Power calculation, which is similar to our consumption mix[75,76]. A summary of these values is shown in Table 2; both are estimates, and the total difference is less than 20%.

Table 2: Comparison of California Energy Commission Net System Power versus model calculated consumption mix[76]

	CEC Net System Power	*Model Results*
Coal	15.7%	21.4%
Natural Gas	35.1%	38.4%
Petroleum	1.3%	1.0%
Nuclear	17.2%	15.0%
Hydroelectric	21.8%	15.0%
Other	8.9%	9.2%

Some of the difference, especially the higher fossil fuel and lower hydroelectric numbers in the trading model, are likely due to difference in the way the results were calculated. The CEC numbers are based on purchases that California utilities make. The utilities purchase hydroelectric power from Oregon and Washington, which run along dedicated north-south DC lines. These states are net importers, however, so while they may be selling California their hydroelectric power, they are in turn importing power from Idaho and Wyoming. A good amount of the excess power in Wyoming is coal-fired. Our model cuts out the middle-man and assumes that the coal-fired electricity is shipped directly to California.

The final import-export matrix and the new consumption mixes for each net importer are included in Appendices C and E. A summary of the top 10 importers and their new consumption mixes is included in Table 3. These new consumption mixes for each importing state are combined with the original generation mixes for each exporting state and are used in the same industrial sector disaggregation process explained earlier, which assigns a consumption mix to each industrial sector. In Table 3, the original 2000 state generation mix is on the top and the consumption mix is below in italics.

Table 3: Electricity Mixes for top 10 electricity importers

	Imported Amount (TWh)	*% Consumption Imported*	*Coal*	*Petroleum*	*Natural Gas*	*Nuclear*	*Hydroelectric*	*Other*
Washington DC	10.5	99%	0%	100%	0%	0%	0%	0%
			97%	*1%*	*0%*	*0%*	*1%*	*0%*
Delaware	6	53%	69%	14%	14%	0%	0%	3%
			63%	8%	7%	20%	0%	2%
Idaho	11.9	52%	1%	0%	8%	0%	86%	4%
			26%	*1%*	*5%*	*0%*	*66%*	*3%*
Massachusetts	16.5	32%	29%	20%	27%	14%	6%	5%
			36%	*14%*	*19%*	*22%*	*5%*	*5%*
Virginia	30.1	30%	51%	4%	6%	36%	0%	3%
			65%	*3%*	*4%*	*25%*	*0%*	*2%*
Rhode Island	2	27%	0%	1%	97%	0%	0%	2%
			15%	1%	71%	10%	0%	2%

California	67	26%	1%	1%	50%	17%	19%	12%
			21%	*1%*	*38%*	*15%*	*15%*	*9%*
Mississippi	11.5	25%	37%	8%	22%	28%	0%	4%
			41%	*6%*	*18%*	*31%*	*0%*	*3%*
Maryland	15.4	25%	58%	5%	6%	27%	3%	2%
			66%	*4%*	*4%*	*22%*	*3%*	*1%*
New Jersey	17.5	25%	16%	2%	28%	50%	0%	3%
			27%	*2%*	*22%*	*47%*	*0%*	*3%*

2.2 Analyzing Sector Consumption Profiles

With the optimization and two sets of disaggregations complete, there are two sets of data to compare. The first is the initial disaggregation which does not include interstate electricity trading and the second includes the results of the import-export model. Each set has 519 arrays of six percentages – one array for each US industry sector. In order to assess the impact of disaggregation, we compare each of these arrays to the 2000 average US generation mix, since, prior to disaggregation, these are the values which were being used to calculate environmental impact.

To compare the two data sets, first a correlation calculation was done. Although this should show how much of a difference there is between corresponding arrays, the correlation calculation will not capture any monotonic transformations – so two sets of numbers with similar proportions would have a high correlation even if the magnitudes were different. Instead a root mean square calculation is used which will take into account both differences in proportion and magnitude. The calculation for this is as follows:

$$\sqrt{\left(x_1-\bar{x}_1\right)^2+\ldots+\left(x_6-\bar{x}_6\right)^2}$$

Figure 14: Calculating difference between mixes

The results of these calculations for all sector mixes are grouped and plotted in Figure 15.

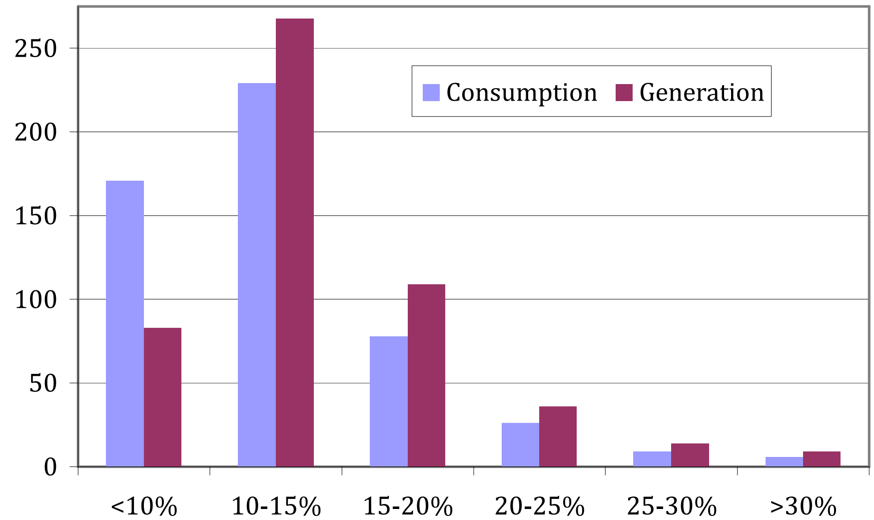

Figure 15: Difference measure of sector mixes to US average mix

Before the analysis was begun we expected to see that disaggregation had a significant impact on the consumption mixes for all industrial sectors. "Impact" in this case was defined as a measure of how different the process-generated consumption mix was from the originally assigned US average mix. We had further expected that adding imports and exports would exacerbate this result: the consumption mixes would be more different than the US averages. But analysis done on the results of the disaggregation lead us to reject our initial hypotheses – while some sectors have disaggregated consumption mixes quite different from the US average, most are very similar to it. Additionally the inclusion of imports and exports has an averaging effect, which makes consumption mixes more like the US average rather than more different.

An important conclusion shown here is that most sectors have mixes which are within 15% of the United States average mix, and very few of the sectors have mixes which are more than 25% different. However, the tail of the distribution is quite long – although it's trimmed in Figure 15 – and knowing which sectors make up that tail is important. Also, there is a definite shift to the left for the consumption as opposed to the generation mix. This is because, as was said before, the trading of power makes things look more like the average.

The most likely explanation for the trend towards the average, both for the standard disaggregation consumption mix and the disaggregation with trading consumption mix, is spatial diffusion. Sectors spread out across the country will have profiles much like the country itself. This is obvious for sectors such as restaurants, hospitals and oil change shops. What is interesting is how many other sectors, which we were not expecting to be diffused across the country actually are, or at least appear to be, based on their consumption mixes with low differential index values.

That interstate trading would have an averaging effect on consumption mixes should have, in retrospect, been obvious. As states get power from a wider variety of sources, the chances that those sources together will look like the US average increases. When we look at some simple comparisons we can see this effect quite clearly. Prior to including imports and exports, the three states most different from the average were Idaho (due to large amounts of hydroelectric power), Rhode Island (generates internally with mostly natural gas), and Hawaii (generates electricity with petroleum). When the optimization was run, and the new generation mixes were compared to the old, the two states that had changed the most were Idaho and Rhode Island. Looking again at a comparison to the US average mix, but this time using the new generation mixes, Rhode Island and Idaho are no longer even in the top ten for difference from the average. The inclusion of imports made them more like the average and dropped them out of the top spots. Overall, however, the effect of adding imports and exports is small, with the total difference between the normal disaggregate results and those including interstate trading being about 3%.

Although the difference in results for this particular use is small, it is still interesting to be able to quantify the difference. This comparison would have been made much easier with better data availability. Gross import and export data, such as that available from the Canadian National Energy Board and certain states, such as

California, should be regularly collected and made available either through the EPA or Department of Energy. This information could be used to answer many other questions where the source of electricity – and its associated pollutants – is important. Simply providing the gross import and export data would allow researchers to create their own methods for deciding where the imports and exports end up.[40] It could be a simple optimization such as ours, or a more complex physical model where specific transmission lines are included.

Despite many of the sectors being close to the average, it is nonetheless interesting to look at the 5% which are most different from the average. More so than the hundreds of sectors that trend towards the average, these top sectors are good verification of the disaggregation process. Oil and gas equipment are manufactured in states that use lots of natural gas. Sightseeing transportation is the top sector for petroleum; not coincidentally, Hawaii, with its large inter-island tourism industry is the top petroleum state. Aircraft manufacturing, the consumption mix of which is shown Figure 16, has long made its home in hydro-heavy Washington and California, and the disaggregated results show about 30% hydroelectric generation. There are also more wineries in California than anywhere else in the country, and California has a large amount of "Other" power; wineries are a top sector for use of other generation types such as geothermal and wind. The top sectors for each type of electricity are included in Appendix D.

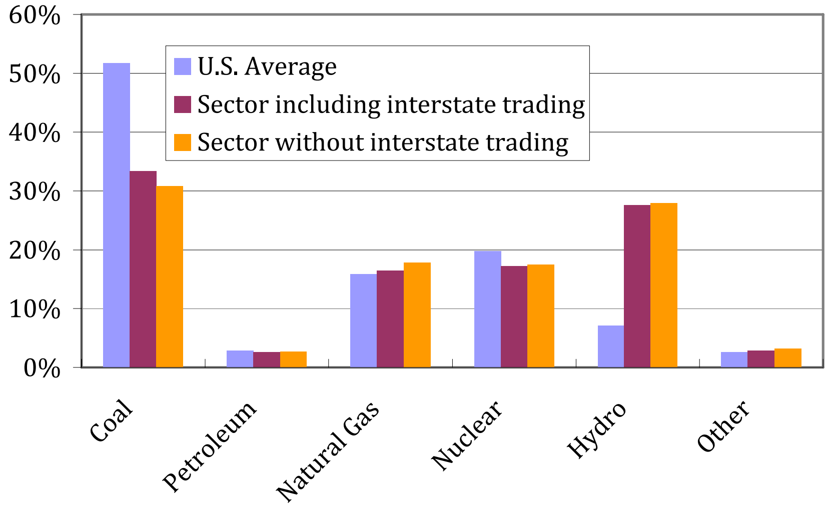

Figure 16: Sector Consumption: Aircraft Manufacturing

Also among the list of top sectors for use of each generation type are some of the most critical sectors of the economy – fundamental resource and material production sectors like aluminum, steel production and coal mining on which many products are based. While it seems a rather unexciting conclusion to draw that most sectors have the same generation mix that they would have had before disaggregation or modeling of interstate trading, this is nonetheless an important result. It validates the assumption made in many environmental assessments that the impacts are average impacts based on average generation mixes.

A more general conclusion is to be sure that the particular product or process being assessed is looked at carefully. The results of an LCA looking at the production of a washing machine are very different when the production uses an electricity consumption mix consisting of 80% coal rather than 50%. So too with aircraft, or wine. It is important to accurately quantify the environmental impacts associated with electricity use in life cycle analyses, especially those which involve large manufacturing sectors such as primary raw materials extraction.

It is important to understand that the sector consumption mixes presented here are static indicators of past electricity consumption. The types of electricity used by a particular sector and the emissions associated with that use are based on a hypothetical snapshot using data from 1997 and 2000. The model does not have any inherent predictive ability beyond providing information upon which assumptions can be based. Using it as a predictive model could produce misleading or unwanted results. Nor does it allow for marginal changes due to demands for different types of power.

Consider the case where a paper manufacturer has a facility located in Georgia. He pays an average of 6.5 ¢/kWh for electricity to power his manufacturing processes. He is looking for ways to reduce his expenses and therefore increase the profitability of his paper production business. Since he purchases large amounts of power along with his wood and water, a reduction in the amount spent on electricity would certainly help.

Prices in Washington state are significantly lower for electricity. Anywhere from .5¢ to 3¢ per kilowatt hour less. Power generators in Washington produce almost ¾ of their electricity from hydroelectric dams, and as a result they are able to sell at a much lower cost than those generators that have to buy fuel. A move to a facility near all this cheap hydro power might produce the sorts of cost savings and profit increases the paper mill owner was looking for.

And this is likely true for individual facility owners: a move to an area with cheap renewable electricity production will result in lower electricity costs. But as more individuals make this choice, the model results will no longer show what's going on in the market.

Very little new hydroelectricity generation is being installed in the United States due to the large ecological cost associated with dam and reservoir construction. And the hydroelectric power currently being generated is sold as soon as it is produced because it can be produced so cheaply. So, new capacity that is required to power facilities such as the relocated paper mills will not come from hydroelectric dams. It is also not likely to come from nuclear or other renewable sources due to the high prices of those types of facilities. Finally it is unlikely to come from coal generation because coal-fired generators are poor peak producers – they can't produce electricity on short notice for high demand periods because of the time required to ramp up and ramp down the facility. So the new generation is likely going to come from natural gas fired power plants.

Increased demand in the state will result in one of four possible outcomes:

1. Increased production in the state from coal, gas or other renewable energy sources
2. Increased production, and reduced export of power
3. Reduced electricity exports
4. Increased imports from another state

Now, as more individual entities make the choice to move to cheap – and carbon-free – hydroelectric producing states, the power they are using will likely come from more expensive fossil fuel fired plants. It is important to understand these small changes at the margin might actually change the structure of the economy due to changing supplies and demands, but this isn't accounted for in the model. However, input-output models are robust to small changes in demand – in this case, the existing (static) amount of hydro power will be reallocated among all previous and the new demands.

2.3 Comparing Results

In order to compare a life-cycle analysis which uses an average mix to those using consumption or generation profiles, a basic disaggregation of the power generation and supply sector needs to be completed and put into an input-output framework. This means splitting the existing Power Generation and Supply sector into six separate sectors, one for each generation type discussed in this chapter. The mechanics of disaggregation are discussed in detail in Chapter 3, and is the main focus of this dissertation, but for the purposes of this comparison, a much simpler version is used. In this version, only the four most economically important sectors are allocated to specific generation type: coal mining, oil and gas extraction, rail transportation and pipeline transportation. The remaining sectors are allocated based on kilowatt-hours generated and an average electricity price.

One important enhancement done here is that three complete sets of supply chains are created for the other 490 sectors in the economy, and each one has different values for their purchases from Power Generation & Supply.

1. Electricity treated as a single sector – this is the US average mix, and the current method of dealing with electricity purchases
2. Six separate electricity purchases, with purchases based on the sector-specific generation mix, ignoring trading
3. Six separate purchases, using a sector specific consumption mix, with trading

Once the new supply chains are complete, a total requirements matrix is created according to the BEA process for building their input-output model from the economic census[77]. Details on this process, and the MATLAB code used to implement it are included later. A single emission factor, that for CO_2, is used in this analysis, for simplicity of comparison. Four scenarios were used to compare the consumption and generation mixes to the average mix. To run these scenarios, the amount specified is entered into the model as a final demand.

The first scenario models the purchase of a new 777 airliner from Boeing. This is the purchase of the unit itself only, not the use of it, so there are no fuel costs. A new 777 costs about $220M according to Boeing, and assuming it costs Boeing about 70% of the price to make it, the construction is reflected as a $155M purchase in the aircraft manufacturing sector, which is IO code 336411. We would expect that because this industry had a very different profile from the US average, that its CO_2 numbers would be lower as well.

The second scenario looks at the purchase of a new domestic luxury sedan for $50,000. Using the same cost/price assumption, this is modeled as a $35,000 final demand from automobile manufacturing. The third scenario looks at $1 million worth of coal from the coal mining sector, and finally, the fourth looks at $1 million in retail purchases, which we would expect to have a mix very similar to the rest of the United States.

For each scenario, the results show the tons of CO_2 emitted due to total electricity use over the life-cycle of the purchase specified above. The "Average" results shows the carbon emitted with the US average mix – electricity is purchased from an aggregated sector. The "Generation" and "Consumption" results are disaggregated into six sectors, but of those six, only three – coal, petroleum and natural gas – had direct carbon emissions.

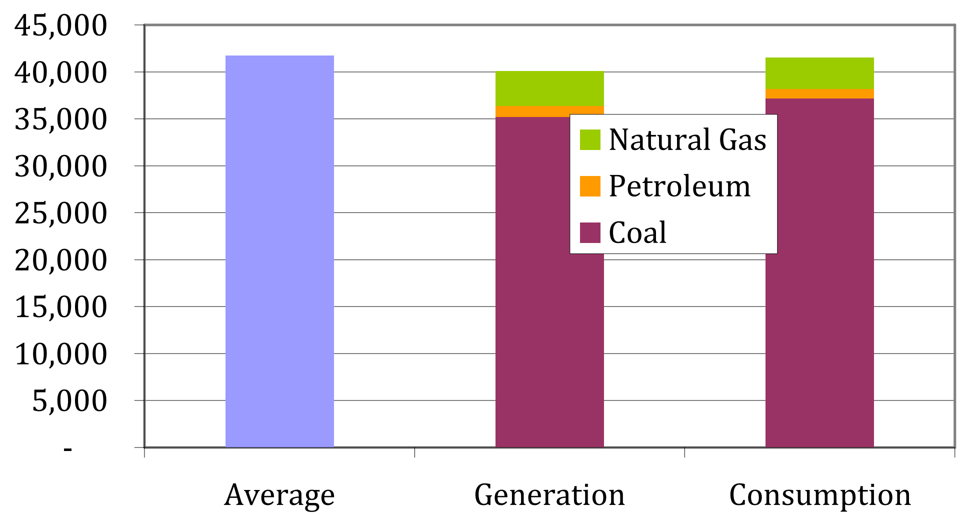

Figure 17: CO_2 (metric tons (MT)) from electricity used by Aircraft Manufacturing

In the first case, shown in Figure 17, comparing emissions from the purchase of the 777, we see that when looking at total emissions, there is not a significant change from the average, in fact, only about a 2% and 1% reduction respectively for generation and consumption. Notice that trading drives the number back up towards the average. This is because while aircraft manufacturers might be located in the northwest, their suppliers are not. The direct purchase of power by the aircraft manufacturing sector had lower carbon numbers – about a 5% reduction, reflecting their location and different electricity profile.

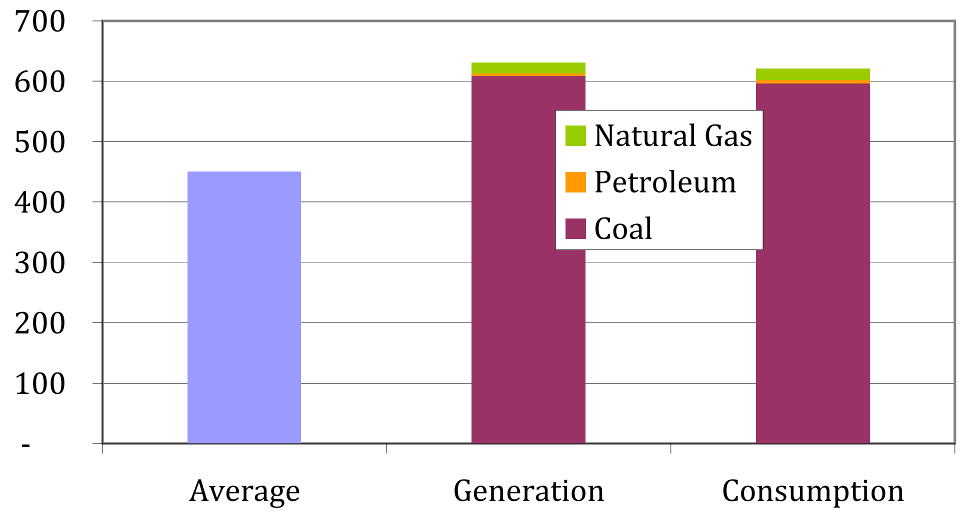

Figure 18: CO_2 (MT) from electricity used by Coal Mining

In Figure 18, we see something quite different from the coal mining purchase. The electricity purchased by the coal mining sector and its suppliers is dominated by coal-fired power, and that is reflected in a 20% increase in total carbon. The direct purchase of power, shown in Figure 21, is even more different, almost a 40% increase in carbon over the US average mix purchase. Again, the averaging effect of interstate trading can be seen – the carbon emissions from the consumption mix are closer to the average than the generation value.

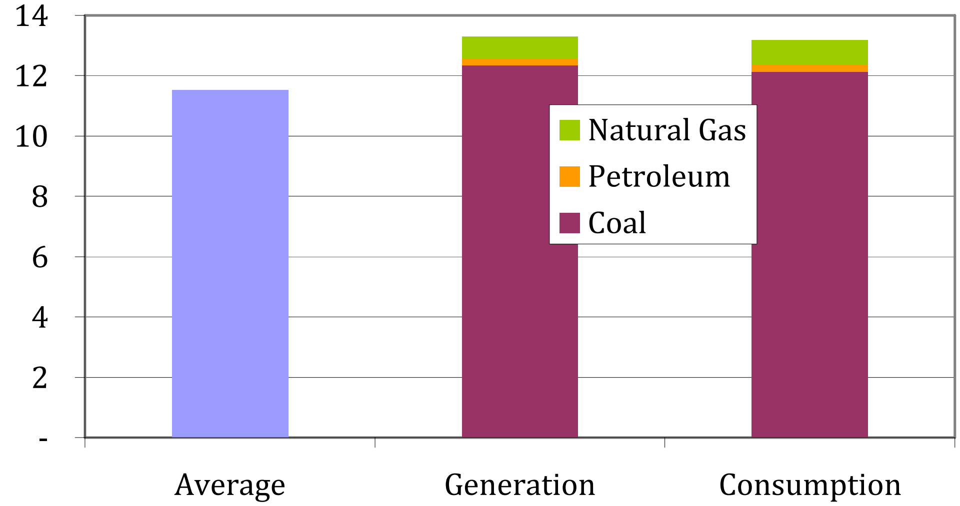

Figure 19: CO_2 (MT) from electricity used by Automobile Manufacturing

The results for the automobile scenario are similar but not quite as dramatic, with a 7% increase in total carbon over the average mix shown in Figure 19. Like coal mining, the direct numbers were higher than the total, with a 15% increase for the generation mix and a 14% increase for the consumption mix. These numbers a likely due to the presence of most domestic car production in the eastern United States, from Michigan to the upper southern states like Tennessee, which are states with lots of coal-fired power.

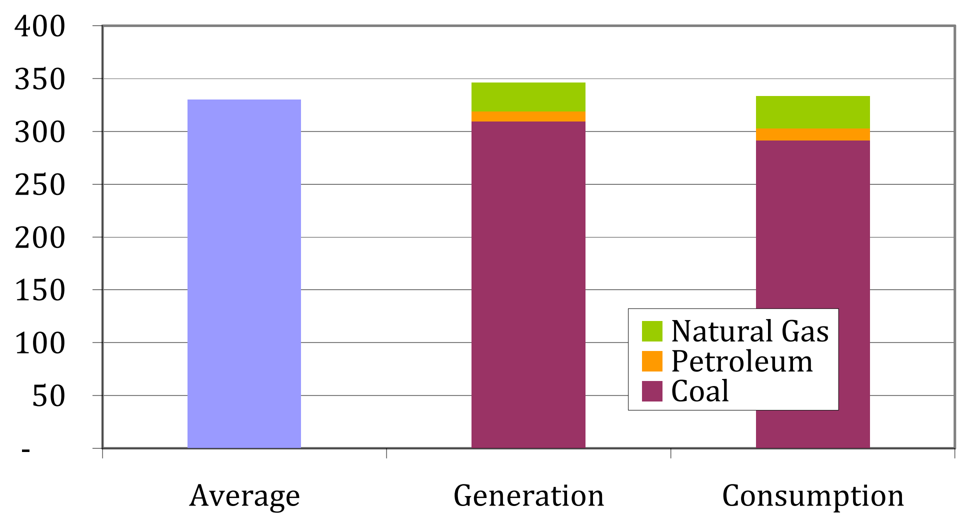

Figure 20: CO_2 (MT) from electricity used by Retail

Retail purchase results show in Figure 20 look like we would expect them to look – very similar to the US average. It is interesting that there is any difference at all. This might indicate that retail sales are not perfectly distributed across the country, but in fact happen more where fossil fuel-fired power is available. These results are also a good verification of the assumptions in general. A well dispersed sector that we expected to have emissions close to the average, had results which were very close.

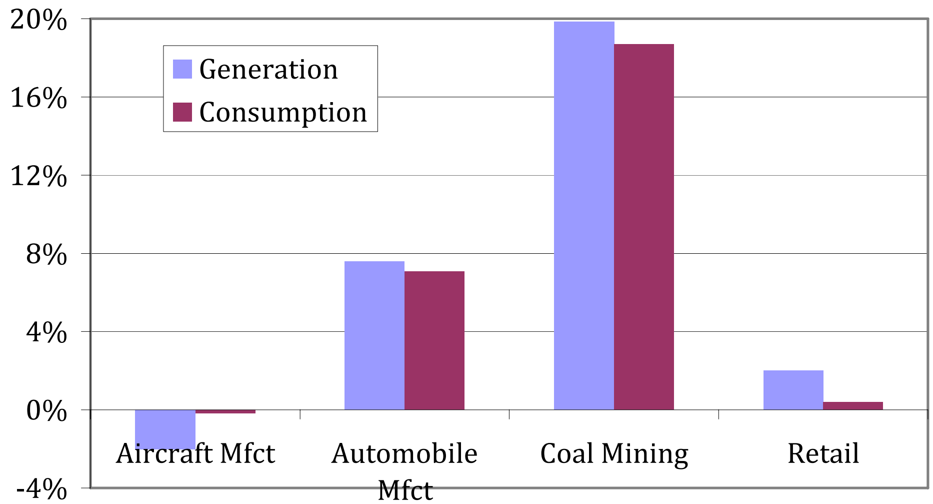

Figure 21: Percent difference of CO_2 compared to US Average Mix

In Figure 21, the percent differences from average CO_2 emissions from direct electricity purchases by the sector of interest are shown. This is a summary chart, not broken out by fuel type There are slight differences between consumption and generation mixes, with consumption mixes always pushing the value towards the average.

With these scenarios done, we wanted to look at how all the sectors in the economy compared to each other in terms of CO_2 emitted, for both the direct purchase of their power mix, and total power purchases – that power purchased by all their suppliers.

A loop was run through the model, plugging in $1 million of final demand for each sector. The changes in direct and total CO2 from the carbon dioxide produced by the US average mix are shown in Figure 22 and Figure 23.

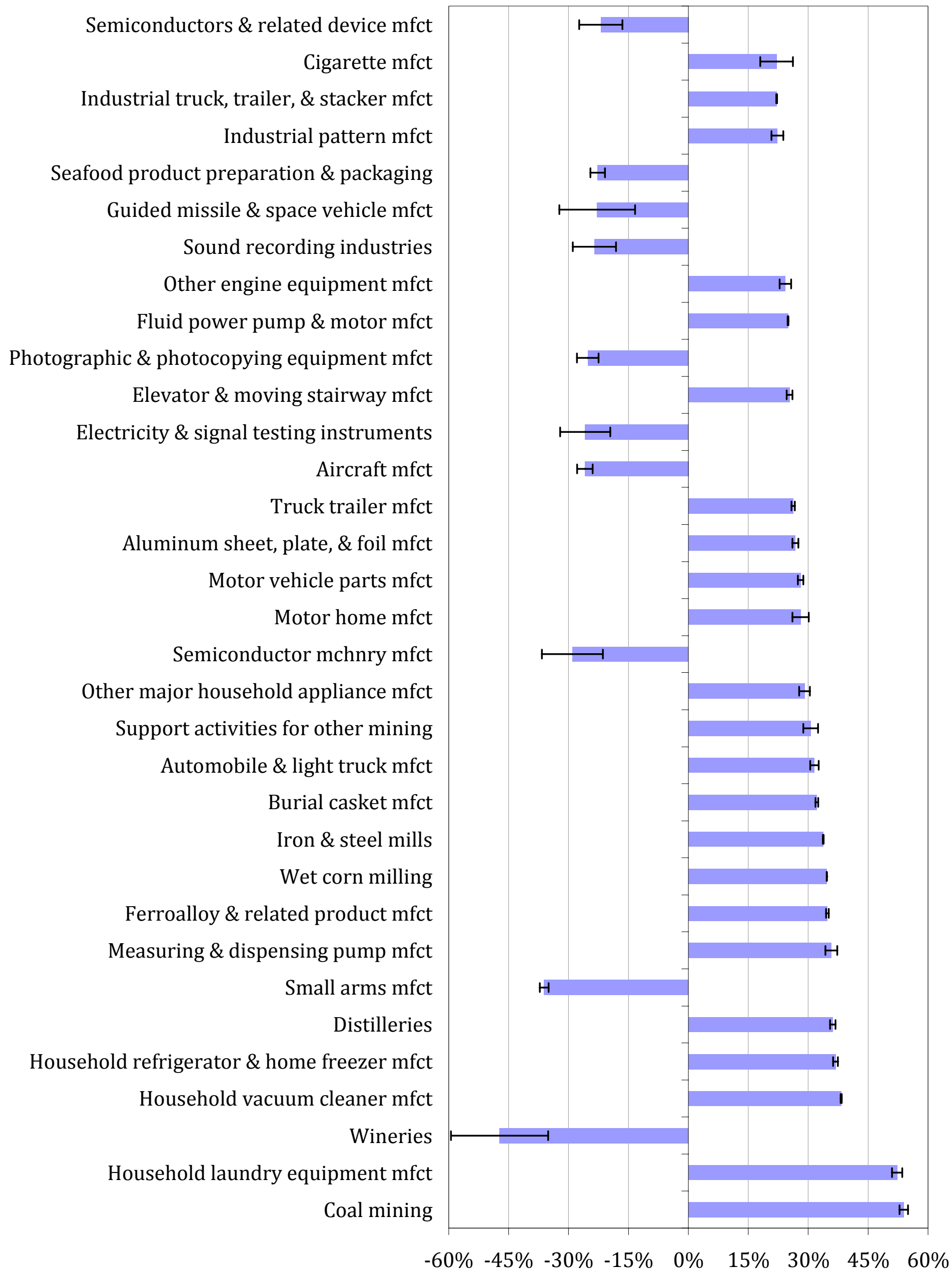

Figure 22: Change in CO_2 emissions from direct purchase of electricity

Figure 22 shows the increase or decrease in CO_2 emissions from the average mix for the direct purchase of electricity from the sector specified. The error bars show difference between consumption and generation mix results, with the bar being the average between the two values. One interesting thing to note is the number of important raw material extraction and processing industries with very different mixes. Coal mining, iron and steel mills, automobile and aircraft manufacturing, semiconductors and aluminum are all very different from the average mix.

Also apparent is the “California effect” where California’s distinct mix is reflected in industries traditionally associated with California, like wineries, semiconductors and missile and rocket manufacturing. Generally these sectors have a large spread between their consumption and generation bars as well – once California is penalized with coal imports, the carbon numbers for those sectors move back towards the average.

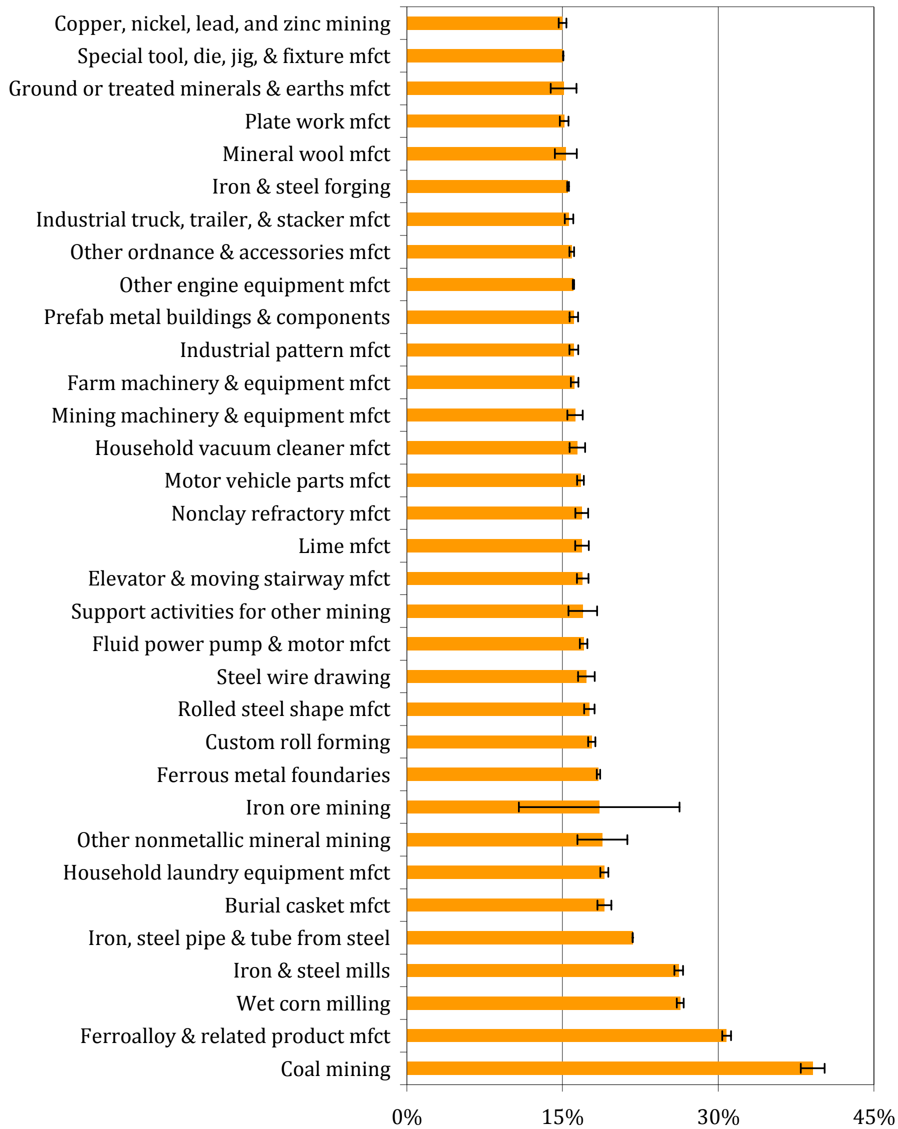

Figure 23: Change in CO_2 emissions from total electricity purchases

Shown in Figure 23 are the changes in carbon from the average mix for total electricity purchases. In total purchases, the "California effect" disappears, since the suppliers for California's industries look much more like the rest of the country than they do like California. But once again, the sectors present here are very important sectors to the US economy – major material extraction and processing sectors and large manufacturing sectors.

Also, once the impact of all suppliers is included, the differences are much smaller – supply chains change the power mix and make it more like the average. For direct CO_2, over 30 sectors had more than a 15% difference, and the largest difference was over 50%. In the total results, only about 20 sectors were greater than 15%, and not by much. The largest difference was just over 40%.

The main conclusion of this analysis is that disaggregation of the electricity sector matters. While many sectors in the economy have similar mixes and similar emissions to the US average mix – the aggregated version of the power generation sector – there are sectors which are different and they are important sectors.

This conclusion is not just important in that it justifies the work shown later, but because it is important that LCA practitioners of all types are aware that for many sectors which they are interested in, the mix of electricity used is important data to gather. Even if the results are simply used as a comparison – to prove that the average mix or emissions is a good assumption – disaggregated electricity matters for accurate environmental inventories

3 Building a disaggregated electricity model

At a high level, this work involves adding detail to the Power Generation & Supply (PG&S) sector of a 491-sector model of the US economy to allow for more detailed economic and environmental analysis of the electricity industry. It can be thought of as splitting up, or disaggregating, this sector into between 6 and 24-plus additional sectors, each representing a specific portion of the electricity industry; for instance, a sector for Pulverized Coal Generation Operations and Maintenance, or Wind Turbine Construction, as seen in Figure 24. Included with each of these disaggregated sectors will be a supply chain – what the sector purchased from the other 500 sectors in order to produce its output (i.e. a power plant, or a kWh of electricity) – and a set of emission factors which will allow calculation of the environmental impact of the sector's output. When all the new sectors are inserted into an existing economic input-output framework, we can build future generation scenarios – each with a specific mix of generation types and investment in future technologies – and we can look at the economic and environmental results which include not only the top-level emissions, but the impacts from the entire supply chain.

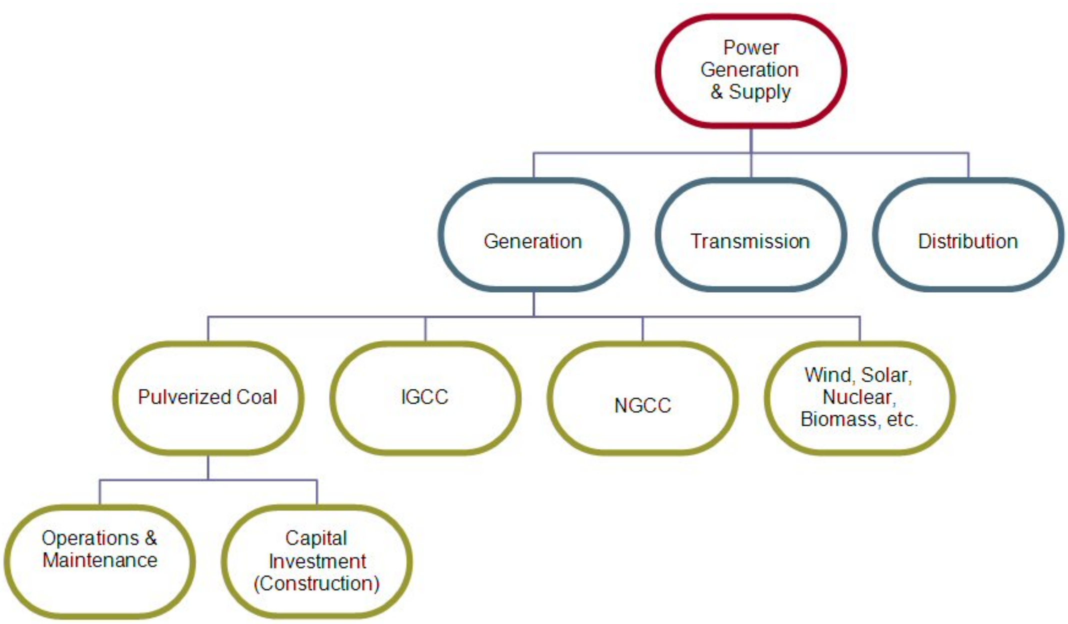

Figure 24: Disaggregating the Power Generation & Supply Sector

The following chapter will discuss building the disaggregated electricity sector model including major inputs and outputs, data sources, and the methods used.

3.1 Model Inputs

The following section details the inputs required for the model to run. There are two important things to note about the inputs for the model. The first is that wherever possible, ranges are used for these inputs rather than point estimates. This enables a range of outputs to be reported, thereby dealing explicitly with the inherent uncertainty of parameter value choice. In some cases, the range will be the maximum and minimum values found or calculated; in other cases, it will be a set percentage above and below an average or median value found or calculated.

The mechanics of how the output range is calculated is less than ideal: a version of the model is calculated using the low end of all ranges, and a version is run with the high end of all ranges. The output of those two runs is used as the high and low end of the output range. This method decreases the amount of time required to complete a scenario, and in a linear model, it is a good approximation of output range. In a non-linear model, we would need to be worried about non-linear response to changes in input parameters.

The second important thing to realize about the ranges collected for input values is that they are ranges on averages. It might help to think of them as the first standard deviation on a mean: it captures a lot of the variability associated with a parameter, but not the extremes – although it is certainly influenced by the presence and magnitude of those extremes. Although the electricity sector is being disaggregated into major generation types, there is still a significant amount of aggregation that is happening.

For instance, all pulverized coal plants, all coal types, and all customers are being aggregated together under the generic sector "Coal-fired Operations &

Maintenance". The values of cost per kilowatt-hour, or tons of carbon per kilowatt-hour, etc. need to be averages for all of those plants and coal types. Collecting and using data on the worst performing coal power plant, and the newest, most sophisticated plant as the low and high points for a range would mean that we expect that on average all plants could perform at that data point, and we know that this is not true. This makes the data collection and uncertainty analysis more complicated.

In practice, when these ranges are used, care is taken to make sure they are used correctly. Although an input parameter's "low" range value may be below the average, its influence may push the output result higher. In this text, the labels "low" and "high" refer to standard numerical ordering, though in the model the use may be opposite – a lower value affects the upper bound.

3.1.1 Supply Chains

In order to build a new input-output model, we need to modify the components that go into making it, and the first of these is the use table, which can be thought of as the supply chains for all the industrial sectors in the economy. So, for every disaggregated sector to model, a listing of the commodities and corresponding dollar values (or the relative proportions of a dollar) needed to produce the output of the new sector must be created. This is true for both the Operations & Maintenance and Construction sectors, although the construction sectors will not be inserted into the final model of the economy. This point will be explained in more detail in 3.4.3.

In addition to the supply chains for each new sector, the existing supply chains for every other sector in the model which uses electricity needs to be modified as well. Where in the aggregated model, each of these sectors would have purchased electricity from a single sector, Power Generation & Supply, now they purchase from a mix of generation sectors. This mix can be determined in two ways: first, an average mix can be used, based on the assumed overall mix of generation types, second, a specific sector mix based on the work shown in Chapter 2. Note that these sector specific mixes will only be used if the scenario being run includes all the generation types used in that analysis. For instance, if a sector mix includes use of natural gas, but there are no natural gas plants included in the scenario, then a different mix assumption will need to be used.

3.1.2 Sector Output

The make table, which is a matrix of commodities produced by industries, needs to be created for the disaggregated power generation sectors. In the existing make table, the entry is more complex than a 1-to-1 industry-to-commodity relationship. In addition to power, the Power Generation & Supply provided other utility commodities in the form of delivered steam heat from combined heat and power (CHP) units. Other industries make the commodity “power generation” as well. The dollar values and commodities need to be put into proper disaggregated sector make entry.

3.1.3 Emission Factors

In order to generate environmental output from an economic model, the data which is normally available in units of mass per unit output needs to be converted to mass per dollar output. The emissions tracked in this model will be CO_2 and the major criteria pollutants SO_X and NO_X.

For the most part, the emission factors are adapted the from the Environmental Protection Agency’s eGRID model, which in turn are based on the AP-42 emission factor data source.[39]

3.1.4 Electricity Costs

To connect the physical quantities normally associated with electricity such as kilowatt-hours and tons of emissions per kilowatt-hour with the dollars in the input-output model it is important to have good estimates of the costs per kilowatt-hour. These are not retail prices, levelized or overnight costs which include the cost of capital, but the pure cost of operation. The cost of operation is needed for each generation type.

We are making the assumption that all capital investment in the power generation sector, such as new plant construction, will happen outside the model of the economy built with the make and use tables. If the supply chains for operations and construction were combined, then we could use levelized capital costs rather than operations costs.

3.1.5 Final Demand

In order to generate output from the model, a final demand is needed. If the goal of the analysis is the life-cycle assessment of some other sector with disaggregated electricity output, then the final demand would be placed in that sector. If the analysis is more complex electricity scenario, the final demands need to be put into the a mix of disaggregated electricity sectors – both operations and whatever construction occurs in the scenario. If the scenario is based on a demand in kilowatt-hours, then those kilowatt-hours need to be converted to a final demand using the electricity prices discussed above.

3.1.6 Input Summary

- Set of generation operation sectors
  - Each with an emission vector, a supply chain vector, and cost/kWh
- Set of plant construction sectors
  - With emission vector
  - Supply chain vector in $ or relative $/kW
- Sector-by-sector consumption mixes (US average or spatially specific)
- Scenario annual generation mix (%)
- Scenario annual construction mix (%)
- Annual electricity demand (kWh)
- Annual construction investment ($)

3.2 Model Outputs

The final outputs of the model are economic and environmental results for every sector in the economy. For each of these, results will be given as direct, indirect and total. There are also two intermediate outputs, an updated total requirements matrix of inter-industry purchases, and an updated emissions vector. The original 1997 BEA-supplied sector is 491x491 – the new matrix will remove the original PG&S sector and add n more sectors for a 490+n x 490+n matrix depending on how many sectors are being modeled.

3.3 Data Sources

There are four major types of data sources used in collecting information for the various inputs and scenarios:

1. Government data (Bureau of Economic Analysis, DoE Energy Information Administration, Environmental Protection Agency, etc.)

   This includes industry data collected by these government agencies, and data synthesized from collected data. For instance, the EIA publishes data collected from the industry and also results from the NEMS model.[19] The EPA reports plant-by-plant emissions through eGRID, and also national average emission factors synthesized from those numbers.

   The BEA's input-output model is the synthesis of the economic census. While there is uncertainty in these numbers due to collection methods, assumptions, etc., use of these data sources is widespread, accepted and justifiable. This data is available for every five years (1992, 1997, 2002), with a three to four year lag. The 2002 data should be available in late 2006.
2. Literature sources

   Although many sources in literature are papers synthesizing government data mentioned above, there is a still quite a bit of unique, in-depth analysis being done. While detailed, numbers gathered from these sources do not always have clear assumptions spelled out, and sources of uncertainty are sometimes not specified. Further, the data is rarely in a form that is directly applicable, so further assumptions are needed. Where appropriate, data gathered from literature sources is noted and referenced.

3. Other models

   Another form of data synthesis, energy or electricity models provide another source of input values. The IECM, or Integrated Environmental Control Model, is a probabilistic tool built at Carnegie Mellon to evaluate control technologies for coal-fired and natural gas power plants, including various forms of carbon control. In general, the information that IECM provides is too specific for the data collection needs here, but it is possible to simulate a "typical" or "average" power plant. [78,79] The existing version of the EIO-LCA model provides emissions and environmental data for the other 490 sectors in the model, and other work happening with the model provides data about the construction sector.[80]

4. Industry

   Because this is, at its base, an economic model, getting real world data from the electricity industry would be ideal. However, the information we are looking for is generally considered confidential, since we want to know what they spend their money on and what it costs them to produce their product. However, the federal government requires that utilities make some of this information publicly available in a standardized format to FERC, the Federal Energy Regulatory Commission, through the Form 1, the Annual Report of Major Electric Utilities. The now partially deregulated industry is actively fighting to have the financial reporting requirement removed, or at least made completely confidential.[81]

   There are several problems with the data available in the Form 1. The first is that the data is hard to get to – there is no editable, searchable database to access the data through. Data in this form would be much more useful to the public. The second, and more important, problem is that the while the data is required by Federal Code 18 to conform to a Unified System of Accounts, there is variability in the way different utilities report the data, due to different accounting practices, the size of the utility, and the types and age of the generation assets the utility operates.[81] Lastly, the data in some cases is very general – like fuel purchases, which could be easily mapped to a sector like "coal mining" or "oil and gas extraction", or very detailed, like the purchase of a specific piece of environmental control equipment for a particular power plant. It is difficult to ascertain what the equipment is for and what sector the purchase should be mapped into.

Finally, not all purchase data provided by the utilities in the Form 1 – with the exception of fuel – are attributed to a particular plant or fuel type. Although we could determine generation assets for a particular utility, we would still need to allocate the purchases in the Form to their assets in some way.

In the 2004 form for Southern Company, on page 204, line 14 specifies they spent $926,000 on "Misc. Power Equipment." Page 204, line 14 is in the "Steam Production Plant" section, but the fuel type of those plants is not specified.[82] Although this is a very definitive piece of data from industry, it is indicative of the sorts of problems Form 1 data presented. We know that Southern has a large variety of generation assets, and it is not clear what type of plant this equipment went towards. It is also unclear, which commodity sector we should reflect this purchase in. There are several commodities which list power equipment of various types. Finally, we don't know if that purchase is typical for the industry as a whole, or for 2004.

3.4 Building the Model

To begin the process of building the disaggregated model, a decision needed to be made about what level of disaggregation, and, conversely, aggregation, was appropriate for the Power Generation & Supply sector. Past disaggregation work, discussed in Chapter 2, was limited to six operations sectors, split up by aggregated fuel type, i.e. "coal" as opposed to anthracite, bituminous, sub-bituminous coal. These sectors were given generic, sequential Input-Output codes: 221101, 221102, etc. Although this is an excellent rough cut, as it allows for discernment of the major environmental differences, analysis of future generation scenarios requires a greater ability to focus on renewable generation. The North American Industry Classification System (NAICS) breaks the industry down into only five 6-digit sectors, shown in Table 4. Six digit codes are needed to represent sectors in EIO-LCA and the new electricity-focused model.

Table 4: Original NAICS Sector 2211 Definition[83]

Code	*NAICS Sector Definition*
2211	Electric Power Generation, Transmission and Distribution
22111	Electric Power Generation
221111	Hydroelectric Power Generation
221112	Fossil Fuel Electric Power Generation
221113	Nuclear Electric Power Generation
221119	Other Electric Power Generation
22112	Electric Power Transmission, Control, and Distribution
221121	Electric Bulk Power Transmission and Control
221122	Electric Power Distribution

Table 5 shows selected six digit codes for construction sectors along with their parent sectors. Here, there are only three six digit codes to represent all the different types of construction that happens in the electricity sector, with transmission and distribution being under 234920, hydroelectric construction under 234990 and *all other* types of power plants under 234930.

Table 5: Selected Original NAICS Sector 23 Definition[83]

Code	*NAICS Sector Definition*
23	Construction
234	Heavy Construction
2349	Other Heavy Construction
23492	Power and Communication Transmission Line Construction
234920	Power and Communication Transmission Line Construction
23493	Industrial Non-building Structure Construction
234930	Industrial Non-building Structure Construction
23499	All Other Heavy Construction
234990	All Other Heavy Construction

It is clear from these limited sector definitions that to have reasonable granularity in the updated model, that new – though not official – sector definitions will be needed. In Table 6, a new sector definition scheme is laid out, which allows for the necessary detail. Remember, though, that there is still significant aggregation happening at this level. Under the "Pulverized Coal" plants sector, all different coal types are grouped together, as are different plant designs and levels of environmental control. Under "Nuclear", PWR and BWR plants are grouped together, as are advanced plants like the AP-1000 or fluidized pebble-bed reactors. All classes and designs of wind turbines are under a single "Wind" sector, and both single and combined-cycle natural gas plants are under "Natural Gas."

Table 6: PG&S O&M Sector Redefinitions

Code	*NAICS Sector Definition*
2211	Power Generation and Supply
22111	Fossil Fuel Power Generation
221111	Pulverized Coal
221112	IGCC
221113	Natural Gas
221114	Petroleum
22112	Renewable Power Generation
221121	Hydroelectric
221122	Solar
221123	Wind
221124	Geothermal
221125	Biomass
22113	Other Power Generation
221131	Nuclear
22114	Power Supply
221141	Transmission
221142	Distribution

For construction, a similar redefinition is necessary, while at the same time making sure that data isn't currently being collected and reported by the BEA in the sectors being redefined, as well as using existing definitions if appropriate.

Table 7: PG&S Construction Sector Redefinitions

Code	*NAICS Sector Definition*

23	Construction
234	Heavy Construction
2349	Other Heavy Construction
23492	Power Transmission Line Construction
234920	Power Transmission Line Construction
23493	Power Plant Construction
234931	Pulverized Coal Power Plant Construction
234932	IGCC Construction
234933	Natural Gas & Petroleum Plant Construction
234934	Hydroelectric Power Plant Construction
234935	Nuclear Power Plant Construction
234936	Wind Turbine Construction
234937	Solar Construction
234938	Biomass Construction
234939	Geothermal Construction

Despite the redefinitions, these are obviously not comprehensive lists of generation technologies – either current or future – or a full set of construction work that could take place in the industry. Because from the outset, it was known that no disaggregation could ever be complete, the framework is open and infinitely expandable. If the goal was to model and compare the construction and operation of two sub-bituminous pulverized coal plants, one with minimum environmental controls, and another with best available technology, sectors could be created to do the job, if the data was available. Likewise, if you wanted to compare the Hoover Dam to the Grand Cooley Dam over their lifetimes, sector supply chains and emissions factors could be created to do that as well if data could be collected.

3.4.1 Estimating Electricity Costs

Although there are many alternative sources to choose from[84], we chose to use Department of Energy information to create our estimates for electricity costs. Coming up with the price of electricity is generally a very complicated process that must take into consideration the spot prices of fuels, depreciating capital costs, taxes and regulatory environment, transmission infrastructure, type of consumer, etc.[85]

Coming up with operating costs, by contrast is a much easier exercise. These costs, in dollars per kilowatt-hour ($/kWh), include annual fixed operations &

maintenance costs which are dependent on plant size (capacity), and variable O&M costs, like fuel, which are dependent on output generated. To convert fixed costs to output-based costs, we used ranges of capacity factors from the National Renewable Energy Laboratory.[86]

Recall that these costs do not include any capital costs. These are not busbar, but operations costs only. The reasoning behind using operations costs only is explained further in section 3.4.3. Department of Energy estimates of various fossil fuel costs are shown in Figure 25, in real dollar terms. Coal prices are increasing, but look stable relative to petroleum (No. 2 fuel oil & diesel) and natural gas prices which have quadrupled since 1998.

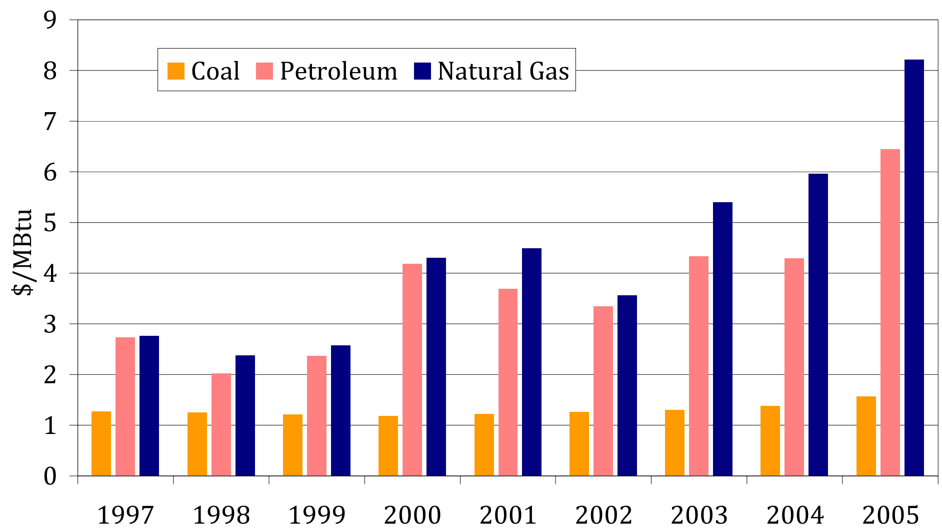

Figure 25: Fossil-fuel prices paid by Electricity Generators[1]

In the estimate of electricity cost shown in Figure 26, an average is shown in the column graph, with variability in fuel price over an 8-year span, in capacity factor and heat rate accounted for by the error bars. For the fossil fuel generation types, the variability is almost entirely due to fuel price since there is little uncertainty associated with the technology associated with those plants. For generation types to the right of Figure 26, the variability has more to do with differences in technology implementations and operations reliability. In this case, costs are in nominal 1997 dollars to match the rest of the input-output economic data.

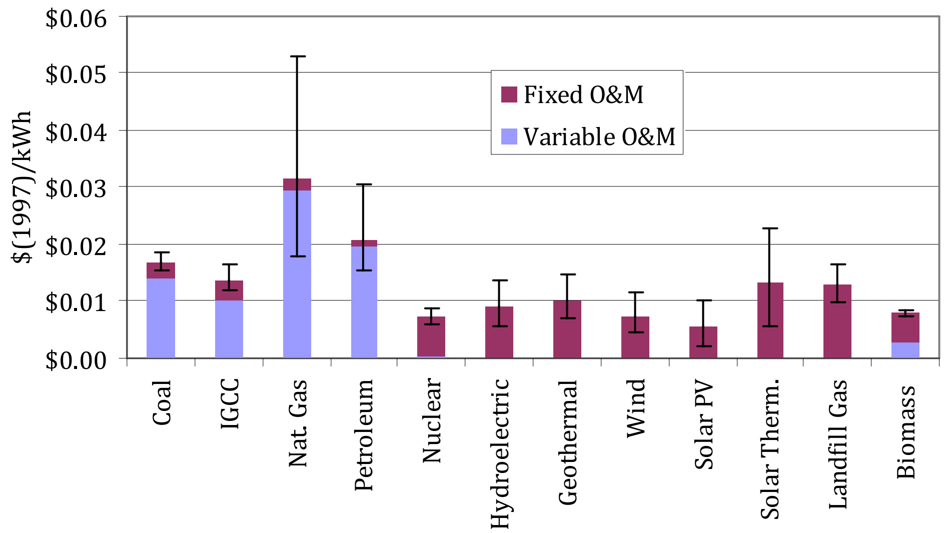

Figure 26: Electricity O&M Prices by Generation Type[7,8,86-93]

The same information is included in table form below. These are intended to be average electricity costs taking into account a wide range of technologies and fuel prices. The estimates are important, though, because they will be used for the default allocation method which will be shown below, and also for the creation of dollar-based emission factors. However, these prices, could be made much more specific – to be representative of a specific year or technology type, and those changes will be made for some of the scenarios.

Table 8: Electricity O&M prices by Generation type ($1997/kWh) [7,8,86-93]

Technology	*Average*	*High*	*Low*
Coal	$ 0.017	$ 0.018	$ 0.015
IGCC	$ 0.014	$ 0.017	$ 0.012
Natural Gas	$ 0.031	$ 0.053	$ 0.018
Petroleum	$ 0.021	$ 0.030	$ 0.015
Nuclear	$ 0.007	$ 0.009	$ 0.006
Hydroelectric	$ 0.009	$ 0.014	$ 0.006
Geothermal	$ 0.010	$ 0.015	$ 0.007
Wind	$ 0.007	$ 0.012	$ 0.005
Solar PV	$ 0.006	$ 0.010	$ 0.002
Solar Thermal	$ 0.013	$ 0.023	$ 0.006

Landfill Gas	$ 0.013	$ 0.017	$ 0.010
Biomass	$ 0.008	$ 0.009	$ 0.007

3.4.2 Creating Operations Supply Chains & Industrial Output

Originally, when the idea of disaggregating the electricity sector came up, the intention was to build new supply chains from scratch. A coal-fired power plant, for instance, must purchase a certain amount of coal (from the coal mining sector), the transportation happens by rail and barge. Additionally, it requires ammonia for NO_x reduction with SCR and calcium for sulfur emissions control with FGD. They utilities probably have lawyers and consultants. It seemed that the supply chain would be relatively small and easy to create.

However, the initial investigation showed that the BEA supply chain (in the form of a use table) for the Power Generation and Supply sector (IO/NAICS code 221100) included purchases of 183 separate commodities, which was far more than came from the original estimation. Table 9 shows the top 17 sectors of the BEA supplied use table in producer prices. There are some obvious sectors near the top: coal mining and rail transportation supplying coal to coal-fired power plants, and oil and gas extraction and pipeline transpiration supplying natural gas and petroleum fired plants. There are some surprises, however, like the large maintenance and repair contribution, money spent on real estate, or on courier and messenger services. The power of the input-output type of life-cycle assessment is the eradication of the boundary issue, and shortening these chains might reintroduce some of those problems.

Table 9: 1997 Benchmark use table for PG&S[3]

Sector	*Use Value ($M)*	*% of Total*
Coal mining	$15,098	18.9%
Oil and gas extraction	$14,905	18.6%
Pipeline transportation	$6,669	8.3%
Rail transportation	$5,844	7.3%
Other maintenance and repair construction	$3,389	4.2%
Legal services	$3,232	4.0%
Petroleum refineries	$2,151	2.7%

Monetary authorities and depository credit	$1,855	2.3%
Wholesale trade	$1,754	2.2%
Advertising and related services	$1,749	2.2%
Food services and drinking places	$1,660	2.1%
Real estate	$1,582	2.0%
Truck transportation	$860	1.1%
Couriers and messengers	$626	0.8%
Water transportation	$597	0.7%
Wiring device manufacturing	$536	0.7%
Switchgear and switchboard apparatus	$529	0.7%

Although the supply chain is long and contains some surprises, it is extraordinarily top heavy, with most of the money being spent on the top commodities, and the contribution of commodities lower in the chain being very small, percentage-wise. The top 12 sectors accounted for 75% of the economic value, the top 35 accounted for 90%. Put another way, the bottom 146 sectors have only 10% of the economic value of the supply chain. Additionally, most of the sectors at the top are the most environmentally important, as well, although additively service-related commodities have a large impact as well.[94] And, some assumptions can be made about these top sectors. The $15 billion spent on coal mining was a purchase from the coal-fired generators. This is a direct-use value, and it makes no sense for coal to be purchased by any other generator at any point in their supply chain.

Table 10: Assumption-based allocation across generation types

Commodity	*PG&S Supply Chain Value ($M)*	*Coal Allocation*	*Petroleum Allocation*	*Natural Gas Allocation*
Coal mining	$ 15,098	100%	0%	0%
Oil and gas extraction	$ 14,905	0%	9%	91%
Pipeline transportation	$6,669	0%	9%	91%
Rail transportation	$5,844	100%	0%	0%
Petroleum refineries	$2,151	0%	9%	91%
Water transportation	$597	100%	0%	0%

Table 10 shows some of the other important sectors about which we have made assumptions. There are other sectors in the supply chain about which we can make these sorts of assumptions, but the economic impact of those decisions is limited because of the small relative contribution of the commodity to the overall supply chain. For sectors like "Oil and gas extraction" which have a 9%/91% allocation, it is assumed that all use of that sector comes from petroleum and natural gas generation, and the money is spent in proportion to the weighted kilowatt-hours produced, explained below.

The other sectors, about which there is limited or no information, are a bit more difficult. Rather than introduce additional uncertainty by using external sources or attempting to justify assumptions, a default allocation method is used. Originally, the idea was to use the current US generation mix as a means of allocating these dollars. So 49.9% of the money spent on a commodity would be allocated to coal-fired generators, since that percentage of kilowatt-hours were generated by those plants. However, since this is an economic model, the allocation should probably be based on how the dollars were spent to generate output, not the output itself.

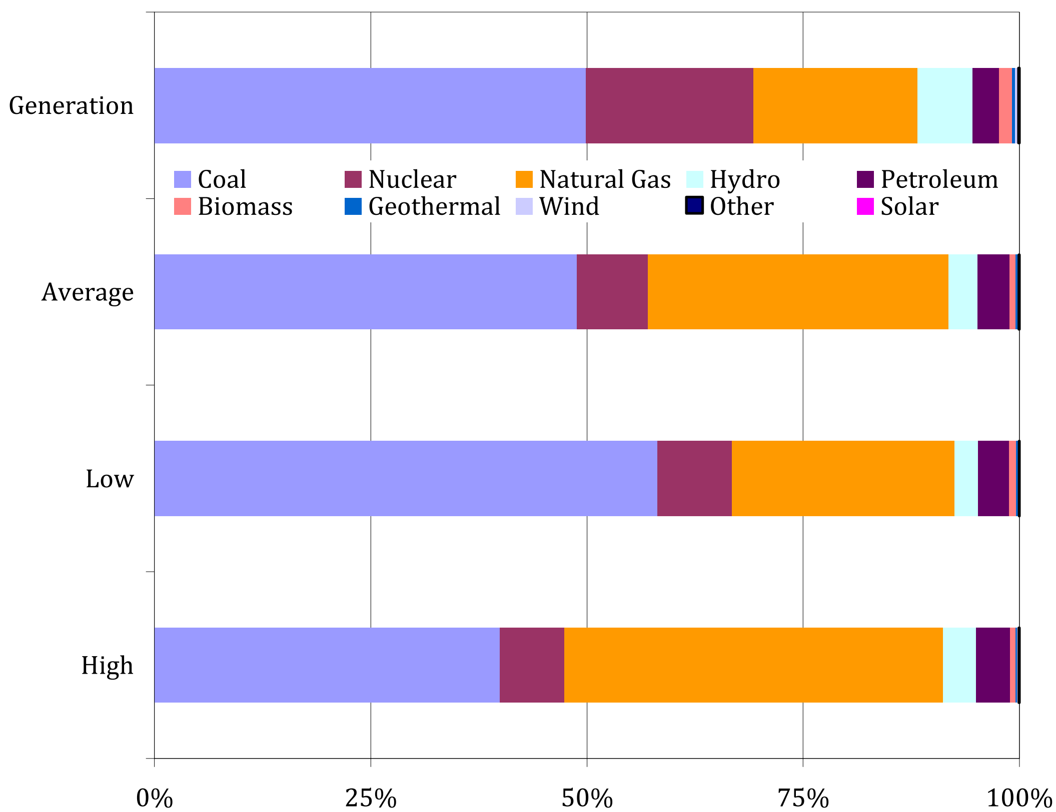

Figure 27: Priced-based Default Allocation

Figure 27 shows the US average generation mix, and then the price-based "mix" using average, high and low price per kilowatt-hour estimates. There are dramatic differences in how the money in the supply chain gets allocated. Coal-fired electricity (49.9% of generation) goes from an average 48% to as high as 60% when coal prices are low to 40% when coal prices are high. Natural gas is only 19% of the generation mix, but can account for as much as 44% of the money spent if natural gas prices are high enough.

Table 11: Priced-based Default Allocation

Technology	*Generation*	*Average*	*High*	*Low*
Coal	49.9%	48.9%	39.9%	58.2%
Nuclear	19.3%	8.2%	7.5%	8.6%
Natural Gas	19.0%	34.8%	43.8%	25.7%
Hydro	6.4%	3.4%	3.8%	2.8%
Petroleum	3.0%	3.7%	4.0%	3.5%
Biomass	1.5%	0.7%	0.6%	0.9%
Geothermal	0.4%	0.2%	0.2%	0.2%
Wind	0.4%	0.2%	0.2%	0.1%
Other	0.1%	0.1%	0.1%	0.0%
Solar	0.0%	0.0%	0.0%	0.0%

So, all other sectors are allocated based on this assumption that the commodities in the supply chain were used in proportion to the amount of output generated. This may not be strictly true – in fact it most certainly isn't. Nuclear plants may spend more on safety equipment, and coal plants may spend more on environmental control equipment, but the output proportionality assumption is a good first order estimate for most sectors.

But before a final allocation is settled on, spending on transmission and distribution needs to be taken into account, since those sectors, or functions of the industry, will be part of the disaggregation. Adjusted for inflation, spending on distribution has stayed relatively constant over since 1994, at around $4.5-5 billion annually.

Transmission spending has increased in recent years, from a low of about $2.4 billion in 1996 to over $5 billion in 2005.

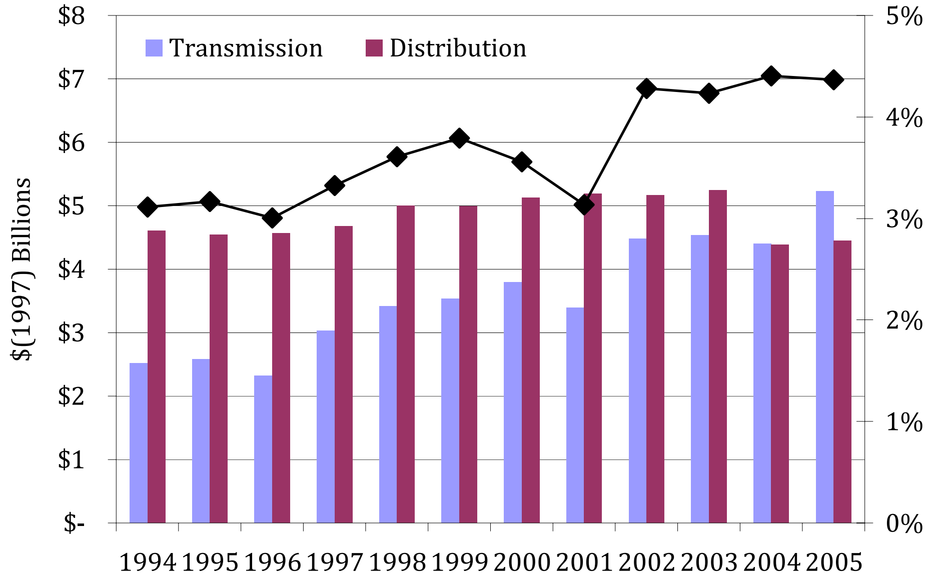

Figure 28: T&D expenditures, and as percent total utility expenditures[1]

The spending on both of these areas is rising as a percentage of total industry expenditures, from around 3% to about 4.5%.[1] Since our sector of interest includes both generation and *supply*, the list of commodities used should have a percentage allocated to the supply of the electricity. Figure 28 shows this information – by contrast, spending on biomass, geothermal, wind and solar generation combined was less than the amount spent on transmission and distribution.

Investment in transmission and distribution has been over $13 billion a year since 1975, and in the last ten years has been increasing each year, faster than the increase in electricity demand, so this percentage will increase.

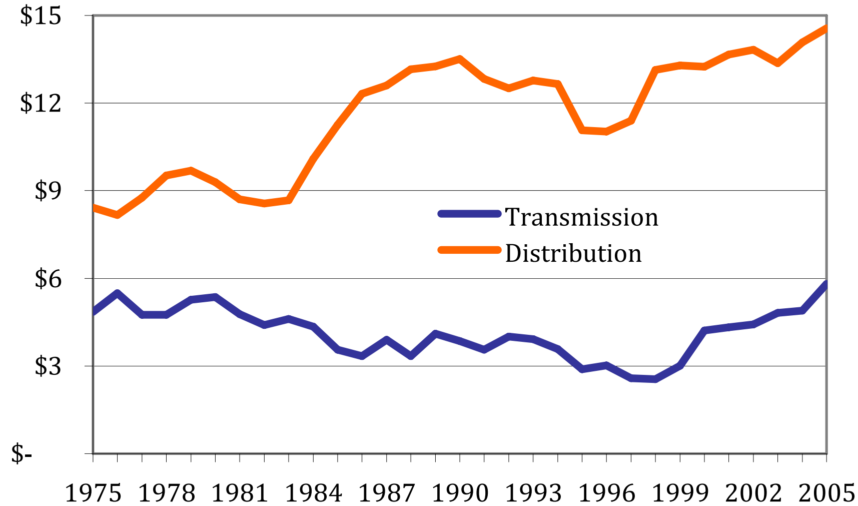

Figure 29: Transmission and distribution investment 1990-2005 ($B, 2005)[95]

The amounts shown in Figure 28 are combined with the allocations for generation only created above, and the results are shown in Table 12. These results are for the average case, although a range of value was generated and different allocations created based on them. Notice that relative to the generation-only allocations shown in Table 11, the percentages for each generation type are lower, since about 4% of spending overall is now allocated to transmission and distribution. So, of the money spent by the electricity industry, about 4% was spent on supply, not generation. So the weighted kWhs are now normalized across the remaining 96%.

Table 12: Default allocation, with transmission and distribution accounted for

Technology	*Average*
Coal	46.88%
Nuclear	7.83%
Natural Gas	33.35%
Hydro	3.26%
Petroleum	3.51%
Biomass	0.68%
Geothermal	0.21%
Wind	0.15%
Other	0.05%
Solar	0.01%
Transmission	1.95%
Distribution	2.13%

This allocation, along with any generation-specific assumptions discussed above, are used to build the operations and maintenance supply chains. Note that in 1997, the Power Generation & Supply use table included $20.7 million in purchases from itself. It is not clear if this is power purchased by utilities to make up for supply short falls, or if this is power used on site to power various systems. The assumption used for this analysis is that a generation type will purchase from a similar generation type, so that all power purchased by a nuclear generator will be generated by nuclear, and some will be used for power supply. This allocation is shown in Table 13. It shows the portion of the $20.7 million spent by the sector on the left on the sector across the top. Notice that each sector purchases some power supply as well.

Table 13: Use table PG&S intersection allocation ($M)

	221111 Coal	*221114 Petrol.*	*221113 Nat. Gas*	*221131 Nuclear*	*221121 Hydro*	*221125 Biomass*	*221124 Geoth.*	*221123 Wind*	*221122 Solar*	*221141 Trans.*	*221142 Dist.*
221111	9.71									0.20	0.22
221114		0.73								0.01	0.02
221113			6.91							0.14	0.15
221131				1.62						0.03	0.04
221121					0.67					0.01	0.02
221125						0.14				0.00	0.00
221124							0.04			0.00	0.00
221123								0.03		0.00	0.00
221122									0.00	0.00	0.00

In addition to supply chains, there are also outputs, or make table entries to be allocated. Table 14 shows the sectors (other than Power Generation & Supply – that entry is an intersection similar to the use intersection shown in Table 13) which produced the commodity "Power Generation & Supply". These are sectors which in the course of producing their other output produce some power to sell – or purchase some power and then resell it, like a local cooperative utility. It was assumed that the power produced here would be similar to the average generation mix since no better information was available. A case could be made for cooperative utilities having a different average – more hydroelectric plants might be cooperatively owned and operated because of the other benefits provided by dams, but the analysis was not done to assess this. The framework is flexible to allow for those sorts of additions.

Table 14: Output of industries producing commodity "PG&S" in $millions

	221111 Coal	*221114 Petrol.*	*221113 Nat. Gas*	*221131 Nuclear*	*221121 Hydro*	*221125 Biomass*	*221124 Geoth.*	*221123 Wind*	*221122 Solar*
S00202 Local Utilities	10,396	778	7,395	1,737	723	150	47	33	2
S00101 Federal Utilities	3,896	292	2,772	651	271	56	18	12	1
3221A0 Paper Mills	121	9	86	20	8	2	1	0	0
S00203 Other local Gvmt	3	0	2	1	0	0	0	0	0

Power Generation & Supply, in addition to making the commodity "Power Generation & Supply", produces other types of commodities such as "Natural Gas Distribution". This production was allocated in a similar fashion to the allocation done in Table 13. The PG&S – PG&S intersection was treated the same way. Again, no clear information was available about which types of generation were producing these other outputs, so a default allocation was used.

An example of a complete supply chain for one of the disaggregated sectors is included in Appendix K.

3.4.3 Creating Construction Supply Chains

The construction sectors in EIO-LCA are a known problem area due to double counting of on-site emissions and fuel purchases, and poor reporting from an industry with many small businesses, and are a field of study by themselves.[80,96] As such, the supply chains for the construction sectors are treated slightly differently. Initially, the plan was for the construction use tables to be included in the total requirements matrix along with the operations and maintenance sectors. Some form of allocation would occur to form each of those supply chains. However, several things became obvious over the course of the research which led to the construction supply chains being handled differently.

First, there are only two constructions sectors represented in the 1997 Power Generation & Supply commodity use table. Table 15 shows those commodities and the value of the purchase by the power generation sector, the total purchases of those same commodities by all other sectors. Although 19% is a significant amount of commodity 230340, it is important to look at that purchase in the context of the rest of the construction industry.

Table 15: Construction sectors in 1997 PG&S Use table, in $ billions[3]

Sector	*Description*	*PG&S Use*	*Total Use*	*PG&S %*
230320	Maintenance & repair of nonresidential buildings	$111	$56,012	0.2%
230340	Other maintenance & repair construction	$3,389	$17,833	19.0%

Sector 230320 is only 7.4% of the total construction sector, so 0.2% of that is about 0.015% of the total, and sector 230340 is only 2.4% of the total industry, so 19% of that is only 0.449%. Together, the PG&S purchase of construction and maintenance is only 0.464% of the total industry purchases, a pretty small fraction.

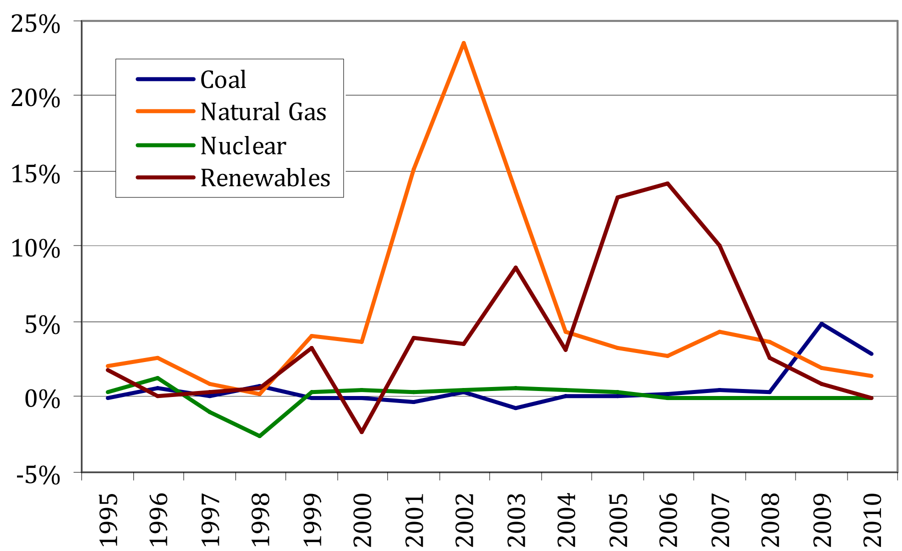

Figure 30: U.S. new electric generating capacity by fuel type[1]

In order to confirm that little construction happened in 1997, we can look at the kilowatts of capacity added at that time. Figure 30 shows the percent of kilowatts of new capacity added annually between 1995 and planned expansion to 2010, broken down by generation type. It can be seen that in 1997, there is little or no additions to capacity. Natural gas prices would reach their lowest point in 1998, and there would be a huge spike in capacity three years later when plants built because of those low prices started to come online. But in 1997, the year represented in the input-output table used for this model, there is virtually no construction. Certainly, if there was any new construction in that year, it is not representative of expansion in the industry in general overall.

In some ways, this year of relative inactivity in the electricity industry is a benefit, since it allows the 1997 use table to be considered an exclusively operations and maintenance supply chain.

However, it does mean that supply chains for construction of new power plants need to be created from scratch. But when it comes to creating those supply chains, a similar problem to the operations and maintenance sectors is found – while it is possible to come up with a list of 20 or so major material inputs to the construction of a power plant, the average supply chain for a construction sector provided by the BEA includes over 200 commodity purchases.[3] Table 16 shows several heavy construction supply chains from the 1997 BEA input-output model. Notice that both services, such as architects, and materials, such as concrete, are included in the supply chain.

Table 16: Selected 1997 heavy construction sector supply chains, in billions[3]

Sector	*Description*	*230210*	*230220*	*230230*	*230240*	*230250*
V00100	Compensation of employees, "Labor"	$13,131	$82,551	$17,245	$6,231	$41,304
541300	Architectural & engineering services	$1,525	$16,043	$2,084	$1,513	$8,865
V00300	Other value added	$611	$6,994	$2,636	$455	$4,402
4A0000	Retail trade	$300	$8,917	$646	$272	$1,793
420000	Wholesale trade	$929	$5,103	$985	$577	$2,318
332312	Fabricated structural metal mfct	$129	$2,852	$660	$231	$1,556
532400	Machinery & equipment rental & leasing	$299	$1,642	$1,240	$467	$1,780
324110	Petroleum refineries	$237	$1,738	$1,404	$304	$1,290
32619A	Plastics plumbing fixtures	$296	$2,451	$489	$154	$1,081
484000	Truck transportation	$315	$1,814	$1,114	$341	$633
335120	Lighting fixture mfct	$961	$2,508	$209	$86	$431
327320	Ready-mix concrete mfct	$222	$1,507	$1,454	$97	$743

In order to maintain the completeness of the service sectors included in these supply chains but have materials specific to each power plant type, a hybrid approach will be used. First, an "average" heavy commercial/industrial construction sector will be created by averaging the dollar amounts spent in the construction sectors shown in Table 16. Then, materials commodities will be cut from that supply chain, leaving a service-only supply chain for a heavy construction sector. These supply chain will then be used as a "template" for the creation of generation-type specific construction supply chains which will include materials for the construction of a typical plant of that type.

The template supply chain includes purchases from 120 commodities, which mostly represent services. Because more materials sectors were cut out from the template than will likely be replaced by our researched material supply chains, there will likely be some components missing from the power plants purchased using this model.

Construction material commodity estimates for each type of power plant came from a variety of sources, including the Energy Information Administration and several literature sources.[7-9,87-93,97] The values found were converted from material amounts, prices for those materials, dollars spent in a variety of years, and dollars per kilowatt into a the fraction of a $/kW spent on a particular type of plant. Industrial sectors were then chosen to represent each material and service commodity.

Estimates for capital costs for various power plants and for transmission lines are included below in Figure 31. These are "overnight costs", which assume that the plants are built overnight, without financing, taxes, or depreciation accounted for. Included with IGCC and the natural gas/petroleum combined cycle plants are the additions of carbon capture and sequestration systems. Although it is possible to retrofit existing pulverized coal plants or build new super- or ultra-critical pulverized coal plants with carbon capture systems, consistent data wasn't available so it is not included here. The framework is expandable, so in the future this information could be included. Note also that the "solar" values shown below are an un-weighted average of data for solar thermal and solar photovoltaic technologies, which is part of the reason for the large uncertainty range on the cost. Because of the small role which solar plays in the current mix of electricity, this isn't considered to be a very large source of uncertainty, but if a scenario were built which concentrated on solar, more effort should be put into creating accurate representations of the various sectors.

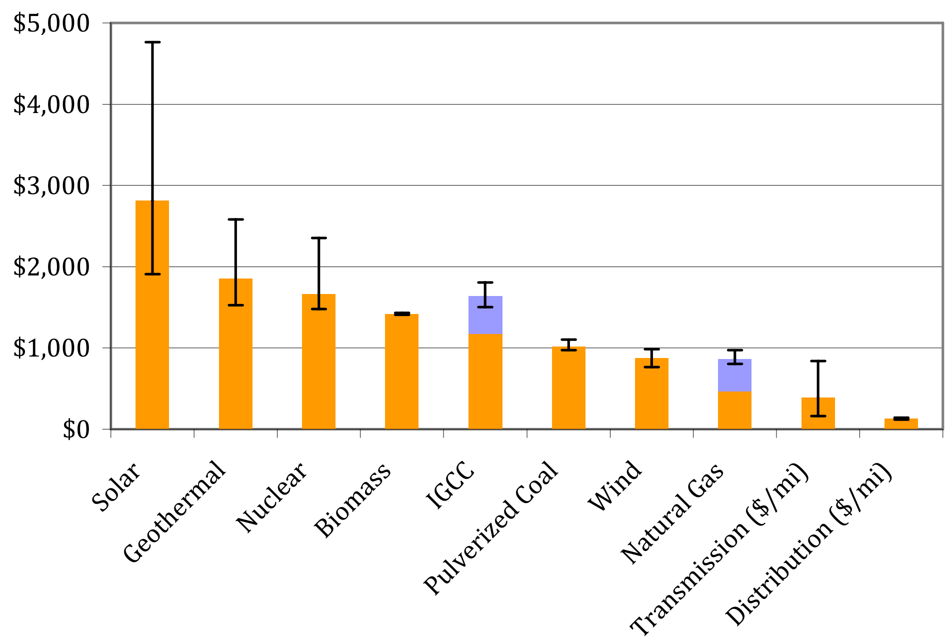

Figure 31: Overnight capital costs for new construction, 1997 $/kW[7,8,87-93,98]

Because we now know how much many dollars per kilowatt-hour were spent on materials, and we know the total overnight cost of each type of plant, we can figure out what portion of the overnight cost is spent on materials versus the service sector template developed above. Table 17 shows these fractions. It is interesting to note that as the complexity of the plant itself increases, the percentage spent on services and labor as opposed to materials. Note also that these are percentages calculated using the method above, and not researched fractions.

Table 17: Fraction of materials vs. services for construction

Plant Type	*% Materials*	*% Service & Labor*
Solar	33.6%	66.4%
Wind	12.0%	88.0%
Coal	12.0%	88.0%
Natural Gas	17.0%	83.0%
Nuclear	7.5%	92.5%
IGCC	10.3%	89.7%
Transmission	19.3%	80.7%

A decision was also made to not treat these supply chains as additional sectors to enter into the use tables as had been done with the operations and maintenance sectors, but as final demand. This means that when a model of the economy is built, the heavy construction industry will look similar to how it looked in 1997. New construction in the electricity sector will be treated as a set of 200 or so purchases from those industries.

3.4.4 Emission Factors

Emission factors, or the output of an pollutant per unit input, are available from many different sources. Some are based on top-down methods, where the amount of a pollutant is divided by the output of the process that created it, like those created by the EPA[39] and some are bottom-up, where the input and efficiencies of a process are analyzed with a mass balance to figure out the emission factor, like those created with IECM[78]. EIO-LCA currently includes a large number of what are probably better referred to as "externality factors", which include obvious pollutants such as carbon, NO_x, and SO_x, and also less obvious factors such as OSHA deaths, TRI pollutants, water usage, etc. Although the framework is flexible enough to allow for the addition of an infinite number of additional factors, in this analysis, we are collecting data on carbon dioxide, sulfur dioxide and annual average nitrous oxides, as opposed to seasonal. Also, we will not be valuing the emissions from the model in dollar terms, since this would add additional uncertainty, but such an exercise is possible.[99]

In our case, we need average data, for all power plants of a certain type in the United States, so a top-down approach seems better. The Environmental Protection Agency generates emission factors for coal, natural gas and petroleum fired plants based on aggregated plant-level data. This data is available for 1998-2000, and should soon be available for 2001-2004. This information was combined with data found through literature review to generate the ranges found in Table 18. The ranges do not include extreme values, since we are looking for values that are representative of the average plant, but still captures some of the variation in plants, and uncertainty in the collection. The values are in tons per gigawatt-hour.

Table 18: Average emission factor ranges in tons/GWh[13,39]

Technology	*CO_2*	*NO_x*	*SO_2*
Coal	900 – 1,400	2.3 – 4.4	2.8 – 7.4
Natural Gas	410 – 1,100	0.8 – 2.2	0.0 – 0.4
Petroleum	810 – 846	1.9 – 2.2	4.1 – 5.9
Nuclear	-	-	-
Hydroelectric	-	-	-
Geothermal	-	-	-
Biomass	0 – 600	0.1 – 0.6	0.6 – 2.0
Wind	-	-	-
Solar	-	-	-
IGCC	870 – 1,000	0.1 – 0.4	0.1 – 0.7
Transmission	-	-	-
Distribution	-	-	-

These quantities need to be converted into tons per dollar, since the model is economic, using electricity costs. This is a problematic exercise when dealing with a process – generation of electricity – which has costs that are very subject to fuel price fluctuation. An emission factor in tons/GWh converted to tons per dollar at an electricity cost of $0.02 per kilowatt-hour is going to be very different than one based on a cost of $0.06 per kilowatt-hour. Rather than choosing a “conversion rate”, a range of costs, shown in a previous section in Table 8, was used, meaning the range of per dollar emission factors is wider than the corresponding range for the tons/GWh rate.

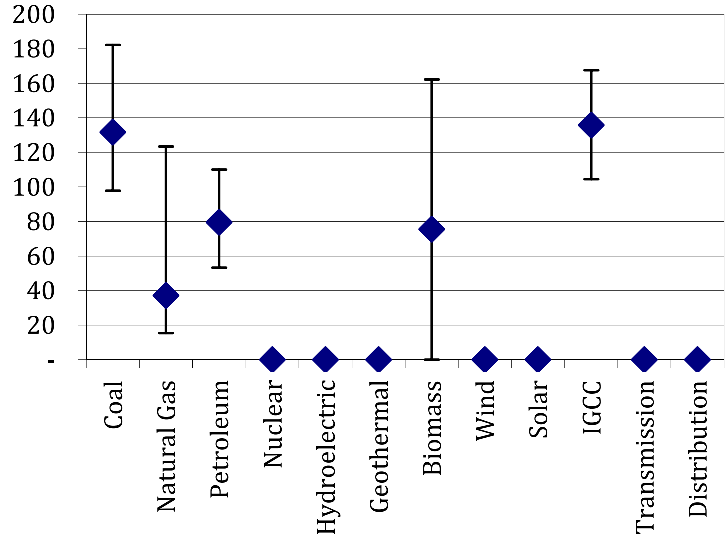

Figure 32: CO_2 Emission rate average and range, in lbs/$

Figure 32 shows the carbon dioxide emission rates for each new electricity sector in pounds per dollar. The uncertainty is apparent – CO_2 from a natural gas plant could be anywhere from 18 lbs/$ to 125 lbs/$, with an average of around 35 lbs/$. The good news is that there is very little uncertainty about the direct CO_2 emissions from nuclear, hydroelectric, geothermal, wind, solar or transmission and distribution, since there are no pollutants emitted during the operation of those sectors.

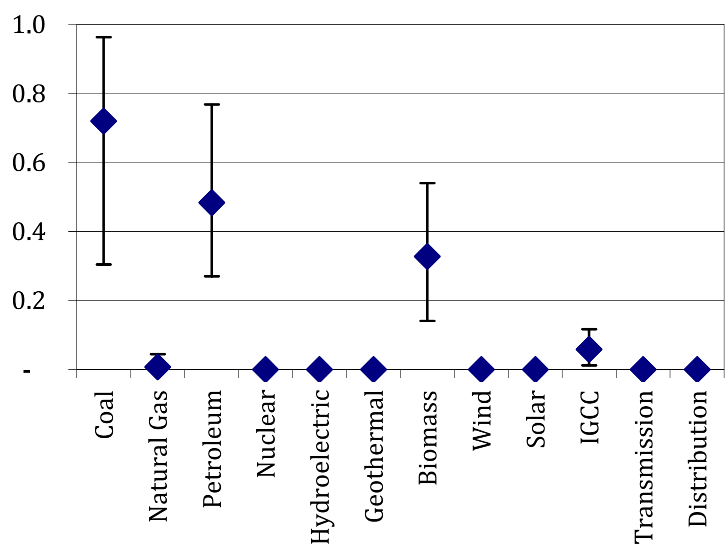

Figure 33: SO_2 Emission rate average and range, in lbs/$

The sulfur dioxide emission rates are show in Figure 33. Ranges here are just as large, percentage wise as those for carbon dioxide. The gasification process for coal removes most of the sulfur from the fuel stream, so although the same types of fuel are being used, the value is significantly lower and less uncertain than that for a pulverized-coal plant.

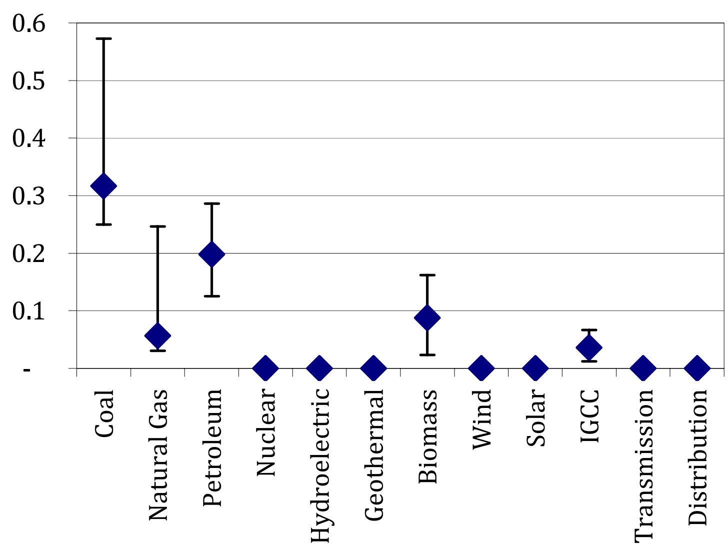

Figure 34: NO_x Emission rate average and range, in lbs/$

The nitrous oxides emissions are similarly uncertain, as shown in Figure 34.

The construction sectors need emission factors as well to represent the release of carbon dioxide, SO_x and NO_x from the operations on site. Absent any better information about how emissions at power plant construction site are different (on a ton per dollar spent basis) than those for other construction projects, we use a range based on existing heavy construction sector emission factors already developed for use in EIO-LCA. Those ranges are summarized below in Table 19.

Table 19: Construction Emission Factors, in lbs/$

	Average	*Low*	*High*
NO_x	0.0014	0.0032	0.0085
SO_2	0	0	0

CO_2	0.4876	0.8462	1.7544

These values will be applied to the amount of final demand spent to construct whatever generation asset specified and added to the output generated by the supply chain purchases.

The values for any emission factor could be changed, or the ranges reduced, depending on the types of assumptions that are made, and the model framework is meant to be flexible to allow this to happen. More emission factors could be added, as well, if we are concerned about a particular pollutant not accounted for here; the only limit is whether or not the data could be collected, not only for the power generation sector, but for all the other sectors of the economy as well.

3.4.5 Total Requirements Matrix

With all the data gathered, the process of "building" the model begins. This sector briefly walks through this process. Code, in both C++ and MATLAB script formats, is included in the Appendix. The final product will be a new total requirements matrix, which is the primary component of the Leontief equation discussed in section 1.2.2. This matrix will be an approximately 500 by 500 table where each entry is the fraction of a dollar's worth of commodity 'x' needed to produce a dollar's worth of output for sector 'y'. The new matrix will obviously include the disaggregated electricity sectors, their purchases, and all other sector's purchases of the split up electricity.

The basic building blocks, as stated earlier, are the original make and use tables, available from the Bureau of Economic Analysis. These tables are available in comma separated text files, so all initial manipulation is done in text editors and in Excel. They are flattened matrices, so the format is generally: Sector 1, Sector 2, value; where Sector 1 and 2 are the indices in the matrix, and "value" is the entry at that cell.

The first step is to strip these files of all references to the single Power Generation & Supply sector, since it will be replaced by the new supply chains created above. Then, the new supply chains, also in "flattened" form, are appended to the end of the truncated original files. Various support files are created as well, such as names for all the sectors, the emission factors for each emission type and sector, etc.

These files are all read into MATLAB using the script included in the Appendix. Originally an attempt was made at doing the matrix creation and manipulation in C++, but while the creation of the make and use matrices from the flattened files was easy enough, doing matrix inversion and multiplication was significantly more difficult, and the attempt was eventually abandoned. It should be noted, however, that a more experience programmer with knowledge of C++ matrix manipulation libraries could create a tool which ran in significantly less time than the eventual, and current, MATLAB script method. Both the C++ and the MATLAB code are included in Appendices F through J.

The process the BEA uses to create the matrix from the raw make and use tables is detailed in the documentation which accompanies the downloaded tables.[77] It basically involves normalizing the values in the make and use tables with the total output of each sector, then multiplying them together and inverting the product. The details are actually much more complicated, as there are special provisions for the "Value Added" sectors and for the scrap sectors. The completed MATLAB code can – without additional sectors added – recreate the downloadable version of the total requirements matrix to within very high tolerances. For all intents and purposes, even the purposes of creating an engineering model, the matrices are the same.

To "run" the model, an additional vector or set of vectors is created to model the final demand of the scenario being run. This could be some future amount of kilowatt-hours of electricity demand converted to dollars, or a life-cycle assessment of a $200 million purchase from the aircraft manufacturing sector, or some combination. This vector, and the vector of emission factors are multiplied using the Leontief equation to create the total and direct economic and environmental activity generated as a result of the final demand purchase entered.

3.5 Verification, Uncertainty & Sensitivity

This section contains the process used for verifying the model inputs and results, and for assessing the uncertainty and sensitivity associated with various parameters in the model.

3.5.1 Verification of Inputs and Results

Most of the inputs to the model are based on data gathered and verified by other parties. Many assumptions, such as allocating the majority of the operations supply chain using a cost-based method, were made because data didn't exist in the form needed. That data still doesn't exist, so it can't be used to verify the inputs. In some cases, similar data does exist, but it is necessary to make assumptions to make a direct comparison. There is uncertainty associated with these assumptions, so the power of the verification is lost.

Verification of outputs is slightly easier, because we can look to make sure, for instance, that the direct carbon dioxide emissions from natural gas plants is close to the value collected by the EPA in a given year. Attempting to forecast the future would make finding validation data more difficult as well.

Where verification values can be found, comparisons are made along with the corresponding results in Chapter 4.

3.5.2 Uncertainty

There is uncertainty inherent in the original BEA input-output model. This uncertainty comes from the survey data, and the process of aggregating it into sectors. And although we are disaggregating the electricity sector, there is still uncertainty about where we are making those cuts. For instance in an economic input-output model, low-price long-term contracts for something like hydroelectric power should be treated separately from standard residential consumption of the same type of power, but it is not. Additional uncertainty is then added at every step of the disaggregation process, whenever outside data is added, or assumptions made.[57]

At each of these steps, we have used likely ranges of values, tracking the uncertainty along with each input. Whenever outputs are calculated with the model, we have used the full range as an input to produce a range of outputs. These ranges are reported along with the results in Chapter 4. Additionally, there is some qualitative assessment of uncertainty done with each scenario.

3.5.3 Sensitivity Analysis

Because of the complexity of the model and the multimodal process to create the output, it is difficult to create an automated sensitivity analysis process, i.e. hold all other things equal and change each input continuously within its possible range and see how much the answer changes.

Instead, sensitivity analysis is done on the most important of the input parameters only, and the values are changed in discrete increments and the outputs monitored. Because of their connection to both the allocation of the operations supply chains and the conversion of the emission factors, the electricity costs are highlighted as the most sensitive parameters in the model.

Scenario input parameters, such as amount of new construction, or the generation mix used, are assumed not to need sensitivity analysis, since there is no base case to compare a scenario to.

4 Scenarios, Results & Conclusions

This final chapter includes the set up and results of scenarios run using the model constructed as described in Chapter 3. It also includes a discussion on the limits of the model and disaggregating a sector within this framework. Some overall conclusions from this body of work are drawn, and the original research questions laid out for this work are revisited.

4.1 Scenarios

There are an infinite number of scenarios that can be run with the framework as it exists. The model is capable of handling drastic restructuring of the industry and still produce reasonable results without affecting the rest of the economy. Of course, it can be argued, that in fact the changes *will* occur and this model will not reflect them. Those concerns will be address later in this chapter. The scenarios shown here were developed to provide insight into the model's operation and confirm some major assumptions.

4.1.1 Emissions & Economics of Power Generation in 2005

The first scenario presented here is a recreation of the electricity generated in 2005, and the operations in the industry required to produce and deliver it. It assumes the fleet of generation assets is static during that period and that the megawatts delivered were produced as specified by the 2005 Electric Power Annual published by the Department of Energy.

To model this scenario, the aggregated electricity sector was split into 11 separate sectors, nine for generation and two for power supply. Table 20 shows those sectors and some other assumptions made as part of this scenario.

Table 20: 2005 Electricity Production Scenario Average Assumptions[1]

Sector	*TWh*	*$/kWh*	*$Trillion*
Coal	2,014.2	$0.017	$34.0
Nuclear	780.5	$0.007	$5.7
Natural Gas	767.2	$0.031	$24.2

Hydro	258.5	$0.009	$2.4
Petroleum	121.9	$0.021	$2.5
Biomass	61.8	$0.008	$0.5
Geothermal	15.1	$0.010	$0.2
Wind	14.6	$0.007	$0.1
Solar	0.5	$0.010	$0.1
Transmission			$5.2
Distribution			$4.4
Total	4,034.3		$76.4

In the table, the published megawatt-hours – a little over 4 trillion kilowatt-hours – are converted to purchases from the operations sectors using the operations costs discussed earlier. Shown here are the average costs, although the high and low prices were used in calculating the uncertainty of the model. Most of the assumptions described in Chapter 3 are included in this scenario, such as the methods of allocating the supply chains, other sectors' purchases of electricity, and the way the intersections of the make and use tables are handled.

A final demand vector with the appropriate dollar amounts was used along with the emissions vector (actually three emissions vectors, for high, low and average) and the total requirements matrix built from the make and use tables were combined to produce three sets of environmental and economic output.

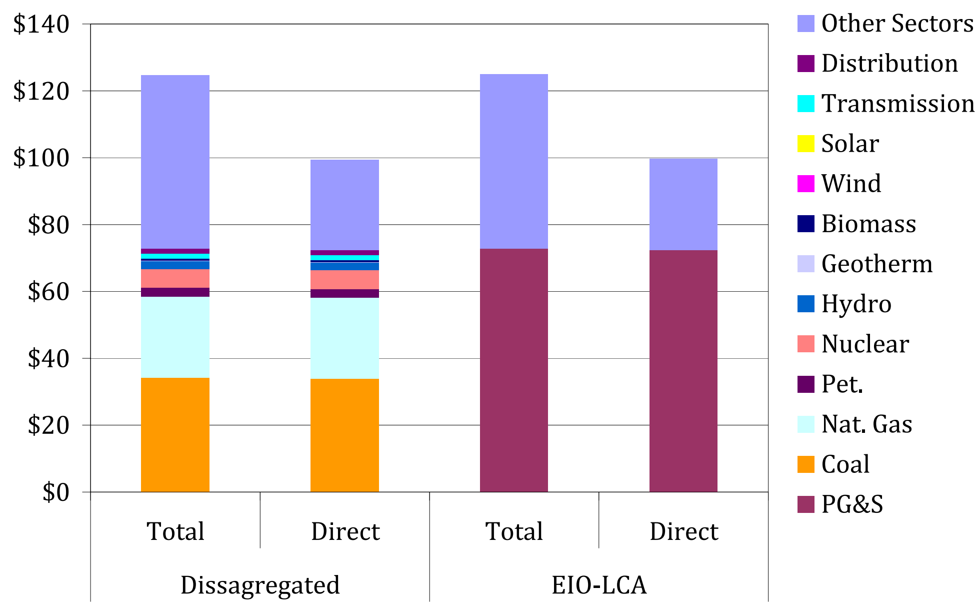

Figure 35: Economic comparison for 2005 generation, in $billions

Figure 35 shows the summary economic results for the disaggregated model and, for comparison, a similar run through the aggregated EIO-LCA model for the 1997 benchmark year, available via the internet. The most basic result is that both the total and direct columns produced the same answer to within a few dollars. This, if nothing else, is a verification that the math is done correctly throughout the model: if the same total final demand is plugged in, the same values are pushed out the other side. It can also be seen that the values for the Power Generation & Supply sector (disaggregated for our model, and aggregated for EIO-LCA) have the same totals as well.

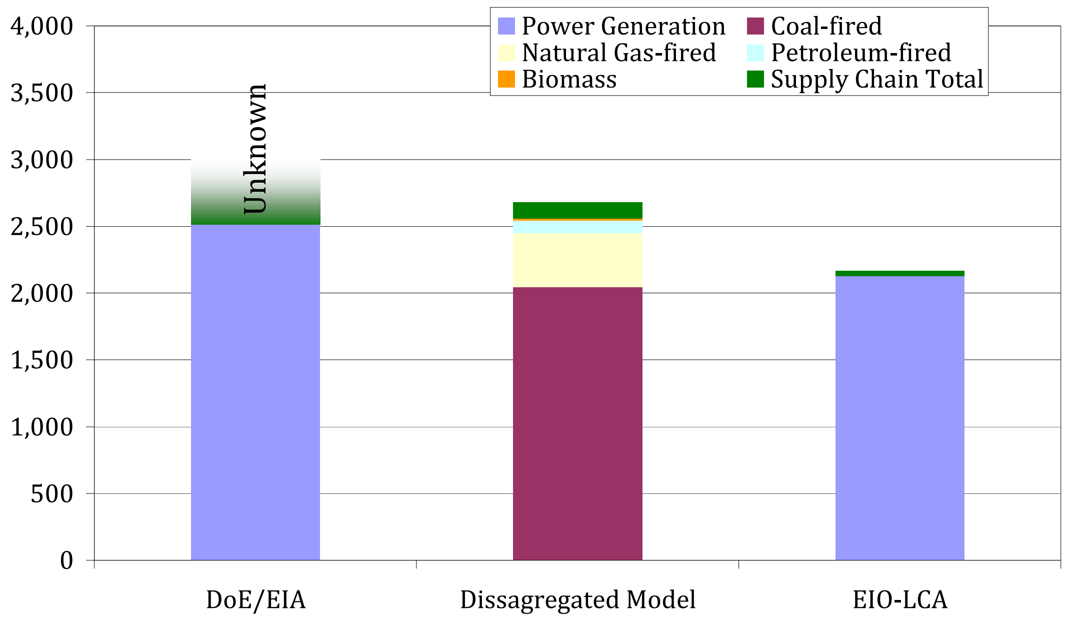

Figure 36: CO_2 Total Emissions from 2005 Generation, million MT

In Figure 36 the CO_2 emissions from our disaggregated model are compared to the emissions from the comparison run of EIO-LCA and to the Department of Energy's estimated total emissions for 2005 from the Electric Power Annual. Because the DOE does not collect information about the emissions from the suppliers of the utilities, we are not able to compare those values. However, the direct emissions from our model compare favorably to the DOE total of about 2.5 billion metric tons of carbon dioxide. The disaggregated model is about 2% higher when the output of biomass, natural gas, petroleum and coal plants are combined. This difference could be due to the assumption that biomass is not carbon neutral in our average case. EIO-LCA is undercounting emissions compared to the DOE and our model. The DOE does not report life-cycle emissions so the "Unknown" portion signifies the unknown magnitude of the life-cycle impacts.

Although it is not indicated on the graph, there is significant uncertainty associated with this result. The output could range between 21% lower or 18% higher – an uncertainty mostly due to the wide range on the emission factors for natural gas plants.

The results are similar for the NO_x emissions for the 2005 scenario, though our average value is well above the direct emissions estimate from the DOE.

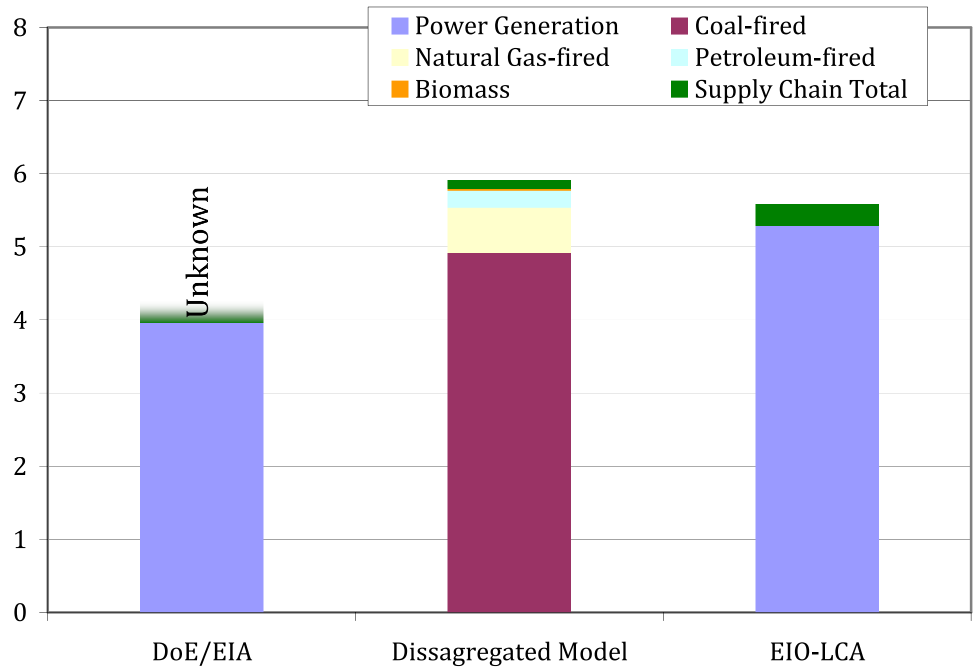

Figure 37: NO_x Total Emissions from 2005 Generation, million MT

Figure 37 shows these results for NO_x. Here, the values from EIO-LCA are much closer to our results, making the discrepancy with CO_2 shown earlier (and the subsequent discrepancy shown for sulfur dioxide) more unusual. However, given some conclusions we will make about estimating ton/$ emission factors for commodities with volatile prices, the difference is not surprising.

And again, there are significant uncertainties associated with these results. The emitted NOx could range from 26% lower to 15% higher.

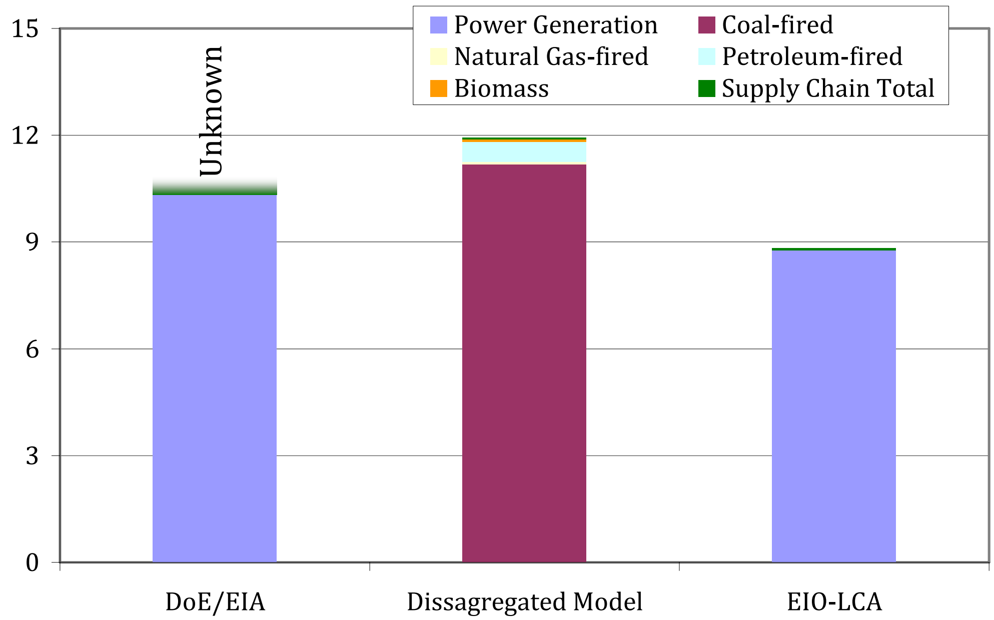

Figure 38: SO_2 Total Emissions from 2005 Generation, million MT

The sulfur dioxide results are shown in Figure 38. Our value is about 10% higher than the DOE estimate, and almost 25% higher than the results from EIO-LCA. It is interesting that there are almost no SO_2 emissions from the supply chain, even with all the rail transportation and oil and gas extraction. The uncertainty ranged between 27% lower and 18% higher.

4.1.2 Carbon-free Future? IGCC and Wind in 2040

This scenario looks at the operations of a hypothetical future electricity generation system. This system takes advantage of the large amounts of coal available in the United States and Canada for power generation, but acknowledges that the carbon dioxide contained in that fuel needs to be kept out of the atmosphere.

The DOE-projected electricity demand, which is based on a 1.5% growth rate between 2006 and 2040 was 6,162 TWh. It was assumed that 70% of this demand would be met with IGCC power plants with carbon capture and sequestration technology included, and 30% with wind turbines. It is unlikely that our electricity system will have this little diversity unless there is some overwhelming economic or policy reason. It is far more likely that our society will meet our carbon goals with a diverse portfolio of fuels, technologies, and policies. But the 70/30% is a scenario, not a forecast. Also, viable location, reliability and feasibility of carbon sequestration process are assumed.

To complete this scenario, the construction of these assets was modeled as well. Using a 30% capacity factor over 500,000 MW of wind turbines would be needed, and some 12,000 loop-miles of additional transmission capacity would need to be installed as well to deliver this power from presumably remote wind farms to distance demands centers. At an 85% capacity factor for the IGCC plants, over 500,000 MW of IGCC plants are needed as well. The overnight capital costs for an average n-th of a kind wind turbine are $875/kW and $1700/kW for the IGCC plants with carbon capture. The 12,000 loop-miles are charged at $130,000 per loop-mile. These are the estimates from DOE projections.

This is a total of almost $1.2 trillion to produce all the infrastructure necessary for our scenario, or, with a 2% inflation assumption, $1.6 trillion in 2040. Likewise, our assumed electricity operations costs of $.007/kWh for wind become $.015/kWh in 2040, and the $.017/kWh becomes a $0.34/kWh cost. Note that this price is higher than the non-CCS IGCC plant operation to account for the increased amount of input energy necessary to overcome the inefficiency of the CCS process. This will mean over $170 billion in electricity costs spread across IGCC, wind, transmission and distribution operations sectors.

A cost-weighted allocation was calculated to create new supply chains and make tables for the IGCC and wind sectors. Coal-related sectors such as coal mining and rail transportation were allocated 100% to IGCC. Sectors which had been allocated to natural gas and petroleum plants were removed from the supply chain and the dollars were spread throughout the supply chain to increase its value accordingly. Other sectors were assumed to use electricity in proportion to the amount they generated, with no other specific differentiation.

The carbon capture process on the IGCC plants is expected to be 90% efficient, so at 4313 TWh of electricity produced with coal, we would still expect to see a large amount of carbon emissions from those plants.

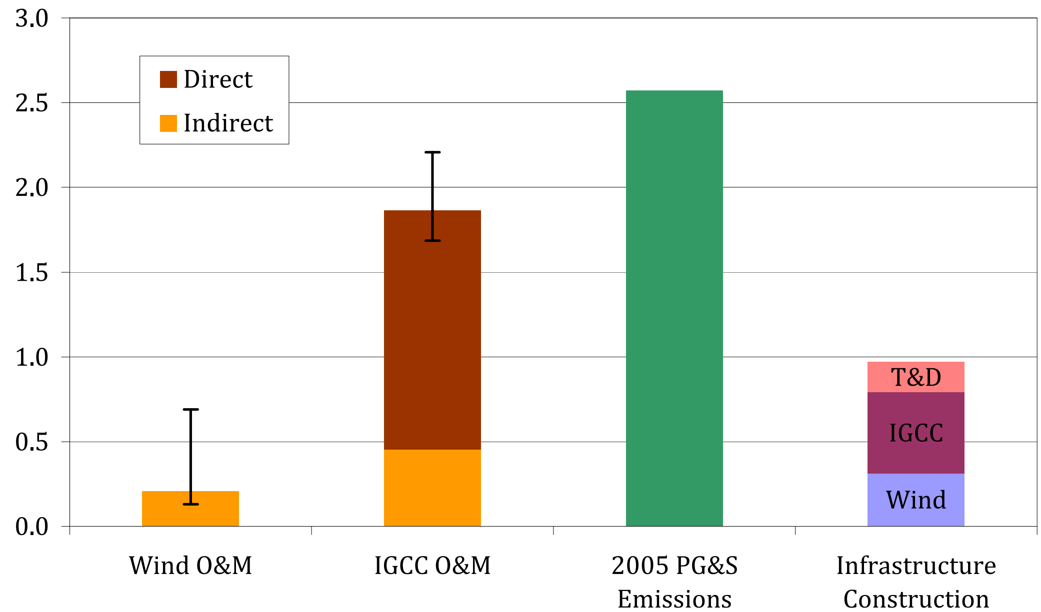

Figure 39: CO_2 from power generation in 2040, in billion MT

Figure 39 shows that this is true: about 1.9 billion metric tons of carbon – or close to the total from 2005 – was emitted from the IGCC plants despite the carbon capture. Add on to that the carbon emitted during the construction of the plants (over a period of 35 years), and the CO_2 emitted by the other sectors during the operations phase, and the total carbon emitted was 4.2 billion metric tons – just for power generation. There is some uncertainty associated with this process, which is indicated in Figure 39. This is obviously only indicative of uncertainty generated by the model, and not uncertainty of the scenario assumptions.

At first glance, these results would make it seem that IGCC is off the table as a piece of the low-carbon future. Even with very high values of carbon capture, the amount of carbon released by IGCC plants directly and from the direct and indirect supply chains is large enough that Kyoto-like carbon limits are unattainable unless there is significant control and regulation of carbon throughout the supply chain. It is much harder to control the carbon from a coal mine than a power plant. But in fact, much of the carbon emitted – even through direct and indirect purchases through the supply chain – are from electricity generation. And while the total CO_2 from 2040, even with an aggressive 85% carbon capture in place, is still greater than the 2005 amount from PG&S, much of this is emissions from power plants rather than upstream from the supply chain.

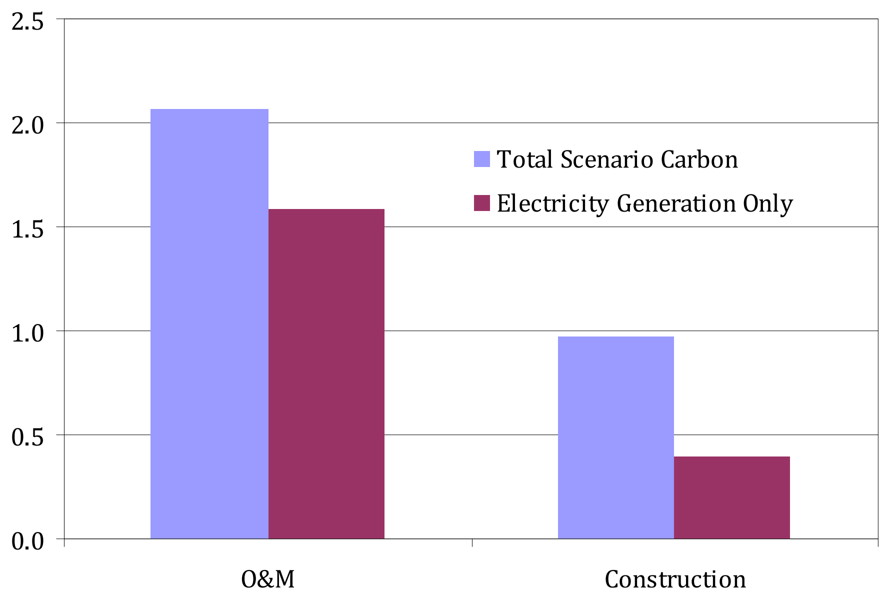

Figure 40: CO_2 from 2040 scenario, separating carbon from electricity generation, in billion MT

Figure 40 shows these results – the total carbon emitted from both construction and operations and maintenance, as well as the carbon generated from the electricity generation only. It is surprising that about 70% of the O&M carbon comes from power generation. With carbon capture installed, and coal mining and rail transportation both emitting a significant amount of carbon, one would expect that this percentage would be lower. A lower percentage would have necessitated supply chain carbon control.

4.2 Limits of Disaggregation

In the course of building and using this model, significant limits of the process became apparent. In this section, we will detail some of those limits and their implications.

The first and perhaps most important limit is the lack of detail in the base input-output model. Although the 500-sector provides more granularity than most economic input-output models available, there are still significant gaps. Perhaps this should have been obvious: as has been pointed out, the power generation industry has only a single sector. It is likely that other processes or products will not have the detail expected either.

Photovoltaic panels of all types are included in the sector 334413, "Semiconductor Manufacturing". This means that a purchase from this sector could be a PV panel, or a computer chip. Nuclear fuel enrichment and reprocessing are both included in sector 325180, "Other basic inorganic compound manufacturing", which includes dozens of other processes including some as benign as the manufacturing of iodine. The handling of radioactive materials and hazardous waste reside in a sector alongside garbage collection. Rather than having a separate sector for the carefully shaped advanced carbon-fiber materials used to build large-scale windmills, all turbines are included in a single sector: 333611, "Turbines and turbine generators." This includes hydroelectric turbines, gas turbines, and huge 800MW steam turbines.

One of the goals of this work was to look for supply chain "hot spots" – areas where new large demands from increased electricity use were causing problems that were not noticeable at small levels of economic activity. But without granularity in electricity-specific suppliers, these hot spots are limited to fossil-fuel burning industries like transportation, mining, construction and manufacturing.

In order to implement a more effective model, it might be necessary to create more new sectors to better model the items we want to model. At this level of aggregation, with economy-wide scenarios, it is not even clear what impacts are being over or under represented. An analysis would be need to be structured to find those important areas. There would be concerns about where to end this effort, as well – a reintroduced boundary issue to life-cycle assessment.

The second limitation is more of a limitation on the user than of the model. Our original criticism of models like MARKAL and NEMS and to a certain extent, IECM, was that they were too complex for LCA practitioners to access. However, in retrospect, this model requires just as much knowledge to operate – unless a very simple assessment is being done.

Instead of being able to simply provide a set of operations and construction sectors, decisions need to be made about issues as complex and uncertain as fuel heat rates, plant lifetimes, and learning curves. This uncertainty becomes greater as the user moves away from the present and into the future. The quality of the output is almost entirely dependent on the quality of the inputs.

The next limitation is model's lack of response to "large" changes in the economy relating to "chokepoint" sectors. Large changes are relative, of course. With a national GDP in excess of $8 trillion (it is currently $12.5 trillion), it is difficult to come up with any realistic purchase or investment large enough to trigger anything close to even a 1% change in the economy. However, the model will not respond if demand for a commodity or service increases beyond the ability of that sector to supply it. Railroad transportation is a consistently cited example from energy studies. In the 70% IGCC scenario, a significant issue is crowding on the country's rail system. A scenario like that might realistically require investment in new rails and engines. This investment might in turn requirement the growth of another sector beyond its current ability. While labor isn't accounted for explicitly in the model, there is an expected shortage of power engineers approaching as the current workforce ages and retires. Rapid growth might be limited by labor as well.

The final limitation of this model is the fundamental connection in an economic and environmental model between quantity of pollutants and dollars spent in a sector. Especially for volatile commodity sectors like fuel, where emissions are tied to the quantity of the commodity purchased and consumed and *not* the dollars spent on it, this connection causes problems. Imagine a quantity of coal is purchased one year, and the emission factor, in tons of carbon per dollar is perfect for that year. The amount of money spent on the tons of coal will create just the correct amount of greenhouse gases, and that purchase creates just the right amount of demand for coal miners, trains, diesel fuel, etc.

Now, in the next year, the price of coal goes up by 15%. The higher amount of money goes in to purchase coal – conceivably the same amount of coal – yet in the model, it seems that more coal has been purchased, more carbon produced, and more demand created for coal miners and headlamps. One solution is to create a "new" economy every year which is reallocated based on the latest commodity prices. The other solution, and one currently being explored, is a mixed-unit model where both dollars and tons of a commodity are tracked.[100]

4.3 Research Questions and Contributions Revisited

In this section, we look at the original research questions asked, and the predicted contributions of the work which would answer them. The contributions are updated or discussed.

1. *How can future electricity scenarios be modeled using data currently available?*

   Life-cycle assessments of both the operation and construction phases of future electricity scenarios, including full supply chain detail; analysis of potential future electricity scenarios, and their associated policy implications; a tool to create economic input-output LCA input data from new sector supply chains;

generation-type specific electricity detail for life-cycle assessments of all other product and services analyses

The model described here is an answer to this question, and the proposed contributions have all been finished. There is a bit of optimism in the contributions – the development and use of the model were much more complex than originally anticipated and the sense that *all* electricity questions would be answered was not satisfied.

2. What power generation technologies would be involved?

An assessment of viable and interesting current and advanced power generation methods

Creating the current set of technologies took a significant portion of the effort, and there is a limited set of viable future technologies. Many of these are varieties of existing types, and not distinguishable at this level of aggregation from the existing versions. An advanced nuclear plant like an AP-1000 is really only distinguishable from existing nuclear plants built in the 1970s by the estimated operations and construction costs. Certainly the plant designs are different and different equipment will be included, but it is really a reallocation of the standard construction materials sectors: steel, concrete, copper, turbines, etc. This is true for IGCC plants and their differences from existing coal and NGCC plants, and new large wind turbines compared to older versions.

The goal of the proposed assessment was to establish some measure of viability, but that point became moot because of the lack of granularity outside of cost and emissions estimates.

3. What do the future electricity scenarios look like?

Unlimited scenario creation ability, and quick and easy modification of these scenarios

While there is certainty the ability to create unlimited – in fact infinite – scenarios, creating them and modifying them is more labor and knowledge intensive than anticipated.

4. *How can the economic contributions and environmental emissions of electricity be allocated to disaggregated electricity industry sectors?*

   A flexible framework which allows for the addition of new generation technologies, their supply chains and their emission factors, as well as the easy updating of existing data; framework allows for the addition of sectors which are indirectly related to power generation and supply, such as construction and fuel production and delivery

The methods described in Chapter 3 are in fact a flexible framework which allows for the addition of new data, though it is perhaps more flexible and requires more data than is indicated by this proposed contribution. The final point, that the framework would allow for tangentially-related sectors to be added gets at a solution to the one of the major limitations discussed earlier, namely the lack of detail in the model.

5. *What are the uncertainties, issues and policy implications of using this model?*

   Method for estimating and evaluating input uncertainties in the disaggregated electricity model

The brute force method of driving input uncertainties through the model to the outputs is effective, if inelegant. It also assumes uncertainties are additive, when a good portion of them might be overlapping, meaning that estimates of uncertainties are larger than they might be if a Monte Carlo type of analysis could be run.

The source of much of the uncertainty in the model comes from the conversion of emission factors from tons/kWh to tons/$ by means of the electricity price. Future versions of the model should strive to reduce this uncertainty by using a mixed-unit model. As it is, the model is good at showing the relative scale of emissions between various generation types and distinguishing between electricity generation and supply chain emissions. Care should be taken when trying to look too far into the future, as assumptions are needed about operations costs in addition to technology and fuel prices.

4.4 Conclusions

Despite the limitations of the model described above, we can still draw some interesting conclusions from this work. This section contains these conclusions.

The first conclusion is that disaggregation does matter. As shown in Chapter 2, despite the problems with this implementation, splitting coal generation from hydro or nuclear or wind, etc. is going to make a large difference if the LCA practitioner picks a particular profile of generation. And, as shown in Chapter 3, and the first section of this chapter, if uncertainties about fuel prices are handled disaggregation allows for more accurate assessments of future scenarios.

This work confirms the importance of supply chains – particularly the environmental impacts associated with supply chains – when making decisions about future energy sources. While the impacts of combustion can be controlled at the smokestack of fossil fuel plants, there are no similar controls on the suppliers to those plants. Supply chain control may be the new low hanging fruit of environmental control.

When this work was first proposed, there were visions of it being a fundamental new data source which would provide invaluable information to LCA practitioners and policy makers. And if its limitations are understood, it has the potential to be a useful model. But it is not a tool in the sense that it can be used simply for easy tasks. Like all models, it demands an understanding of its flaws. Electricity is very much a critical sector of the economy and for the environment and deserves special attention.

If asked by an LCA practitioner or policy maker to choose a version of the model for them to use, I would suggest a simple form of the disaggregated model, or at the very least, to use both and compare the results. There is a significant user burden to using the model – more than was originally anticipated. Extensive knowledge about the electricity system and the model are required for the results to be meaningful.

Previously, in the 500 sector input-output model of the US economy, power generation and supply were aggregated into a single sector. By contrast, so were the impacts associated with tortilla manufacturing, or household laundry equipment. A very diverse set of technologies and supply chains were represented in this single electricity sector. Comparing a kWh of electricity generated with hydro power to a kWh generated using coal power is difficult when the economics and emissions involved are so different. The model and results described by this work can, with the right amount and types of assumptions, provide a new level of economic and environmental detail to decision makers, tied to the very simple metric of dollars with full supply chains accounted for as well.

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Appendix A: Original Distance Matrix (Chapter 2)

Importers (columns); Exporters (rows)

	AR	CA	CN	CO	DC	DE	FL	GA	IA	ID	MA	MD	ME	MI	MN	MO	MS	MX	NC	NJ	NY	OH	OR	RI	TN	VA	WI
AL	352	1904	1911	1138	683	759	388	174	743	1667	1041	702	1266	792	1010	503	168	1270	465	836	926	535	1984	1032	208	561	839
AZ	1151	447	1931	500	1980	2060	1820	1664	1145	675	2249	2001	2386	1582	1260	1163	1329	1020	1884	2104	2056	1663	795	2265	1478	1900	1373
CA	1554	0	1912	802	2326	2402	2248	2070	1443	595	2559	2347	2664	1863	1477	1519	1745	1438	2263	2437	2358	2000	506	2580	1862	2259	1637
CN	1745	1912	0	1509	1654	1672	2254	1961	1247	1350	1566	1655	1465	1149	933	1507	1902	2579	1818	1594	1370	1460	1523	1610	1714	1709	1097
CT	1164	2519	1577	1726	294	225	1055	852	1076	2075	65	277	306	673	1107	1049	1105	2129	549	144	180	548	2398	130	838	419	904
IL	379	1649	1398	846	677	754	880	585	259	1283	945	698	1106	373	501	161	482	1389	646	795	759	353	1612	957	326	614	336
IN	490	1834	1429	1032	491	567	810	504	419	1454	765	512	939	304	597	336	522	1488	487	609	586	167	1783	775	279	435	389
KS	439	1161	1505	363	1175	1253	1162	934	371	886	1443	1196	1590	799	597	359	648	1077	1102	1297	1252	855	1200	1457	706	1100	621
KY	440	1902	1601	1101	456	538	644	338	541	1563	783	478	986	462	753	383	407	1415	367	598	633	207	1891	785	135	364	552
LA	247	1648	2006	938	999	1079	602	503	756	1500	1351	1019	1566	969	1051	510	183	827	797	1152	1216	791	1798	1347	455	882	936
MT	1222	875	1063	575	1715	1777	1929	1665	845	286	1860	1733	1912	1165	728	1044	1428	1711	1745	1789	1658	1401	572	1889	1410	1688	936
MX	1006	1438	2579	1141	1825	1908	1273	1317	1460	1633	2184	1838	2397	1748	1682	1196	1010	0	1622	2004	2080	1629	1798	2176	1291	1723	1629
ND	976	1229	878	631	1315	1372	1628	1341	503	685	1441	1331	1492	752	313	744	1164	1707	1373	1378	1240	1012	992	1471	1081	1299	530
NE	609	1133	1305	351	1201	1274	1315	1059	309	755	1426	1221	1543	737	433	440	813	1274	1177	1305	1226	875	1082	1446	810	1147	523
NH	1267	2557	1505	1775	436	375	1207	994	1120	2086	100	421	158	694	1109	1127	1227	2241	697	293	209	640	2403	139	955	560	923
NM	778	805	1820	323	1629	1710	1445	1289	850	804	1917	1651	2072	1282	1030	817	953	842	1518	1760	1731	1320	1036	1929	1110	1542	1096
NV	1400	246	1676	619	2125	2199	2113	1912	1231	354	2342	2145	2437	1641	1243	1333	1601	1469	2082	2229	2139	1799	366	2364	1690	2066	1412
OK	296	1258	1697	508	1151	1233	1003	812	502	1067	1457	1173	1630	880	773	365	490	905	1031	1288	1280	854	1367	1465	624	1059	746
PA	903	2267	1504	1469	146	170	896	648	826	1844	320	150	523	457	895	785	860	1868	386	172	181	283	2170	327	587	236	680
SC	645	2188	1904	1398	404	468	386	170	879	1888	759	419	997	631	1088	694	496	1482	146	550	689	425	2214	742	327	282	880
SD	781	1160	1102	460	1242	1308	1462	1187	360	689	1421	1261	1507	717	319	571	978	1480	1260	1327	1218	923	1016	1446	929	1208	485
TX	479	1252	2007	656	1370	1452	1029	928	821	1214	1702	1391	1894	1180	1090	657	587	582	1202	1517	1540	1105	1476	1704	814	1263	1062
UT	1101	486	1593	322	1841	1916	1815	1612	957	378	2074	1862	2184	1380	1011	1039	1302	1266	1787	1951	1874	1515	590	2094	1392	1777	1157
VT	1225	2498	1430	1718	421	369	1199	973	1063	2024	133	408	192	634	1048	1077	1194	2216	685	290	162	597	2341	175	920	542	863
WA	1687	718	1325	938	2231	2292	2408	2158	1355	371	2367	2248	2405	1677	1238	1538	1896	1991	2256	2302	2166	1916	212	2397	1908	2202	1450
WV	702	2138	1598	1335	194	276	706	436	723	1759	526	216	742	461	862	624	642	1655	234	335	400	155	2088	524	373	132	643
WY	1029	719	1238	291	1662	1733	1752	1514	763	296	1862	1682	1953	1159	759	903	1238	1453	1645	1758	1659	1337	616	1886	1272	1613	929

Appendix B: Modified Distance Matrix (Miles)

Importers

Exporters		E	W		W	E	E	E	E	E	W	E	E	E	E	E	E	E		E	E	E	E	W	E	E	E	E
		AR	CA	CN	CO	DC	DE	FL	GA	IA	ID	MA	MD	ME	MI	MN	MO	MS	MX	NC	NJ	NY	OH	OR	RI	TN	VA	WI
E	AL	35	1904	1911	1138	68	76	39	17	74	1667	104	70	127	79	101	50	17	1270	47	84	93	54	1984	103	21	56	84
W	AZ	1151	45	1931	50	1980	2060	1820	1664	1145	68	2249	2001	2386	1582	1260	1163	1329	1020	1884	2104	2056	1663	80	2265	1478	1900	1373
W	CA	1554	0	1912	80	2326	2402	2248	2070	1443	60	2559	2347	2664	1863	1477	1519	1745	1438	2263	2437	2358	2000	51	2580	1862	2259	1637
	CN	1745	1912	0	1509	1654	1672	2254	1961	1247	1350	1566	1655	1465	1149	933	1507	1902	2579	1818	1594	1370	1460	1523	1610	1714	1709	1097
E	CT	116	2519	1577	1726	29	23	106	85	108	2075	7	28	31	67	111	105	111	2129	55	14	18	55	2398	13	84	42	90
E	IL	38	1649	1398	846	68	75	88	59	26	1283	95	70	111	37	50	16	48	1389	65	80	76	35	1612	96	33	61	34
E	IN	49	1834	1429	1032	49	57	81	50	42	1454	77	51	94	30	60	34	52	1488	49	61	59	17	1783	78	28	44	39
E	KS	44	1161	1505	363	118	125	116	93	37	886	144	120	159	80	60	36	65	1077	110	130	125	86	1200	146	71	110	62
E	KY	44	1902	1601	1101	46	54	64	34	54	1563	78	48	99	46	75	38	41	1415	37	60	63	21	1891	79	14	36	55
E	LA	25	1648	2006	938	100	108	60	50	76	1500	135	102	157	97	105	51	18	827	80	115	122	79	1798	135	46	88	94
W	MT	1222	88	1063	58	1715	1777	1929	1665	845	29	1860	1733	1912	1165	728	1044	1428	1711	1745	1789	1658	1401	57	1889	1410	1688	936
	MX	1006	1438	2579	1141	1825	1908	1273	1317	1460	1633	2184	1838	2397	1748	1682	1196	1010	0	1622	2004	2080	1629	1798	2176	1291	1723	1629
E	ND	98	1229	878	631	132	137	163	134	50	685	144	133	149	75	31	74	116	1707	137	138	124	101	992	147	108	130	53
E	NE	61	1133	1305	351	120	127	132	106	31	755	143	122	154	74	43	44	81	1274	118	131	123	88	1082	145	81	115	52
E	NH	127	2557	1505	1775	44	38	121	99	112	2086	10	42	16	69	111	113	123	2241	70	29	21	64	2403	14	96	56	92
W	NM	778	81	1820	32	1629	1710	1445	1289	850	80	1917	1651	2072	1282	1030	817	953	842	1518	1760	1731	1320	104	1929	1110	1542	1096
W	NV	1400	25	1676	62	2125	2199	2113	1912	1231	35	2342	2145	2437	1641	1243	1333	1601	1469	2082	2229	2139	1799	37	2364	1690	2066	1412
E	OK	30	1258	1697	508	115	123	100	81	50	1067	146	117	163	88	77	37	49	905	103	129	128	85	1367	147	62	106	75
E	PA	90	2267	1504	1469	15	17	90	65	83	1844	32	15	52	46	90	79	86	1868	39	17	18	28	2170	33	59	24	68
E	SC	65	2188	1904	1398	40	47	39	17	88	1888	76	42	100	63	109	69	50	1482	15	55	69	43	2214	74	33	28	88
E	SD	78	1160	1102	460	124	131	146	119	36	689	142	126	151	72	32	57	98	1480	126	133	122	92	1016	145	93	121	49
T	TX	479	1252	2007	656	1370	1452	1029	928	821	1214	1702	1391	1894	1180	1090	657	587	582	1202	1517	1540	1105	1476	1704	814	1263	1062
W	UT	1101	49	1593	32	1841	1916	1815	1612	957	38	2074	1862	2184	1380	1011	1039	1302	1266	1787	1951	1874	1515	59	2094	1392	1777	1157
E	VT	123	2498	1430	1718	42	37	120	97	106	2024	13	41	19	63	105	108	119	2216	69	29	16	60	2341	18	92	54	86
W	WA	1687	72	1325	94	2231	2292	2408	2158	1355	37	2367	2248	2405	1677	1238	1538	1896	1991	2256	2302	2166	1916	21	2397	1908	2202	1450
E	WV	70	2138	1598	1335	19	28	71	44	72	1759	53	22	74	46	86	62	64	1655	23	34	40	16	2088	52	37	13	64
W	WY	1029	72	1238	29	1662	1733	1752	1514	763	30	1862	1682	1953	1159	759	903	1238	1453	1645	1758	1659	1337	62	1886	1272	1613	929

E - Eastern Interconnect

W - Western Interconnect

T - Texas Interconnect

Appendix C: Completed Optimization, showing electricity transferred in TWh

Importers

Exporters		W	E	E	E	E	E	E	E		E	W	E	E	E	E	E	E	E	E	E	W	W		E	E	E	E	
		CA	OH	VA	FL	NY	NJ	MA	MD	CN	MN	ID	WI	MS	MI	DC	NC	TN	GA	DE	MO	OR	CO	MX	AR	RI	IA	ME	
E	WV			30.1					12.1							10.5	3.4												56.2
E	PA					9.8	17.5	13.2	3.3											6.0						2.0			51.7
	CN					7.8					13.5		11.8		10.8														44.0
W	WY	24.8										4.2																	29.1
E	AL				23.6														5.2										28.8
E	IL		11.7											6.4				7.0											25.1
W	AZ	20.1																											20.1
E	ND		1.9							12.0											3.3						1.7		18.8
E	IN		17.8																										17.8
W	NM	9.2																					3.1						12.3
W	MT									1.9		7.7										2.2							11.8
W	UT	10.2																											10.2
E	SC																6.4		0.0										6.5
E	KY																	2.1	3.1										5.2
W	NV	4.8																											4.8
E	KS													2.5											1.8				4.4
E	NH							3.0																				0.4	3.3
W	CA																							2.1					2.1
E	NE													1.9															1.9
W	WA																					1.1							1.1
E	SD																				0.4								0.4
E	LA													0.4															0.4
E	OK													0.3															0.3
E	CT							0.3																					0.3
T	TX																								0.1				0.1
	MX													0.1															0.1
E	VT							0.0																					0.0
		69.1	31.4	30.1	23.6	17.7	17.5	16.5	15.4	13.9	13.5	11.9	11.8	11.5	10.8	10.5	9.9	9.1	8.4	6.0	3.6	3.3	3.1	2.1	2.0	2.0	1.7	0.4	

E - Eastern Interconnect

W - Western Interconnect

T - Texas Interconnect

NOTE: Unshaded values are less than 1% of total electricity transferred

Appendix D: Top 10 Sectors for each Generation Type

	NAICS	Description	Coal	Oil	Gas	Nuclear	Hydro	Other
Coal	**335224**	**Household laundry equipment mfg**	81.40	0.33	1.68	12.86	2.86	0.87
	213113	Support activities for coal mining	81.08	0.76	2.82	12.23	2.53	0.58
	2121	Coal mining	79.63	0.71	3.79	12.34	2.71	0.82
	31214	Distilleries	75.06	2.88	5.90	11.50	3.03	1.63
	311221	Wet corn milling	74.71	0.71	3.29	16.80	2.89	1.60
	331111	Iron & steel mills	71.03	0.99	5.56	18.14	2.84	1.44
	333913	Measuring & dispensing pump mfg	70.84	1.27	4.70	18.76	2.61	1.82
	335222	Household refrigerator & home freezer mfg	70.72	0.59	4.07	19.21	3.53	1.87
	335212	Household vacuum cleaner mfg	69.95	0.81	9.86	16.16	1.89	1.32
	331112	Electrometallurgical ferroalloy product mfg	69.34	1.06	6.47	18.44	3.21	1.49
Gas	**333132**	**Oil & gas field machinery & equipment mfg**	41.23	1.12	43.53	10.40	1.41	2.32
	331311	Alumina refining	39.85	1.06	42.21	13.06	0.92	2.91
	32511	Petrochemical mfg	40.89	1.25	40.49	14.29	0.72	2.36
	336419	Other guided missile & space vehicle parts & auxiliary equip mfg	24.68	4.26	40.17	19.61	4.77	6.51
	213112	Support activities for oil & gas operations	43.36	1.56	39.01	10.51	2.94	2.63
	213111	Drilling oil & gas wells	44.42	1.37	37.69	11.19	2.53	2.80
	211	Oil & gas extraction	47.38	1.15	36.59	10.01	2.58	2.29
	334611	Software reproducing	38.41	2.18	35.27	14.60	6.20	3.34
	31213	Wineries	22.48	1.80	34.29	15.39	18.35	7.68
	33991	Jewelry & silverware mfg	31.39	5.62	33.14	17.68	9.05	3.12
Oil	**487**	**Scenic & sightseeing transportation**	36.77	17.31	18.38	15.45	7.59	4.51
	332994	Small arms mfg	24.88	9.07	14.51	37.17	9.31	5.06
	325312	Phosphatic fertilizer mfg	42.69	8.15	17.54	19.42	8.67	3.54
	336412	Aircraft engine & engine parts mfg	45.75	7.22	13.30	25.50	4.56	3.66
	325992	Photographic film, paper, plate, & chemical mfg	33.34	7.14	21.08	23.32	12.84	2.28
	333315	Photographic & photocopying equipment mfg	30.45	7.03	22.74	22.37	14.50	2.92
	31131	Sugar mfg	42.78	6.86	19.01	13.71	13.95	3.69
	311911	Roasted nuts & peanut butter mfg	43.76	6.66	18.88	18.30	7.36	5.04
	332211	Cutlery & flatware (except precious) mfg	42.04	6.31	14.10	25.13	9.31	3.10
Hydro	**336411**	**Aircraft mfg**	33.39	2.58	16.46	17.19	27.58	2.81
	321213	Engineered wood member (except truss) mfg	44.58	0.65	12.63	12.84	26.83	2.48
	321212	Softwood veneer & plywood mfg	35.45	1.56	19.15	14.57	26.79	2.48
	33321	Sawmill & woodworking machinery mfg	45.93	0.92	9.22	16.85	24.94	2.15
	331312	Primary aluminum production	52.17	1.51	10.34	11.87	23.02	1.09
	334119	Other computer peripheral equipment mfg	37.81	2.79	17.97	15.78	22.09	3.56
	3117	Seafood product preparation & packaging	29.32	5.57	25.02	15.48	21.15	3.46
	31141	Frozen food mfg	42.74	2.04	14.29	16.94	20.76	3.23
	321113	Sawmills	46.21	1.93	11.28	18.27	19.43	2.88
Nuclear	331423	Secondary smelting, refining, & alloying of copper	51.63	1.67	6.09	37.34	2.01	1.25
	325222	Noncellulosic organic fiber mfg	53.69	2.08	3.36	37.30	1.57	2.01
	332994	Small arms mfg	24.88	9.07	14.51	37.17	9.31	5.06
	333292	Textile machinery mfg	49.56	3.08	5.97	36.52	2.74	2.13
	326192	Resilient floor covering mfg	43.34	2.05	15.10	34.24	2.82	2.46
	325613	Surface active agent mfg	46.12	1.89	12.14	33.90	3.45	2.50
	31321	Broadwoven fabric mills	53.63	1.92	5.24	33.74	2.92	2.57
	334414	Electronic capacitor mfg	36.97	3.68	11.50	33.08	9.58	5.19
	315111	Sheer hosiery mills	58.64	1.09	3.17	32.58	2.68	1.84
Other	**31213**	**Wineries**	22.48	1.80	34.29	15.39	18.35	7.68
	336419	Other guided missile & space vehicle parts & auxiliary equip mfg	24.68	4.26	40.17	19.61	4.77	6.51
	334613	Magnetic & optical recording media mfg	40.54	2.07	21.75	18.70	10.73	6.21
	311212	Rice milling	35.99	1.38	29.42	19.60	7.82	5.79
	336414	Guided missile & space vehicle mfg	36.44	0.81	30.32	15.72	10.97	5.73
	333295	Semiconductor machinery mfg	31.14	4.14	27.90	20.15	10.96	5.71
	336611	Ship building & repairing	38.52	6.03	19.64	22.04	8.22	5.54
	32212	Paper mills	43.29	4.71	11.85	20.46	14.20	5.49
	334414	Electronic capacitor mfg	36.97	3.68	11.50	33.08	9.58	5.19

Appendix E: State Consumption Mixes

	2000 Generation Mix						2000 Consumption Mix (Interstate Trading Included)					
State	Coal	Oil	Gas	Nuclear	Hydro	Other	Coal	Oil	Gas	Nuclear	Hydro	Other
Alaska	8.7%	10.4%	64.6%	0.0%	16.3%	0.0%	8.7%	10.4%	64.6%	0.0%	16.3%	0.0%
Alabama	62.3%	0.3%	4.1%	25.2%	4.7%	3.4%	62.3%	0.3%	4.1%	25.2%	4.7%	3.4%
Arkansas	54.7%	0.5%	9.3%	26.4%	5.4%	3.7%	55.5%	0.5%	9.3%	26.1%	5.1%	3.5%
Arizona	46.1%	0.2%	9.8%	34.1%	9.7%	0.0%	46.1%	0.2%	9.8%	34.1%	9.7%	0.0%
California	1.1%	1.4%	49.5%	16.9%	18.8%	12.3%	21.4%	1.0%	38.4%	15.0%	15.0%	9.2%
Colorado	80.0%	0.2%	16.3%	0.0%	3.4%	0.0%	80.4%	0.2%	16.1%	0.0%	3.2%	0.0%
Connecticut	9.1%	20.7%	12.3%	49.3%	2.3%	6.4%	9.1%	20.7%	12.3%	49.3%	2.3%	6.4%
Washington DC	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	97.2%	1.5%	0.1%	0.0%	1.2%	0.0%
Delaware	68.5%	14.2%	14.2%	0.0%	0.0%	3.1%	62.6%	7.7%	7.4%	19.5%	0.5%	2.3%
Florida	38.7%	17.9%	22.4%	16.8%	0.0%	4.2%	41.5%	15.7%	20.2%	17.8%	0.6%	4.1%
Georgia	64.4%	1.4%	3.5%	26.3%	1.9%	2.5%	65.2%	1.3%	3.5%	25.6%	2.0%	2.5%
Hawaii	14.8%	76.1%	0.0%	0.0%	1.0%	8.1%	14.8%	76.1%	0.0%	0.0%	1.0%	8.1%
Iowa	84.4%	0.2%	1.0%	10.7%	2.2%	1.4%	85.8%	0.2%	0.9%	8.9%	3.0%	1.2%
Idaho	0.6%	0.1%	8.5%	0.0%	86.5%	4.5%	25.5%	0.8%	5.0%	0.0%	65.9%	2.8%
Illinois	45.6%	0.3%	2.7%	50.4%	0.1%	0.8%	45.6%	0.3%	2.7%	50.4%	0.1%	0.8%
Indiana	96.4%	0.3%	1.6%	0.0%	0.4%	1.3%	96.4%	0.3%	1.6%	0.0%	0.4%	1.3%
Kansas	72.5%	1.0%	6.3%	20.2%	0.0%	0.0%	72.5%	1.0%	6.3%	20.2%	0.0%	0.0%
Kentucky	96.8%	0.2%	0.5%	0.0%	2.5%	0.0%	96.8%	0.2%	0.5%	0.0%	2.5%	0.0%
Louisiana	25.2%	2.2%	49.8%	17.0%	0.6%	5.3%	25.2%	2.2%	49.8%	17.0%	0.6%	5.3%
Massachusetts	28.9%	19.7%	26.5%	13.6%	5.9%	5.4%	35.9%	14.2%	18.6%	22.0%	4.8%	4.5%
Maryland	57.5%	4.6%	5.6%	27.1%	3.4%	1.7%	65.6%	3.6%	4.3%	22.3%	2.8%	1.4%
Maine	4.4%	20.7%	22.1%	0.0%	25.4%	27.4%	5.1%	20.1%	21.4%	1.7%	24.9%	26.7%
Michigan	65.4%	1.1%	12.2%	18.1%	0.3%	2.8%	60.7%	1.2%	11.5%	17.5%	6.6%	2.6%
Minnesota	65.0%	0.2%	2.6%	26.1%	1.9%	4.2%	54.6%	0.6%	3.1%	22.9%	15.2%	3.5%
Missouri	82.6%	0.3%	3.3%	13.1%	0.5%	0.1%	82.8%	0.3%	3.2%	12.5%	1.1%	0.1%
Mississippi	36.9%	7.9%	22.3%	28.4%	0.0%	4.5%	41.3%	6.1%	18.1%	30.8%	0.2%	3.5%
Montana	61.2%	2.0%	0.1%	0.0%	36.4%	0.3%	61.2%	2.0%	0.1%	0.0%	36.4%	0.3%
North Carolina	62.1%	0.7%	1.0%	32.0%	2.7%	1.6%	62.1%	0.7%	0.9%	32.3%	2.5%	1.6%
North Dakota	92.8%	0.2%	0.0%	0.0%	6.8%	0.2%	92.8%	0.2%	0.0%	0.0%	6.8%	0.2%
Nebraska	65.3%	0.2%	1.6%	30.5%	2.4%	0.1%	65.3%	0.2%	1.6%	30.5%	2.4%	0.1%
New Hampshire	26.4%	3.1%	0.9%	52.7%	9.5%	7.4%	26.4%	3.1%	0.9%	52.7%	9.5%	7.4%
New Jersey	16.5%	1.8%	28.2%	50.3%	0.0%	3.3%	26.6%	1.8%	21.5%	47.0%	0.2%	2.8%
New Mexico	85.4%	0.3%	13.6%	0.0%	0.6%	0.0%	85.4%	0.3%	13.6%	0.0%	0.6%	0.0%
Nevada	53.5%	0.1%	35.9%	0.0%	6.8%	3.7%	53.5%	0.1%	35.9%	0.0%	6.8%	3.7%
New York	18.1%	10.8%	29.0%	22.8%	17.2%	2.1%	20.9%	9.7%	25.8%	23.1%	18.5%	2.0%
Ohio	87.0%	0.2%	0.6%	11.3%	0.4%	0.5%	85.2%	0.3%	0.8%	12.7%	0.4%	0.6%
Oklahoma	63.6%	0.1%	32.1%	0.0%	3.8%	0.4%	63.6%	0.1%	32.1%	0.0%	3.8%	0.4%
Oregon	7.3%	0.1%	17.6%	0.0%	73.6%	1.4%	9.8%	0.2%	16.6%	0.2%	71.9%	1.3%
Pennsylvania	57.3%	1.9%	1.4%	37.0%	0.9%	1.5%	57.3%	1.9%	1.4%	37.0%	0.9%	1.5%
Rhode Island	0.0%	1.0%	97.0%	0.0%	0.1%	1.9%	15.3%	1.2%	71.5%	9.9%	0.3%	1.8%
South Carolina	42.0%	0.5%	1.0%	54.5%	0.5%	1.6%	42.0%	0.5%	1.0%	54.5%	0.5%	1.6%
South Dakota	34.9%	0.5%	2.5%	0.0%	62.2%	0.0%	34.9%	0.5%	2.5%	0.0%	62.2%	0.0%
Tennessee	64.9%	0.6%	0.7%	26.9%	5.9%	1.0%	64.2%	0.6%	0.8%	28.1%	5.4%	0.9%
Texas	37.1%	0.7%	50.1%	9.9%	0.2%	1.9%	37.1%	0.7%	50.1%	9.9%	0.2%	1.9%
Utah	94.8%	0.2%	2.4%	0.0%	2.0%	0.6%	94.8%	0.2%	2.4%	0.0%	2.0%	0.6%
Virginia	51.1%	3.8%	6.0%	36.4%	0.0%	2.8%	65.4%	2.7%	4.2%	25.4%	0.4%	1.9%
Vermont	0.0%	1.0%	1.4%	72.2%	19.4%	6.1%	0.0%	1.0%	1.4%	72.2%	19.4%	6.1%
Washington	8.8%	0.5%	6.6%	8.0%	74.6%	1.6%	8.8%	0.5%	6.6%	8.0%	74.6%	1.6%
Wisconsin	71.3%	0.6%	3.8%	19.3%	3.4%	1.6%	61.9%	0.9%	4.0%	18.0%	13.7%	1.5%
West Virginia	98.4%	0.3%	0.1%	0.0%	1.2%	0.0%	98.4%	0.3%	0.1%	0.0%	1.2%	0.0%
Wyoming	95.9%	0.1%	1.0%	0.0%	2.2%	0.7%	95.9%	0.1%	1.0%	0.0%	2.2%	0.7%

Appendix F: C++ Matrix-write Code

```
#include <fstream>
#include <cstdlib>
#include <string>

using namespace std;

int main( int argc, char *argv[] )
{
  ifstream fin ( argv[1] ); // read input file from command line

  int totalSectors = 498;
  int MAXcol = totalSectors;
  int MAXrow = totalSectors;

  ofstream fout;

  int coldim = 0;
  int rowdim = 0;
  double usematrix [MAXrow][MAXcol];
  char NAICScol[6];
  char NAICSrow[6];
  double value;
  double dump;

  for(int i=0; i<MAXrow; i++){
    for(int j=0; j<MAXcol; j++){
      usematrix [i][j]=0;
    }
  }

  ifstream IOcodes ("IOcodelist.txt");
  char NAICSlookup [totalSectors][6];
  char NAICScode[6];
  int i = 0;

  while (!IOcodes.eof()){
    IOcodes >> NAICScode;
    for(int c=0; c<6; c++){
      NAICSlookup[i][c] = NAICScode[c];
    }
    i++;
  }
  IOcodes.close();

  int k=0;

  while(!fin.eof()) {

    fin >> NAICSrow;
    fin >> NAICScol;
    fin >> value;

    int i = 0;
    int goodsectora = 0;
    int goodsectorb = 0;
    while(i<totalSectors){
      for(int c=0; c<6; c++){
        NAICScode[c] = NAICSlookup[i][c];
      }
      if(strcmp(NAICScode,NAICScol)==0){
        coldim = i;
        goodsectora = 1;
        break;
      } else {
        goodsectora = 0;
```

```
        i++;
      }
    }

    i=0;
    while(i<totalSectors){
      for(int c=0; c<6; c++){
        NAICScode[c] = NAICSlookup[i][c];
      }
      if(strcmp(NAICScode,NAICSrow)==0){
        rowdim = i;
        goodsectorb = 1;
        break;
      } else {
        goodsectorb = 0;
        i++;
      }
    }

    if(goodsectora == 1 && goodsectorb ==1) {
      usematrix[rowdim][coldim] = value;
      cout << k << ": " << NAICScol << " (" << coldim << "), "
           << NAICSrow << " (" << rowdim << "): " << value << endl;
    } else {
      cout << k << ": " << NAICScol << " (xxx), " << NAICSrow
           << " (xxx): Bad sector, no value inserted" << endl;
    }

    k++;
  }

  fin.close();

  fout.open("out.txt");
  for(int i=0; i<MAXrow; i++){
    for (int j=0; j<MAXcol; j++){
      fout << usematrix[i][j] << " ";
    }
    fout << endl;
  }

  fout.close();

  return 0;
}
```

Appendix G: MATLAB Code – BuildIOModel.m

```
function [TotalRequirementsInd, IndustrySectors, CommoditySectors, FinalDemand,
UseMatrix, MakeMatrix] = BuildIOModel();

% Read industry sectors
    fid = fopen('Data\IOIndustrySectors.txt','r');
        Ind = textscan(fid,'%q');
        status = fclose(fid);
        IndustrySectors = Ind[1];
        clear Ind fid status;
% Read commodity sectors
    fid = fopen('Data\IOCommoditySectors.txt','r');
        Comm = textscan(fid,'%q');
        status = fclose(fid);
        CommoditySectors = Comm[1];
        clear Comm fid status;

% Read the make table from the file provided by BEA - the returned matrix
% has only valid commodity-industry combinations in it, and figure out how
% big it is
    MakeMatrix = LoadMake(IndustrySectors, CommoditySectors);
    dimMakeMatrix = size(MakeMatrix);

% According to the math set up by the BEA, set values in the columns for
% the commodities "Noncomparable Imports", "Scrap" and "Used and Secondhand
% Goods" to zero in the Make table.  The columns will still be there, but
% populated with zeros.
    MakeMatrix(:,strmatch('S00300',CommoditySectors)) = zeros(dimMakeMatrix(1,1),1);
    MakeMatrix(:,strmatch('S00401',CommoditySectors)) = zeros(dimMakeMatrix(1,1),1);
    MakeMatrix(:,strmatch('S00402',CommoditySectors)) = zeros(dimMakeMatrix(1,1),1);

% Now read use table from BEA file - this is a bit more complicated.
    [UseMatrix, UseMatrix_wFinalUseAndValueAdded, UniqueListUseColumn1,
UniqueListUseColumn2, DataNotIncludedInUseMatrix] =
LoadUse(CommoditySectors,IndustrySectors);
    dimUseMatrix = size(UseMatrix);
    dimUseMatrix_wFinalUseAndValueAdded = size(UseMatrix_wFinalUseAndValueAdded);

% Now, calculate the Total Output: sum columns of Make and Use tables
% Set max index for calculating row sums.
    if dimMakeMatrix(1,1) > dimUseMatrix_wFinalUseAndValueAdded(1,1)
        imax = dimMakeMatrix(1,1);
    else
        imax = dimUseMatrix_wFinalUseAndValueAdded(1,1);
    end

% Calculate row sums
    for i = 1:imax
        if i <= dimUseMatrix(1,1)
            UseRowSum(i,1) = sum(UseMatrix_wFinalUseAndValueAdded(i,:));
        else
        end
        if i <= dimMakeMatrix(1,1)
            MakeRowSum(i,1) = sum(MakeMatrix(i,:));
        else
        end
    end

%Set max index for calculating column sums
if dimMakeMatrix(1,2) > dimUseMatrix_wFinalUseAndValueAdded(1,2)
    jmax = dimMakeMatrix(1,2);
else
    jmax = dimUseMatrix_wFinalUseAndValueAdded(1,2);
end

%ScrapIndex = strmatch('S00401',CommoditySectors,'exact');
```

```
%UseColumnSum_Scrap  = UseMatrix_wFinalUseAndValueAdded(ScrapIndex,:);

%Calculate column sums
for j = 1:jmax
    if j <= dimUseMatrix(1,2)
        UseColumnSum(1,j) = sum(UseMatrix_wFinalUseAndValueAdded(:,j));
    else
    end
    if j <= dimMakeMatrix(1,2)
        MakeColumnSum(1,j) = sum(MakeMatrix(:,j));
    else
    end
end

TotalIndustryOutput             = MakeRowSum;
%TotalIndustryScrapOutput        = UseColumnSum_Scrap.';
TotalCommodityOutput            = MakeColumnSum.';

% Redefine variables in terms of BEA Conventions
% TotalCommodityOutput: Total commodity output.  It is a commodity-by-one vector.
% TotalIndustryOutput: A column sector in which each entry shows the total amount
%    of each industry's output, including its production of
%    scrap.  It is an industry-by-one vector.

%TotalCommodityOutput = TotalCommodityOutput;
%TotalIndustryOutput = TotalIndustryOutput;

% Perform BEA Calculations
% B: Direct input coefficients matrix in which entries in each column show
% the amount of a commodity used by an industry per dollar of output of that
% industry.  It is a commodity-by-industry matrix.

B = UseMatrix * inv(diag(TotalIndustryOutput));

% D: A matrix in which entries in each column show, for a given commodity
% (excluding scrap), the proportion of the total output of that commodity
% produced in each industry.  It is assumed that each commodity (other
% than scrap) is produced by the various industries in fixed proportions
% (industry technology assumption).  D is an industry-by-commodity matrix.
% D is also referred to as the market share matrix or transformation matrix.
% This routine is so that TotalCommodityOutput can be inverted.

q_wOnesSubstitutedForZeros = TotalCommodityOutput;
for i = 1:length(TotalCommodityOutput)
    if TotalCommodityOutput(i,1) == 0
        q_wOnesSubstitutedForZeros(i,1) = 1;
    else
    end
end

D = MakeMatrix * inv(diag(q_wOnesSubstitutedForZeros));

% e: A column vector in which each entry shows the total final demand purchases
% for each commodity from the use table.

FinalDemandIndices = strmatch('F',UniqueListUseColumn2);

% Note: This method of calculating the total final demand purchases relies
% on the fact that the final demand sectors are grouped together in the
% UseMatrix_wFinalUseandValueAdded

dimUseMatrix_wFinalUseAndValueAdded = size(UseMatrix_wFinalUseAndValueAdded);
ValueAddedIndices = strmatch('V',UniqueListUseColumn1);

% Note: This method of defining "e" relies on the fact that the Value Added
% sectors are located together at the very bottom of the
% UseMatrix_wFinalUseAndValueAdded
% for i = 1:dimUseMatrix_wFinalUseAndValueAdded(1,1) % <--This was the old
% way of looping to calculate the e vector

for i = 1:(ValueAddedIndices(1,1)-1)
```

```
    e(i,1) =
sum(UseMatrix_wFinalUseAndValueAdded(i,FinalDemandIndices(1,1):FinalDemandIndices(length(
FinalDemandIndices))));
end

% h: A column vector in which each entry shows the total amount of each
% industry's production of scrap.  Scrap is separated to prevent its use
% as an input from generating output in the industries in which it originates.

ScrapIndex = strmatch('S00401',CommoditySectors);
h = MakeMatrix(:,ScrapIndex);

% p: A column vector in which each entry shows the ratio of the value of scrap
% produced in each industry to the industry's total output.

for i = 1:length(h)
    p(i,1) = h(i,1)/TotalIndustryOutput(i,1);
end

% W: An industry-by-commodity matrix in which the entries in each column
% show, for a given commodity, the proportion of the total output of that
% commodity produced in each industry adjusted for scrap produced by the
% industry.

W = inv(eye(length(p)) - diag(p)) * D;

% And the industry-by-industry total requirements matrix: which shows the
% industry output required per dollar of each industry product delivered to final users.

dimW = size(W);
TotalRequirementsInd = inv(eye(dimW(1,1)) - W*B);       %( 14 )

% Initialize FinalDemand vector of correct size

FinalDemand = zeros(length(IndustrySectors),1);
```

Appendix H: MATLAB Code – LoadUse.m

```
function [UseMatrix, UseMatrix_wFinalUseAndValueAdded, UniqueListUseColumn1,
UniqueListUseColumn2, DataNotIncludedInUseMatrix] =
LoadUse(CommoditySectors,IndustrySectors);

% Read in the text file containing the data for the Use Matrix.
    fid = fopen('Data\IOUseDetail.txt','r');
    ListUse = textscan(fid,'%q %q %n','delimiter',' ,');
    status = fclose(fid);
    clear fid status;

% Create list of unique IO codes in each column into new lists
    UniqueListUseColumn2 = unique(ListUse[2]);
    UniqueListUseColumn1 = unique(ListUse[1]);

% Initialize the 2 Use matrices - with and without Final/Value Add
    UseMatrix = zeros(length(CommoditySectors),length(IndustrySectors));
    UseMatrix_wFinalUseAndValueAdded =
zeros(length(UniqueListUseColumn1),length(UniqueListUseColumn2));

    m = 1;

% Fill the UseMatrix
    for i = 1:length(ListUse[1])
        commodityindex = strmatch(ListUse[1](i,1),CommoditySectors,'exact');
        industryindex = strmatch(ListUse[2](i,1),IndustrySectors,'exact');

        if commodityindex & industryindex
            UseMatrix(commodityindex,industryindex) = ListUse[3](i,1);
        else
            DataNotIncludedInUseMatrix[1](m,1) = ListUse[1](i,1);
            DataNotIncludedInUseMatrix[2](m,1) = ListUse[2](i,1);
            DataNotIncludedInUseMatrix[3](m,1) = ListUse[3](i,1);
            m = m+1;
        end

        %Fill the complete Use Matrix Including the Final Use and Value Added data
            rowindex = strmatch(ListUse[1](i,1),UniqueListUseColumn1,'exact');
            columnindex = strmatch(ListUse[2](i,1),UniqueListUseColumn2,'exact');

                if rowindex & columnindex
                       UseMatrix_wFinalUseAndValueAdded(rowindex,columnindex) =
                            ListUse[3](i,1);
                else
                    Error = 'Data not read correctly - UseMatrix'
                end
    end
```

Appendix I: MATLAB Code – LoadMake.m

```
function [MakeMatrix] = LoadMake(IndustrySectors, CommoditySectors)

% Read in the text file containing the data for the Make Matrix
    fid = fopen('Data\IOMakeDetail.txt','r');
        ListMake = textscan(fid,'%q %q %n','delimiter',',');
        status = fclose(fid);
        clear fid;

% Initialize the MakeMatrix
    MakeMatrix = zeros(length(IndustrySectors),length(CommoditySectors));

% Fill the MakeMatrix - match the two sector names against the imported
% list, and then insert the associated value if both sectors were valid
    for i = 1:length(ListMake{1})
        commodityIndex = strmatch(ListMake{1}(i),IndustrySectors,'exact');
        industryIndex = strmatch(ListMake{2}(i),CommoditySectors,'exact');

        if commodityIndex & industryIndex
            MakeMatrix(commodityIndex,industryIndex) = ListMake{3}(i,1);
        else
            Error = 'Data not read correctly (Make)'
            sprintf('%d',i);
        end
    end
```

Appendix J: MATLAB Code - DoLCA.m

```
% Load dynamic list of IO/NAICS codes
fid = fopen('Data\IOIndustrySectors.txt','r');
  TxtInput = textscan(fid,'%q');
  status = fclose(fid);
  IndustrySectors = TxtInput[1];
  clear TxtInput fid status;
% Load list of corresponding sector names
fid = fopen('Data\SectorNames.txt','r');
  TxtInput = textscan(fid,'%q');
  status = fclose(fid);
  SectorNames = TxtInput[1];
  clear TxtInput fid status;
% Load list of emission factor names (relatively static)
fid = fopen('Data\EmissionFactorNames.txt','r');
  TxtInput = textscan(fid,'%q');
  status = fclose(fid);
  EmFactNames = TxtInput[1];
  clear TxtInput fid status;
% Load emission factors: # of factors is static, the # of sectors is not.
% It's flipped because that's how the math works.
EmissionFactors = transpose(load('Data\EmissionFactors.txt'));
EmissionDims = size(EmissionFactors);

% Calculate back to direct requirements matrix from total requirements
DirectRequirements = eye(size(TotalRequirementsInd)) - inv(TotalRequirementsInd);

% Direct econ activity from that matrix
DirectEconomicActivity = FinalDemand + (DirectRequirements * FinalDemand);

% Calculate total economic activity
TotalEconomicActivity = TotalRequirementsInd*FinalDemand;

% Calculate the overall env inventory
TotalEnvInv = EmissionFactors*TotalRequirementsInd*FinalDemand;

% Calculate the sector-by-sector environmental inventory
SectoralEnvInv = transpose(EmissionFactors * diag(TotalEconomicActivity));

% Put total & direct econ and sectoral inventory into a single matrix
FullResults = [TotalEconomicActivity,DirectEconomicActivity,SectoralEnvInv];

% This section prints out complete results to a text file, 'EIOout.txt'
fid = fopen('LCAoutput.txt','w+');
  % Prints headings in top row
  for i = 1:length(EmFactNames)
    fprintf(fid, ';%s', char(EmFactNames(i)));
  end
  % Next row: a heading then all totals
  fprintf(fid,'\n;Total, All Sectors');
  fprintf(fid, ';%8.4f;%8.4f', sum(TotalEconomicActivity), sum(DirectEconomicActivity));
  for i = 1:EmissionDims(1,1)
    fprintf(fid, ';%8.4f', TotalEnvInv(i,1));
  end

  % New line, then the main block of results
  for i = 1:EmissionDims(1,2)
    fprintf(fid, '\n');
    fprintf(fid, '%s;', char(IndustrySectors(i)));
    fprintf(fid, '%s;', char(SectorNames(i)));
    for j = 1:length(EmFactNames)-1
      fprintf(fid, '%8.4f;', FullResults(i,j));
    end
  end

status = fclose(fid);
```

Appendix K: Disaggregated O&M Supply Chain

Example of complete supply chains for disaggregated PG&S sectors, in millions of 1997 dollars, producer prices.

Com.	Coal	Pet.	Nat. Gas	Nuc.	Hyd.	Bio.	Geo.	Wind	Sol.	Tx	Dx
212100	15,098										
211000		1,419	13,485								
486000		635	6,034								
482000	5,844										
230340	1,590	119	1,131	266	110	23	7	5	0	66	72
541100	1,516	113	1,078	253	105	22	7	5	0	63	69
324110		205	1,946								
52A000	870	65	619	145	60	13	4	3	0	36	40
420000	823	62	585	137	57	12	4	3	0	34	37
541800	820	61	584	137	57	12	4	3	0	34	37
722000	778	58	554	130	54	11	4	2	0	32	35
531000	742	56	528	124	52	11	3	2	0	31	34
5419A0	435	33	310	73	30	6	2	1	0	18	20
484000	403	30	287	67	28	6	2	1	0	17	18
541610	375	28	266	63	26	5	2	1	0	16	17
522A00	307	23	219	51	21	4	1	1	0	13	14
611A00	303	23	215	51	21	4	1	1	0	13	14
492000	293	22	209	49	20	4	1	1	0	12	13
561300	281	21	200	47	20	4	1	1	0	12	13
483000	597										
491000	258	19	184	43	18	4	1	1	0	11	12
335930	251	19	179	42	17	4	1	1	0	10	11
335313	248	19	176	41	17	4	1	1	0	10	11
561900	228	17	162	38	16	3	1	1	0	10	10
332710	219	16	156	37	15	3	1	1	0	9	10
523000	218	16	155	36	15	3	1	1	0	9	10
541300	212	16	151	35	15	3	1	1	0	9	10
54151A	196	15	139	33	14	3	1	1	0	8	9
335929	196	15	139	33	14	3	1	1	0	8	9
327390	174	13	124	29	12	3	1	1	0	7	8
524100	170	13	121	28	12	2	1	1	0	7	8
561400	170	13	121	28	12	2	1	1	0	7	8
514200	142	11	101	24	10	2	1	0	0	6	6
541200	130	10	92	22	9	2	1	0	0	5	6
331491	125	9	89	21	9	2	1	0	0	5	6
332720	116	9	82	19	8	2	1	0	0	5	5
550000	114	9	81	19	8	2	1	0	0	5	5
331222	112	8	79	19	8	2	1	0	0	5	5
327320	109	8	77	18	8	2	0	0	0	5	5
326120	103	8	74	17	7	1	0	0	0	4	5
333611	103	8	74	17	7	1	0	0	0	4	5
481000	101	8	72	17	7	1	0	0	0	4	5
332812	101	8	72	17	7	1	0	0	0	4	5
541700	85	6	60	14	6	1	0	0	0	4	4
326220	81	6	57	13	6	1	0	0	0	3	4
332813	80	6	57	13	6	1	0	0	0	3	4
812300	78	6	56	13	5	1	0	0	0	3	4
3221A0	73	6	52	12	5	1	0	0	0	3	3

561700	73	5	52	12	5	1	0	0	0	3	3
321114	71	5	51	12	5	1	0	0	0	3	3
533000	70	5	50	12	5	1	0	0	0	3	3
513300	69	5	49	12	5	1	0	0	0	3	3
813B00	68	5	49	11	5	1	0	0	0	3	3
221300	68	5	48	11	5	1	0	0	0	3	3
321992	67	5	48	11	5	1	0	0	0	3	3
335314	66	5	47	11	5	1	0	0	0	3	3
541512	66	5	47	11	5	1	0	0	0	3	3
335312	63	5	45	11	4	1	0	0	0	3	3
335921	62	5	44	10	4	1	0	0	0	3	3
327310	58	4	41	10	4	1	0	0	0	2	3
325190	58	4	41	10	4	1	0	0	0	2	3
32121B	57	4	40	9	4	1	0	0	0	2	3
327113	53	4	38	9	4	1	0	0	0	2	2
33211A	53	4	38	9	4	1	0	0	0	2	2
230320	52	4	37	9	4	1	0	0	0	2	2
7211A0	50	4	36	8	4	1	0	0	0	2	2
325520	48	4	34	8	3	1	0	0	0	2	2
322210	48	4	34	8	3	1	0	0	0	2	2
324121	47	4	33	8	3	1	0	0	0	2	2
4A0000	46	3	33	8	3	1	0	0	0	2	2
324122	46	3	33	8	3	1	0	0	0	2	2
561600	45	3	32	8	3	1	0	0	0	2	2
325991	45	3	32	7	3	1	0	0	0	2	2
332811	45	3	32	7	3	1	0	0	0	2	2
332312	44	3	32	7	3	1	0	0	0	2	2
332323	41	3	29	7	3	1	0	0	0	2	2
562000	40	3	28	7	3	1	0	0	0	2	2
32619A	40	3	28	7	3	1	0	0	0	2	2
332321	37	3	26	6	3	1	0	0	0	2	2
327420	36	3	26	6	3	1	0	0	0	2	2
337110	35	3	25	6	2	1	0	0	0	1	2
48A000	35	3	25	6	2	1	0	0	0	1	2
32222A	34	3	24	6	2	0	0	0	0	1	2
321113	32	2	23	5	2	0	0	0	0	1	1
514100	29	2	20	5	2	0	0	0	0	1	1
541400	28	2	20	5	2	0	0	0	0	1	1
333992	27	2	19	4	2	0	0	0	0	1	1
811400	27	2	19	4	2	0	0	0	0	1	1
331421	26	2	19	4	2	0	0	0	0	1	1
811200	24	2	17	4	2	0	0	0	0	1	1
32311A	22	2	16	4	2	0	0	0	0	1	1
332311	22	2	16	4	2	0	0	0	0	1	1
327910	21	2	15	4	1	0	0	0	0	1	1
333618	19	1	14	3	1	0	0	0	0	1	1
335120	19	1	14	3	1	0	0	0	0	1	1
S00300	19	1	14	3	1	0	0	0	0	1	1
532400	19	1	14	3	1	0	0	0	0	1	1
334513	19	1	14	3	1	0	0	0	0	1	1
323116	16	1	12	3	1	0	0	0	0	1	1
334514	15	1	11	3	1	0	0	0	0	1	1
333411	14	1	10	2	1	0	0	0	0	1	1
325998	13	1	9	2	1	0	0	0	0	1	1
335110	12	1	9	2	1	0	0	0	0	1	1
332212	12	1	9	2	1	0	0	0	0	0	1
485000	12	1	9	2	1	0	0	0	0	0	1
325110	10	1	7	2	1	0	0	0	0	0	0

561100	10	1	7	2	1	0	0	0	0	0	0
5416A0	10	1	7	2	1	0	0	0	0	0	0
8111A0	10	1	7	2	1	0	0	0	0	0	0
335991	9	1	7	2	1	0	0	0	0	0	0
711500	9	1	6	1	1	0	0	0	0	0	0
333515	9	1	6	1	1	0	0	0	0	0	0
322232	8	1	6	1	1	0	0	0	0	0	0
325180	7	1	5	1	0	0	0	0	0	0	0
811300	7	0	5	1	0	0	0	0	0	0	0
332999	6	0	4	1	0	0	0	0	0	0	0
331319	6	0	4	1	0	0	0	0	0	0	0
336300	6	0	4	1	0	0	0	0	0	0	0
332991	6	0	4	1	0	0	0	0	0	0	0
325120	6	0	4	1	0	0	0	0	0	0	0
32721A	6	0	4	1	0	0	0	0	0	0	0
532100	5	0	4	1	0	0	0	0	0	0	0
33399A	5	0	4	1	0	0	0	0	0	0	0
332600	5	0	4	1	0	0	0	0	0	0	0
713940	5	0	4	1	0	0	0	0	0	0	0
511120	5	0	4	1	0	0	0	0	0	0	0
713A00	4	0	3	1	0	0	0	0	0	0	0
322231	4	0	3	1	0	0	0	0	0	0	0
711200	4	0	3	1	0	0	0	0	0	0	0
334611	4	0	3	1	0	0	0	0	0	0	0
561500	4	0	3	1	0	0	0	0	0	0	0
333924	4	0	3	1	0	0	0	0	0	0	0
332500	4	0	3	1	0	0	0	0	0	0	0
339940	4	0	3	1	0	0	0	0	0	0	0
611B00	4	0	3	1	0	0	0	0	0	0	0
S00203	4	0	3	1	0	0	0	0	0	0	0
331111	4	0	3	1	0	0	0	0	0	0	0
323118	3	0	2	1	0	0	0	0	0	0	0
333923	3	0	2	1	0	0	0	0	0	0	0
334613	3	0	2	1	0	0	0	0	0	0	0
493000	3	0	2	1	0	0	0	0	0	0	0
333120	3	0	2	0	0	0	0	0	0	0	0
327332	3	0	2	0	0	0	0	0	0	0	0
711A00	3	0	2	0	0	0	0	0	0	0	0
333991	3	0	2	0	0	0	0	0	0	0	0
33999A	2	0	2	0	0	0	0	0	0	0	0
333412	2	0	2	0	0	0	0	0	0	0	0
3261A0	2	0	1	0	0	0	0	0	0	0	0
321920	2	0	1	0	0	0	0	0	0	0	0
711100	2	0	1	0	0	0	0	0	0	0	0
326210	2	0	1	0	0	0	0	0	0	0	0
324191	2	0	1	0	0	0	0	0	0	0	0
333319	2	0	1	0	0	0	0	0	0	0	0
316900	1	0	1	0	0	0	0	0	0	0	0
321912	1	0	1	0	0	0	0	0	0	0	0
321999	1	0	1	0	0	0	0	0	0	0	0
335311	1	0	1	0	0	0	0	0	0	0	0
512100	1	0	1	0	0	0	0	0	0	0	0
331315	1	0	1	0	0	0	0	0	0	0	0
315200	1	0	1	0	0	0	0	0	0	0	0
326110	1	0	1	0	0	0	0	0	0	0	0
326160	1	0	1	0	0	0	0	0	0	0	0
335912	1	0	1	0	0	0	0	0	0	0	0
323122	1	0	1	0	0	0	0	0	0	0	0

31499A	1	0	0	0	0	0	0	0	0	0	0
511130	1	0	0	0	0	0	0	0	0	0	0
327410	1	0	0	0	0	0	0	0	0	0	0
339920	0	0	0	0	0	0	0	0	0	0	0
332430	0	0	0	0	0	0	0	0	0	0	0
339991	0	0	0	0	0	0	0	0	0	0	0
511110	0	0	0	0	0	0	0	0	0	0	0
111400	0	0	0	0	0	0	0	0	0	0	0
339910	0	0	0	0	0	0	0	0	0	0	0
32222B	0	0	0	0	0	0	0	0	0	0	0
325612	0	0	0	0	0	0	0	0	0	0	0
721A00	0	0	0	0	0	0	0	0	0	0	0
333912	0	0	0	0	0	0	0	0	0	0	0
33451A	0	0	0	0	0	0	0	0	0	0	0
325510	0	0	0	0	0	0	0	0	0	0	0
561200	0	0	0	0	0	0	0	0	0	0	0

Appendix L: Construction Supply Chains

The following table has percentages, which are the percent of a $/kW of overnight construction cost of a type of an average power plant or transmission line.[7-9,87-93,97]

Sector	*Solar*	*Wind*	*Coal*	*Natural Gas*	*Nuclear*	*IGCC*	*Transmission*
327320	1.2%	1.9%	0.5%	0.3%	0.4%	0.5%	2.5%
333611	0.6%	3.2%	7.3%	11.3%	4.5%	6.3%	0.0%
332410	0.1%	0.7%	1.5%	2.4%	0.9%	1.3%	1.7%
331111	17.6%	5.5%	2.5%	3.0%	1.6%	2.1%	8.4%
331421	11.3%	0.2%	0.0%	0.0%	0.0%	0.0%	5.9%
331491	2.2%	0.4%	0.1%	0.0%	0.0%	0.1%	0.8%
326120	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
32721A	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
V00100	39.7%	52.6%	52.7%	49.6%	55.3%	53.6%	48.3%
541300	7.4%	9.9%	9.9%	9.3%	10.4%	10.0%	9.0%
V00300	3.7%	5.0%	5.0%	4.7%	5.2%	5.0%	4.5%
532400	1.3%	1.8%	1.8%	1.7%	1.9%	1.8%	1.6%
324110	1.2%	1.6%	1.6%	1.5%	1.7%	1.7%	1.5%
484000	1.0%	1.4%	1.4%	1.3%	1.5%	1.4%	1.3%
524100	0.8%	1.1%	1.1%	1.0%	1.1%	1.1%	1.0%
V00200	0.8%	1.1%	1.1%	1.0%	1.1%	1.1%	1.0%
513300	0.7%	1.0%	1.0%	0.9%	1.0%	1.0%	0.9%
52A000	0.7%	0.9%	0.9%	0.9%	0.9%	0.9%	0.8%
531000	0.7%	0.9%	0.9%	0.8%	0.9%	0.9%	0.8%
561300	0.7%	0.9%	0.9%	0.8%	0.9%	0.9%	0.8%
811300	0.5%	0.7%	0.7%	0.7%	0.7%	0.7%	0.6%
336300	0.4%	0.5%	0.5%	0.5%	0.6%	0.5%	0.5%
8111A0	0.4%	0.5%	0.5%	0.5%	0.5%	0.5%	0.4%
333319	0.4%	0.5%	0.5%	0.5%	0.5%	0.5%	0.4%
811200	0.3%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
221100	0.3%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
523000	0.3%	0.4%	0.4%	0.3%	0.4%	0.4%	0.3%
561700	0.3%	0.3%	0.3%	0.3%	0.4%	0.3%	0.3%
522A00	0.3%	0.3%	0.3%	0.3%	0.4%	0.3%	0.3%
541200	0.2%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
532100	0.2%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
550000	0.2%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
541100	0.2%	0.3%	0.3%	0.2%	0.3%	0.3%	0.2%
481000	0.2%	0.3%	0.3%	0.2%	0.3%	0.3%	0.2%
561100	0.2%	0.2%	0.2%	0.2%	0.3%	0.3%	0.2%
541610	0.2%	0.2%	0.2%	0.2%	0.3%	0.3%	0.2%
333923	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
332710	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
33399A	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
813B00	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
492000	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
482000	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
48A000	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
230320	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
326210	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%
541800	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
562000	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
722000	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

561600	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
221200	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
7211A0	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
324191	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
561400	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
491000	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
5416A0	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
S00300	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
483000	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
514100	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
S00203	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
54151A	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
514200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
333992	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
221300	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5419A0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
561900	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
541512	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
327125	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
212390	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
533000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
339994	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
333912	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
333120	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
333991	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
331315	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
332430	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
512100	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
541400	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
711500	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
532A00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
31499A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
334511	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
313230	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
332313	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
325920	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
486000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
485000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
339991	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
335911	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
33211A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
334513	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
611A00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
493000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
713940	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
325110	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
325611	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
335110	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
323116	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
336999	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
331319	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
713A00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
333924	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
711100	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
325612	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
332212	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
339940	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
335311	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

334514	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
541700	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
33451A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
334613	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
336500	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
339910	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
32222B	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
711A00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
323118	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
711200	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
322232	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
327410	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
322233	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
32311A	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
322231	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
721A00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
321920	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
611B00	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
325992	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
S00402	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
332211	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
337124	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
335912	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
316900	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5111A0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
334611	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%