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Water's Dependence on Energy: Analysis of Embodied Energy in Water and Wastewater Systems

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Water's Dependence on Energy:

Analysis of Embodied Energy in Water and Wastewater Systems

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
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DEDICATION

This dissertation is dedicated to my parents, Wenjie Mo and Ensu Wu, my fiancé, Shiwei Lu, and Mr. and Mrs. Wei for their tremendous love and support throughout the years of my Ph.D. study.

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ABSTRACT

Water and wastewater treatment is a critical service provided for protecting human health and the environment. Over the past decade, increasing attention has been placed on energy consumption in water and wastewater systems for the following reasons: (1) Water and energy are two interrelated resources. The nexus between water and energy can intensify the crises of fresh water and fossil fuel shortages; (2) The demand of water/wastewater treatment services is expected to continue to increase with increasing population, economic development and land use change in the foreseeable future; and (3) There is a great potential to mitigate energy use in water and wastewater systems by recovering resources in wastewater treatment systems. As a result, the goal of this dissertation study is to assess the life cycle energy use of both water supply systems and wastewater treatment systems, explore the potential of integrated resource recovery to reduce energy consumption in wastewater systems, and understand the major factors impacting the life cycle energy use of water systems.

To achieve the goal, an input-output-based hybrid embodied energy model was developed for calculating life cycle energy in water and wastewater systems in the US. This approach is more comprehensive and less labor intensive than the traditional life cycle assessment. Additionally, this model is flexible in terms of data availability. It can give a rough estimation of embodied energy in water systems with limited data input. Given more site specific data, the model can modify the embodied energy of different energy paths involved in water related sectors.

Using the input-output-based hybrid embodied energy model, the life cycle energy of a groundwater supply system (Kalamazoo, Michigan) and a surface water supply system (Tampa, Florida) was compared. The two systems evaluated have comparable total energy embodiments based on unit water production. However, the onsite energy use of the groundwater supply system is approximately 27% greater than the surface water supply system. This was primarily due to more extensive pumping requirements. On the other hand, the groundwater system uses approximately 31% less indirect energy than the surface water system, mainly because of fewer chemicals used for treatment. The results from this and other studies were also compiled to provide a relative comparison of embodied energy for major water supply options. The comparison shows that desalination is the most energy intensive option among all the water sources. The embodied energy and benefits of reclaimed water depend on local situations and additional treatment needed to ensure treated wastewater suitable for the desired application.

A review was conducted on the current resource recovery technologies in wastewater treatment systems. It reveals that there are very limited life cycle studies on the resource recovery technologies applied in the municipal wastewater treatment systems and their integrations. Hence, a life cycle study was carried out to investigate the carbon neutrality in a state-of-art wastewater treatment plant in Tampa, FL. Three resource recovery methods were specifically investigated: onsite energy generation through combined heat and power systems, nutrient recycling through biosolids land application, and water reuse for residential irrigation. The embodied energy and the associated carbon footprint were estimated using the input-output-based hybrid embodied energy model and carbon emission factors. It was shown that the integrated resource (energy, nutrient and water) recovery has the potential to offset all the direct operational energy; however, it is not able to offset the total embodied energy of the treatment plant to achieve carbon neutrality. Among the three resource recovery methods, water reuse has the highest potential of offsetting carbon footprint, while nutrient recycling has the lowest.

A final application of the model was to study on the correlation between embodied energy in regional water supply systems and demographic and environmental characteristics. It shows that energy embodied in water supply systems in a region is related to and can be estimated by population, land use patterns, especially percentage of urban land and water source, and water sources. This model provides an alternative way to quickly estimate embodied energy of water supply in a region. The estimated embodied energy of water supply can further be used as a supporting tool for decision making and planning.

CHAPTER 1: INTRODUCTION

1.1 Background Significance

Water and wastewater treatment is a critical service provided for protecting human health and the environment. Currently, developed countries have around 99% coverage of this service, while developing countries have an average of around 50% coverage (WHO/UNICEF, 2006). In addition to their important service functions, water and wastewater systems play a significant role in energy use nationally and globally, demanding not only large amounts of energy onsite, such as electricity used for pumping and aeration, but also a considerable amount of energy offsite for producing and transporting constructional materials and treatment chemicals. It has been estimated that around 4% of the US electricity demand is for the movement and treatment of water and wastewater, both publicly and privately (Goldstein et al., 2002). This percentage can be much higher considering energy used offsite for providing materials and administrative services.

Over the past decade, increasing attention has been placed on energy consumption in water and wastewater systems for the following reasons:

(1) Water and energy are two interrelated resources. The nexus between water and energy can intensify the fresh water and fossil fuel shortages;

(2) The demand of water/wastewater treatment services is expected to increase with growing population, economic development and land use

change in the foreseeable future; and,

(3) There is a great potential to mitigate energy use in water and wastewater systems by recovering resources in wastewater treatment systems.

The following sections provide further discussions on the three reasons affecting the importance of energy consumption in water and wastewater systems.

1.1.1 Water-Energy Nexus

Studies have shown a noticeable relationship between water and energy (DOE, 2006; Gleick, 1994). Providing and treating water has an impact on energy resources, while energy production also has a profound impact on water resources. More specifically, providing water and wastewater service consumes a large amount of energy in water conveyance, treatment and distribution and wastewater collection, treatment and discharge. It has been estimated that around 123,450 GWh of electricity was used for water supply and wastewater treatment both publicly and privately in 2000, and this number will increase by 100% in 2050 (Goldstein et al., 2002). On the other hand, providing energy, especially electricity, requires a large amount of water for system cooling, fuel extraction and mining. The total amount of freshwater withdrawal at the US thermoelectric power plants in 1995 was 132,000 MGD, of which 3,310 MGD was evaporated (DOE, 2006; Torcellini et al., 2003; USGS, 2009). Additionally, reservoirs used for hydroelectric power production evaporate an average of 9,063 MGD of water in the US (Torcellini et al., 2003).

As a result of the nexus between water and energy, the consumption of water and energy forms a reinforcing feedback loop. It means when water use increases, energy use associated with water and wastewater services will also increase, which will further increase water consumed in energy production. Hence, the water and energy nexus speeds up the consumption of both water and energy resources. Figure 1.1 illustrates this positive reinforcement between water and energy using a causal loop diagram. The systems with reinforcing loops without balancing feedbacks are very unstable. They are usually associated with exponential increases and/or decreases. With population growth, economic development, and limited freshwater and fossil energy resources, the water-energy reinforcing feedback could eventually lead to the collapse of both water and energy systems. To slow down the depletion and find out sustainable solutions for both resources, it is important to reduce energy use associated with water and wastewater systems and water use in energy production in addition to innovations in renewable energy technologies, resource recovery and alternative water sources.

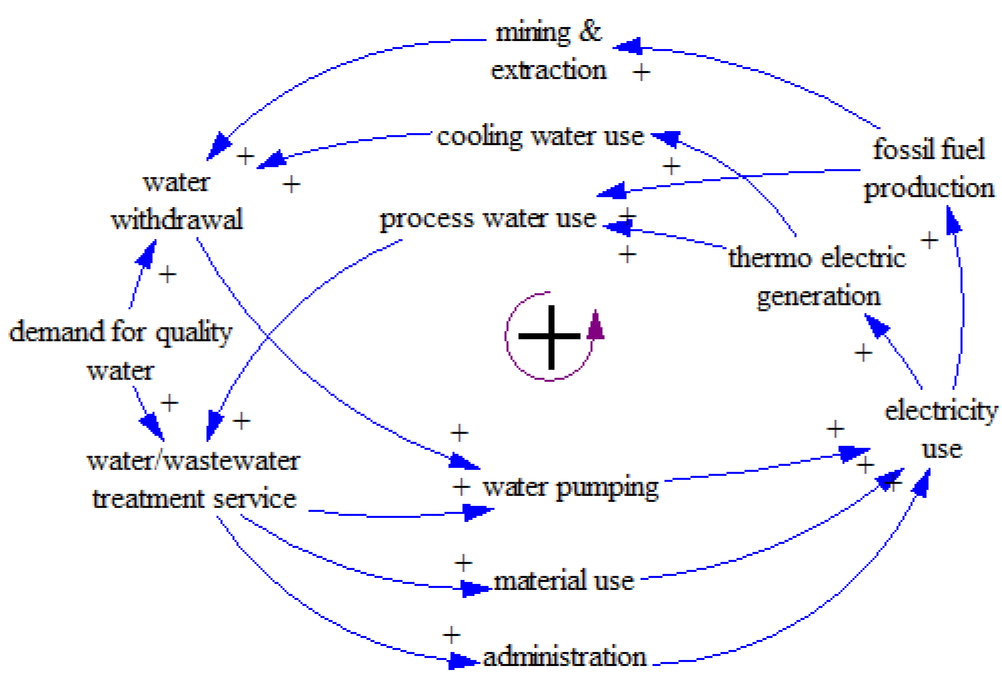


Figure 1.1 Causal loop diagram of the reinforcing relationship between water and energy

1.1.2 Water-Population-Economy-Land Use Interactions

With the rapid development of society and economy, human impacts on water quantity and quality have become a major global concern. The depleting and deteriorating water resources require more energy and chemicals for providing water and wastewater treatment services. As the causal factors driving water depletion and quality degradation have been widely studied, there is an urgent need to quantify the relationships between these factors with energy consumption in providing water and wastewater services and minimize their impacts.

1.1.2.1 Global and US Water Situations

Water stress and scarcity occurs when the demand for water exceeds the available amount or when poor quality restricts its use (UNEP, 2004). Quantitatively, countries with a freshwater availability between 1,000 and 1,700 m^3 per year per person are undergoing water stress. Countries with a fresh water availability of less than 1,000 m^3 per year per person are undergoing water scarcity (UNEP, 2004).

Currently, a substantial amount of areas around the world are suffering from water scarcity, especially those with limited fresh water resources, such as the vast majority of Middle East, North Africa, the west coast of South America, and the southwest part of North America. It has been estimated that nearly 1.4 billion people, amounting to a quarter of the world's population, or one-third of the population in developing countries will live in regions with severe water scarcity by 2025 (Arnell, 2004; Seckler et al., 1999). Water scarcity is not only caused by the severe geographical conditions, but also other factors such as demand increase, quality deterioration and so on.

Nevertheless, the global water withdrawals are still growing very rapidly, and are expected to continue to grow inevitably in the foreseeable future (Konikow and Kendy, 2005; Shah et al., 2003; USGS, 2012).

In addition to water shortage and scarcity, extensive water withdrawals have also led to environmental problems, such as groundwater depletion, land subsidence, seawater intrusion, and surface water quality deterioration, which have consequently impacted water availability in many regions (Barlow, 2003; Bartolino et al., 2003; Konikow and Kendy, 2005; Taylor and Alley, 2001). These local environmental problems can also lead to larger-scale ecological problems, such as changes in surface vegetation and biodiversity of the hydrological system (Danielopol et al., 2003).

In the US, the demand on fresh water supplies is also continuously growing in spite of limited surface water storage and depleting groundwater source in the nation. A survey in the US showed that most of the US states will experience local, regional or statewide water shortage over the next decade (Hill, 2006). It includes some states with known abundance of fresh water resources.

Water quality degradation refers to the deterioration in the chemical, physical and biological characteristics of water. It has become a serious worldwide problem. It has been estimated that about 5 million people die each year from poor quality of drinking water and lack of sanitation (Prüss-Üstün et al., 2008). Water quality degradation has been and will be much more significant in developing countries than in developed countries (Zimmerman et al., 2008). It is caused by less emphasis and capability on pollution control while undergoing rapid economic development at the same time in the developing countries. In spite of the different development levels, the growing industries, expanding urban lands, improving living standards and increasing population makes the deterioration of water quality inevitable both in developed and developing countries.

In the US, particularly, the widespread increases in nitrate, chloride, arsenic and cadmium concentrations in the nation's rivers have been noticed long ago (Smith et al., 1987). In a study of contaminant source for groundwater aquifers in 26 states, volatile organic compounds, petroleum compounds, metals, pesticides and nitrate are identified as the most frequently detected contaminants (EPA, 2000).

Above all, water quantity and water quality are not isolated, but interrelated. Water shortage is not only caused by the overwhelming water withdrawal for supporting socioeconomic development, but also because of the increasing pollutant loadings in the water body (Postel, 1997; Zimmerman et al., 2008). These pollutant loadings have made water quality degrade to certain levels which are not appropriate for potable water supply in some areas. On the other side, the large withdrawal and consumption of water also result in further water quality deterioration. This is because not only exterior substances are commonly added into the water body after its use, but also the characteristics of water are changed when it returns to its source after the use. Large water withdrawal and consumption also diminish the self-cleaning abilities of the water body. Hence, it is important to consider the water quantity and quality problems from a system view, and understand the drivers of these problems.

1.1.2.2 Global and US Water Stressors

The driving forces behind the decreasing water quantity and deteriorating water quality are mainly anthropogenic factors including population growth, economic/industrial development, and land use changes.

Population growth is one of the major stressors of water quantity and quality. Population is growing rapidly worldwide during the past two or three hundred years. In 2011, world population is growing at a rate of 1.2%, and the population in the largest cities is growing at a rate of 16% (World Bank, 2012). Population is also growing steadily at a rate of around 1% in the US during the past decade (World Bank, 2012). Such population growth drives water demands for residential, industrial and agricultural uses. Population growth also significantly reduces return flows to the water body (Ehrlich and Holdren, 1971), which can eventually exhaust the available water resource or destroy the environmental balance.

Economic development is another important water stressor. While modern economic development provides short-term benefits for the relatively poor population, it also induces uneven resource distribution and overconsumption in the well developed countries. Economic development is partly associated with population growth. Industrial and agricultural production has to increase in order to satisfy the growing needs due to population growth, which consequently increases water consumption. On the other hand, economic development also changes people's life style and consumption behavior that result in the increased water use. For example, many industrial products invented in the past century are water and pollution intensive at the use phase, such as dishwashers, laundry machines and so on (Gerbens-Leenes et al., 2009).

Land use change can also affect water quantity and quality. For instance, urban development increases the amount of impervious surfaces in the area, which can cause flash flooding, impact groundwater system recharge, and increase pollutants and biological contaminants in the water body through runoff. Furthermore, urbanization also brings large amounts of people to urban areas, and causes uneven population distribution. The overloaded population can greatly stress the local water, energy and other resources. Another common example of land use change is the conversion of natural lands into farmlands. The use of fertilizers and insecticides in farmlands can increase the amounts of nutrients and hazardous organic chemicals in the water body, which may lead to further problems such as eutrophication.

In the US, loss of natural lands and farmlands to urban development is a serious threat to local ecosystems. It increased the amounts of pollutants and suspended solids in the water bodies because of the increasing pollution associated with urbanization and the increase of urban impervious lands. It has been projected that the US developed area will increase by 79% from 1997 to 2025 (Alig et al., 2004).

The changing rates of the water stressors discussed above are accelerating. It has been reported that population, total real gross domestic product (GDP), amount of domesticated land, and nitrogen flux to coastal zone are increasing exponentially over the past 250 years (Zimmerman et al., 2008). These rapid changing stressors will further speed up water depletion and quality degradation. There is an urgent need to study and mitigate the impacts of these stressors on the water environment.

1.1.2.3 Impacts of Changing Water Stressors on Energy

The rapid changing water stressors affect the quantity and quality of fresh water sources, which further impact the amount of energy needed for providing water and wastewater treatment services. For instance, when local groundwater and/or surface water sources are depleted, communities have to seek for alternative water supply options such as desalination or water importation, which are more energy intensive than traditional water supply. When the raw freshwater and/or wastewater quality is poor, more energy intensive treatment technologies, more complex treatment process chains and more treatment chemicals have to be applied to treat water to meet the regulations. Overall, Figure 1.2 illustrates the impacts of water stressors on water quantity and quality and consequently on the amount of energy used in water and wastewater systems.

Clearly, energy associated with water supply and wastewater treatment will increase due to the decreasing water quantity, degrading water quality and more stringent regulations. In the US, although renewable energy has been widely studied and strongly recommended, around 84% of the total energy consumption still depends on traditional fossil fuels (EIA, 2008). The problems associated with the overuse of fossil fuels include: (1) depletion of nonrenewable energy resources which may severely interrupt social and economic systems if a transition to a more diverse energy supply does not occur, and (2) various environmental problems caused by emissions (hazardous air pollutants and greenhouse gases) from burning fossil fuels. Therefore, it is critical to understand and evaluate energy consumption associated with water and wastewater systems under various water stressors so the appropriate strategies can be developed to mitigate the impacts of changing stressors.

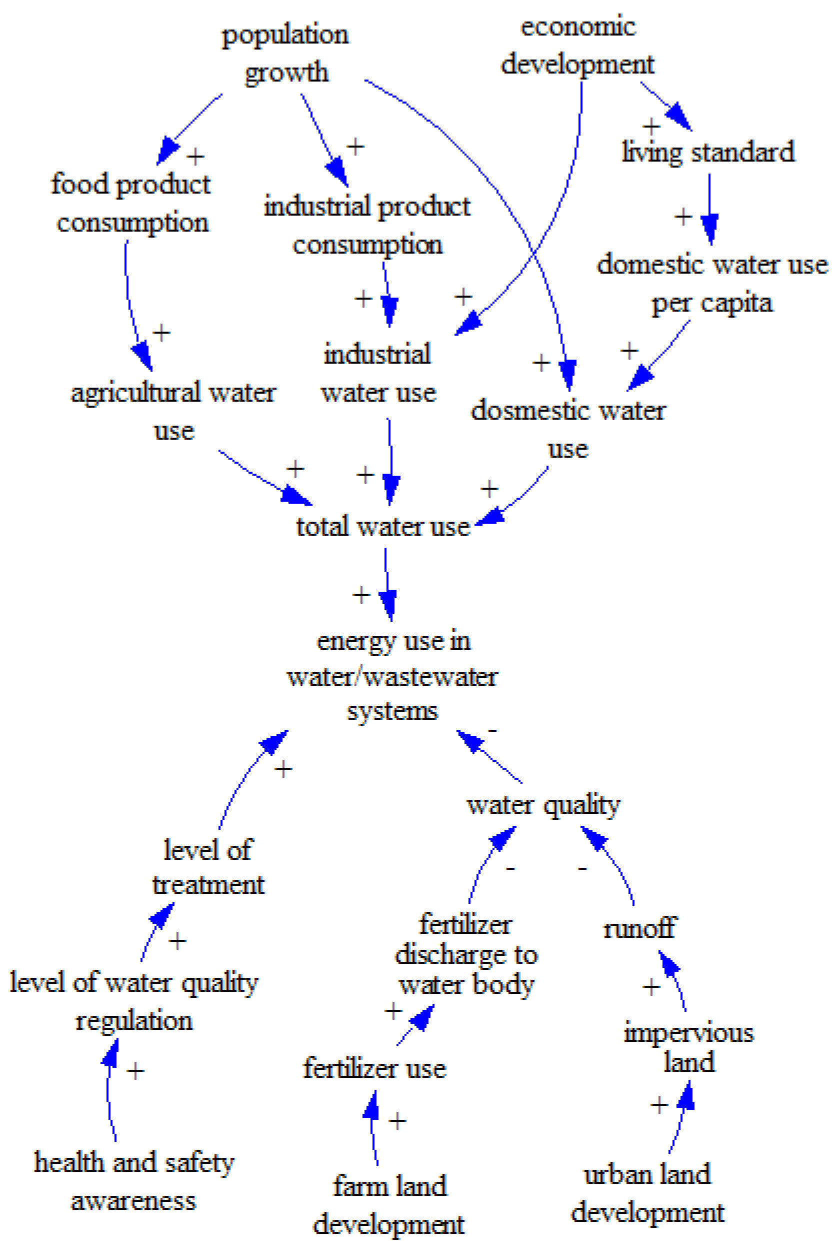


Figure 1.2 The correlations between water stressors, water quantity and quality and energy associated with water systems

1.1.3 Resource Recovery in Wastewater Treatment Systems

The intensive energy and material input in the anthropogenic water use cycle also makes water a potential source for resource recovery, especially the wastewater. Currently, there are over 15,000 municipal wastewater treatment plants (WWTPs) providing wastewater collection and treatment services to around 78% of the US population. They are considered as large resource consumers in the US, but they also have great potential of recovering resources contained in wastewater. Various research has been done to recover resources in wastewater for secondary uses (Hospido et al., 2005; Houillon and Jolliet, 2005; Meneses et al., 2010; Muñoz et al., 2010; Nouri et al., 2006; Ortiz et al., 2007; Pasqualino et al., 2009; Peters and Lundie, 2001; Suh and Rousseaux, 2002; Wett et al., 2007). There are three common ways to recover resources from wastewater systems: (1) onsite energy generation, (2) biosolids land application, and (3) water reuse. Onsite energy generation makes use of the organic loads of wastewater or other unique characteristics of the WWTPs (water flow, residue heat, large space) to produce energy, mainly in the form of electricity. Nutrient recycling recovers nutrients from wastewater as fertilizers to offset the environmental loads associated with producing the equivalent amount of fertilizers from fossil fuels. Moreover, treated wastewater can be reused for various purposes to provide ecological benefits, reduce the demand of potable water and augment water supplies.

Although there are applications of each resource recovery method, the existing applications are rarely justified by life cycle assessment. There are limited life cycle studies that can serve as the guidance for the future application of the resource recovery technologies. Additionally, there is a lack of studies thoroughly reviewing the current status and sustainability of these individual methods as well as their integrations under different scales. Therefore, there is a need to review the pros and cons of the existing onsite energy generation, nutrient recycling and water reuse methods, their application status, and life cycle studies for each resource recovery approach as well as the integration of these approaches under different scales. There is also a need to explore the potential of resource recovery for mitigating energy consumption and associated carbon emissions in municipal wastewater treatment systems.

1.2 Embodied Energy of Water Systems

In order to fully understand and evaluate the energy associated with water supply and wastewater treatment, the life cycle thinking is applied in this study. In addition to the energy consumed directly onsite of water/wastewater systems, there is also energy consumed indirectly in the supply chains for constructing and operating water/wastewater systems and during the end-of-life phase of the constructional and operational materials. A thorough analysis shall include energy used both directly and indirectly for the water supply and wastewater treatment systems. The terms that are frequently used in this study for energy are defined as follows.

(1) Direct energy: Energy used directly and onsite during different life stages of water/wastewater systems. Common types of direct energy include, but are not limited to electricity used for pumping water, aeration, fuel used for any onsite motor equipment, and natural gas or electricity used for system heating.

(2) Indirect energy: Energy used indirectly and offsite during different life stages of water/wastewater systems. Common types of indirect energy include, but are not limited to energy used for producing treatment chemicals, energy used for extracting, producing and delivering constructional materials, and energy used for providing administrative

supplies.

(3) Total embodied energy: The total amount of energy used during the life cycle of a water system. Total embodied energy is the sum of direct energy and indirect energy. It is considered as a very important sustainability indicator of water systems (Lundin and Morrison, 2002; Mels et al., 1999).

1.3 Statement of Needs and Goal of the Study

According to Sections 1.1 and 1.2, current water and energy problems and the research needs can be summarized as follows:

(1) Water and energy are interrelated and there is a reinforcing relationship between them. The reinforcing relationship speeds up the depletion of both fresh water sources and fossil fuels. It is important to understand the total embodied energy of water supply and wastewater systems to find the leverage points for system sustainability.

(2) Global and national water stressors are changing rapidly and have dramatic impacts on water quantity and quality. The depleting water quantity and deteriorating water quality further increases the demand of energy for water supply and wastewater treatment. It is critical to understand and evaluate energy consumption associated with water and wastewater systems under various water stressors.

(3) Although there is great resource recovery potential in wastewater treatment systems to mitigate the energy burden of water and wastewater

systems, there are very limited studies on the life cycle benefits and impacts of the resource recovery methods. There is a need to thoroughly review the current status and sustainability of existing individual methods as well as their integrations under different scales and evaluate the energy and carbon offset potential of commonly used resource recovery methods.

Therefore, the overall goal of this study is to assess the embodied energy of both water supply systems and wastewater treatment systems, explore the potential of integrated resource recovery to reduce embodied energy of wastewater systems, and understand the major factors impacting the embodied energy of water systems. Figure 1.3 shows phases in the urban water cycle that were included in this study.

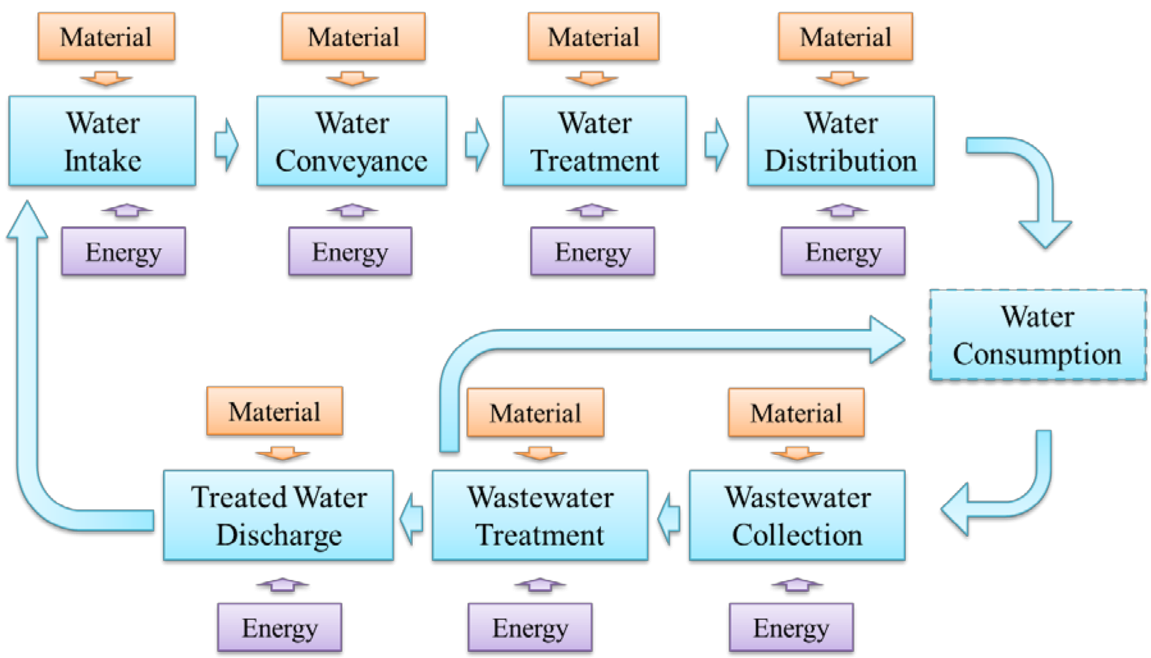


Figure 1.3 Structure of an urban water cycle and the phases included in this study (Dashed box represents the phase in the water cycle that was not examined in this study)

1.4 Hypotheses

Based on the statement of the research needs and the goal of this study, the following hypotheses are proposed.

(1) Hypothesis 1: Indirect energy accounts for a significant proportion of the total embodied energy of water systems, including water supply systems and wastewater treatment systems.

(2) Hypothesis 2: Different water sources have different direct, indirect and embodied energy intensities.

(3) Hypothesis 3: Large scale advanced wastewater treatment systems can achieve carbon neutrality under integrated resource recovery of onsite energy generation through combined heat and power systems, nutrient recycling through biosolids land application and water reclamation for residential irrigation.

(4) Hypothesis 4: Energy embodied in water supply systems is related with land use, water source, and population of the area.

1.5 Research Tasks

To achieve the goal of this study and test the hypotheses, four tasks were performed as highlighted in orange box in Figure 1.4.

(1) Develop an embodied energy model which is capable of analyzing both direct and indirect energy consumption associated with providing water and wastewater services.

(2) Examine embodied energy intensities of different water supply systems (e.g., different raw water sources and different economic context).

(3) Investigate the resource recovery methods in municipal wastewater treatment plants and evaluate the potential of offsetting embodied energy and carbon footprint of the municipal wastewater treatment plant.

(4) Identify the relationship between total embodied energy in water systems and water stressors, such as population and land use, and establish the statistical correlation between these stressors and the embodied energy of water supply systems in a region.

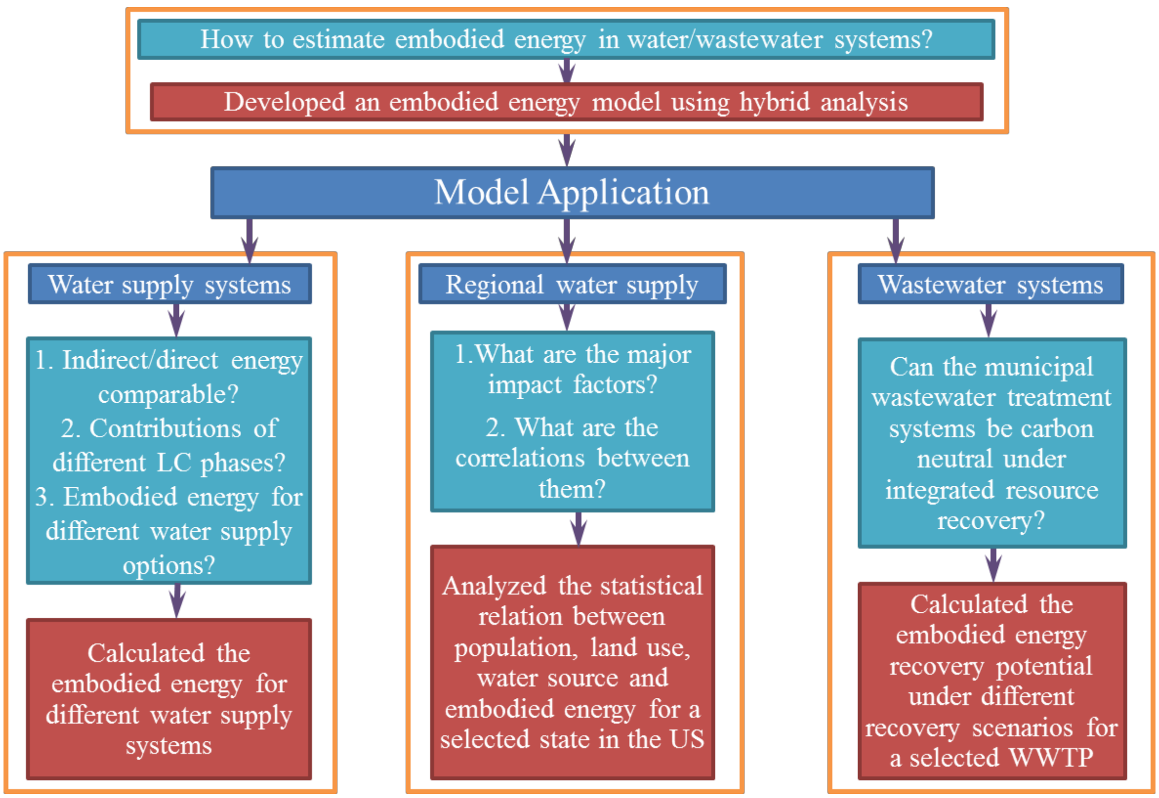


Figure 1.4 The overall flowchart of the four tasks conducted in the dissertation study and associated research questions (LC: life cycle; WWTP: wastewater treatment plant; Boxes in dark blue: different applications of the embodied energy model; Boxes in light blue: research questions; Boxes in red: research tasks.)

1.6 References

Alig, R.J., Kline, J.D., Lichtenstein, M., 2004. Urbanization on the US landscape: looking ahead in the 21st century, Landscape Urban Planning 69, 219-234.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environmental Change 14, 31-52.

Barlow, P.M., 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. US Geological Survey.

Bartolino, J.R., Cunningham, W.L., 2003. Ground-Water Depletion Across the Nation. US Department of the Interior, US Geological Survey.

Danielopol, D.L., Griebler, C., Gunatilaka, A., Notenboom, A., 2003. Present state and future prospects for groundwater ecosystems, Environmental Conservation 30, 104-130.

DOE, 2006. Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water, http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf (last accessed on 6.1.2012).

Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth, Science 171, 1212-1217.

EIA, U., In, D., 2008. Annual energy review, US Energy Information Administration.

Gerbens-Leenes, P., Hoekstra, A., Van der Meer, T., 2009. The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply, Ecological Economics 68, 1052-1060.

Gleick, P.H., 1994. Water and energy, Annual Review of Energy and the Environment 19, 267-299.

Goldstein, R., Smith, W., ICF Consulting Associates, Electric Power Research Institute, 2002. Water & Sustainability (Volume 4): US Electricity Consumption for Water Supply & Treatment-the Next Half Century. Electric Power Research Institute.

Hill, B.T., 2006. Freshwater Supply: States' Views of how Federal Agencies could Help them Meet the Challenges of Expected Shortages. DIANE Publishing.

Hospido, A., Moreira, T., Martín, M., Rigola, M., Feijoo, G., 2005. Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes The International Journal of Life Cycle Assessment 10, 336-345.

Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis, Journal of Cleaner Production 13, 287-299.

Konikow, L.F., Kendy, E., 2005. Groundwater depletion: A global problem, Hydrogeology Journal 13, 317-320.

Lundin, M., Morrison, G.M., 2002. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems, Urban Water 4, 145-152.

Mels, A.R., van Nieuwenhuijzen, A.F., van der Graaf, J.H.J.M., Klapwijk, B., Koning, J., Rulkens, W.H., 1999. Sustainability criteria as a tool in the development of new sewage treatment methods, Water science and technology 39, 243-250.

Meneses, M., Pasqualino, J.C., Castells, F., 2010. Environmental assessment of urban wastewater reuse: Treatment alternatives and applications, Chemosphere 81, 266-272.

Muñoz, I., Milà-i-Canals, L., Fernández-Alba, A.R., 2010. Life Cycle Assessment of Water Supply Plans in Mediterranean Spain, Journal of Industrial Ecology 14, 902-918.

Nouri, J., Jafarinia, M., Naddafi, K., Nabizadeh, R., Mahvi, A., Nouri, N., 2006. Energy recovery from wastewater treatment plant, Pakistan Journal of Biological Sciences 9, 3-6.

Ortiz, M., Raluy, R., Serra, L., 2007. Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town, Desalination 204, 121-131.

Pasqualino, J.C., Meneses, M., Abella, M., Castells, F., 2009. LCA as a decision support tool for the environmental improvement of the operation of a municipal wastewater treatment plant, Environmental Science and Technology 43, 3300-3307.

Peters, G.M., Lundie, S., 2001. Life-Cycle Assessment of Biosolids Processing Options, Journal Industrial Ecology 5, 103-121.

Postel, S., 1997. Last Oasis: Facing Water Scarcity. WW Norton & Company.

Prüss-Üstün, A., Bos, R., Gore, F., Bartram, J., 2008. Safer water, better health: costs, benefits and sustainability of interventions to protect and promote health, World Health Organisation, Geneva.

Seckler, D., Barker, R., Amarasinghe, U., 1999. Water scarcity in the twenty-first century, International Journal of Water Resources Development 15, 29-42.

Shah, T., Roy, A.D., Qureshi, A.S., Wang, J., 2003. Sustaining Asia’s groundwater boom: An overview of issues and evidence, 27, 130-141.

Smith, R.A., Alexander, R.B., Wolman, M.G., 1987. Water-quality trends in the nation's rivers, Science 235, 1607-1615.

Suh, Y.J., Rousseaux, P., 2002. An LCA of alternative wastewater sludge treatment scenarios, Resources, Conservation and Recycling 35, 191-200.

Taylor, C.J., Alley, W.M., 2001. Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data. US Geological Survey.

Torcellini, P.A., Long, N., Judkoff, R., 2003. Consumptive water use for US power production, NREL/TP-550-33905.

UNEP. Division of Early Warning and Assessment, GRID-Geneva, 2004. Freshwater in Europe: Facts, Figures and Maps. UNEP/DEWA-Europe.

USGS, 2012. Groundwater use in the United States, http://ga.water.usgs.gov/edu/wugw.html (last accessed on 7.15. 2010).

USGS, 2009. Estimated use of Water in the United States in 2005. US Geological Survey, Reston, VA.

Wett, B., Buchauer, K., Fimml, C., 2007. Energy self-sufficiency as a feasible concept for wastewater treatment systems, IWA Leading Edge Technology Conference, Asian Water, Singapore , 21-24.

WHO/UNICEF, Joint Water Supply and Sanitation Monitoring Programme, 2006. Meeting the MDG Drinking Water and Sanitation Target: The Urban and Rural Challenge of the Decade. World Health Organization.

World Bank, 2012. Population growth (annual%), http://data.worldbank.org/indicator/SP.POP.GROW/countries/1W?display=default (last accessed on 9.2.2012).

Zimmerman, J.B., Mihelcic, J.R., Smith, J., 2008. Global stressors on water quality and quantity, Environmental Science and Technology 42, 4247-4254.

CHPATER 2: INPUT-OUTPUT-BASED HYBRID EMBODIED ENERGY MODEL

2.1 Previous Studies on Energy Use in Water Systems

Previous research on energy use in water systems primarily aimed at reducing the energy cost of drinking water and wastewater treatment systems. As a result, the direct energy consumption in water systems, especially the direct electricity consumption, has been widely studied (Elliott et al., 2003; Goldstein et al., 2002; Scott et al., 2007; Wilkinson, 2000). For example, Wilkinson (2000) estimated the electricity use in the water systems of California, including water acquisition, wastewater treatment, and water reuse. While the study was relatively complete in terms of the urban water use cycle, energy associated with material and service supplies was ignored. Although direct energy in the water systems is a significant component of the total embodied energy, this simplification may lead to underestimation and inaccuracies when supporting design, operation, and policy associated with drinking water and wastewater treatment systems. Overall, these studies play an important role in local grid planning and financial planning, but they do not provide sufficient information on the sustainability of water systems and cannot be used as guidance for future regional and national planning of water systems.

This Chapter is adapted with permission from "Mo, W., Nasiri, F., Eckelman, M.J., Zhang, Q., Zimmerman, J.B., 2010. Measuring the embodied energy in drinking water supply systems: a case study in The Great Lakes region, Environmental Science and Technology 44, 9516-9521", Copyright (2010) American Chemical Society, and "Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options, Water Research 45, 5577-5586", Copyright (2011) Elsevier.

Embodied energy in water systems, on the other hand, has been studied by several researchers in the past using life cycle assessment (LCA). LCA is an accounting framework for quantifying environmental impacts across the entire life cycle of a product or process. There are three main methods used by previous researchers: process LCA, input-output LCA and process-based hybrid LCA.

2.1.1 Process LCA

Process LCA, in which individual flows of material and energy are tracked at the process engineering level (Lenzen and Treloar, 2002; Scheuer et al., 2003), has been utilized to analyze the environmental impacts associated with various water treatment options in England (Dennison et al., 1999), South Africa (Friedrich, 2002), Australia (Peters and Rouse, 2005), Spain (Raluy et al., 2005a), and the United States (Lyons et al., 2009), while analyses of the impacts of entire municipal drinking water and wastewater systems have been undertaken on the basis of a single unit of water (Lassaux et al., 2007) and in total (Lundie et al., 2004). Options for water reuse and recycling have also been considered (Crettaz et al., 1999). Table 2.1 summarizes the main LCA studies on the embodied energy of water systems.

Although material consumption were considered, almost all the process LCA studies reviewed in Table 2.1 did not provide a particular number of the total embodied energy of water systems; however, they all show that electricity generation has been the largest contributor to the greenhouse emissions and operation stage has the highest environmental impact. In conventional treatment, material use is always the second

Table 2.1 Process life cycle assessment studies on the embodied energy of water systems

System considered	Life cycle stages	Energy use calculation	Key findings	Source
Conventional water treatment; Membrane filtration treatment	Construction; Operation; Decommissioning	Material use was estimated, but was not converted into indirect energy consumption; Environmental impacts based on both material and energy use was analyzed.	Operation stage is the dominant stage in water production while the decommissioning stage is the least important one; Electricity generation causes the most environmental burdens for both treatment methods.	(Friedrich, 2002)
From the bulk water supplies, to water filtration plants, water system areas, customer areas, wastewater system areas and sewage treatment plants of Sydney Water System	Construction; Operation Maintenance	Material use was estimated, but was not converted into indirect energy consumption; Direct energy used during the construction process was excluded; Total climate change potential based both material and energy use was analyzed.	Electricity consumption and material use were the largest contributors to total energy, climate change indicators and other environmental impact indicators.	(Lundie et al., 2004)
Brackish water reverse osmosis, seawater reverse osmosis and water transfer from a distant river; All three scenarios are considered from raw water intake and conveyance, water treatment and water distribution	Construction; Operation; Disposal of wastes and emissions	Material use was estimated, but was not converted into indirect energy consumption; Total climate change potential based on both material and energy use was analyzed.	The electricity consumption in pumping and water treatment had significant environmental burdens; Pipeline construction was another important environmental burden contributor; The recurrent material demands of the desalination scenarios were two or three times greater than those for the building materials.	(Peters and Rouse, 2005)

Table 2.1 (continued)

Commercial desalination technologies: MSF, MED and RO	Assembly; Operation; Final disposal	Material use was estimated, but was not converted into indirect energy consumption; Different integrations with renewable energies were studied	The integration with hydro-power resulted in the highest reduction in airborne emissions, and the solar energy the lowest; The production capacity of wind plant has positive effects in all desalination technologies, solar plant as well.	(Raluy et al., 2005c)
The supply of potable water to an industrial zone in South Africa, including water purification and pumping, boosting system, reservoir storage and gravitational system	Operation; Disposal	Material use was estimated, but was not converted into indirect energy consumption; Environmental impacts based on both material and energy use were analyzed.	The extraction of water from the ambient environment has the highest impacts; The impacts of the required chemicals of the water supply system are of low importance.	(Landu and Brent, 2007)
Commercial desalination technologies: MSF, MED and RO	Assembly; Operation; Final disposal	Both material and energy use were considered for giving scores, but no specific data was given.	The main contributor to the global environmental impacts is the operation, while construction and disposal are almost negligible; The environmental loads change a lot depending on the technology used for providing the energy used in the desalination process.	(Raluy et al., 2005a)

Table 2.1 (continued)

Reverse osmosis desalination and river transfer; Both scenarios are considered from raw water intake, conveyance, treatment and distribution	Extraction and processing raw materials; Manufacturing; Transportation and distribution; Operation; Final waste disposal	Energy embodied in material use was considered, but no specific data were given.	For reverse osmosis, operation stage has a large environmental impact, while for river transfer, the contribution of the operation stage is also important, but the construction phase has an important contribution too.	(Raluy et al., 2005b)
Water catchment, distribution, water and wastewater treatment, waste disposal and direct discharge in Walloon region in Belgium	Construction (putting pipes into the ground are not considered); Operation; Disposal of wastes and emissions	Material use was estimated, but was not converted into indirect energy consumption; Total environmental loads based on both material and energy use was analyzed.	Increased level of wastewater treatment can lower the environmental burdens	(Lassaux et al., 2007)
Three different system scales were studied: water treatment process only; in plant water intake, treatment and delivery; water intake, water treatment, water distribution to customers	Construction; Operation	Material use was estimated, but was not converted into indirect energy consumption; Total greenhouse gases emission based on both material and energy use was estimated.	At the scale of the water treatment process, energy consumption is shown to carry the highest environmental burden of potable water production, chemical production represents the second major contribution to impacts; At the scale of the potable water production plant, energy consumption due to intake pumping and water distribution is the major contributors to the environmental impacts of the plant.	(Vince et al., 2008)

Table 2.1 (continued)

Water importation, reclamation and seawater desalination; For all three scenarios, water conveyance and treatment were studied	Infrastructure; Operation & Maintenance	Material use was estimated, but was not converted into indirect energy consumption; The impacts of energy use and material use were compared.	Seawater desalination has the highest impact whereas reclamation shows a relatively lower impact; The impacts of facility operations are significantly higher than the construction phase; In the water importation option, conveyance consumed more energy than the treatment process, while the contrary was found for the other two options.	(Lyons et al., 2009)
No-reuse scenario, Brine dilution scenario, potable water replacement scenario, desalinated water replacement scenario; For all four scenarios, from wastewater collection to final disposal or reuse was studied, but the first two scenarios do not include tertiary treatment.	Include all phases except the construction and dismantling of the wastewater treatment plant	Cumulative energy demand was estimated and compared for different treatment units.	No reuse, brine dilution and potable water replacement have similar environmental profiles and that replacement of desalinated water has the greatest environmental benefits.	(Pasqualino et al., 2011)

Table 2.1 (continued)

For disinfection: chlorination plus UV, ozonation, ozonation plus hydrogen peroxide were studied; For water reuse: reclaimed water for agricultural irrigation, reclaimed water for urban applications, potable water (conventional), and desalinated water were compared.	Only the operation stage of the tertiary treatment of the plant was included within the system boundaries	Cumulative energy demand was estimated and compared for the four water reuse scenarios.	Non-potable uses (both agricultural and urban uses) of reclaimed water have environmental and economic advantages. Reuse of treated wastewater is particularly beneficial when it can replace desalinated water. Consequently, reclaimed water should be promoted for non-potable uses.	(Meneses et al., 2010)
Conventional activated sludge system, conventional activated sludge system with filtration treatment, immersed membrane biological reactor, and external membrane biological reactor was studied.	Include construction, operation and maintenance, and dismantle and final disposal (without any recycling) of the plant	Material use was estimated, but was not converted into indirect energy consumption; air emissions and total environmental impacts of the four scenarios were estimated and compared.	The results show that tertiary treatment does not increase significantly the environmental loads but provide new uses for that purified water, thus justifying the intensive use of reclaimed water in water scare areas.	(Ortiz et al., 2007)

Table 2.1 (continued)

ERWT: based on a single interbasin transfer; AGUA: excludes new transfers and focuses instead on different types of resources, including seawater/brackish water desalination, wastewater reuse and so on.	Include the whole anthropic cycle of water, from water abstraction to wastewater treatment, construction, operation, dismantling	Global warming potential was estimated, but embodied energy consumption was not reported.	The AGUA programme performs slightly better than the ERWT in most categories with the exception of ozone depletion potential. The AGUA has 49% lower Freshwater Ecosystem Impact than the ERWT.	(Muñoz et al., 2010)

largest environmental impact contributor, but in seawater desalination, the material use is negligible because of the high energy demand of the desalination process.

In the LCA studies listed in Table 2.1, some concluded that the construction phase is negligible (Lyons et al., 2009; Raluy et al., 2005a), while some showed it to be important (Peters and Rouse, 2005). These contradictory results may due to the different selection of system boundaries. In process analysis, it is very difficult to set system boundaries, making sure the additional upstream production stages have little effect on the whole system. Hence, the traditional life cycle assessment tends to underestimate the energy embodiments because of limited data sources and truncated system boundaries (Crawford, 2008). Although results from process analysis might be accurate and specific with sufficient data, the large amount of data needed may not be easy to obtain. The data collecting process can be very labor and time intensive.

2.1.2 Input-Output LCA

To avoid the problems associated with process analysis, input-output LCA (e.g., Economic Input-Output Life Cycle Assessment) was used by some researchers for estimating energy consumption. Input-output analysis is a top-down economic technique, which uses sectoral monetary transaction matrices describing complex interdependencies of industries in order to trace resource requirements throughout the economy (Lenzen, 2002). The basis of EIO-LCA is the Leontief inverse matrix, which shows the economic structure of a certain state or country (Hendrickson et al., 2006).

Troy et al. (2003) estimated the embodied energy consumption of city construction in six selected study areas in Australia. In their research, embodied energy coefficients derived from input-output analysis were applied to calculate the energy embodied in the various materials used for the city construction, including water supply and sewage systems. Due to data limitation, the total energy embodied in the water supply network was estimated by multiplying the estimated embodied energy supply per housing area with the total housing area. The study suggests that embodied energy consumption in city may be more significant than previously thought.

Similarly, Filion et al. (2004) incorporated input-output analysis in the study of life-cycle energy of a water distribution system to quantify the energy use in production, operation, maintenance and disposal life stages of the distribution system. EIO-LCA was used for calculating the energy embodied in the production of the pipelines. Energy consumption for the use and disposal stage was calculated by extrapolating from the unit estimations. The study found that using a 50-year pipe replacement frequency, the total energy expenditure could be minimized and a balance between energy expenditures in all life stages can be achieved.

Racoviceanu et al. (2007) analyzed the total embodied energy and greenhouse gas emissions for three phases of the water treatment facilities: chemical production, transportation of materials and water treatment plant operation. In their study, the impacts of chemical manufacturing were also estimated using the EIO-LCA, and the inventories for transportation and operational environmental effects were based on data from the GHGenius model and regionally averaged data. The operation stage was estimated to be the largest contributor of total energy use, accounted for 94% of total energy use and 90% of greenhouse gases emissions. On the other hand, transportation related energy use and emissions were calculated to be insignificant.

The system boundary is more complete using the input-output analysis. Plus, there is no need to choose a system boundary, because it is determined by the scale of the input-output tables, which usually are very complete. Thus, results from input-output analysis can be complete and comprehensive and the calculation is much less labor and time intensive. However, the total embodied energy intensities calculated from the input-output analysis are based on national average data, which may contain various errors (Alcorn and Baird, 1996). In addition, a circular effect associated with EIO-LCA may cause double counting the conversion between different types of energy.

2.1.3 Process-Based Hybrid LCA

The process based hybrid approach sums the direct energy and the input-output results of the energy embodied in each type of materials. It is more complete than the traditional life cycle assessment and more accurate than the input-output analysis; however, it usually suffers from limited data sources for material use, and thus cannot be readily applied to other systems.

Stokes et al. (2006) used the process-based hybrid approach to estimate the embodied energy of three alternative water supply systems: water desalination, importation and reclamation. In this study, the types and amounts of material used in the system were collected from individual water systems. EIO-LCA was used to calculate energy intensities for different materials. Embodied energy was calculated through adding energy embodied in each type of material together. Desalination was found to have the largest total embodied energy demand. Operational stage has largest energy consumption for all three water sources. For importation, water conveyance is the most energy intensive phase due to the local geographical conditions. For desalination, treatment is the dominant one. For reclamation, water distribution to the customer is the most energy intensive phase. Later, Stokes et al. (Stokes and Horvath, 2009) applied the same methodology in another study which compared the life cycle energy use and air emissions for different water supply options. Desalination is able to achieve high energy efficiency by incorporating solar thermal technology.

2.1.4 Input-Output-Based Hybrid LCA

To avoid the disadvantages of both process analysis and input-output analysis, an input-output-based hybrid analysis combining both process analysis and input-output analysis was developed (Treloar, 1997; Treloar et al., 2001). This approach involves substituting available process data into an input-output model in order to minimize the errors associated with the traditional LCA and the process-based hybrid analysis (Crawford, 2008). One major step of the input-output-based hybrid analysis is the energy path pruning procedure. Energy paths with the highest embodied energy will be extracted and modified using site specific data. This will substantially reduce the amount of work and improve accuracy. This approach has been used by a study in Australia to estimate energy embodied in buildings (Treloar, 1997), but it has not been used for water systems.

Previous studies (Crawford, 2008; Mattila et al., 2010) have shown that the input-output based hybrid approach is more comprehensive and less labor intensive than the traditional life cycle assessment. Additionally, the input-output based hybrid approach enables flexibility by first providing a rough estimation, and then allowing detailed modifications based on site and system specific data using structural path analysis. One weakness of this approach is that neither differences in water consumption patterns nor temporal differences associated with water systems can be reflected in the model results. A comparison of the four embodied energy calculation approaches was provided by Table 2.2.

Table 2.2 Advantages and disadvantages of the four approaches for calculating the embodied energy of water systems

Approaches	Advantages	Disadvantages
Process LCA	Specific and accurate	Truncated system boundary, and labor and time intensive
Input-output LCA	Complete and convenient	Based on national or regional data, inaccurate application to individual systems
Process-based Hybrid LCA	More complete than traditional LCA, and more accurate than the input-output analysis	Still truncated system boundary, and labor and time intensive
Input-output-based Hybrid LCA	More complete than traditional LCA and process-based hybrid analysis, more accurate than the input-output analysis	Difficult to reflect temporal changes of embodied energy

2.2 Introduction into Input-Output-Based Hybrid Analysis

The input-output-based hybrid analysis combines both process analysis and input-output analysis. Input-output analysis will first be used to capture the national averaged direct and total embodied energy intensities (physical amount of energy per dollar) for each life cycle stage of water systems. Initial total embodied energy intensities can be adjusted to fit for either drinking water supply systems or wastewater treatment systems. Process analysis is then applied to estimate total costs of selected water systems. Initial total embodied energy was calculated through multiplying the initial embodied energy intensities with the total costs. In order to make the embodied energy value more specific for the selected water systems, the estimated embodied energy was modified through a structural path analysis which will be further discussed in Section 2.4. Basic steps involved in developing the input-output-based hybrid embodied energy model are presented in Figure 2.1.

The system boundary in this study includes the construction and operation stages of water intake infrastructures (wells/exposed tower), treatment plants (administrative buildings included), water storage tanks, pipeline systems, pumping stations and wastewater treatment plants. The end-of-life stage was not considered because the embodied energy associated with it has been shown to be insignificant in previous studies (Friedrich, 2002; Raluy et al., 2005c).

This input-output-based hybrid embodied energy model can be used for estimating energy embodied in drinking water supply systems, wastewater treatment systems, and other industrial systems as long as the user has identified appropriate economic target sectors and has access to system specific data. The following sections in this chapter introduce the processes of the model development step by step.

2.3 Model Development

2.3.1 Estimation of Initial Energy Intensities

The Input-Output matrix used in this study is based on the latest 2002 Use table (U) and Make table (M) published by US Bureau of Economic Analysis (BEA, 2011). The Make table shows the production of commodities by industries, while the Use table

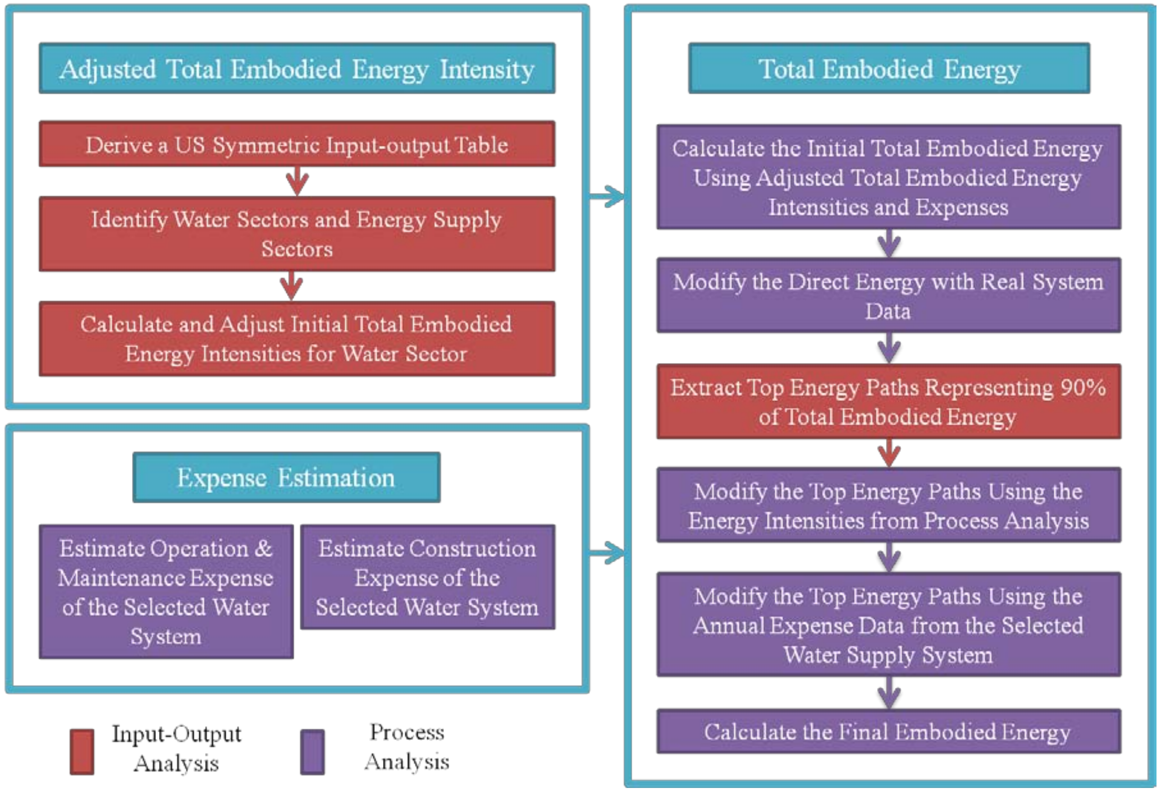


Figure 2.1 Steps involved in establishing the input-output-based hybrid embodied energy model

shows the uses of commodities by intermediate and final users (Horowitz and Planting, 2006). Because neither Make table nor Use table is diagonal, they are not able to be used for calculation directly. As a result, the Use table and the Make table were manipulated in the MATLAB R2010a software to create a commodity-by-commodity direct coefficient table (CC) through the following steps:

$$\begin{aligned} CC &= B \times D; \\ B &= Ug^{-1}; \\ D &= Mq^{-1} \end{aligned} \qquad (2\text{-}1)$$

where

CC = Commodity-by-commodity direct coefficient table;

B = Commodity-by-industry direct coefficient matrix;

D = Industry-by-commodity direct coefficient matrix;

U = Use table;

M = Make table;

g = A column vector showing the total \$ output of each industry;

q = A column vector showing the total \$ output of each commodity.

The coefficients in the commodity-by-commodity direct coefficient matrix show the monetary amount of different commodities (in columns) directly needed to produce one dollar of output of a certain commodity (in rows).

There are, in total, 424 commodity sectors in the BEA tables. These sectors were classified based on the North American Industry Classification System (NAICS). NAICS is based on the assumption that industries should be classified on the basis of their production processes (Horowitz and Planting, 2006). Of the 424 commodity sectors, two target sectors were selected to represent water systems (r = 1,2):

(1) The water, sewage and other systems sector (WSOS): It is used to represent the operation and maintenance of water systems (both drinking water systems and wastewater treatment systems),

(2) The other nonresidential structures sector (NS): It is used to represent a proxy for the construction of water systems (both drinking water systems and wastewater treatment systems).

These sectors clearly include economic activities not directly related to the provision of water. The WSOS sector is originally defined as water supply and irrigation systems, sewage treatment facilities and steam and air-conditioning supply by NAICS. The NS sector includes industrial and commercial building construction, water and sewer line and related structures construction, oil and gas pipeline and related structures construction, power and communication line and related structures construction, highway, street and bridge construction and so on. Thus, it is necessary to make appropriate adjustments to the CC table and the initial embodied energy intensities to fit for water systems. Processes of making the adjustments are described in later sections. These adjustments require the use of the direct requirements table used in this study, as opposed to the more aggregated total material requirements table used in other I-O formulations (Hendrickson et al., 2006).

The direct and total (direct + indirect) embodied energy per unit output of the adjusted WSOS and NS sectors are calculated by examining the inputs to both target sectors from other energy-related sectors. Direct energy for WSOS is the energy used for operating and maintaining the water system, such as electricity for pumping; indirect energy for WSOS is the energy used to manufacture and deliver non-energy inputs used for operation or maintenance, such as treatment chemicals. Direct energy for NS is that used for constructing the water system, such as diesel fuel for mixing the concrete, while indirect energy for NS is that used to manufacture and deliver the cement to the site, for example.

Five energy supply sectors are identified from the 424 commodity sectors:

(1) Oil and gas extraction,

(2) Coal mining,

(3) Power generation and supply,

(4) Natural gas distribution, and

(5) Petroleum refineries.

The distribution of coal and petroleum are not included in these energy supply sectors as they represent a small fraction (<0.2%) of the cost of these fuels. Several input coefficients in the CC table were modified in order to avoid double counting of the fuel used for electricity generation. For example, the upstream use of coal by the power utilities was set to be zero because this energy is already accounted for in the output of the power generation sector. The upstream use of oil by petroleum refineries was also set to be zero to avoid double counting.

Further adjustment is needed to account for losses during power generation, transmission and distribution for each type of fuel, which was done through using a series of primary energy factors (Gowdy and Miller, 1987). An alternate approach that has been pursued is to consider only the non-fossil portion of US electricity, that is, 31% of the total, by multiplying this factor by the output value of the power generation and supply sector which was adopted by the Economic Input-Output Life Cycle Assessment Software (EIO-LCA) created by the Carnegie Mellon University. After these adjustments, the five energy supply sectors were then combined and the monetary value of each energy supply sector translated into consistent physical units using energy tariffs, which specify the average monetary cost of each fuel. The energy tariffs used in this study are based on U.S. EIA estimates (EIA, 2003) and are shown, with the primary energy factors, in Table 2.3.

Table 2.3 National primary energy factors and energy tariffs for each energy supply sector

Energy Supply Sectors	**Primary Energy Factor (α)**	**Energy Tariff (GJ/$)**
Oil and gas extraction	1.05	0.27
Coal mining	1.13	0.86
Power generation and supply	3.44	0.09
Natural gas distribution	1.05	0.25
Petroleum refineries	1.42	0.17

The modifications described above allow the I-O model to calculate the physical amounts of primary energy needed to provide a specific dollar quantity of goods and services specified by the user. This can be done either through standard Leontief inversion (Leontief, 1970) or through a power series approximation method (Ronald and Peter, 1985), which is the approach used here because it provides deeper insights into structure of energy supply chains. For each stage, or level of the supply chain, the embodied energy is calculated from the energy embodied in the previous stage:

$$\varepsilon_k^{(r)} = \sum_{1}^{N_k} DC_i^{(r)} \times \varepsilon_{(k-1)i} \tag{2-2}$$

where

k = stage index;

$\varepsilon_k^{(r)}$ = stage k energy intensity of the target sector r (GJ/$ output);

N_k = number of sectors in stage k;

DC_i = direct coefficient from sector "i" into the target sector r;

$\varepsilon_{(k-1)i}$ = energy intensity of sector i at k-1 stage with respect to sector i (GJ/$ output).

Direct energy (as stage 0) needs to be calculated first. This is the fuel input directly from energy supply sectors into the adjusted WSOS and NS, such as diesel fuel used to operate maintenance equipment. It is calculated by the following equation:

$$\varepsilon_0^{(r)} = \sum_{i=1}^{5} DC_i^{(r)} \times tariff_i \times \alpha_i \quad (2\text{-}3)$$

where

ε_0 = direct energy intensity of target sector r (GJ/$ output);

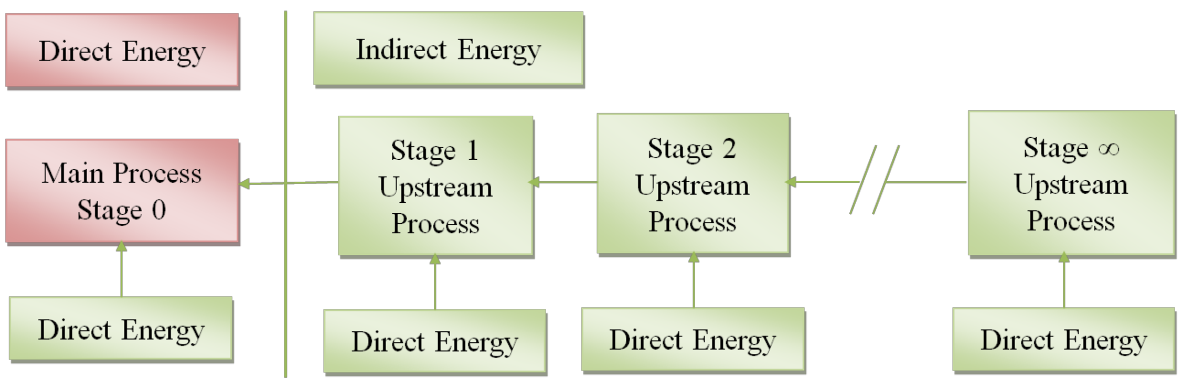
i = energy supply sector index

DC_i = direct coefficient from energy supply sector i into the target sector r;

$tariff_i$ = energy tariff of the energy supply sector i (GJ/$ energy);

α_i = primary energy factor of energy supply sector i.

The total embodied energy intensity of a target water sector can then be calculated by adding up the energy intensities of all upstream stages. The basic framework of calculating the embodied energy intensity of a sector is expressed in Figure 2.2.



Source: after Treloar et al., 2001

Figure 2.2 Basic framework of calculating the embodied energy of an economic sector

It is however impossible to track back all the stages upstream, because the amount of the stages can be infinite. Figure 2.3 reflects the energy intensities of different stages of all the commodity sectors. It shows that after a certain number of stages, the energy intensities are almost negligible. The highest energy intensities are mostly concentrated in stage 0 and stage 1. For more than 72% of the sectors, energy intensities in stage 0-12 represent more than 98% of the total embodied energy intensities and all the sectors have higher than 95% of the total embodied energy intensities in stages 0-12. Thus, to minimize unnecessary complexity, no more than 12 stages were considered in this study, as the energy contributions of non-energy sectors beyond the 12th stage are negligible (<0.01% of the total embodied energy for the WSOS and the NS sectors).

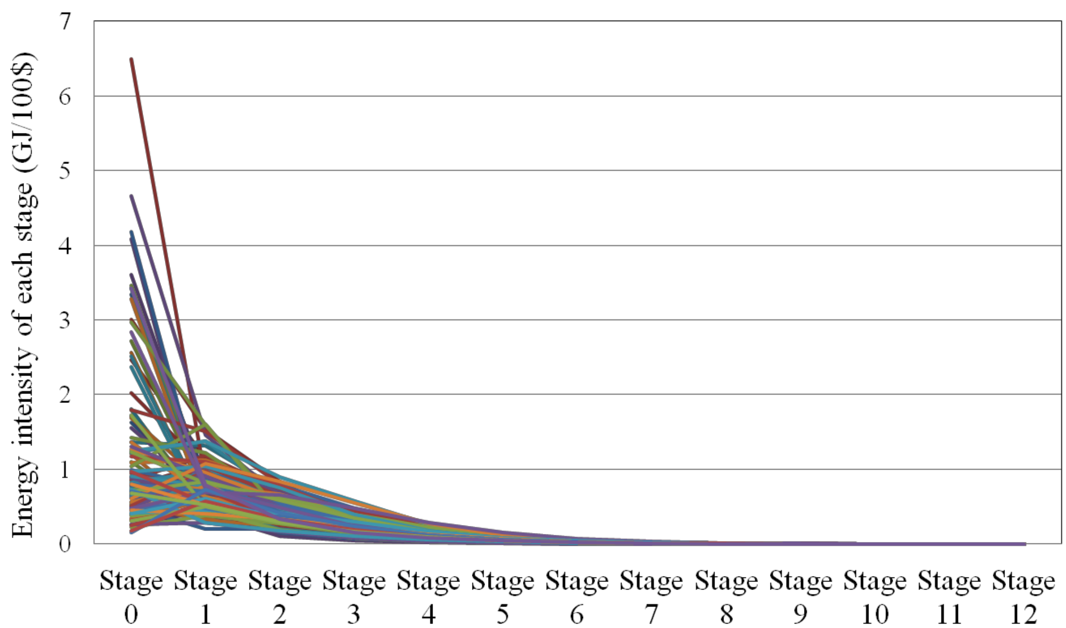


Figure 2.3 Energy intensity distribution at different upstream stages for the commodity sectors in the input-output tables

2.3.2 Modifications of Initial Energy Intensities

There are a number of modifications that can be made to the direct and embodied energy results that increase the specificity, both in statistical and contextual terms, of the model described here. As the target sectors considered here (WSOS and NS) include but are not limited to water supply and wastewater treatment activities, the embodied energy results from the I-O model are firstly modified to be more representative of only the activities associated with water supply systems or only the activities associated with wastewater treatment systems. This is done by isolating the water supply portion or wastewater treatment portion of the WSOS and NS sectors with detailed commodity output and energy use information for the water supply or wastewater treatment portion:

$$\varepsilon_{s0}^{(r)} = \frac{E_S^{(r)}\%}{C_S^{(r)}\%} \times \varepsilon_0^{(r)} \qquad (2\text{-}4)$$

where

$\varepsilon_{s0}^{(r)}$ = Energy intensity of target sector r after modification to the water supply system of interest (GJ/$ output)

$E_S^{(r)}\%$ = percentage of water supply system energy use in target sector r;

$C_S^{(r)}\%$ = percentage of water supply system commodity output in target sector r;

$\varepsilon_0^{(r)}$ = Initial energy intensity of target sector r (GJ/$ output).

For the WSOS sector, the values of *Es%* of both water supply systems and wastewater treatment systems were calculated based on data provided by an EPRI report (Goldstein et al., 2002). The private wastewater systems are not included in the total energy consumption because they are not included as part of the WSOS sector by the definition of NAICS. *Cs%* of both water supply systems and wastewater treatment systems were obtained from the 2002 economic census provided by the US Census Bureau (US Census Bureau, January, 2012). For the NS sector, the values of Es% of both water supply systems and wastewater treatment systems were estimated combining the

1997 input-output tables. That is because the classifications of the commodities in 1997 and 2002 are slightly different. There was a sector called the water, sewer and pipeline construction in 1997 tables, but this sector is combined with other sectors as the other nonresidential structures sector in 2002 tables. It was assumed that the energy intensity for constructing water systems is the same in 1997 and 2002 and the energy intensities of constructing water supply systems is similar to wastewater systems (United Nations, 1999). Therefore the 1997 energy intensity is used with the commodity output value of water supply systems and wastewater treatment systems adjusted for 2002. Values of *Cs%* of both water supply systems and wastewater treatment systems were sourced from 2002 detailed item output provided by the Bureau of Economic Analysis.

In order to improve spatial specificity, model results can be further adjusted to reflect either a surface water-based system or a groundwater-based system, depending on the site in question. The energy intensities of the surface- or ground- water-based systems may vary significantly based on the different water intake and pumping structures and treatment technologies required. A study by EPRI estimated that groundwater systems require approximately 30% more electricity per unit of water delivered than surface water systems (Goldstein et al., 2002). This value can be combined with the proportion of groundwater and surface water for the site in question, relative to the national average (approximately 40% groundwater) (EPA, 2002), in order to adjust the national I-O results to better reflect individual systems.

A final possible adjustment concerns the power generation sector. The environmental impacts associated with electricity use depend crucially on the mix of local generation sources, electricity trading across regions, and the efficiency of electricity production, for example (Eckelman et al., 2008). In the context of the present study, the embodied energy associated with electricity use can be made location-specific by determining an appropriate primary energy factor for power generation, as described in Table 2.1. Site-specific factors can be derived at several geographic levels, for example using data from eGRID (EPA, 2008).

2.3.3 Expense Estimation

The WSOS sector represents the operation and maintenance activities in water supply systems or wastewater treatment systems. The monetary output of the WSOS sector is the annual expenses for operating and maintaining water systems, which can be obtained either from the selected water systems or estimated through cost curves or equations.

The NS sector represents the activities in constructing water supply systems or wastewater treatment systems. The monetary output of the NS sector is the capital costs of water systems. Because normally it is very difficult to obtain the total capital costs directly from the water systems due to expansions and renovations over time, cost equations and curves were carefully selected to best estimate the capital costs of the existing systems including the capital costs of the treatment processes, equipments, and administrative buildings (McGivney and Kawamura, 2008; Traviglia et al., 2008).

Table 2.4 provides the cost equations and sources that were used to estimate the cost of the selected water systems when necessary. The operational cost of water delivery was included as the operation of pipeline instead of pumping stations. Operational costs for the storage tanks were neglected.

Costs estimated by the equations and curves from years other than 2002 were adjusted to 2002 $USD using the Consumer Price Index (InflationData, June, 2012).

2.3.4 Structural Path Analysis

In order to modify the initial embodied energy, energy paths (supply chains starting from the energy involved in one material or service supply sector, and ending at the water-related sector) representing high percentages of the total embodied energy intensities were extracted through structural path analysis. The terms of energy paths and stages are illustrated in Figure 2.4.

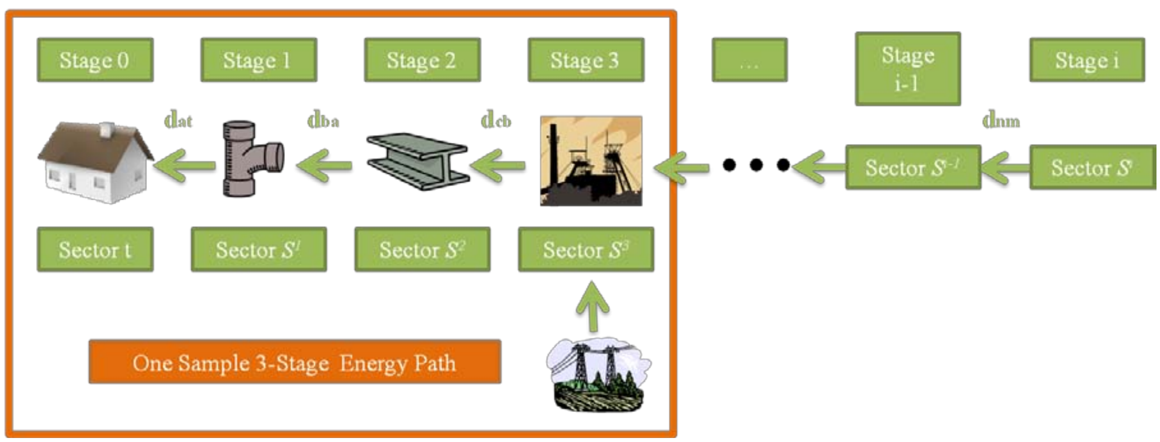


Figure 2.4 Description of energy path, stages and relationship between different stages with a sample of a 3-stage energy path (d_{at} represents direct coefficient from sector “a” to sector “t”, others are the same; Sector “t” represents the target section (i.e., water-related sectors in this study), others represents any commodity sector in the US input-output tables.)

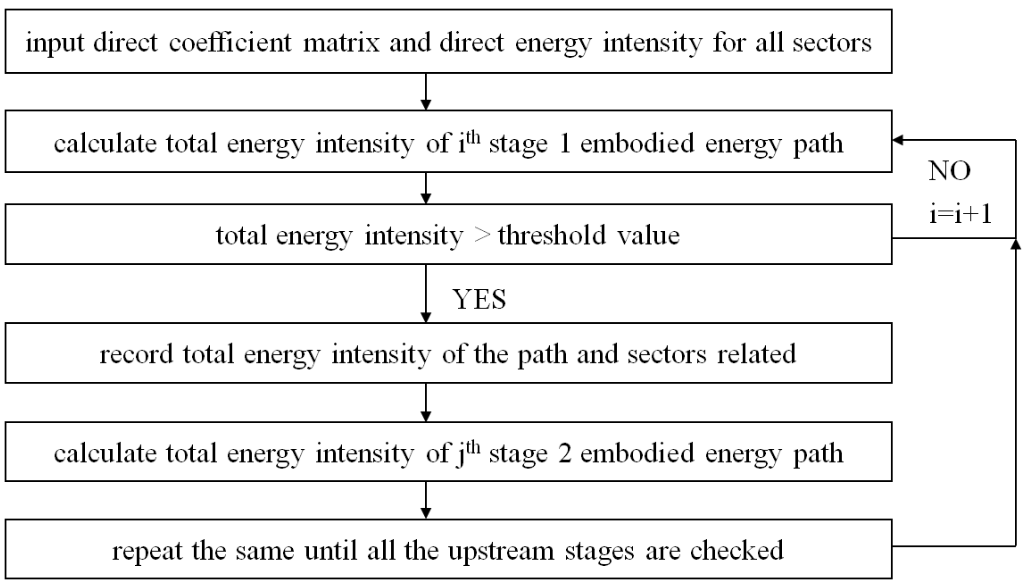
Table 2.4 Cost estimation equations and sources for both operation and construction of water systems

Infrastructures	Equations for operation	Equations for the construction	Sources
Wells	$O_w = Q \times (mg(d+h)) \times e \times y / P_e$ O_w = Operational cost of a groundwater well, \$/year; Q = Design flow, MGD; d = Depth to water level, m; h = Head loss, m; e = Unit cost of electricity, \$/Kwh; y = Days per year, 365 days/year; P_e = Pump efficiency.	$C_w = f_a + f_b \times D_i + f_c \times D_e$ C_w = Constructional cost of a groundwater well, \$1000; D_i = Diamater of the well, inches; D_e = Depth of the well, ft; f_a = Factor a, -288; f_b = Factor b, 145.9; f_c = Factor c, 0.754.	2007 dollars McGivney et al., 2008
Surface water intake infrastructures	$O_i = f_d \times Q_a \times H_a \times e / P_e + f_e \times Q_a^{0.32} \times R + E$ Q_i = Operational cost of surface water intake, \$/year; f_d = Factor d, 1.14×10^5; Q_a = Average flow, MGD; H_a = Average heat, ft; R = Standard labor rate, \$30/hr; E = Equipment replacement costs, \$/year; e = Unit cost of electricity, \$/Kwh; P_e = Pump efficiency.	$C_i = f_f \times Q_m^{0.46} \times H^{0.92} + f_g \times Q_m^{0.76}$ $+ f_f \times Q_m^{0.46} \times D^{0.92} + f_h \times H_m \times Q_m^{0.935}$ C_i = Constructional cost of surface water intake structures, \$; Q_m = Maximum flow, MGD; H = Exposed tower height, ft; D = Depth of wet well at the water intake pumping station, 10 ft; H_m = Maximal head for water intake pumping, ft; f_f = Factor f, 1451; f_g = Factor g, 324; f_h = Factor h, 386.	2003 dollars Linaweaver et al., 1964 Traviglia et al., 2004

Table 2.4 (continued)

Pipelines	$O_{pi} = f_i \times (f_j \times S_l + f_k \times S_f) \times e / P_e$ O_{pi} = Operational cost of pipeline, \$/Kgal/mile; f_i = Factor a, 0.0166; f_j = Factor b, 0.75; f_k = Factor c, 0.667; S_l = Average uphill/downhill slope, ft/1000 ft; S_f = Friction loss from Hazen-Williams equation, ft/1000 ft; e = Unit cost of electricity, \$/Kwh; P_e = Pump efficiency.	$C_{pi} = f_l \times D_i^{1.3983}$ C_{pi} = Constructional cost of pipeline, \$/mile; D_i = Diameter of pipe, inches; f_l = Factor i, 5792.16.	2003 dollars Linaweaver et al., 1964 Traviglia et al., 2004
Water treatment plant	Cost curves selected based on treatment technologies	Cost curves selected based on treatment technologies	2007 dollars McGivney et al., 2008
Pumping stations	Included in the pipeline operation part	$C_{pu} = f_m \times Q + f_n$ Cpu = Constructional cost of pumping stations, \$; Q = Pumping station capacity, MGD; f_m = Factor m, 18888; f_n = Factor n, 140743.	2007 dollars McGivney et al., 2008
Storage tanks	None	$C_s = f_o \times Q + f_p$ C_s = Constructional cost of storage tanks, \$; Q = Storage tank capacity, MGD; f_o = Factor, 604450; f_p = Factor, 215121.	2007 dollars McGivney et al., 2008

To reduce the amount of calculations, up to 5-stage energy paths were checked. Threshold values were selected to determine the amount of energy paths to be extracted. The structural path analysis process is described by Figure 2.5. The large amount of commodity sectors in the US input-output tables leads to an extremely large number of energy paths to be extracted. Thus, in order to represent greater than 90% of the initial total embodied energy intensities, threshold values were selected to extract paths representing 90% of the initial total embodied energy intensities for the two water-related sectors in this study.



Source: after Treloar et al., 2001

Figure 2.5 Detailed process of structural path analysis to extract the top energy paths

2.3.5 Modification of the Total Embodied Energy

To modify the initial direct energy, system-specific data from the water supply systems were substituted in to replace the initial model estimations. Due to data limitations, however, this adjustment was only thoroughly performed for the WSOS sector.

To modify the initial indirect energy, the method presented by Treloar (Treloar, 1997) and Lenzen et al. (Lenzen and Crawford, 2009) was used. For a certain 1-stage energy paths (from sector s^1 to target sector), the energy involved can be calculated as:

$$E_{s^1,0} = \varepsilon_{s^1} C_{s^1} = \varepsilon_{s^1} d_{s^1,t} C_t \qquad (2\text{-}5)$$

where:

$E_{s^1,0}$ = the initial energy for the energy path from sector "s^1" (the sector in stage 1) to the target sector "t", TJ;

ε_{s^1} = direct energy intensity of sector "s^1", TJ/$ output of sector "s^1";

C_{s^1} = direct purchase from sector "s^1" by the target sector "t", $;

$d_{s^1,t}$ = direct coefficient from sector "s^1" to the target sector "t", $/$ output of the target sector "t";

C_t = total monetary output of the target sector "t", $.

According to Equation 2-5, the calculation of a 1-stage energy path contains two parts, the direct energy intensity of "s^1" sector (ε_{s^1}) and the amount of "s^1" commodity directly used by the target sector (C_{s^1}). Both parts were adjusted based on available data. As shown in Equation 2-5, C_{s^1} was calculated by multiplying the direct coefficient with the total monetary output of the water-related sector "t" in the input-output analysis. It can be adjusted using detailed expenses associated with different items obtained from the selected water supply systems. To adjust ε_{s^1}, energy use for manufacturing sectors in 2002 was obtained from the Energy Information Administration (EIA, 2007). The modified energy can be calculated using Equation 2-6:

$$E_{s^1,\Delta} = E_{s^1,0} r_{s^1} = E_{s^1,0}\left(\frac{\varepsilon_{s^1}^{adj}}{\varepsilon_{s^1}}\right)\left(\frac{C_{s^1}^{adj}}{C_{s^1}}\right) \quad (2\text{-}6)$$

where

r_{s^1}= ratio of the modified energy to the initial energy for the energy path from sector "s^1" to the target sector "t";

$E_{s^1,\Delta}$ = modified energy for the energy path from sector "s^1" to the target sector "t", TJ;

$\varepsilon_{s^1}^{adj}$ = adjusted direct energy intensity of sector "s^1", TJ/$ output of sector "s^1";

$C_{s^1}^{adj}$ = adjusted direct purchase from sector "s^1" by the target sector "t", $.

For energy paths with *i* stages, the initial energy involved can be determined using Equation 2-7:

$$E_{s^i,0} = \prod_{k=1}^{i}\left(\varepsilon_{s^i} d_{s^k,s^{k-1}} C_t\right) \quad (2\text{-}7)$$

where

$E_{s^i,0}$ = initial energy for the energy path from the sector in stage *i* "s^i" to the target sector "t" (target sector is the sector in stage 0, s^0), TJ;

ε_{s^i} = direct energy intensity of the sector in stage *i* "s^i", TJ/$ output of sector "s^i";

$d_{s^k,s^{k-1}}$ = direct coefficient from sector "s^k" to sector "s^{k-1}", (s^0 represent the sector in stage 0 which is the target sector "t").

Similarly, the modified energy for energy path from the sector "s^i" to the target sector "t" can be calculated using Equation 2-8 with r_{s^i}.

$$E_{s^i,\Delta} = E_{s^i,0} r_{s^i} = E_{s^1,0}\left(\frac{\varepsilon_{s^i}^{adj}}{\varepsilon_{s^i}}\right)\left(\frac{C_{s^1}^{adj}}{C_{s^1}}\right) \quad (2\text{-}8)$$

For the commodity use at stage "i", an assumption has been made that the change of direct commodity use will cause the upstream supply of this commodity to change proportionally. Also, the indirect energy was modified by substituting the original energy embodied in each energy path with the modified energy.

2.3.6 Indirect Contributing Sectors

Non-energy sectors of the economy contribute embodied energy to the water system through energy-intensive goods and services, such as steel or truck transportation. A single sector will contribute embodied energy to water sectors via multiple supply chains (as represented by multiple energy paths here), and these contributions can be summed to quantify the relative significance of each non-energy sector. The following equation captures the energy contribution of each non-energy sector to target water sectors:

$$EC_i^{(r)} = \sum_{k=1}^{12} \varepsilon_{ki} \times p_{ki}^{(r)} \tag{2-9}$$

where

r = target water sector index;

k = stage index;

$EC_i^{(r)}$ = energy contribution of sector j in target water sector i (GJ/$ output);

ε_{ki} = direct energy intensity of sector j at stage k (GJ/$ output);

$p_{ki}^{(r)}$ = energy path starting from sector j to target sector i at stage k.

2.4 References

Alcorn, J., Baird, G., 1996. Use of a hybrid energy analysis method for evaluating the embodied energy of building materials, Renewable Energy 8, 319-322.

BEA, 2011. Benchmark input-output data, 2012.

Crawford, R.H., 2008. Validation of a hybrid life-cycle inventory analysis method, Journal of Environmental Management 88, 496-506.

Crettaz, P., Jolliet, O., Cuanillon, J.M., Orlando, S., 1999. Life cycle assessment of drinking water and rain water for toilets flushing, Aqua 48, 78-83.

Dennison, F., Azapagic, A., Clift, R., Colbourne, J., 1999. Life cycle assessment: Comparing strategic options for the mains infrastructure—Part I, Water science and technology 39, 315-319.

Eckelman, M.J., Anastas, P.T., Zimmerman, J.B., 2008. Spatial assessment of net mercury emissions from the use of fluorescent bulbs, Environmental Science and Technology 42, 8564-8570.

EIA, January, 2007. 2002 Energy Consumption by Manufacturers-Data Tables, http://www.eia.gov/emeu/mecs/mecs2002/data02/shelltables.html (last accessed on 6.10. 2011).

EIA, U., 2003. Annual energy review 2002, US Energy Information Administration.

Elliott, T., Zeier, B., Xagoraraki, I., Harrington, G.W., 2003. Energy use at Wisconsin's drinking water facilities, Department of Civil and Environmental Engineering, University of Wisconsin–Madison, Report 222-221.

EPA, 2008. eGRID2007 Version1.1 Year 2005 GHG Annual Output Emission Rates, 2012.

EPA, 2002. Community Water System Survey 2000. DIANE Publishing.

Filion, Y.R., 2004. Life-cycle energy analysis of a water distribution system, Journal of Infrastructure Systems 10, 120-130.

Friedrich, E., 2002. Life-cycle assessment as an environmental management tool in the production of potable water, Water science and technology 46, 29-36.

Goldstein, R., Smith, W., ICF Consulting Associates, Electric Power Research Institute, 2002. Water & Sustainability (Volume 4): US Electricity Consumption for Water Supply & Treatment-the Next Half Century. Electric Power Research Institute.

Gowdy, J., Miller, J., 1987. Technological and demand change in energy use: an input-output analysis, Environment and Planning A 19, 1387-1398.

Hendrickson, C.T., Lave, L.B., Matthews, H.S., 2006. Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Resources for the Future, Washington DC.

Horowitz, K., Planting, M., 2006. Concepts and methods of the US input-output accounts, BEA Papers, www.bea.gov/papers/pdf/IOmanual_092906.pdf (last accessed on 6.1.2010).

InflationData, June, 2012. Historical CPI-U data from 1913 to the present, ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt (last accessed on 6.1.2010).

Landu, L., Brent, A.C., 2007. Environmental life cycle assessment of water supply in South Africa: The Rosslyn industrial area as a case study, Water SA 32, 249-256.

Lassaux, S., Renzoni, R., Germain, A., 2007. LCA Case Studies Life Cycle Assessment of Water: From the Pumping Station to the Wastewater Treatment Plant, International Journal of Life Cycle Assessment 12, 118-126.

Lenzen, M., 2002. A guide for compiling inventories in hybrid life-cycle assessments: some Australian results, Journal of Cleaner Production 10, 545-572.

Lenzen, M., Crawford, R., 2009. The path exchange method for hybrid LCA, Environmental Science and Technology 43, 8251-8256.

Lenzen, M., Treloar, G., 2002. Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson, Energy Policy 30, 249-255.

Leontief, W., 1970. Environmental repercussions and the economic structure: an input-output approach, Review of Economics and Statistics 52, 262-271.

Lundie, S., Peters, G.M., Beavis, P.C., 2004. Life cycle assessment for sustainable metropolitan water systems planning, Environmental Science and Technology 38, 3465-3473.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M., Chen, Y., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination, Water science and technology: water supply 9, 439-448.

Mattila, T.J., Pakarinen, S., Sokka, L., 2010. Quantifying the Total Environmental Impacts of an Industrial Symbiosis-a Comparison of Process-, Hybrid and Input− Output Life Cycle Assessment, Environmental Science and Technology 44, 4309-4314.

McGivney, W., Kawamura, S., 2008. Cost Estimating Manual for Water Treatment Facilities. Wiley Online Library.

Meneses, M., Pasqualino, J.C., Castells, F., 2010. Environmental assessment of urban wastewater reuse: Treatment alternatives and applications, Chemosphere 81, 266-272.

Muñoz, I., Milà-i-Canals, L., Fernández-Alba, A.R., 2010. Life Cycle Assessment of Water Supply Plans in Mediterranean Spain, Journal of Industrial Ecology 14, 902-918.

Ortiz, M., Raluy, R., Serra, L., 2007. Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town, Desalination 204, 121-131.

Pasqualino, J.C., Meneses, M., Castells, F., 2011. Life Cycle Assessment of Urban Wastewater Reclamation and Reuse Alternatives, Journal of Industrial Ecology 15, 49-63.

Peters, G., Rouse, K., 2005. Environmental sustainability in water supply planning–an LCA approach for the Eyre Peninsula, South Australia.

Racoviceanu, A.I., Karney, B.W., Kennedy, C.A., Colombo, A.F., 2007. Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems, Journal of Infrastructure Systems 13, 261-270.

Raluy, R.G., Serra, L., Uche, J., 2005a. Life Cycle Assessment of Water Production Technologies-Part 1: Life Cycle Assessment of Different Commercial Desalination Technologies (MSF, MED, RO)(9 pp), The International Journal of Life Cycle Assessment 10, 285-293.

Raluy, R.G., Serra, L., Uche, J., Valero, A., 2005b. Life Cycle Assessment of Water Production Technologies-Part 2: Reverse Osmosis Desalination versus the Ebro River Water Transfer (9 pp), The International Journal of Life Cycle Assessment 10, 346-354.

Raluy, R., Serra, L., Uche, J., 2005c. Life cycle assessment of desalination technologies integrated with renewable energies, Desalination 183, 81-93.

Ronald, M., Peter, B., 1985. Input-Output Analysis: Foundations and Extensions, Englewood Cliffs, NY: Prentice-Hall.

Scheuer, C., Keoleian, G.A., Reppe, P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications, Energy and Buildings 35, 1049-1064.

Scott, C.A., Varady, R.G., Browning-Aiken, A., Sprouse, T.W., 2007. Linking water and energy along the Arizona-Sonora Border, Southwest Hydrology 6, 26-27.

Stokes, J., Horvath, A., 2006. Life cycle energy assessment of alternative water supply systems, The International Journal of Life Cycle Assessment 11, 335-343.

Stokes, J.R., Horvath, A., 2009. Energy and air emission effects of water supply, Environmental Science and Technology 43, 2680-2687.

Traviglia, A.M., Characklis, G.W., 2008. An Expert System for Decisionmaking in the use of Desalination for Augmenting Water Supplies. US Department of the Interior, Bureau of Reclamation, Water Treatment Engineering Research Team.

Treloar, G.J., 1997. Extracting embodied energy paths from input–output tables: towards an input–output-based hybrid energy analysis method, Economic Systems Research 9, 375-391.

Treloar, G.J., Love, P.E.D., Holt, G.D., 2001. Using national input–output data for embodied energy analysis of individual residential buildings, Construction Management & Economics 19, 49-61.

Troy, P., Holloway, D., Pullen, S., Bunker, R., 2003. Embodied and operational energy consumption in the city, Urban Policy and Research 21, 9-44.

United Nations, 1999. Studies in Methods: Handbook of National Accounting, ST/ESA/STAT/SER.F/74.

US Census Bureau, January, 2012. 2002 Economic Census, Summary Statistics by 2002 NAICS United States, 2012.

Vince, F., Aoustin, E., Bréant, P., Marechal, F., 2008. LCA tool for the environmental evaluation of potable water production, Desalination 220, 37-56.

Wilkinson, R., 2000. Methodology for Analysis of The Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits Through Integrated Water-Energy Efficiency Measure.

CHAPTER 3: NATIONAL AVERAGED EMBODIED ENERGY OF WATER AND WASTEWATER SYSTEMS

This chapter provides the initial US national averaged results from the input-output based hybrid embodied energy model. The national averaged results show the embodied energy intensities of the water sectors, drinking water systems and wastewater treatment systems. Structural path analysis was carried out, but the specific paths were not adjusted for individual systems in this chapter. Thus, results may not be applicable to individual drinking water systems or wastewater treatment systems.

3.1 National Averaged Direct Energy Intensities of Water Sectors

The initial national averaged direct energy intensities of water sectors were calculated and presented in Table 3.1. Direct energy intensity was calculated as the physical amount of primary energy needed onsite of water systems for $100 of monetary transaction. The WSOS sector has higher direct energy intensity than the NS sector, which means operation and maintenance is more direct energy intensive than construction on economic activity basis.

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Table 3.1 National averaged direct energy intensities of the target sectors of WSOS (the "water, sewage and other systems" sector) and NS (the "other nonresidential structures" sector)

Target Sectors	WSOS	NS
Direct energy intensity (GJ/100$)	0.90	0.59

Figure 3.1 shows the distribution of direct energy intensities of the non-energy commodity sectors of the 2002 input-output tables, as well as the positions of WSOS and NS among these sectors. According to Figure 3.1, direct energy intensities of most US commodity sectors (almost 250 of the US commodity sectors) are concentrated in the interval between 0 and 0.5 GJ/100$. As a result, the direct energy intensities of WSOS and NS are both higher than more than half of the US commodity sectors. To be specific, the direct energy intensity of the NS sector is higher than 66% of all sectors, while the WSOS sector has higher direct energy intensity than 77% of all sectors.

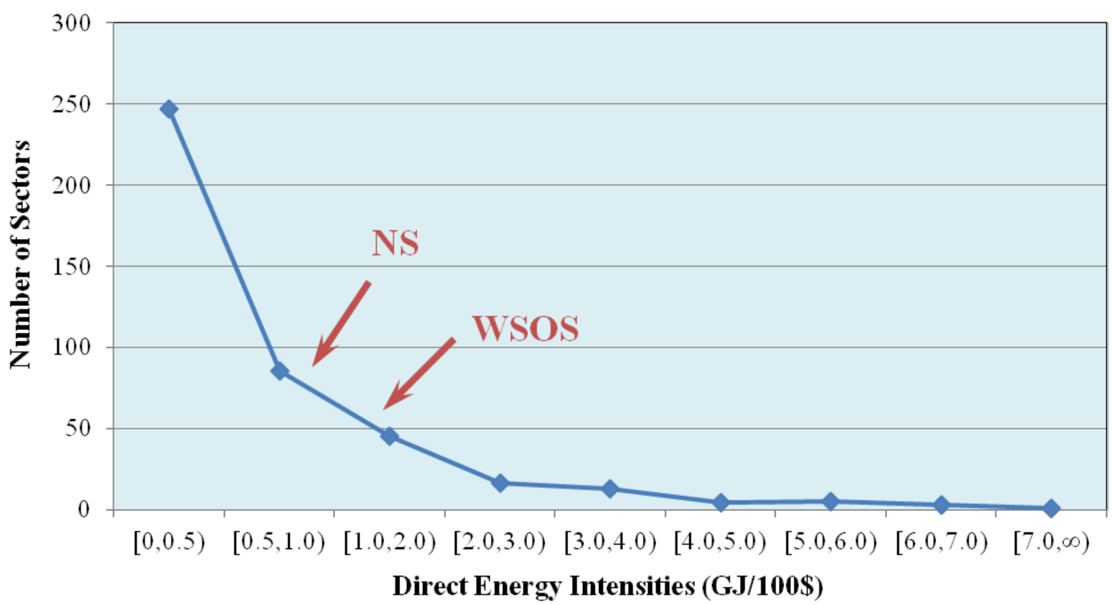

Figure 3.1 Distribution of direct energy intensities of the non-energy commodity sectors of the 2002 input-output tables and the positions of WSOS (the "water, sewage and other systems" sector) and NS (the "other nonresidential structures" sector) among these sectors

3.2 National Averaged Total Embodied Energy Intensities of Water Sectors

The initial national averaged total embodied energy intensities for water sectors were calculated and presented in Table 3.2. Total embodied energy intensity was calculated as the physical amount of primary energy needed during the whole life cycle of water systems for $100 of monetary transaction. The WSOS sector has higher total embodied energy intensity than the NS sector, which means operation and maintenance phase is still more energy intensive than the construction phase on economic activity basis. Indirect energy intensities can be calculated when deducting direct energy intensities from the corresponding total embodied energy intensities. Unlike direct energy and total embodied energy intensities, indirect energy intensities of the WSOS sector and the NS sector are almost comparable, while the indirect energy intensity of the NS sector is slightly higher than the WSOS sector.

Table 3.2 National averaged total embodied energy intensities of the target sectors of WSOS (the "water, sewage and other systems" sector) and NS (the "other nonresidential structures" sector)

Target Sectors	WSOS	NS
Total embodied energy intensity (GJ/100$)	1.42	1.17

Figure 3.2 provides the distribution of total embodied energy intensities of the non-energy commodity sectors of the 2002 input-output tables, as well as the positions of WSOS and NS among these sectors. According to Figure 3.2, most of the US commodity sectors have total embodied energy intensities between 0 and 2.0 GJ/100$ (Around 120 sectors have intensities between 0 to 1.0 GJ/$100, and around 180 sectors have intensities between 1.0 to 2.0 GJ/$100.). Both water sectors have higher total embodied energy intensities than 1.0 GJ/$100, and thus can be considered as energy intensive commodity

sectors. The total embodied energy intensity of the NS sector is higher than 39% of all sectors. The water, sewage and other systems sector has higher total embodied energy intensity than 55% of all sectors.

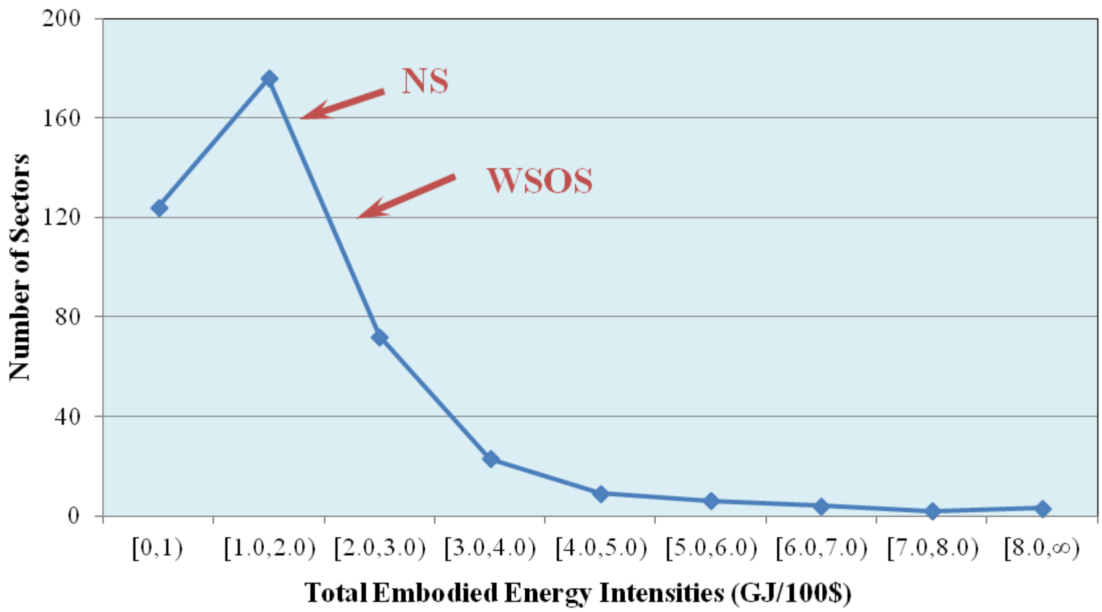

Figure 3.2 Distribution of total embodied energy intensities of the non-energy commodity sectors of the 2002 input-output tables and the positions of WSOS (the "water, sewage and other systems" sector) and NS (the "other nonresidential structures" sector) among these sectors

Comparing direct energy intensities with indirect energy intensities for both target sectors, it is manifest that indirect energy intensity takes a substantial portion of total embodied energy intensity for both sectors as shown in Figure 3.3. Since the national economic activities for water sectors are certain, percentages of direct and indirect energy intensities are the same as percentages of direct and indirect energy for the US water sectors. More specifically, for the WSOS sector, indirect energy intensity represents 37.1% of the total embodied energy intensity, while for the NS sector, indirect energy intensity represents almost half of the total embodied energy intensity. The WSOS sector has a higher direct energy percentage might be because it is onsite energy intensive, and less materials are associated with system operation and maintenance. On the other hand, the indirect energy percentage of the NS sector is relatively higher than the WSOS sector because it is more material intensive.

On national scale, the results support Hypothesis 1 in this study that indirect energy is an important part of total embodied energy and it should not be neglected when estimating energy use in water systems.

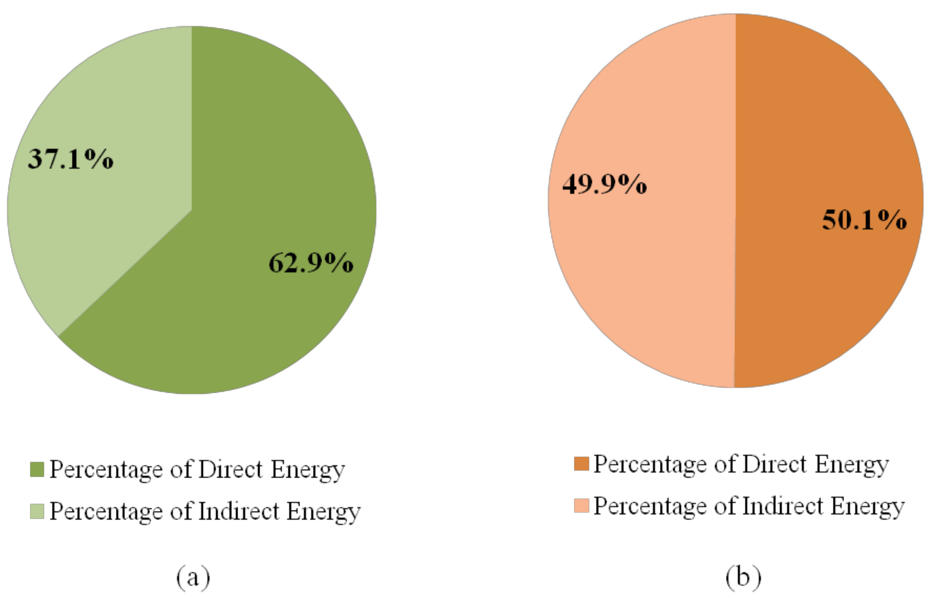

Figure 3.3 Percentages of direct energy and indirect energy intensities of the two target sectors. 3.3(a) shows the percentages of direct energy and indirect energy intensities of the water, sewage and other systems (WSOS) sector, and 3.3(b) shows the percentages of direct energy and indirect energy intensities of the other nonresidential structures (NS) sector.

3.3 Adjustment Factors for the Direct Energy

The original water sectors include both water supply systems, wastewater treatment systems and other related systems. Initial adjustment was carried out in order to modify the initial direct energy intensities for water supply systems and wastewater treatment systems. Indirect energy intensities were not adjusted at this stage due to lack of data availability on national averaged indirect energy use in water systems. The adjustment factors for both water sectors were calculated and listed in Table 3.3. According to Table 3.3, wastewater treatment systems have higher direct energy intensities than water supply systems. It might be because wastewater treatment not only involves pumping similar as freshwater treatment but also aeration which requires a large amount of energy.

On the other hand, wastewater treatment systems (separate sewer systems) usually treat less water than the water supply systems in the same serving area based on the fact that part of the water consumed cannot be collected by the wastewater treatment systems. It is because there are great water losses during the water use cycle. For example, water may evaporate during end use, and water used for irrigation is impossible to be captured by the sewage systems. It implies that even all the treated wastewater is reclaimed; energy saved from replacing the original water supply with the reclaimed water would always be lower than energy needed for wastewater treatment. It further indicates that theoretically, water reuse can only reduce the energy consumption, but it can never offset all the energy required in the water use cycle.

3.4 Top Energy Paths for the Target Sectors

In order to carry out the structural path analysis, the threshold values were selected for both water sectors. The numbers of energy paths in each of the five stages checked, as well as the final selected threshold values are provided in Table 3.4. Table 3.5 and Table 3.6 provide further information on the selection details of the threshold values, and the amount of top energy paths related with different threshold values.

Table 3.3 Adjustment factors for direct energy intensities of target sectors for different types of water systems

Type of water systems	Target sectors	Es%	Cs%	Es% / Cs%
Water supply systems	WSOS	66.60%	79.94%	0.83
	NS	2.58%	3.94%	0.66
Wastewater treatment systems	WSOS	25.79%	11.30%	2.28
	NS	5.15%	4.39%	1.17

According to Table 3.4, Stage 2 has the most energy paths extracted for the WSOS sector; while stage 3 has the most energy paths for the NS sector. Overall, the NS has significantly more energy paths than the WSOS sector in the top 90% of the initial total embodied energy intensity, and the paths in the NS sector are more evenly distributed in different stages than in the WSOS sector. The results show the NS sector has contributions from a wider range of other sectors than the WSOS sector. It is understandable because system construction usually requires different kinds of constructional materials, equipment and professional services.

Figure 3.4 provides the distribution of the top energy paths of the WSOS sector and the NS sector. Most of the top 10 energy paths are 1-stage energy paths. Details of the top 10 energy paths for both water sectors were listed in Table 3.7. For the WSOS sector, the top 10 energy paths are related with energy consumed in system maintenance and repair, material transportation and material production. For the NS sector, the top energy paths are mainly related with energy consumed in material manufacturing, and transportation.

Table 3.4 Threshold value that represents 90% of the initial total embodied energy intensity for WSOS (the "water, sewage and other systems" sector) and NS (the "other nonresidential structures" sector)

Sector	**WSOS**	**NS**
Threshold Value (GJ/$)	1.48E-07	2.40E-09
1-stage energy paths*	179	190
2-stage energy paths	1031	8889
3-stage energy paths	240	19356
4-stage energy paths	8	4819
5-stage energy paths	0	499

*Energy path: Supply chains start from the energy involved in one material or service supply sector, and end at the water sector.

Table 3.5 Amount of top energy paths associated with different threshold values for the "water, sewage and other systems" (WSOS) sector

Threshold Value (GJ/$)	1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08	1.00E-09	1.00E-10
Percentage	71.18%	81.72%	86.80%	90.58%	92.85%	94.24%	95.89%
1 stage paths	6	45	125	187	247	297	315
2 stage paths	0	11	169	1417	5800	13878	24525
3 stage paths	0	0	12	412	5419	44473	228407
4 stage paths	0	0	0	17	759	14162	185379
5 stage paths	0	0	0	0	43	1595	37115

Table 3.6 Amount of top energy paths associated with different threshold values for the "other nonresidential structures" (NS) sector

Threshold Value (GJ/$)	1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-08	1.00E-09	1.00E-10
Percentage	59.81%	75.36%	82.17%	86.61%	89.05%	90.45%	91.28%
1 stage paths	6	53	121	165	185	192	194
2 stage paths	0	12	184	1440	5123	11448	18035
3 stage paths	0	0	20	441	5246	39467	185220
4 stage paths	0	0	0	40	818	13331	152973
5 stage paths	0	0	0	2	82	1672	28757

Most of the top 100 energy paths are 1-stage energy paths, but some of them are 2-stage energy paths. Similarly as the top 10 energy paths, the top 100 energy paths of the WSOS sector are mainly related to maintenance and engineering services, production of the treatment and maintenance materials, and transportation. The top 100 energy path of the NS sector are mainly involved with the production of the building materials, such as asphalt, steel, cement, stone etc., engineering services and transportation.

Engineering services have a large impact on the indirect energy use of water systems because energy is required to provide such services; for example, energy is needed to supply and maintain a service office. Material production is another major contributor to the indirect energy because a large amount of energy is consumed during each of the production processes. Lastly, transportation plays a significant role in energy consumption for both constructing and operating water systems.

3.5 Top Indirect Contributing Sectors

The top 30 indirect contributing sectors to the energy intensity of the two target sectors (WSOS and NS) were calculated and presented in Table 3.8 and 3.9. Similarly as the top energy paths, the top indirect contributing sectors of the WSOS sector are also mainly related to maintenance and engineering services, production of the treatment and maintenance materials, and transportation. The top indirect contributing sectors of the NS sector are mainly involved with the production of the building materials, such as metals, asphalt, plastic, cement, stone etc., engineering services and transportation.

Table 3.7 The top ten energy paths for WSOS (the “water, sewage and other systems” sector) and NS (the “other nonresidential structures” sector)

Rank	WSOS	NS
1	“Non-residential maintenance and repair” to WSOS	“Asphalt shingle and coating materials manufacturing” to NS
2	“Pipeline transportation” to WSOS	“Asphalt paving mixture and block manufacturing” to NS
3	“Real estate” to WSOS	“Truck transportation” to NS
4	“Truck transportation” to WSOS	“Iron and steel mills and ferroalloy manufacturing” to “Plate work and fabricated structural product manufacturing” to NS
5	“Other state and local government enterprises” to WSOS	“Architectural, engineering and related services” to NS
6	“Asphalt paving mixture and block manufacturing” to WSOS	“Cement manufacturing” to “Ready-mix concrete manufacturing” to NS
7	“Services to building and dwellings” to WSOS	“Petroleum lubricating oil and grease manufacturing” to NS
8	“Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying” to WSOS	“Stone mining and quarrying” to NS
9	“Lime and gypsum product manufacturing” to WSOS	“Cement manufacturing” to NS
10	“Architectural, engineering, and related services” to WSOS	“Fertilizer manufacturing” to NS

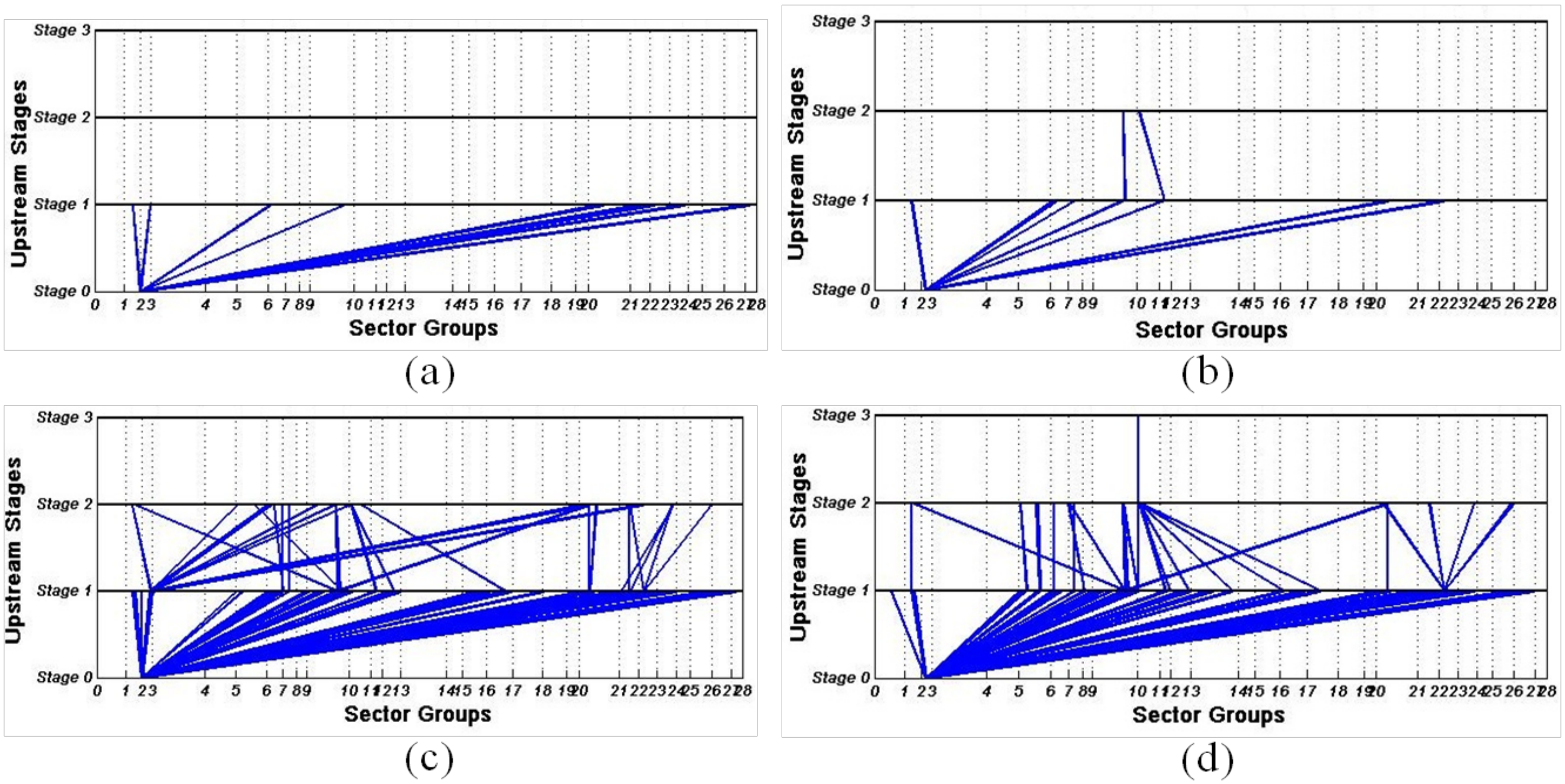

Figure 3.4 The distribution of the top 10 and top 100 of the energy paths for the two water sectors (The intervals on the x-axis represent different sector groups. For example, the first line in the Figure 3.4(a) shows that among the top 10 energy paths for the “water, sewage and other systems” sector, there is one path from “mining and utilities” sector group to the “water, sewage and other systems” sector. (a) Distribution of top 10 energy paths of the “water, sewage and other systems” sector; (b) Distribution of top 10 energy paths of the “other nonresidential structures” sector; (c) Distribution of top 100 energy paths of the “water, sewage and other systems” sector; (d) Distribution of top 100 energy paths of the “other nonresidential structures” sector.)

Interval	Sector Groups	Interval	Sector Groups
(0,1]	Agriculture, Livestock, Forestry, and Fisheries	(14,15]	Computers, Audio-Video, and Communications Equipment
(1,2]	Mining and Utilities	(15,16]	Semiconductors, Electronic Equipment, and Media Reproduction
(2,3]	Construction	(16,17]	Lighting, Electrical Components, Batteries
(3,4]	Food, Beverage, and Tobacco	(17,18]	Vehicles and Other Transportation Equipment
(4,5]	Textiles, Apparel, and Leather	(18,19]	Furniture, Medical equipment, and Supplies
(5,6]	Wood, Paper, and Printing	(19,20]	Other Miscellaneous Manufacturing
(6,7]	Petroleum and Basic Chemical	(20,21]	Trade, Transportation, and Communications Media
(7,8]	Resin, Rubber, Artificial Fibers, Agric. Chems, and Pharm	(21,22]	Finance, Insurance, Real Estate, Rental and Leasing
(8,9]	Paint, Adhesives, Cleaning, and Other Chemicals	(22,23]	Professional and Technical Services
(9,10]	Plastic, Rubber, and Nonmetallic Mineral Products	(23,24]	Management, Administrative, and Waste Services
(10,11]	Ferrous and Nonferrous Metal Production	(24,25]	Education and Health Care Services
(11,12]	Cutlery, Handtools, Structural and Metal Containers	(25,26]	Arts, Entertainment, Hotels and Food Services
(12,13]	Other Metal Hardware and Ordnance manufacturing	(26,27]	Other Services, Except Public Administration
(13,14]	Machinery and Engines	(27,28]	Government and Special Services

Figure 3.4 (continued)

Table 3.8 Top 30 contributing sectors to the water, sewage and other systems (WSOS) sector and their contributions to the embodied energy intensity of WSOS

Sector Name	Total contribution (GJ/1000$)
Nonresidential maintenance and repair	0.345
Real estate	0.323
Iron and steel mills and ferroalloy manufacturing	0.281
Pipeline transportation	0.268
Truck transportation	0.238
Services to buildings and dwellings	0.196
Other basic organic chemical manufacturing	0.164
Asphalt paving mixture and block manufacturing	0.163
Other State and local government enterprises	0.136
Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	0.106
Cement manufacturing	0.104
Lime and gypsum product manufacturing	0.095
Plastics material and resin manufacturing	0.093
Architectural, engineering, and related services	0.088
Fertilizer manufacturing	0.081
Stone mining and quarrying	0.079
Alkalies and chlorine manufacturing	0.077
Wholesale trade	0.076
Asphalt shingle and coating materials manufacturing	0.075
Other plastics product manufacturing	0.069
Petroleum lubricating oil and grease manufacturing	0.067
Water, sewage and other systems	0.066
Alumina refining and primary aluminum production	0.060
Air transportation	0.059
Food services and drinking places	0.054
Couriers and messengers	0.052
Petrochemical manufacturing	0.052
Industrial gas manufacturing	0.050
Waste management and remediation services	0.049
Management of companies and enterprises	0.042

Table 3.9 Top 30 contributing sectors to the other nonresidential structures (NS) sector and their contributions to the embodied energy intensity of NS

Sector Name	Total contribution (GJ/1000$)
Iron and steel mills and ferroalloy manufacturing	0.524
Asphalt shingle and coating materials manufacturing	0.415
Truck transportation	0.300
Cement manufacturing	0.282
Asphalt paving mixture and block manufacturing	0.246
Services to buildings and dwellings	0.155
Other basic organic chemical manufacturing	0.140
Stone mining and quarrying	0.130
Petroleum lubricating oil and grease manufacturing	0.129
Architectural, engineering, and related services	0.127
Real estate	0.121
Plastics material and resin manufacturing	0.115
Wholesale trade	0.113
Fertilizer manufacturing	0.110
Other plastics product manufacturing	0.078
Retail trade	0.074
Sawmills and wood preservation	0.074
Air transportation	0.068
Paperboard mills	0.067
Steel product manufacturing from purchased steel	0.067
Management of companies and enterprises	0.065
Alumina refining and primary aluminum production	0.065
Plate work and fabricated structural product manufacturing	0.063
Ready-mix concrete manufacturing	0.062
Brick, tile, and other structural clay product manufacturing	0.061
All other crop farming	0.059
Lime and gypsum product manufacturing	0.058
Couriers and messengers	0.056
Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	0.056
Petrochemical manufacturing	0.055

CHAPTER 4: EMBODIED ENERGY IN WATER SUPPLY SYSTEMS

4.1 Comparison between a Groundwater System and a Surface Water System

4.1.1 Introduction

Global water withdrawals have increased rapidly over the past several decades, and are expected to continue to grow in the near future (Konikow and Kendy, 2005; Shah et al., 2003; USGS, March, 2012). Extensive groundwater and surface water withdrawals have led to environmental problems, such as groundwater depletion, land subsidence, seawater intrusion, and surface water quality deterioration, which have consequently impacted water availability in many regions (Barlow, 2003; Bartolino et al., 2003; Konikow and Kendy, 2005; Taylor and Alley, 2001).

The environmental impacts associated with water supply are further compounded by energy requirements during withdrawal, treatment, and distribution. Direct energy consumption for constructing, operating, and maintaining water supply systems comprises around 33% of a typical city's government energy budget for public utilities in California (CEC, 1992; Means, 2004) and around 2-3% of global energy demand (James et al., 2002). On the other hand, previous study has suggested that indirect energy

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associated with water supply systems can be comparable to direct energy (Mo et al., 2010). The embodied energy (direct energy+indirect energy) associated with water provision also increases with growing water demand. For instance, direct energy increases with a declining water table and well yield, while indirect energy increases when more sophisticated technologies and additional chemicals are used to treat water sources of poorer quality.

Reduction of energy use and associated carbon emissions from water supply is also gaining increased attention. For example, in the US, states like California (under Assembly Bill 32) are requiring a reduction in carbon emissions from water supply and treatment. In light of global water management issues, consideration of the energy embodied in water systems should become more important in the future. Accordingly, this part of study examined the energy embodiment in different kinds of water supply systems, especially groundwater supply and surface water supply. Other impact categories associated with material use were not considered as they are beyond the scope of the study.

In the last decade, efforts have been made to evaluate the embodied energy of water importation, reclamation, and desalination, driven by the specific regional needs (Lyons et al., 2009; Peters and Rouse, 2005; Raluy et al., 2005; Stokes and Horvath, 2006; Tangsubkul et al., 2005). The energy embodied in surface water systems has also been studied in countries such as Canada (Racoviceanu et al., 2007) and South Africa (Friedrich, 2002). Embodied energy values associated with specific water supply options are summarized in Table 4.1. Although environmental impacts such as greenhouse effects, acidification, and nutrient enrichment of groundwater and surface water supply have been compared (Godskesen et al., 2010), no direct comparison has been made in terms of energy embodiment between surface water and groundwater systems as shown in Table 4.1.

Table 4.1 Life cycle energy associated with water supply systems identified in previous studies

Water Sources	Embodied Energy (MJ/m^3 of water)[1]	Methodology	Comments	Source
Imported water	18	Process based hybrid LCA	Conveyance pipe length: 575 km	Stokes et al. 2009
	5	Process LCA	Conveyance pipe length: 261 km	Lyons et al., 2009
Desalinated water	42	Process based hybrid LCA	Reverse osmosis with conventional pretreatment	Stokes et al. 2009
	41	Process based hybrid LCA	Reverse osmosis with membrane pretreatment	Stokes et al. 2009
	27	Process based hybrid LCA	Brackish groundwater	Stokes et al. 2009
	24	Process LCA	Reverse osmosis	Lyons et al., 2009
Recycled water	17	Process based hybrid LCA		Stokes et al. 2009
	3	Process LCA		Lyons et al., 2009
Surface water	3	Process based hybrid LCA	Only considers operation phase of the treatment plant	Racoviceanu et al., 2007
	2	Process LCA		Friedrich, 2002

[1]Energy was reported in the primary energy form, which includes the direct use of energy found in nature and the use of secondary energy such as electricity in forms of fossil fuels, nuclear energy and renewable energy.

Direct energy use associated with groundwater and surface water supply systems, on the other hand, has previously been examined on large scales (e.g., Wilkinson (Wilkinson, 2000) performed a study for the state of California; EPRI (2002) performed a study for the US). Specifically, the study published by the Electric Power Research Institution (Goldstein et al., 2002) concluded that a groundwater supply system requires about 30% more electricity on a unit basis than a surface water supply system. Neither of the studies, however, addresses indirect energy consumption.

The objective of this part of study was therefore to estimate the “cradle to gate” (source to customer) energy embodiment (direct and indirect energy) of one groundwater and one surface water supply system and to provide a relative comparison of embodied energy for major water supply options through the compilation of results from this and previous studies. The novelty of this study lies in the use of an input-output based hybrid approach with structural path analysis to provide more comprehensive results with insights into the energy flow.

4.1.2 Description of Selected Water Supply Systems

One groundwater supply system (Kalamazoo Public Water Supply System, Michigan) and one surface water supply system (City of Tampa Waterworks, Florida) were studied. These two systems were chosen because: (1) both of them are classified as “very large” water supply systems by the US Environmental Protection Agency according to the population they serve (both systems serve > 100,000 people) (EPA, April, 2012); (2) they represent typical groundwater and surface water treatment processes; and (3) data for these two systems are readily available to the authors. Geographic differences of the two systems were not considered in this study. A detailed comparison of the two systems is provided in Table 4.2.

Table 4.2 Key information of the Kalamazoo system and the Tampa system

Water supply systems	Water source	Daily flow (thousand m^3/day)	Serving population	Percentage of chemical cost with total O&M cost	Length of the pipelines (km)
The Kalamazoo system	Groundwater	76.8	121,000	2%	1276
The Tampa system	Surface water	287	657,000	13%	3541

4.1.2.1 Kalamazoo Public Water Supply System

The Kalamazoo Public Water Supply System (referred to as Kalamazoo system) is the largest groundwater based water supply system in the Kalamazoo River watershed, serving over 121,000 customers. The Kalamazoo system pumps an average of 76.8 thousand m^3 of water per day and deploys 1276 km of water mains. Raw water is withdrawn from 101 local wells with an average well depth of around 58 meters. Limited treatment (disinfection) is provided in two of the total 18 pumping stations, after which the water is supplied to the end users (Kalamazoo, 2008).

The annual O&M expense in the Kalamazoo system is approximately $11.1 million. Of the $11.1 million annual expense, $1.16 million are used for purchasing electricity, and $0.08 million are used for purchasing natural gas (CKWD, 2010). The commodity output of the NS sector (construction) was estimated based on the capital cost of the Kalamazoo system. Since the Kalamazoo system only has limited treatment within the pumping stations, the water treatment infrastructure was not considered separately. The well data of the Kalamazoo system were obtained from the "Water Well Viewer" (MDEQ, June, 2012a) and "Wellogic" (MDEQ, June, 2012b) managed by the Michigan Department of Environmental Quality.

4.1.2.2 City of Tampa Waterworks

The City of Tampa Waterworks (referred to as Tampa system) is one of the largest water supply systems in Florida, serving a population of 657,000. The average daily flow in the system is approximately 287 thousand m^3, about 3.7 times higher than the average flow in the Kalamazoo system. However, the impact of such differences on direct energy use per unit water produced is negligible at the production scale between 38 thousand m^3 per day (10 MGD) and 380 thousand m^3 per day (100 MGD) (Goldstein et al., 2002). As a result, it is allowable for us to compare the total embodied energy of the two systems.

The Tampa system has more than 3541 km of water mains. Raw water is withdrawn from the Hillsborough River, and treated with pre-ozonation and GAC filters in addition to a conventional process that consists of flash mix, flocculation and sedimentation. The raw water has a turbidity of 15-220 NTU with an average of 117 NTU. The detected dissolved oxygen has a range of 1.9-14.3 mg/L with an average of 4.1 mg/L. The bromide detected ranges from 31-180 µg/L with an average of 85 µg/L. This is greater than the Maximum Daily Level of 0.5 µg/L. Total organic carbon ranges from 3.3-24.2 mg/L with an average of 15.1 mg/L.

The annual O&M expense is $68.3 million. Of the $68.3 million annual expense, $3.95 million is used for purchasing electricity. The commodity output of the NS (construction) is estimated based on the capital cost of the Tampa system. Key information used for estimating capital cost was collected directly from the Tampa system.

4.1.3 Results and Discussion

4.1.3.1 Expense Estimation

The estimated total capital expense in the Kalamazoo system is $118.4 million, and the total capital expense in the Tampa system is $416.0 million. The breakdowns of the capital costs in both systems are provided in Figure 4.1. Assuming life spans for both systems of 100 years (Peters and Rouse, 2005; Stokes and Horvath, 2006), the unit capital expense for the Kalamazoo system is around $42 per thousand m^3 of water produced, and the unit O&M expense is around $394 per thousand m^3 of water produced. The total cost (construction and O&M) for producing one thousand m^3 of water in the Kalamazoo system is $436. Similarly, the unit capital expense for the Tampa system is around $40 per thousand m^3 of water produced, and the unit O&M expense is around $653 per thousand m^3 of water. The total cost for producing one thousand m^3 of water in the Tampa system is $692.

The unit O&M expense of the Tampa system is much larger than the Kalamazoo system. This may be because of the much greater use of water treatment chemicals in the Tampa system. On the other hand, the unit capital expenses of both systems are similar, even though the Tampa system has an additional water treatment plant. The percentage of the Kalamazoo system pipeline capital expense within the total capital expense is much larger than that of the Tampa system. This may result from the more distributed water intake infrastructure in the Kalamazoo system compared with the Tampa system and the lower population density in the City of Kalamazoo compared with the City of Tampa (USCB, 2010). For both systems, pipeline construction is the largest capital cost contributor.

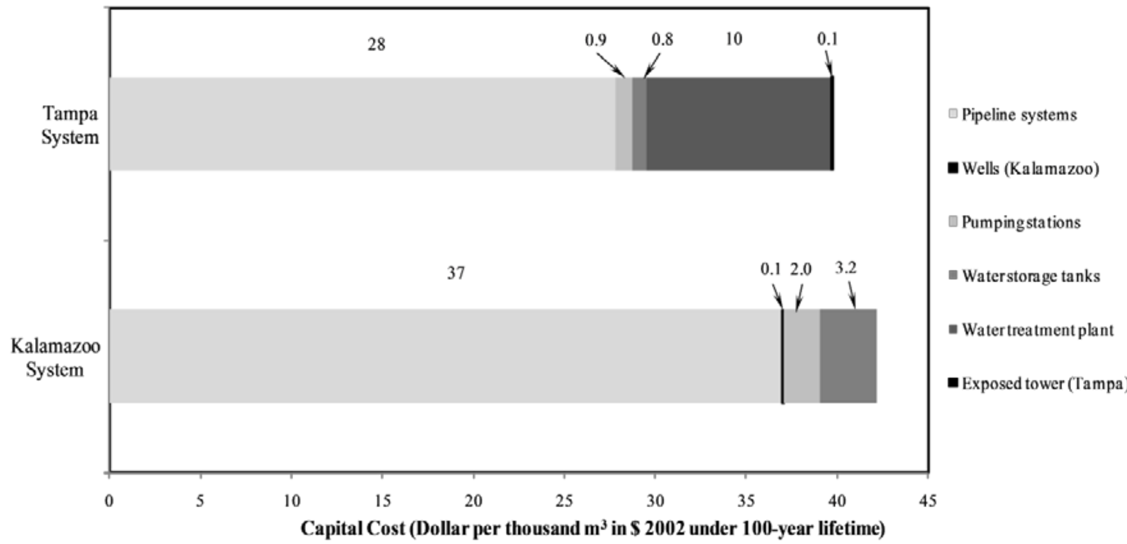


Figure 4.1 Breakdown of capital costs per thousand cubic meter of water produced under 100 year life-time associated with the groundwater sourced Kalamazoo system and the surface water sourced Tampa system in $ 2002

Overall, the results show that surface water supply systems may be more expensive to operate than the groundwater supply systems depending on the raw water quality, but may be less expensive to construct than the groundwater supply systems depending on the length of pipelines.

4.1.3.2 Modification and Calculation of the Total Embodied Energy

The system-specific O&M direct energy use was estimated through the annual energy expenditures and local average energy prices. The average electricity retail price in Michigan is 9.18 cents/kWh, and the average price of natural gas is 6.1 dollars/GJ. Thus, the direct energy for operating and maintaining the Kalamazoo system was estimated to be 170 TJ. The direct energy for both O&M and construction amounts to 6.3 MJ per m^3 of water produced at the Kalamazoo system. On the other hand, the average electricity retail price in Florida is 10.13 cents/kWh. Thus, the direct energy for the O&M

of the Tampa system was estimated to be 497 TJ. The direct energy for both O&M and construction amounts to 5.0 MJ/m^3 of water produced at the Tampa system.

For indirect energy, the available system specific data from the Kalamazoo system and the Tampa system were substituted to adjust the original embodied energy of the two systems. The direct energy intensities of 25 manufacturing sectors were also modified (EIA, January, 2007). Under a 100-year life span, the indirect energy used for the Kalamazoo system to supply 1 m^3 of water is 4.0 MJ, and the indirect energy used for the Tampa system to supply 1 m^3 of water is 5.8 MJ after modification.

After the modification of both direct and indirect energy, the total embodied energies for the two water supply systems are provided in Table 4.3. The total embodied energy in the Kalamazoo system for supplying 1 m^3 of water is 10.3 MJ, and the total embodied energy in the Tampa system for supplying 1 m^3 of water is 10.8 MJ. The unit total embodied energy in the Tampa system is slightly larger than that of the Kalamazoo system. Compared with initial total embodied energy, the modified total embodied energy of the Kalamazoo system increased by 68%, and the modified total embodied energy of the Tampa system increased by 10%. The differences show the necessity of the modification step using the system specific data in the analysis.

Although direct energy represents important portions in both the Kalamazoo system and the Tampa system, indirect energy cannot just be simply neglected. In both systems, indirect energy is comparable as the direct energy, and represents around half of the total embodied energy. In the Tampa system, indirect energy is even higher than direct energy. This indicates that indirect energy is very important in understanding the energy burden of water, and planning and implementing both energy and water managements.

The unit direct energy consumption of the Kalamazoo system is 27% higher than the Tampa system, which is consistent with EPRI's estimation. This result can be explained by the large pumping requirement for water delivery in the Kalamazoo system. It is also consistent with a previous result that the pipeline system in the Kalamazoo system accounts for a more important portion of energy consumption than the Tampa system. Groundwater supply systems usually have deep and widely distributed wells for water intake, which may increase their pumping energy requirements.

Unlike the direct energy consumption, the unit indirect energy consumption at the Kalamazoo system is around 31% less than the Tampa system. This is primarily because of the greater use of chemicals and engineering services at the Tampa system. Groundwater supply systems typically have better raw water quality than surface water supply systems. Systems such as the Kalamazoo system require only limited treatment, which significantly reduces the amount of required chemicals. In contrast, the Tampa system uses a large quantity of chemicals to treat the lower quality raw water. In addition to disinfectants, other chemicals such as ferrous sulfate (for coagulation) and ozone (for pre-ozonation) are used. Manufacturing these chemicals is very energy intensive based on the data from the input-output tables. Moreover, the surface water supply systems are usually more complicated than the groundwater supply systems, thus more engineering services are involved, which also contributes to the large indirect energy demand of the Tampa system. Breakdown of the major contributors to the total O&M embodied energy of the two systems is provided in Table 4.4.

Table 4.3 Total embodied energy for groundwater sourced Kalamazoo system and the surface water sourced Tampa system

Water Supply Systems	Direct Energy (MJ/m^3)			Indirect Energy (MJ/m^3)			Total Embodied Energy (MJ/m^3)		
	O&M	Construction	Total	O&M	Construction	Total	O&M	Construction	Total
The Kalamazoo system	6.1	0.2	6.3	3.7	0.3	4.0	9.8	0.5	10.3
The Tampa system	4.8	0.2	5.0	5.5	0.3	5.8	10.3	0.5	10.8
Differences[1]	28%	6%	27%	-32%	9%	-31%	-5%	8%	-4%

[1] Differences = [(Data from the Kalamazoo System -Data from the Tampa System)/Data from the Tampa System]

Table 4.4 Breakdown of the major contributors to the total O&M embodied energy

Energy use categories	Direct energy use	Chemicals	Maintenance	Engineering service	Customer service
Kalamazoo System	61.9%	5.7%	12.6%	0.7%	0.4%
Tampa System	46.1%	9.6%	13.9%	3.2%	0.4%

4.1.3.3 Energy Source Separation

The energy breakdowns among fuel types for direct and total embodied energy intensities of the two target sectors for both the Kalamazoo system and the Tampa system are presented in Table 4.5 and Table 4.6. Comparing the direct and embodied energy intensities for the water supply components of the WSOS and NS sectors reveals that the WSOS sector in both Kalamazoo and Tampa is associated with a relatively high share of direct energy use (except for coal, which is rarely utilized directly in this sector). This is not unexpected as WSOS represents the operation and maintenance activities of the water system, including electricity for pumping. On the other hand, the NS sector represents construction activities associated with water system, and so its largest direct use of energy is in the form of petroleum, likely diesel fuel for heavy machinery. As water systems include large amounts of steel and concrete, the NS sector is also associated with a relatively high share of indirect energy use embodied in these materials. Interestingly, petroleum is also the most important indirect energy supply sector for NS, perhaps reflecting the upstream fuel use in transporting materials and labor.

Table 4.5 Breakdown of direct and embodied energy intensities of the Kalamazoo system by energy source

Target Sectors	**Coal (GJ/$100)**	**Electricity (GJ/$100)**	**Natural gas (GJ/$100)**	**Petroleum (GJ/$100)**
WSOS (Direct)	0	1.41	0.12	0
NS (Direct)	0	0.08	0.02	0.3
WSOS (Embodied)	0.037	1.77	0.22	0.2
NS (Embodied)	0.058	0.34	0.12	0.51

Table 4.6 Breakdown of direct and embodied energy intensities of the Tampa system by energy source

Target Sectors	**Coal (GJ/$100)**	**Electricity (GJ/$100)**	**Natural gas (GJ/$100)**	**Petroleum (GJ/$100)**
WSOS (Direct)	0	0.73	0	0
NS (Direct)	0	0.11	0.03	0.45
WSOS (Embodied)	0.054	1.06	0.14	0.32
NS (Embodied)	0.048	0.3	0.11	0.63

4.1.3.4 Comparison with Other Studies

The direct energy of a unit of water in Kalamazoo and in Tampa was estimated here to be 6.1 MJ/m^3 and 4.8 MJ/m^3 respectively. Comparing this result with previous work, research by EPRI estimated direct electricity use of approximately 1824 kWh per million gallons, or 1.7 MJ/m^3 (Goldstein et al., 2002). In primary energy terms, this is equivalent to 6.7 MJ/m^3, or within 10% and 30% of the direct energy portion of the results of the Kalamazoo system and the Tampa system.

The results from this study are higher than the embodied energy provided by Racoviceanu et al. (2007) and Friedrich (2002) partly due to the different system boundaries selected. Unlike this study, Racoviceanu et al. (2007) only considered the operation phase of the treatment plant, while Friedrich considered all operation, construction, and decommission phases of the treatment plant. In addition to Table 4.1,

Figure 4.2 provides visualized results of embodied energy of water supply from different studies including this one.

Furthermore, the estimated embodied energy varies a lot based on different estimation methods used, different raw water qualities and treatment technologies, and different geographical locations. For instance, as shown in Table 4.1, even the energy embodiments of the similar three water supply options studied by Stokes et al. (2009) and Lyons et al. (2009) differ by 2 to 4 fold. Although there is some variance in previous results, desalination consistently appears as the most energy intensive water supply option. Furthermore, the embodied energy of surface and groundwater supplies is comparable with options of water reclamation and importation. Additional studies are needed to compare groundwater, surface water, and reclaimed water supply options in a similar geographical area, with more details on raw water quality and treatment process characteristics, in order to better understand the energy and material use of these options.

4.1.3.5 Uncertainty and Sensitivity Analysis

Uncertainties in this study are primarily from the input-output tables, varied life span of different components, different geographical location of the selected systems, and capital expense estimation. Bullard and Sebald (1988) found a standard error of 1% for row sums in the US 1967 input-output tables, while Lenzen (2000) assumed an error bound of 3% for the Australian input-output tables. Because there is a lack of studies on the truncation errors and sensitivity of the recent US input-output tables, uncertainty of our results was not quantified.

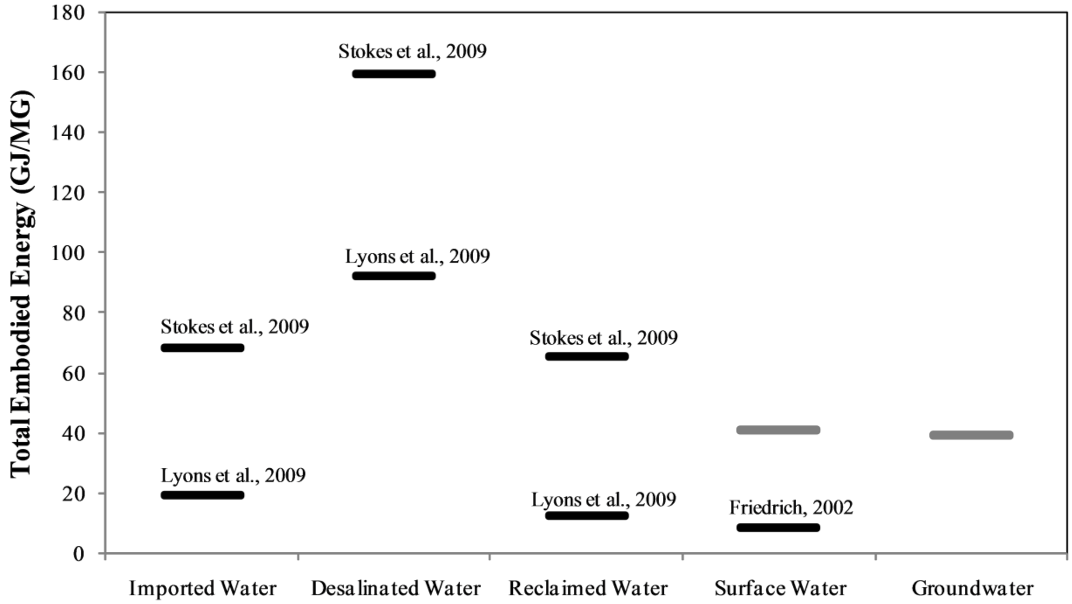


Figure 4.2 Ranges of the total embodied energy (GJ) reported in previous studies and in this study per million gallons of provided water for different sources (The " ▬▬ " represents the results from previous studies, and the " ▬▬ " represents the results from this study.)

A sensitivity analysis was carried out to determine how direct energy and different inputs used for the estimation would affect the results (Table 4.7). The analysis showed that the results are very sensitive to the direct energy consumption because it accounts for the largest portion of the total embodied energy. Additionally, the Kalamazoo system is more sensitive to direct energy than the Tampa system, which is consistent with the previous discussion that the Kalamazoo system has higher unit direct energy use. The results are however not very sensitive to the change of the system life span. This is because the construction life stage only comprises a small portion of the total embodied energy. In regards to chemical use, the Tampa system is more sensitive to it than the Kalamazoo system. This observation is also consistent with the previous discussion that the Tampa system has a larger indirect energy requirement, primarily because of the greater use of chemicals.

Table 4.7 Sensitivity analysis of the Kalamazoo system and the Tampa system

Selected water supply systems	Direct energy	Infrastructure life span	Total chemical use	
	+50%	-50%	+50%	
	Total embodied energy	Total embodied energy	Indirect energy	Total embodied energy
The Kalamazoo system	+30%	+5%	+8%	+3%
The Tampa system	+22%	+4%	+9%	+5%

4.1.4 Conclusions

The results from this part of study show that Kalamazoo groundwater supply system that only employs disinfection with no additional treatment is more energy intensive than Tampa surface water supply system in terms of direct energy. This is caused by higher pumping requirements; however, the surface water supply system is more energy intensive in terms of indirect energy because of greater requirements for material use.

The results from this study are also higher than previous life cycle studies performed on surface water systems due to different system boundaries selected and different estimation methods used. This study shows the flexibility of using the input-output based hybrid analysis based on data availability. It can be easily used by researchers and utilities to evaluate embodied energy of water supply systems. This method, however, still has various uncertainties including errors propagated from input-output tables and uncertainties in the capital cost estimation for the selected water supply systems. Additionally, this study did not consider the geographical differences between the two systems, which may also affect the total embodied energy. The sensitivity analysis indicated that the results are very sensitive to the direct energy use. However, the results are not very sensitive to the system life span. In addition, the embodied energy of the Tampa system is more sensitive to the chemical use than that of the Kalamazoo system.

Although there is no significant difference on the total embodied energy consumption for the specific groundwater and surface water supply systems evaluated, the results suggest there is a tradeoff between direct and indirect energy for different systems. It is thus important for water managers to differentiate direct and indirect energy in future life cycle or energy studies for water supply systems.

4.2 Comparison between a Water System in China and a Water System in the US

4.2.1 Introduction

The water-energy nexus and the large energy embodiment of water supply systems have made it challenging to manage the water supply systems under different social and economic systems. China and the US are two of the leading countries in the developing and the developed world separately. They have very different social and economic structures. In this part of study, the embodied energy of one water supply system from China (referred as the China system) and one water supply system from the US (referred as the US system) was compared; the differences of the embodied energy contributors between the two systems were discussed; different energy use patterns in the US and China for water supply were identified, and suggestions to the US and China water supply systems were provided.

4.2.2 Methodology

In this part of study, the EIO-LCA is used for the embodied energy evaluation based on the following reasons:

(1) The EIO-LCA software provides the input-output models for both the US and China;

(2) The main focus of this study is a general comparison of water supply system in the US and China, thus detailed modification of the input-output results is not necessary;

(3) The EIO-LCA software is an online tool and convenient to use.

As discussed in Chapter 1, the EIO-LCA method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in an economy. It uses input-output tables representing the interactions among economic sectors within the economy of a country and calculates the economic activities across the entire economy caused by a change in one economic sector. The EIO-LCA software extends such calculation to environmental impacts such as the total embodied energy requirement through a matrix representing energy use per sector.

The basic steps involved in the estimation includes: (a) using the EIO-LCA software to estimate the energy intensities of constructing and operating water supply systems, I; (b) collect the total (construction and operation) economic activities for the selected water supply systems, C; (c) calculate the total embodied energy, E, using Equation 4-1; (d) estimate the direct operational energy using system specific data and primary energy factors; (e) replace the original direct operational energy from the EIO-LCA results with the new estimation.

$$E = I \times C \quad (4\text{-}1)$$

Among all the input-output tables provided by the EIO-LCA software, the China 2002 producer price model was selected for estimating the energy intensities of the China system. Especially, the "water production and supply" sector was selected for estimating the operational energy intensity of the China system, and the "construction" sector was selected for estimating the constructional energy intensity of the China system. The US 2002 national producer price model was selected for estimating the energy intensities of the US system. Especially, the "water, sewage and other systems" sector was selected for estimating the operational energy intensity of the US system, and the "other nonresidential structures" sector was selected for estimating the constructional energy intensity of the US system.

The primary energy factors, which were used to convert the direct electricity consumptions into primary energy forms, were obtained for the US system and the China system separately. The primary energy factor of the US electricity production used in this part of study is 3.44. On the other hand, based on Lei (2006), China's energy production efficiency is more than 10% lower than the US. The primary energy factor for China's electricity production was estimated to be 3.78.

4.2.3 Case Study

The China system is located in Jiaxing, Zhejiang Province, and the US system selected in the US is located in Tampa, Florida. These two cities are both medium sized cities with an averaged population density of 1500 per square kilometer. Furthermore, the two systems have very similar treatment processes both with ozonation and GAC treatment. The detailed treatment processes of the two water supply systems are provided in Figure 4.3. Moreover, a comparison of the basic parameters for the two selected water supply systems is provided in Table 4.8. The US system has a higher influent turbidity (117 NTU on average) than the China system (42 NTU on average), but the Fe and Mn contents in the influent of the China system are much higher than those of the US system.

Table 4.8 Basic parameters of the two typical water supply systems in the US and China

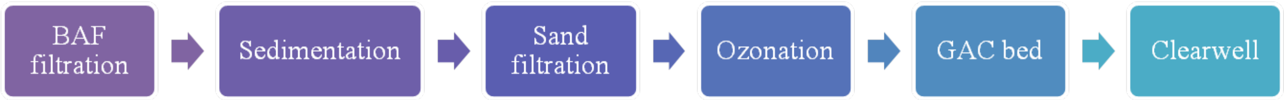
Water supply systems	Daily flow (MGD)	Water source	Serving population	Population density of the serving area (person per sq kilometer)
The China system	58	Surface water	400,000	1438
The US system	76	Surface water	657,000	1299

4.2.4 Results and Discussion

4.2.4.1 General Comparison of the US and China's Water Supply Systems

Using the EIO-LCA results, the top embodied energy contributing sectors of the operation and construction phases of water supply in the US and China were compared. Since EIO-LCA results are based on national aggregated input-output data, the embodied energy of water supply systems were compared from an average on the national scale.

The top 10 embodied energy contributing sectors of the operation phase and their contributions in percentages are presented in Table 4.9. The "other state and local government enterprises" sector in the US table does not have a clear definition, but it can be seen from the economic interactions that this sector partly represents the public power generation systems and partly represents the public water supply systems. Knowing this,



a. Treatment processes in water supply system in China

b. Treatment processes in water supply system in the US

Figure 4.3 Treatment processes of the two selected water supply systems in the US and China the top energy contribution sectors from China and the US can thus be analyzed. It is shown in the table that electricity plays a much more important role in the operation of China's water supply systems than in the US's systems. Around 83% of the embodied energy comes from the power supply sector in China, while more than 39% of the US's comes from the power supply sector. It indicates that China's water supply is more electricity dependent than the US system by using the electricity both onsite and in the upstream processes. The US water supply, however, consumes more energy by using water within the supply infrastructures than the China water supply. Besides, China seems to use more coal while the US uses more oil and petroleum. This is understandable because China's energy production is highly dependent on coal. Additionally, China requires more energy through chemical use than the US. This may be caused by the generally lower raw water quality in China. The US apparently requires more maintenance and repair energy than China, which may be due to the aged infrastructure in the US and higher labor involvement in the US water supply systems. On the other hand, both China and the US's water supply involve large amounts of steel processing and transportation energy.

The top 10 embodied energy contributing sectors of the construction phase and their contribution in percentages are listed in Table 4.10. According to Table 4.10, China has a higher electricity involvement for the construction phase than the US, but the two countries have similar inputs from steel-, cement- and petroleum-related sectors. Moreover, China mainly uses water transportation, while the US mainly uses truck transportation. This may cause a higher energy use in the US because most of the time, road transportation is not as efficient as water transportation (Strahan, 2008).

Table 4.9 Top 10 total embodied energy contribution sectors of the operation phase of water supply in China and the US and their embodied energy contribution percentages

Top 10 energy contributing sectors in China	Percentage	Top 10 energy contributing sectors in the US	Percentage
Electricity and steam production and supply	83.0%	Power generation and supply	38.6%
Water production and supply	5.2%	Other state and local government enterprises	21.9%
Coal mining and processing	1.1%	Water, sewage and other systems	19.5%
Crude petroleum products and Natural gas products	1.0%	Oil and gas extraction	2.2%
Raw chemical materials	0.8%	Petroleum refineries	2.1%
Telecommunication	0.8%	Pipeline transportation	1.8%
Steel-processing	0.7%	Nonresidential maintenance and repair	1.5%
Petroleum refining	0.6%	Iron and steel mills	1.1%
Water freight and passengers transport	0.5%	Truck transportation	1.1%
Chemicals for special usages	0.5%	Cement manufacturing	0.7%

4.2.4.2 Energy Embodiment of the China System

According to the EIO-LCA software, China water supply systems have an averaged operational energy intensity of 5.54 TJ/¥ million (of operational activity), and an averaged constructional energy intensity of 2.98 TJ/¥ million (of constructional activity). Through personal communication, the annual operational activity involved in the China system was obtained to be around ¥49.3 million, and the total capital cost of the system is around ¥129 million. As a result, the operational embodied energy of the China system was calculated to be 273 TJ, and the constructional embodied energy is 384 TJ. Kahrl et al. (2008) has estimated the direct energy intensity for system operation to be around half of the total embodied energy intensity based on the 2002 China input-output table, which means the original direct energy of the China system is around 137 TJ.

Table 4.10 Top 10 total embodied energy contribution sectors of the construction phase of water supply in China and the US and their embodied energy contribution percentages

Top 10 energy contribution sectors in China	Percentage	Top 10 energy contribution sectors in the US	Percentage
Electricity and steam production and supply	47.7%	Other nonresidential structures	38.3%
Steel-processing	5.9%	Power generation and supply	16.3%
Cement and cement asbestos products	5.4%	Petroleum refineries	5.9%
Crude petroleum products and Natural gas products	3.4%	Iron and steel mills	4.7%
Other non-metallic mineral products	3.4%	Cement manufacturing	4.2%
Construction	2.9%	Truck transportation	3.1%
Petroleum refining	2.4%	Oil and gas extraction	2.8%
Fireproof products	2.0%	Other basic organic chemical manufacturing	1.4%
Water freight and passengers transport	1.9%	Paperboard Mills	1.3%
Telecommunication	1.9%	Pipeline transportation	1.0%

For a more accurate estimation, the direct operational electricity use was obtained from the China system, and used to replace the original direct operational energy intensity. Total electricity cost in the China system is around ¥13.1 million, around 27% of the operational cost. Based on the averaged unit electricity price in Jiaxing (¥0.60/kWh), the annual electricity consumption in the China system is 21.8 kWh/year. Considering a primary energy factor of 3.78 for the losses during electricity generation, the total operational direct energy in primary energy form is 297 TJ. Obviously, the actual operational direct energy consumption is much larger than EIO-LCA estimation. After substituting the EIO-LCA estimation with the real system data, we got a new total operational embodied energy of 434 TJ.

Under a 100-year life span, the converted annual total embodied energy of the China system is 438 TJ. Constructional energy consumption is negligible (around 1% of the annual total embodied energy) compared with the operational energy consumption. The volumetric energy use in the China system is 21 GJ/MG, or 5.5 MJ/m^3, which is higher than Kahrl's estimation, 1.8 MJ/m^3 based on national average, and the annual water supply energy use per capita is around 1.1 GJ.

4.2.4.3 Energy Embodiment of the US System

Similarly, the operational energy intensity for the US water supply systems is 18.6 TJ/$ million (of operational activity), while the constructional energy intensity is 7.84 TJ/$ million (of constructional activity) according to the EIO-LCA results. An annual operational economic activity of $68.3 million and a total constructional economic activity of $416.0 million were obtained through personal communication. As a result, the operational embodied energy of the US system was calculated to be 1270 TJ, and the constructional embodied energy was calculated to be 3261 TJ. Mo et al. (2010) has estimated a direct operational energy intensity of 9 TJ/$ million through the 2002 US input-output table. Thus, the initial direct energy from the EIO-LCA result was 615 TJ.

The direct operational energy of the US system was also modified to be consistent with the real system data. The US system uses around $4.0 million for purchasing electricity annually, which is around 6% of the total annual operational cost. The percentage electricity expense is lower in the US system than the China system which is consistent with the general EIO-LCA results that China has a much higher input from the power supply sector than the US. Based on the unit electricity price in Tampa

($0.10/kWh), the annual electricity consumption in the US system is around 40.1 kWh/year. Considering a primary energy factor of 3.44 of the US power generation, the direct operational energy consumption in primary energy form in the US system is 497 TJ, which is lower than the EIO-LCA result. After replacing the EIO-LCA result with the actual data, the new total operational embodied energy was estimated to be 1152 TJ.

Under a 100-year life span, the converted annual total embodied energy of the US system is 1184 TJ. Constructional energy consumption is also negligible (around 3% of the annual total embodied energy) compared with the operational energy consumption; however, the weight of the construction phase in the US system is slightly higher than in the China system. The volumetric energy use in the US system is 43 GJ/MG, or 11 MJ/m^3, and the annual embodied energy for water supply per capita is around 1.8 GJ.

4.2.4.4 Discussion

For a better comparison of the China system and the US system, the energy embodiments in both operation and construction phases in both systems were calculated, and converted into volumetric energy use and energy use per capita. Table 4.11 provided energy data for the two selected systems, and the percentage difference between the two systems.

The US system has higher total direct energy use in the operation phase than the China system. In terms of volumetric energy use, the US system requires 29% more electricity to provide 1 MG of water than the China system, even that China has a 10% lower power generation efficiency. It may be caused by higher electricity requirement in maintaining the administrative buildings. Besides, the serving population density of the

US system is slightly lower than the China system, which may require additional pumping energy in the US system. The per capita energy use of the US system is comparable with the China system, which means people from both Tampa and Jiaxing uses similar amount of energy in terms of water supply. It may be due to the higher industrial water use in Jiaxing than in Tampa.

Considering the energy embodied in the construction phase, the US system exceeds the China system by 4 to 7 times. Since the top energy contribution sectors of the constructional energy intensities of the US and China are very similar (Table 4.11), one explanation for the higher constructional embodied energy in the US might be caused by higher constructional cost in the US system. The higher constructional cost in the US system may be caused by higher labor rates in the US, more engineering services involvement, longer project time frame and lower transportation efficiency.

Overall, the US system uses more embodied energy during its life cycle than the China system in volumetric, capita and total amount. Energy used indirectly in the operation phase is the main reason for the discrepancy. This discrepancy could be explained by higher labor rates, more service involvements, lower transportation efficiency and more water use in the system itself in the US system.

4.2.5 Conclusions

Through the calculation and discussion of this part of study, the following conclusions have been reached:

Table 4.11 Energy use data for the water supply system in China and the water supply system in the US and their percentage differences

Water supply systems	Operation						Construction			Total annual embodied energy (100-year life cycle)		
	Direct energy			Indirect energy								
	Total (TJ)	Volumetric energy use (GJ/MG)	Energy use per capita (GJ/capita)	Total (TJ)	Volumetric energy use (GJ/MG)	Energy use per capita (GJ/capita)	Total (TJ)	Volumetric energy use (GJ/MG)	Energy use per capita (MJ/capita)	Total (TJ)	Volumetric energy use (GJ/MG)	Energy use per capita (GJ/capita)
The China system	297	14	0.74	137	6.5	0.34	384	0.18	9.6	438	21	1.1
The US system	497	18	0.76	655	24	1.0	3261	1.2	50	1184	43	1.8
Percentage difference[1]	67%	29%	3%	378%	269%	194%	749%	567%	421%	170%	105%	64%

[1] Percentage difference = (Energy use in the US system – Energy use in the China system)/Energy use in the China system

(1) The energy embodied in the construction phase is negligible compared with that in the operation phase in both US and China systems. However, constructional energy has a slightly higher weight in the US system than in the China system.

(2) The weight of the electricity cost in the total operation cost in the China system is much higher than in the US system. This similar pattern has also been observed on the embodied energy contributors of the two countries water-related sectors.

(3) The US system has a comparable direct operational energy with the China system, but it has a much higher indirect operational energy than the China system in volumetric, per capita and total amount.

(4) The US system also has a higher constructional embodied energy than the China system in volumetric, per capita and total amount.

Overall, the US system uses more embodied energy during its life cycle than the China system in volumetric, capita and total amount. Energy used indirectly in the operation phase is the main reason for the discrepancy.

For future energy efficiency improvement, the US systems may want to focus on reducing the indirect energy during the operation phase, such as minimizing material and labor consumptions, shortening project timelines etc., while the China systems may want to reduce direct energy costs during the operation phase by conducting energy budgets and adopting energy saving technologies.

4.3 References

Barlow, P.M., 2003. Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast. US Geological Survey.

Bartolino, J.R., Cunningham, W.L., Geological Survey (US), 2003. Ground-Water Depletion Across the Nation. US Department of the Interior, US Geological Survey.

Bullard, C.W., Sebald, A.V., 1988. Monte Carlo sensitivity analysis of input-output models, Review of Economics and Statistics 70, 708-712.

CEC, 1992. Energy efficiency programs for cities, counties and schools, P400-91-030.

CKWD, 2010. City of Kalamazoo Water Department, .

EIA, 2007. 2002 Energy Consumption by Manufacturers-Data Tables, http://www.eia.gov/emeu/mecs/mecs2002/data02/shelltables.html (last accessed on 6.10. 2011).

EPA, 2012. Public drinking water systems: facts and figures, http://water.epa.gov/infrastructure/drinkingwater/pws/factoids.cfm (last accessed on 7.15. 2012).

Friedrich, E., 2002. Life-cycle assessment as an environmental management tool in the production of potable water, Water science and technology 46, 29-36.

Godskesen, B., Zambrano, K.C., Trautner, A., Johansen, N.B., Thiesson, L., Andersen, L., Clauson-Kaas, J., Neidel, T., Rygaard, M., Kløverpris, N., 2010. Life cycle assessment of three water systems in Copenhagen-a management tool of the future, Water science and technology: water supply 10, 953-960.

Goldstein, R., Smith, W., ICF Consulting Associates, Electric Power Research Institute, 2002. Water & Sustainability (Volume 4): US Electricity Consumption for Water Supply & Treatment-the Next Half Century. Electric Power Research Institute.

James, K., Campbell, S.L., Godlobe, C.E., 2002. Watergy: Taking advantage of untapped energy and water efficiency opportunities in municipal water systems, Alliance to Save Energy.

Kalamazoo, 2008. 2007 Water quality report, Environmental Service Division, Public Service Department.

Konikow, L.F., Kendy, E., 2005. Groundwater depletion: A global problem, Hydrogeology Journal 13, 317-320.

Lenzen, M., 2000. Errors in Conventional and Input-Output based Life-Cycle Inventories, Journal of Industrial Ecology 4, 127-148.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M., Chen, Y., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination, Water science and technology: water supply 9, 439-448.

MDEQ, June, 2012a. Michigan Department of Environmental Quality; Water well viewer, http://wellviewer.rsgis.msu.edu/ (last accessed on 8.1.2009).

MDEQ, June, 2012b. Michigan Department of Environmental Quality; Wellogic, http://www.michigan.gov/deq/0,4561,7-135-6132_6828-16124--,00.html (last accessed on 8.15.2009).

Means, E., 2004. Water and wastewater industry energy efficiency: a research roadmap, Awwa Research Foundation .

Mo, W., Nasiri, F., Eckelman, M.J., Zhang, Q., Zimmerman, J.B., 2010. Measuring the embodied energy in drinking water supply systems: a case study in The Great Lakes region, Environmental Science and Technology 44, 9516-9521.

Peters, G., Rouse, K., 2005. Environmental sustainability in water supply planning–an LCA approach for the Eyre Peninsula, South Australia.

Racoviceanu, A.I., Karney, B.W., Kennedy, C.A., Colombo, A.F., 2007. Life-cycle energy use and greenhouse gas emissions inventory for water treatment systems, Journal of Infrastructure Systems 13, 261.

Raluy, R., Serra, L., Uche, J., 2005. Life cycle assessment of desalination technologies integrated with renewable energies, Desalination 183, 81-93.

Shah, T., Roy, A.D., Qureshi, A.S., Wang, J., 2003. Sustaining Asia's groundwater boom: An overview of issues and evidence, Natural Resources Forum 27, 130-141.

Stokes, J., Horvath, A., 2006. Life cycle energy assessment of alternative water supply systems, The International Journal of Life Cycle Assessment 11, 335-343.

Strahan, D., 2008. Green fuel for the airline industry, The New Scientist 199, 34-37.

Tangsubkul, N., Beavis, P., Moore, S., Lundie, S., Waite, T., 2005. Life cycle assessment of water recycling technology, Water Resources Management 19, 521-537.

Taylor, C.J., Alley, W.M., 2001. Ground-Water-Level Monitoring and the Importance of Long-Term Water-Level Data. US Geological Survey.

USGS, March, 2012. Groundwater use in the United States, http://ga.water.usgs.gov/edu/wugw.html (last accessed on 7.15.2010).

Wilkinson, R., 2000. Methodology for Analysis of The Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits Through Integrated Water-Energy Efficiency Measure, No.4910110.

CHAPTER 5: A REVIEW OF INTEGRATED RESOURCE RECOVERY IN WASTEWATER SYSTEMS

5.1 Background Significance

Currently, there are over 15,000 municipal wastewater treatment plants (WWTPs) providing wastewater collection and treatment services to around 78% of the US population. While they are critical to human and environmental health protection, these WWTPs are becoming one of the largest resource consumers in the US (CSS, 2009). They require approximately 23% of the public energy use of a municipality (Means, 2004). In addition, they also need a large amount of materials and treatment chemicals over their lifetime. The life cycle energy of these material consumptions accounts for almost two thirds of the energy directly consumed in the WWTPs (Mo et al., 2009). Furthermore, the consumption of resources will continue to increase with population growth, economic development, infrastructure aging, and more stringent regulations.

As a result of the significance of their essential functions and resource demands, evaluation of the sustainability of WWTPs has been conducted in the past 15 years (Lundin et al., 2000; Mels et al., 1999). According to Lundin et al. (2000), the goal of WWTPs should go beyond wastewater purification. WWTPs may improve their overall sustainability by reducing the use of nonrenewable resources, minimizing waste generation, and enabling resource recycling. Currently, three major approaches are used to improve WWTPs' sustainability: onsite energy generation, nutrient recycling and water reuse. Onsite energy generation makes use of the organic loads of wastewater or other unique characteristics of the WWTPs (water flow, residue heat, large space) to produce energy, mainly in the form of electricity. Nutrient recycling recovers nutrients from wastewater as fertilizers to offset the environmental loads associated with producing the equivalent amount of fertilizers from fossil fuels. Moreover, treated wastewater can be reused for various purposes to provide ecological benefits, reduce the demand of potable water and augment water supplies.

There are different methods for onsite energy generation, nutrient recycling and water reuse. Research has been carried out to study and evaluate these methods individually, but very limited studies have reviewed the integrated energy-nutrient-water recovery in the WWTPs (McCarty et al., 2011; Slater, 2009; Verstraete et al., 2009). While individual resource recovery methods have been studied and the potential of integrated resource recovery has been discussed, there is a lack of studies thoroughly reviewing the current status and sustainability of these individual methods as well as their integrations under different scales. In order to fill this knowledge gap, this review presents the pros and cons of the existing onsite energy generation, nutrient recycling and water reuse methods; along with their application status. Life cycle studies were also reviewed for each resource recovery approach as well as for the integration of these approaches under different scales. Challenges and gaps in these resource recovery approaches were discussed. The rest of the paper mainly consists five sections: (1) Onsite energy generation; (2) Nutrient recycling; (3) Water reuse; (4) Integrated resource recovery; and (5) Conclusions and future directions.

5.2 Onsite Energy Generation

Onsite energy generation utilizes the available resources from wastewater treatment plants to generate energy onsite. The resources that can be used for generating energy include influent organic contents and nutrients, motion power from wastewater flow, residue heat in treated wastewater, and onsite land and spaces. Since the energy generated can be used directly by the wastewater treatment plants and other facilities, this is the most commonly recognized approach to reduce environmental loads in wastewater treatment plants. Sometimes, onsite energy generation helps to not only reduce energy cost, but also remove the hazardous contaminants in the wastewater and improve treated water quality.

5.2.1 Technologies and Applications

5.2.1.1 Combined Heat and Power Systems

Combined heat and power systems (CHPs) utilize biogas produced from anaerobic digestion to generate heat and electricity onsite (EPA, 2007). The electricity produced by the CHPs is reliable and consistent, but the installation requires relatively high one-time capital costs (around $2000/kW for internal combustion engine, $7500/kW for fuel cell and $4500/kW for microturbine). Furthermore, operating the CHPs requires large volume of biogas, which restricted their implementation in small wastewater systems. It has been reported that the CHPs are only cost effective for the WWTPs with a flow rate above 5 MGD.

The CHPs have an electricity generation potential of about 350 kWh per million gallon of wastewater treated (Burton, 1996). It has been estimated that a reduction of

26% of the state-wide electricity use can be achieved if all the wastewater treatment plants adopt CHPs in Texas (Stillwell et al., 2010). Previous studies have also shown that the energy generated through CHPs can meet the onsite energy requirement of individual WWTPs in Austria (Wett et al., 2007) and Iran (Nouri et al., 2006).

Of all the WWTPs operating in the US currently, less than 0.6% utilize the biogas to generate electricity (EPA, 2007). The low application rate is partly due to the dominancy of small wastewater systems in the US. Around 94% of the WWTPs in the US have a flow rate lower than 5 MGD (EPA, 2008). Even among the systems proper for CHP installation, only 19% have installed the CHPs. Again, high capital costs prove to be a big hurdle for the implementation of this technology.

5.2.1.2 Biosolids Incineration

Biosolids incineration refers to recovering energy through biosolids combustion in fluidized beds or multiple-hearth furnaces. It not only generates energy, but also reduces waste volume to the minimal, and thus reduces disposal costs. The cons of biosolids incineration include the release of the persistent environmental pollutants, quality inconsistency, and the relatively high capital investment ($66/dry Mg) and energy cost for dewatering the biosolids (Cartmell et al., 2006; EPA, 2007; Mahmood and Elliott, 2006; Wang et al., 2008).

Biosolids incineration can be net energy producer only when the water content is reduced below 30% (McCarty et al., 2011). It has been estimated that when biosolids incineration is applied to all the WWTPs in Texas, around 57% of the total electricity use can be reduced in the Texas wastewater sector (Stillwell et al., 2010).

Incineration is more attractive to highly populated municipalities because they are commonly lack of readily available disposal space and less tolerant to odor generation (Werther and Ogada, 1999). Japan, US, Denmark, France, Belgium and Germany utilize around 55%, 25%, 24%, 20%, 15% and 14% of their sludge respectively for incineration (Wang et al., 2008; Werther and Ogada, 1999).

5.2.1.3 Effluent Hydropower

Effluent hydropower is the technology using turbines or other devices installed in conduits (pipelines, canals, and aqueducts) to generate electricity from effluent water (CEC, 2005). Except for energy generation, the effluent hydropower systems can also increase the dissolved oxygen concentration in the treated wastewater (Gaiusobaseki, 2010; Zakkour et al., 2002). The main constraint of this technology is that it requires the effluent to have sufficient forces to be worth the investment. Hence, either the head or the flow rate must be significant in order to optimize a hydropower scheme (Gaiusobaseki, 2010).

The potential energy from an effluent driven turbine is proportional to the head, flow rate and generation efficiency (Maine DEP, 2002). It has been estimated that the potential of hydropower capacity in manmade conduits in California is about 255 MW, with an annual production of approximately 1,100 GWh (CEC, 2005).

The effluent hydropower systems were first applied in two wastewater treatment plants in New England in late 1970s and early 1980s with limited success. Since then, this technology has been applied in states such as California, Massachusetts, and Maine.

California, so far, is the leading state on researching and utilizing effluent hydropower systems.

5.2.1.4 Onsite Wind and Solar Power

Onsite wind and solar power is the production of electricity from the wind and/or solar energy by taking advantage of the large land area of the WWTPs. WWTPs are usually away from other developments, and thus are good host sites for onsite wind or solar power generation. Table 5.1 provides some state-of-art wastewater treatment plants integrated onsite wind and/or solar power generation. The major disadvantage of the onsite wind or solar technology is that it usually requires large capital investments. Additionally, the climate conditions and locations of the WWTPs may also restrict the application (Brown, 2009).

Table 5.1 State-of-art wastewater treatment plants with onsite wind and/or solar power generation

Name	State	Wind/solar integration	Energy generation potential	Use	Information source
Atlantic County Utilities Authority	New Jersey	Wind	7.5 MW capacity	Provide 70% of facility needs	(ACUA, 2011)
		Solar	500 kW capacity	Provide 660,000 kWh of energy to the facility per year	
Browning Waste Water Treatment Plant	Montana	Wind	40 kW capacity	Displace grid electricity used at the facility	(Browning, 2001)
Boulder Wastewater Treatment Plant	Colorado	Solar	1 MW capacity	Provide 15% of facility needs	(Boulder, 2012)
Oroville Wastewater Treatment Plant	California	Solar	520 kW capacity	Provide 80% of facility needs	(SPGSolar, 2012)

The wind and solar potential maps provided by the US Department of Energy on its website can be used to assess the economic feasibility of the onsite wind and solar technology. Arizona, New Mexico, southern Nevada, southern California have the highest solar energy potential (DOE, 2012). On the other hand, states in the mid-US, such as Texas, Kansas, Nebraska, South Dakota, North Dakota and Iowa have the highest wind energy potential (DOE, 2010).

The Atlantic County Utilities Authority has the largest wind and solar power generation facilities in the US. Although onsite wind and solar power generation has great energy generation potential, it has not been widely applied in the US yet. Most of the facilities listed in Table 5.1 were installed in recent 1 or 2 years.

5.2.1.5 Heat Pump

Heat pump uses electricity to recover low temperature heat from the wastewater, and to make this heat available at suitable temperatures for both heating and cooling purposes. Except for its energy efficiency, heat pump is very reliable and requires low operation and maintenance costs (Neave, 2010). The heat recovered from heat pumps, however, cannot be delivered over long distances. Thus, heat pumps may only be applied onsite or when there are heating or cooling demands at nearby communities. Heat pumps best perform in moderate temperature areas.

Heat pumps typically provide 3 or 4 units of energy in the form of heat in consumption of 1 unit of energy in the form of electricity (Slater, 2009). For example, a wastewater treatment plant in Stockholm, Sweden with a maximum hydraulic capacity of 450,000 m^3/d produces about 597,000 MWh low-temperature heat energy using 199,000

MWh electrical energy via heat pumps (ESMAP, 2008). On the other hand, if the electricity production is highly dependent on fossil fuels, the heat pump uses nearly as much primary energy as heat energy generated (Tillman et al., 1998).

It has been reported that over 500 wastewater heat pumps are in operation worldwide, with thermal capacities ranging from 10 kW to 20 MW (Schmid, 2008). Large scale district heating using residual heat from wastewater has been applied in some European countries (ESMAP, 2008; Friotherm, ; Turku Energia, 2009).

5.2.1.6 Bioelectrochemical Systems

Bioelectrochemical systems use biocatalysts for oxidation and/or reduction reactions for desired products (Foley et al., 2010; Rabaey et al., 2003). It includes microbial fuel cell (MFC) systems and microbial electrolysis cell (MEC) systems. A MFC is a device that directly converts microbial metabolic or enzyme catalytic energy into electricity by using conventional electrochemical technology (Allen and Bennetto, 1993; Park and Zeikus, 2000; Roller et al., 1984). Beyond energy generation, the MFCs can also reduce the excess sludge to around 20% compared with the conventional treatment, which further reduces the sludge disposal costs. MFCs have been widely studied over the last 15 years (Foley et al., 2010; Kim, 2009), but they have only been applied on pilot scales for wastewater treatment so far. Current problems prohibiting the large scale use of the MFCs include energy loss during the electricity generation process, low organic utilization rates and high capital costs (around 800 times of an anaerobic system) (Liu et al., 2004; McCarty et al., 2011). The MECs are more recently developed. Unlike the MFCs, MECs use electricity to produce biochemicals, especially hydrogen and methane gas (Ditzig et al., 2007; Liu et al., 2005; Logan and Rabaey, 2012; Rozendal et al., 2007). Gas production from MECs has not been widely studied. Only one pilot scale study has been carried out for treating winery wastewater (Cusick et al., 2011; Hays et al., 2011) and found the maximal COD removal was around 62% and the hydrogen recovery was unsatisfactory with an 86% methane composition.

Power generated in MFCs varies from less than 1 MW/m^2 to 3600 MW/m^2, with most of them concentrating on 10-100 MW/m^2 (Liu and Logan, 2004; Liu et al., 2004). Kim (Kim, 2009) calculated that sewage treatment through MFCs in the European Union can save 0.95 million tons of fossil fuel per year and over $2.3 billion of the sludge disposal cost annually. Gas generation potential of the MECs fed by winery wastewater can reach 0.19±0.04 L gas per L wastewater per day under enhanced organic volatile fatty acid content and raised wastewater temperature (Cusick et al., 2011).

5.2.1.7 Microalgae

Microalgae technology recovers energy through cultivating microalgae with wastewater, harvesting microalgae and converting them to energy products using different technologies onsite or offsite of the WWTPs. During the cultivation stage, microalgae uptake the inorganic or organic carbon and nutrients in the wastewater, and therefore reduce waste loadings for treatment. Because microalgae can utilize carbon dioxide much faster than conventional biofuel crops (Kumar et al., 2010), they also have great potential for carbon dioxide reduction and mitigation. Currently, integrating the microalgae technology in WWTPs is still in the research stage. The main challenges of this integration include: (1) algal cultivation cost reduction; (2) harvesting, dewatering and lipid extraction energy reduction; and (3) microalgae species selection for optimal performance (Kumar et al., 2010).

Aresta et al. (2005) has reported a net energy generation of 9500 MJ/ton through microalgae gasification using effluent water as nutrient source. Moreover, a negative greenhouse gas emission of -183 kg CO_2e/MJ has been reported for microalgae biodiesel (Groom et al., 2008).

5.2.2 Life Cycle Studies

Although onsite energy generation in WWTPs has been widely recognized, there are limited life cycle studies evaluating the environmental impacts of the related technologies in the context of the WWTPs. Figure 5.1 provides the number of relevant life cycle studies on different onsite energy generation technologies.

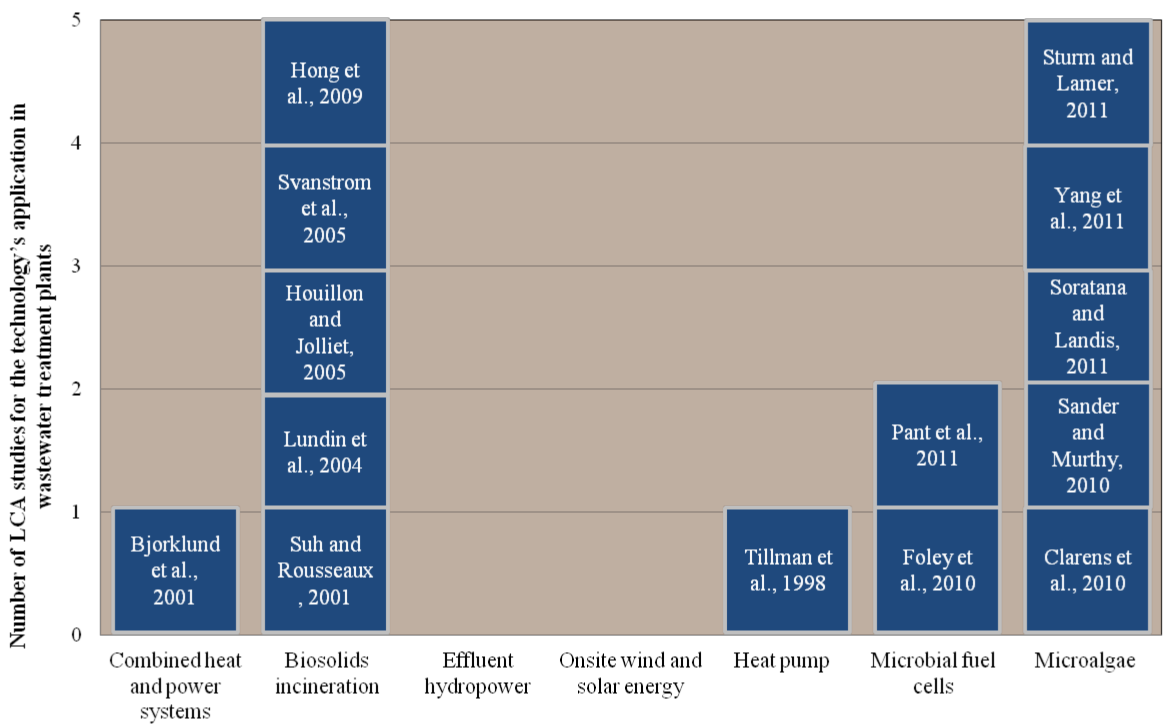


Figure 5.1 Number of relevant life cycle studies on each of the onsite energy generation methods

Although the CHPs have been evaluated for economic benefits (EPA, 2007) and for application to biomass other than biosolids (Guest et al., 2011; Kimming et al., 2011), there is only one life cycle study evaluating the "emergy" of utilizing biosolids for electricity production in Sweden (Björklund et al., 2001). Contradictory with the conventional economic analysis, the "emergy" analysis suggested that production of electricity from a CHP system requires two times of the resources needed for producing electricity from the local power plant. Hence, it is not economical in terms of resource utilization to digest sludge for electricity production. This study, however, did not include the use of the residue heat as part of energy recovery. As a result, there is a great need to investigate the life cycle impacts of the CHPs in WWTPs, especially for those relatively small wastewater treatment plants.

Incineration of the municipal solid wastes was widely studied from the life cycle perspective (Banar et al., 2009; Cherubini et al., 2009; Cleary, 2009; Khoo, 2009; Riber et al., 2008; Zhao et al., 2009); however, only 5 life cycle studies have been carried out for biosolids incineration (Hong et al., 2009; Houillon and Jolliet, 2005; Lundin et al., 2004; Suh and Rousseaux, 2002; Svanström et al., 2005). These studies render very controversial results. Some studies preferred incineration over land application, while others favored land application over incineration. The main reasons for this discrepancy are the specifics of case studies, different system boundaries, scales, and impact categories. For those that support land application, air emissions from incineration are usually the major concern. For those that support incineration, the benefits of energy recovery from incineration usually overweigh the other negative impacts. Current life cycle studies on biosolids incineration do not provide consistent results and general guidance on technology selection under given conditions. As a result, there is a need to establish consistent assessment frameworks (e.g., same system boundary and impact categories) for future life cycle studies.

Although large scale hydropower systems have been widely studied on life cycle basis (Coltro et al., 2003; Gagnon et al., 2002; Pascale, 2010; Pehnt, 2006; Varun et al., 2010), these results can hardly be applied to the effluent hydropower systems in WWTPs because of the uniqueness of these systems: unlike large scale hydropower, they do not interrupt the nutrient flow, reduce aqua species or cause flooding. Thus, it is necessary for future studies to evaluate the life cycle impacts of the effluent hydropower systems for better application guidance.

Wind and solar energy as sources of renewable energy has been widely studied (Ardente et al., 2008; Granovskii et al., 2007; Pehnt, 2006; Tripanagnostopoulos et al., 2005), but none of these studies emphasize their integration with WWTPs, except that Foley (2010) assessed the economic feasibility of the onsite wind and solar energy for a wastewater system in Singapore. It is suggested to justify installation of solar and wind power before implementation because of the high cost of solar panels and wind turbines. Previous life cycle studies on general solar and wind power generation may be applied to the WWTPs because of the similarity of the life cycle inventories of these systems; however, the potentials of solar and wind energy have to be examined carefully for each application location.

Life cycle studies have been carried out for ground sourced heat pumps (Genchi et al., 2002; Nagano et al., 2006; Zhu and Zhou, 2006), air sourced heat pumps (Rey et al., 2004; Zhu and Zhou, 2006) and seawater sourced heat pumps (Li and Songtao, 2006), but there is no study specifically for wastewater sourced heat pumps. Although Tillman et al. (1998) included heat pump as part of their life cycle assessment (LCA) for the municipal wastewater systems, the study did not focus on the heat pump system and the heat distribution systems were not included in their study. Other studies such as Hellstrom (1997) estimated the heat potential in the wastewater, but did not perform LCA for a real heat pump application. Unlike other heat sources, wastewater contains constant low temperature heat from water heating and microbial metabolic activities. As a result, there is a need to look at the environmental benefits of this particular kind of heat and the life cycle benefits of installing wastewater sourced heat pumps for future guidance.

Because the MFC/MEC technology is relatively new, there are not many life cycle studies related with MFCs/MECs. Foley et al. (2010) compared the life cycle impacts of MFC with anaerobic digestion and MEC. The study confirmed the environmental benefits of replacing the fossil fuel based electricity with the electricity generated via MFC; however, anaerobic digestion and MEC outperformed MFC in categories such as global warming potential, resource consumption and carcinogen production because the materials required for MFC construction are resource and emission intensive. Pant et al. (2011), on the other hand, compiled an inventory of inputs and outputs of MFCs to help researchers to evaluate, compare and validate the feasibility of this emerging technology.

Producing bio-energy with microalgae has been studied since last decade; however, it is only the recent two or three years that researchers started to evaluate microalgae cultivation using wastewater through life cycle studies. Clarens et al. (2010) reported that conventional crops are preferred over microalgae in terms of energy use and water use unless wastewater is used for cultivating microalgae. Especially when source separated urine is used as nutrient source, microalgae outperform conventional crops. Sander and Murthy (2010) did a life cycle study on algae biodiesel assuming that the wastewater after secondary treatment was used for algae growth. It was reported that processes utilizing filter press or centrifuge processes had a net energy generation of 278 MJ or 157 MJ per kg of algal biodiesel produced. Yang et al. (2011) investigated the water footprint of algal diesel using different water sources, such as freshwater, seawater or wastewater. They found that using wastewater for algae cultivation could reduce water requirement by 90%, and eliminate the need of all the nutrients except phosphate. Sturm and Lamer (2011) and Soratana and Landis (2011) further confirmed that biofuel production is energetically favorable when wastewater is utilized as nutrient source even without considering energy credit for nutrient removal.

5.2.3 Challenges

The onsite energy generation technologies attract much attention because the resource recovered can directly offset the energy costs of the WWTPs, but they have different limitations and uncertainties, such as large capital costs, lack of reliability and specific requirements for climate and local conditions. These limitations have constrained certain technologies from wide application. New technologies such as MFCs/MECs and microalgae may have the potential to overcome these disadvantages. Yet, more studies have to be done in order to advance those technologies to the commercial scale. Given that over 90% of WWTPs in the US are small plants, the major challenge is to improve/innovate technologies that have low capital costs, are simple and affordable to operate, and are easy to integrate into the existing small plants.

Energy generation potentials have been reported for most of the onsite energy technologies, but these studies focused on direct energy generation. Life cycle energy benefits associated with reducing and reusing organic and nutrient loadings from wastewater and waste volume for downstream handling are rarely studied. Moreover, studies assessing life cycle environmental impacts are lacking for most of the onsite energy generation technologies.

Another gap is the lack of studies examining the integration and tradeoffs of onsite energy generation technologies. For instance, wind and solar technology and effluent hydropower technology can be integrated with other technologies without compensating the generation potential of those technologies. However, tradeoffs may exist between different technologies. For example, energy recovery through biogas production may not integrate with biosolids incineration because increasing biogas production will reduce the amount of biosolids. Studies are needed to evaluate the maximum amount of energy that can be generated onsite with consideration of such integration and tradeoffs.

5.3 Nutrient Recycling

Nutrient recycling recovers nutrients in the wastewater as soil amendments or fertilizers for beneficial uses. Nutrients can be recovered from raw wastewater sources, semi-treated wastewater streams, and treatment byproducts, such as biosolids. From a life cycle perspective, nutrient recycling not only relieves the depletion of resources such as phosphorus ores but also indirectly conserves energy and water. That is because recycling nutrients will reduce the demand for traditional fossil-based fertilizers, consequently save energy and water used to produce the traditional fertilizers.

5.3.1 Technologies and Applications

5.3.1.1 Biosolids Land Application

Biosolids land application involves spreading biosolids on the soil surface or incorporating or injecting biosolids into the soil (EPA, 1999). They are commonly treated by at least one of the following processes depending on the end use: (1) digestion, (2) alkaline treatment, (3) composting, and (4) heat drying. Biosolids treated by digestion or alkaline stabilization can be used as soil amendment or daily landfill cover. Composting produces highly organic and soil-like biosolids for horticultural, nursery and landscape uses. Heat dried biosolids can be directly used as fertilizer. In addition to soil conditioning and fossil fertilizer use reduction, biosolids land application also avoids excess nutrients entering the environment because of their low nutrient contents compared with fossil fuel based fertilizers. The major concerns of the use of biosolids are the health and safety issues, odor and public acceptance.

It has been estimated that around 8.2 million tons of biosolids would be produced in 2010 and around 70% would be used for land application (EPA, 1999). A dry mass of 7 to 50 kg per year per inhabitant is a rough estimation of biosolids production potential in the WWTPs (Kroiss and Zessner, 2010).

Land application of biosolids has been widely practiced in the US and other countries. In 2004, 49% of the US wastewater solids were used for land application, while 45% were disposed. Another 6% were stored or their final use was not reported (NEBRA, 2007).

5.3.1.2 Urine Separation

Urine separation involves separation of urine from other wastewater sources for recovery of nutrients. It is usually practiced at the user end. By separating urine from the main wastewater stream, the nutrient loads of the wastewater treatment plant can be reduced significantly (Larsen et al., 2009), and the nutrients in the urine stream can be more easily recovered using technologies such as struvite precipitation. Additionally, urine separation is very energy efficient compared with many other nutrient recycling technologies (Benetto et al., 2009; Flores et al., 2009; Novotny, 2010). The challenges of applying urine separation are that it requires intensive support and involvements from local communities and large scale new infrastructure installation both at household and community level (Verstraete et al., 2009). Another major challenge is to avoid the cross contamination with feces, which usually contain large amounts of pathogens.

Urine separation is promising in terms of maximizing nutrient recovery from wastewater, because around 70-80% of N and 50% of P in domestic wastewater is contained in urine (Jönsson, 2001; Larsen and Gujer, 1996). Rossi et al. (2009) estimated a urine recovery rate of 70-75% using the urine collecting toilets.

Urine separation has been traditionally practiced in many developing countries for land application, but has not been widely used in most of the developed countries due to the intensive construction requirements and lack of public support. In addition, urine separation technologies, such as the NoMix toilets, still need improvements in a real-life setting (Rossi et al., 2009).

5.3.1.3 Controlled Struvite Crystallization

Controlled struvite ($MgNH_4PO_4 \cdot 6H_2O$) crystallization is a way of recycling nutrients by extracting struvite from sludge digester liquors because of its high concentrations of phosphorus, ammonium and magnesium (Forrest et al., 2008; Martí et al., 2010). Struvite crystallization has high nutrient recovery rates, especially for recovering precious phosphate resources. It is also economically feasible. It has been estimated that a WWTP with an influent flow rate of 20 ml/min has the ability to produce struvite worth £8400~£20,000 per year (Jaffer et al., 2002). On the other hand, there are also problems associated with the struvite crystallization. Unintentional struvite formation can block valves, pipes, centrifuge bowls and pumps (Münch and Barr, 2001), and lead to decreased flow capacity and eventual equipment failure. Other problems include the high cost of the chemical reagents required for pH adjustment and magnesium enhancement (Pastor et al., 2010).

The phosphate concentration in sludge digester liquors can be quite high, i.e. 85-95 gP/m^3 (Battistoni et al., 1997; Jaffer et al., 2002; Münch and Barr, 2001). Theoretical potential of the struvite crystallization approaches 67,000 tons of P_2O_5 fertilizer per year from the UK alone, as well as 270,000 tons from Western Europe (Gaterell et al., 2000).

The controlled struvite crystallization has been operated at full scale at several sites in Japan since 1987, with capacity ranging from 100-500 kL/d and producing 100-500 kg/d of struvite (Münch and Barr, 2001; Ueno and Fujii, 2001). There are three full scale facilities currently in operation in the US utilizing struvite crystallization technologies provided by Ostara Nutrient Recovery Technologies Inc. (Ostara, 2012). Several more sites are under construction. However, this technology has not been widely applied in other countries, and most of the current studies are on pilot scale in Australia, Canada and Spain (Britton et al., 2007; Münch and Barr, 2001; Pastor et al., 2010).

5.3.1.4 Recovering Nutrients through Aqua-Species

Recovering nutrients through aqua-species means using the aqua-species to utilize the nutrients in the wastewater, and harvest and use the aqua-species as fertilizers or animal feeds (Umble and Ketchum, 1997). The aqua-species can be macroalgae (Wilkie and Mulbry, 2002) or microalgae (Umble and Ketchum, 1997; Voltolina et al., 2005), duckweed (Alaerts et al., 1996; Cheng et al., 2002; El-Shafai et al., 2007; Oron, 1990), wetland plants (Dixon et al., 2003; Fuchs et al., 2011; Machado et al., 2007), crops (Boyden and Rababah, 1996) and so on. This method is very attractive because synergy exists between water purification and nutrient recycling. They are also cost and energy efficient compared with a lot of conventional water treatment technologies. On the other hand, seasonal changes of water temperatures and light intensities can largely affect the rates of nutrient uptake and metabolisms of the aqua-species. Sometimes it is also necessary to control and monitor the treated wastewater quality and pH to maintain the organism growth and successive uses (El-Shafai et al., 2004a; El-Shafai et al., 2004b), which requires additional energy and chemicals.

Nutrient removal rates by the aqua-species are very promising. Most studies provided an over 60% nitrogen or phosphorus removal rate by aqua-species (Boyden and

Rababah, 1996; El-Shafai et al., 2007; Rectenwald and Drenner, 2000; Umble and Ketchum, 1997; Voltolina et al., 2005). Culley et al. (1981) found that a mixture of duckweed species could take up to 1378 kg of N, 347 kg of P and 441 kg of potassium from 1 ha of water area in a year under the climatic conditions of Louisiana, US.

Recovering nutrients through aqua-species has not been widely applied. A look into the literatures shows that the constructed wetland is more widely applied than the other technologies, but most of these constructed wetlands do not recycle the nutrients for secondary uses. Nutrient recovery through duckweeds has only been evaluated on pilot scale (El-Shafai et al., 2007). Further, there is still lack of awareness and expertise in developing the technology on a local basis especially in the developing countries (Nichols, 1983).

5.3.2 Life Cycle Studies

Life cycle studies have been carried out for the four nutrient recycling technologies discussed above and the amount of relevant life cycle studies for each technology varies. Most of life cycle studies evaluated the biosolids land application, while only one study examined the controlled struvite crystallization technology. Figure 5.2 provides the number of relevant life cycle studies on different nutrient recycling technologies.

Most of the life cycle studies on biosolids land application were carried out in Europe and Australia. Those studies compared various biosolids management scenarios. Some were focused on the production processes such as lime stabilization, composting,

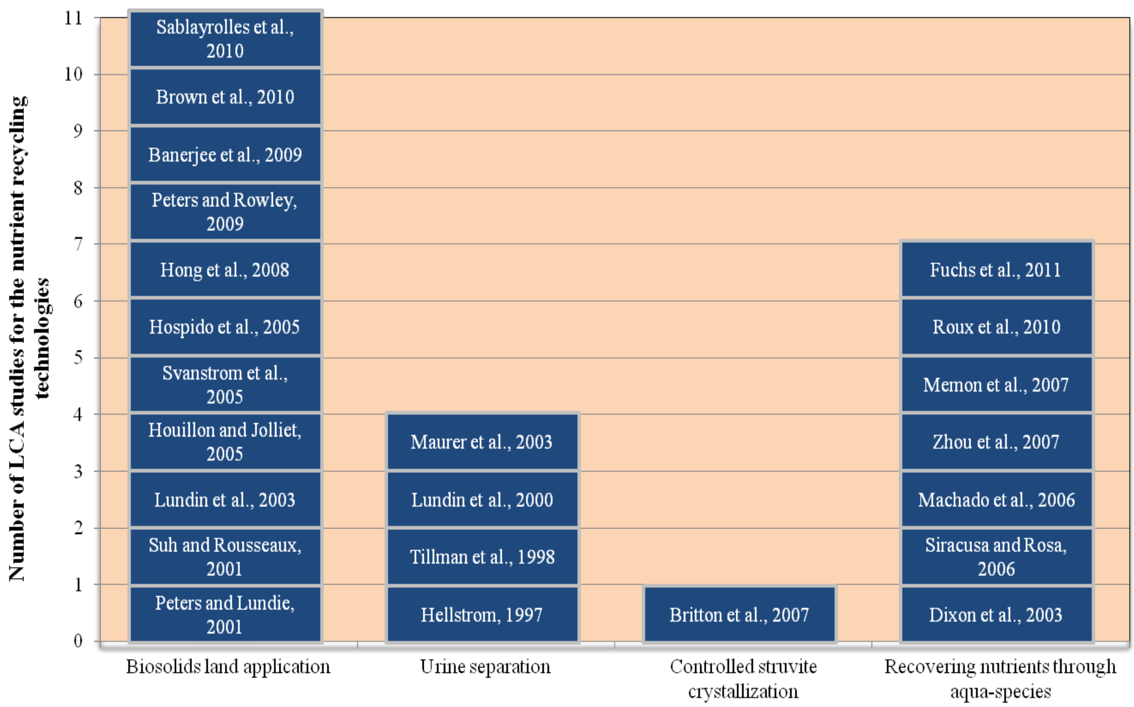


Figure 5.2 Number of relevant life cycle studies on each of the nutrient recycling technologies

anaerobic digestion, thermal drying; some were focused on the end of life options such as landfill, agricultural application, incineration, fuel supplementary; and some were focused on the scenarios combining production processes and end of life options. Some uncommon production processes were also evaluated such as water oxidation (Houillon and Jolliet, 2005; Svanström et al., 2005), pyrolysis (Hospido et al., 2005; Houillon and Jolliet, 2005), dewatered sludge melting (Hong et al., 2009) and incinerated ash melting (Hong et al., 2009). The system boundaries and scales of these life cycle studies were different: some only included operation phase (Brown et al., 2010; Hospido et al., 2005; Houillon and Jolliet, 2005; Lundin et al., 2004; Sablayrolles et al., 2010; Suh and Rousseaux, 2002), some included both construction and operation phases (Hong et al., 2009; Peters and Lundie, 2001; Peters and Rowley, 2009), and some included the operation and the dismantling phases (Svanström et al., 2005). The impact categories assessed by these studies were also very different: some focused on energy (Houillon and Jolliet, 2005); some included broader impact categories, such as human toxicity, ecotoxicity, water use, air/water emissions. The energy offset through fertilizer application was only considered in some of the studies (Brown et al., 2010; Lundin and Morrison, 2002; Peters and Rowley, 2009). Even those who considered such offsets estimated the energy benefits in different ways.

As a result of these differences, these studies rendered very different results. For instance, nutrient recycling through land application was preferred in studies of Suh and Rousseaux (2001), Houillon and Jolliet (2005), and Brown et al. (2010), but not favored in studies of Lundin et al. (2003), Svanstrom et al. (2005) and Peters and Rowley (2009). Of those studies that did not prefer land application, incineration was usually the best alternative. The integration of residue heat from power plant for drying the biosolids was also recommended in some studies (Peters and Lundie, 2001).

There are very limited life cycle studies conducted to compare the overall environmental impacts of the urine separation systems and the conventional wastewater treatment systems. The available life cycle studies were carried out in Europe around a decade ago (Hellstrom, 1997; Lundin et al., 2000; Maurer et al., 2003; Tillman et al., 1998) and they all recommended urine separation over the conventional water systems.

For controlled struvite precipitation from anaerobic digesters, most of the current assessments were carried out for economic benefits (Etter et al., 2011; Türker and Çelen, 2007; Çelen and Türker, 2001). By far, only one study was carried out to evaluate the mitigation of greenhouse gas emissions through the controlled struvite precipitation (Britton et al., 2007). The study showed that a full scale WWTP with struvite recovery can offset approximately 12,000 tonnes of carbon dioxide equivalent per year relative to conventional fertilizer manufacturing.

Most of life cycle studies on recovering nutrients through aqua-species are focused on nutrient removal through constructed wetlands (Dixon et al., 2003; Fuchs et al., 2011; Machado et al., 2007; Memon et al., 2007; Roux et al., 2010; Siracusa and La Rosa, 2006; Zhou et al., 2009). All these studies reported positive results towards wetland treatment over the conventional treatment, based on global warming potential, aquatic toxicity, eutrophication potential and resource consumption, but most studies did not include the end use of the aqua-species as nutrients. Hence, it is necessary to evaluate the life cycle benefits of constructed wetlands under a closed nutrient loop. Additionally, there is a lack of life cycle studies on nutrient recovery through macroalgae, microalgae, duckweed and crops.

5.3.3 Challenges

Beyond biosolids land application, most of the nutrient recycling technologies have not been widely applied. The challenges of nutrient recycling are more complicated than the onsite energy generation technologies, including land and financial resource constraints, integration into existing infrastructure, safety and technology imperfections. For example, application of urine separation needs cooperation from local communities and governments. Besides, changing the existing infrastructure incurs high constructional costs which may hinder the application. As a result, further studies are needed for improving customer confidence and integration to existing infrastructure.

Life cycle studies for the nutrient recycling technologies are still limited, especially for urine separation, controlled struvite precipitation and nutrient recovery through aqua-species. Moreover, the life cycle studies on biosolids land application have their own problems. Most of these studies were carried out in different regions, evaluated by different impact categories and based on different cases. Each study compared different biosolids management methods. The avoidance of fossil-based fertilizers using biosolids for land application was not consistently considered in the studies, which caused various uncertainties in the comparison. Thus, the results can be hardly generalized, and used by the public. Hence, a consistent framework needs to be developed for comparing the processes and end use of biosolids. Furthermore, other nutrient recycling technologies also need more generalized life cycle studies to justify their applications and guide future development.

Another challenge of the future studies on nutrient recycling from WWTPs is the integration of these recycling technologies. Currently, integration of these nutrient recycling technologies is neglected, even though combining these technologies may maximize the potential of nutrient recovery from the wastewater. For example, upstream urine separation could be integrated with downstream constructed wetlands since urine separation does not remove all the nutrients in the wastewater. There are also tradeoffs when these technologies are integrated because they could potentially interfere with each other and each technology has its limits for the amount of nutrients that can be recovered. Hence, it is important to understand the tradeoffs between different technologies and the appropriate scale to implement the technologies (community level or municipal level).

Studies are also needed to investigate the maximal recovery potential under integrated nutrient recycling.

5.4 Water Reuse

Water reuse is the method of recycling treated wastewater for beneficial purposes, such as agricultural and landscape irrigation, industrial processes, toilet flushing, and groundwater replenishing (EPA, 2004). The level of wastewater treatment required, associated technologies and effluent application are shown in Figure 5.3. Currently, around 1.7 billion gallons per day of wastewater is reused in the US, and this reuse rate is growing by 15% every year. Florida and California are the leading states in water reuse in the country. Through water reuse, energy can be indirectly conserved because it saves energy associated with providing the same amount of potable water. Moreover, the amount of water that can be reused is proportional to water demand. It reduces the need for exploring more energy intensive water sources, such as the desalinated water to meet the increasing water demand.

5.4.1 Technologies and Applications

5.4.1.1 Agricultural Irrigation

Reusing water for agricultural irrigation has been practiced in Egypt and China a long time ago (Van der Bruggen, 2010). Currently, irrigation represents around 58% of the US total freshwater withdrawal, and 31% of the total water withdrawal (USGS, 2009). Using the reclaimed water to replace part of the agriculture demand can alleviate local water stress. Furthermore, nutrients contained in the wastewater can also reduce the fertilization application. Effluent from secondary treatment was recommended for irrigating non-food crops, orchards and vineyards, while effluent from tertiary treatment was recommended for food crop irrigation (Figure 5.3). Despite the benefits of agricultural water reuse, there are still concerns over the wastewater sources and quality, which may cause potential soil pollution and crop contamination. Another concern is the high cost to construct and operate the reclaimed water pipeline systems due to the normally long distance between the municipal reclaimed water supplies and the major agricultural demand areas (Leverenz et al., 2011). Furthermore, seasonal change of the agricultural water demand may require winter reclaimed water storage facilities, which may be technologically and economically prohibitive (Leverenz et al., 2011).

To date, California and Florida are the leading states for agricultural water reuse in the US, reusing 48% and 19% of the total volume of reclaimed water respectively (EPA, 2004). There are various projects in Florida, California, and Virginia on reusing water for agricultural purposes (Asano, 2007).

5.4.1.2 Industrial Reuse

Thermoelectric represents around 50% of the total water withdrawal in the US in 2005 (USGS, 2009). Other industries such as petroleum refineries, chemical manufacturers also require substantial amounts of water. These industries, however, do not require water quality as high as for potable supply, thus are suitable for using reclaimed water. Reusing water also helps the industries to reduce cost and improve sustainability. Current industrial reuse mainly includes cooling water, boiler make-up water and industrial process water (EPA, 2004). The US EPA (2004) recommends secondary treatment for industrial cooling processes; however, the requirements of treatment technologies for other industrial purposes are process specific (Figure 3). On the other hand, reclaimed water may cause problems such as corrosion, biological growth, and scaling compared with freshwater (Li et al., 2011).

Industrial reuse has increased substantially since the early 1990s because of water shortages and increased population (EPA, 2004). California, Arizona, Texas, Florida, and Nevada have major industrial facilities using reclaimed water for cooling and process/boiler-feed requirements (EPA, 2004). On the other hand, although a number of power plants have blended reclaimed water with freshwater as cooling system makeup, only a few of them use the reclaimed water as dominant makeup water (Li et al., 2011).

5.4.1.3 Urban Reuse

Urban reuse includes urban irrigation, commercial uses such as car washing, fire protection, toilet flushing, dust control and concrete production. Residential irrigation is the major urban reuse application, which comprises around half of the total residential water consumption. Replacing the freshwater with reclaimed water for urban irrigation can greatly reduce cost and water stress, especially during the peak seasons. The US EPA (2004) recommended secondary treatment for restricted landscape impoundments, and tertiary treatment for unrestricted recreational impoundments, landscape and golf course irrigation, toilet flushing, as well as vehicle washing (Figure 5.3). The human exposure of urban reuse is higher than agricultural irrigation and industrial reuse. Thus, special care should be taken to avoid potential health problems. Moreover, urban reuse requires dual systems for the reclaimed water delivery, which may bring high costs for certain communities.

Water reuse for urban reuse has been widely applied in the United States. Florida is the leading state in urban reuse, reusing 44% of the total reclaimed water for landscape irrigation; while California reuses 21% of the reclaimed water for this purpose.

5.4.1.4 Indirect Potable Reuse

Indirect potable reuse includes planned indirect potable reuse, such as groundwater recharge and unplanned indirect potable reuse, such as discharge of treated wastewater to surface or groundwater which is subsequently used for municipal water supply (Leverenz et al., 2011). This section mainly discusses groundwater recharge. Groundwater recharge can alleviate land subsidence and seawater intrusion in coastal areas. It also provides water storage and further treatment for subsequent retrieval and reuse of the reclaimed water. Furthermore, groundwater recharge eliminates the need for surface storage facilities and the attendant problems associated with uncovered surface reservoirs, such as evaporation losses, algae blooms resulting in deterioration of water quality, and creation of odors. The US EPA (2004) recommends nutrients and residual solids removal for groundwater recharge. The challenges of groundwater recharge include extensive land areas for spreading basins, high costs for treatment, water quality monitoring, and injection/infiltration facility operations. Moreover, recharge under treated wastewater may increase the danger of aquifer contamination while recharge of over purified water may expose the water to the exterior contaminants. Not all recharged water can be recoverable due to movement beyond the capture zone of the extraction well, or mixing with poor quality groundwater.

Major planned indirect potable reuse projects have been carried out in places such as Orange County Water District in California and the Occoquan Reservoir in northern Virginia (Asano, 2007) in the US and in Singapore as “Newater” (PUB, 2011). Plus, aquifer storage and recovery systems are being used in a number of states to overcome seasonal imbalances in both potable and reclaimed water projects (EPA, 2004). The two leading states, Florida and California use 16% and 15% of the reclaimed water for groundwater recharge respectively.

5.4.1.5 Direct Potable Reuse

Direct potable reuse refers to introducing treated wastewater directly into a water distribution system without intervening storage (pipe to pipe) (Cronk and Fennessy, 2001). Using the reclaimed water to augment potable supply can improve overall water supply reliability, especially in coastal or drought areas (Leverenz et al., 2011). Unlike non-potable reuses, dual systems for water delivery can be avoided. Plus the direct potable reuse systems do not need water spreading or injection systems as the groundwater recharge systems. Potential contamination by environmental buffers will not be a concern anymore if directly reused for potable purposes. However, the direct potable reuse has high requirements for water treatment, which may increase the operational cost. Public acceptance is another major barrier for implementing the direct potable reuse (EPA, 2004).

Planned potable recycling has taken place at Windhoek in Namibia since 1968 (Anderson, 1996). Additionally, Cloudcroft in New Mexico and Big Springs in Texas in the US have recently started reusing water for direct potable use (Tchobanoglous et al., 2011). In the US, the most extensive research focusing on direct potable reuse has been conducted in Denver, Colorado; Tampa, Florida; and San Diego, California.

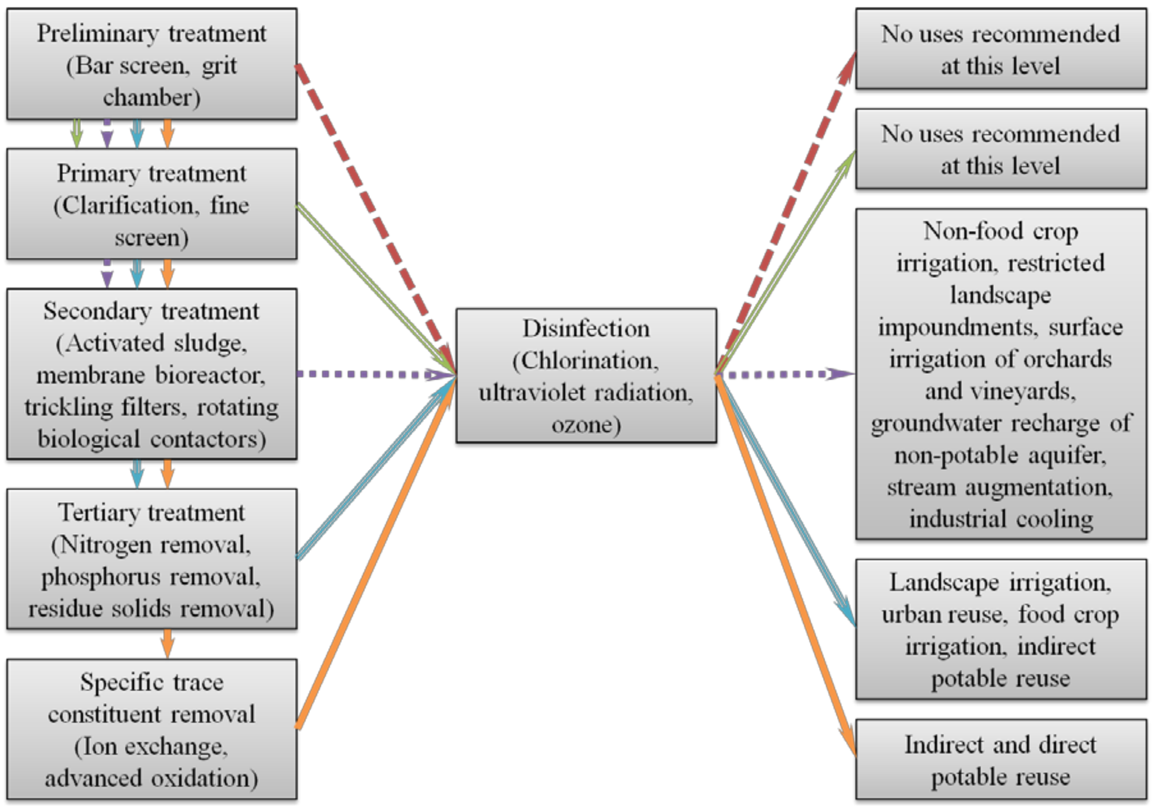


Figure 5.3 Level of wastewater treatment, associated technologies and effluent application. (Each type of line shows a combination of treatment technologies and the associated effluent application. For instance, " ▪▪▪➤" shows that for a treatment train of preliminary treatment, primary treatment, secondary treatment and disinfection, uses such as non-food crop irrigation, groundwater recharge of non-potable aquifer, stream augmentation and so on were recommended for the treated water.)

5.4.2 Life Cycle Studies

Although reclaimed water, as an alternative water source, has been recommended in many studies, there are not many studies comparing water reuse with other water supply options through the life cycle perspective. Spain is the leading country on life cycle studies of water reuse (Meneses et al., 2010; Muñoz et al., 2010; Ortiz et al., 2007; Pasqualino et al., 2009; Pasqualino et al., 2011). This is partly contributed by the unique climate and geographical conditions of the Mediterranean coast and the freshwater shortage. When the treated wastewater is discharged into the sea, it cannot be reused either directly or indirectly (Ortiz et al., 2007). As a result, water reuse becomes a very promising source, which would not be affected by the change of demands. For similar reasons, there are also life cycle studies carried out in California (Stokes and Horvath, 2006) and Arizona (Lyons et al., 2009) in the US.

In those life cycle studies, the most commonly assessed environmental impact categories include acidification potential, global warming potential, ozone depletion potential, eutrophication potential and air emissions. Several studies have included embodied energy (Meneses et al., 2010; Muñoz et al., 2010; Pasqualino et al., 2011; Stokes and Horvath, 2006) and cumulative freshwater use (Meneses et al., 2010; Muñoz et al., 2010; Pasqualino et al., 2011). The calculation method of the embodied energy, however, is quite different between the US and the Spanish studies. The US study integrated the national economic input-output tables for energy evaluation, while the Spanish studies followed traditional process analysis method as presented in Frischknecht et al. (2007).

The water reuse scenarios, both potable and non-potable, were frequently compared to water desalination, conventional potable water production and water importation scenarios. Although different system boundaries (Construction phase was included in Stokes and Horvath (2006), Lyons et al. (2009), Munoz and Fernandes-Alba (2010), but not in Pasqualino et al. (2010), Meneses et al., (2010)), and different system scales were studied (serving population from 5700 to 200,000), all these studies recommended reusing treated wastewater against desalination for its lower environmental impacts and energy consumption. Ortiz et al. (2007) found the tertiary treatments such as ultrafiltration membranes do not increase the environmental loads significantly when compared with conventional activated sludge system.

Given the potential of water reuse in reducing environmental impacts and water scarcity, it is important to evaluate the possibilities and benefits of reusing water through LCA considering various technologies, different applications, and different geographical and climate conditions.

5.4.3 Challenges

One challenge of current water reuse studies is that few studies have linked the treatment technology with the desired water quality associated with certain applications. Most of time, researchers and industries strive for better treated water quality, but neglected the fact that over treated wastewater brings no additional benefits, but higher energy consumption and costs. The current major concern of the tertiary treatment is the associated cost and energy consumption, and the variability of the effluent quality. Health and safety concerns are still the major barriers for broader application of water reclamation.

Current studies on water reuse are mainly focused on technology improvements, reclaimed water applications, reclaimed water quality assessment, environmental and health effects of water quality, outcome comparison, ongoing projects introduction, water reuse practice in different regions and countries, technical and economic feasibility, water management issues and so on; however, there are not many studies justifying water reclamation through life cycle assessments. Although there are various existing and ongoing water reuse projects, few had life cycle studies before their implementations.

Of the current life cycle studies, the water reuse technologies assessed are different, and system scales are also very different. Moreover, the system boundaries included in these studies are varied. One study included the wastewater treatment plant as part of the water reuse scenario (Lyons et al., 2010), while the others do not. The delivery of the reclaimed water needs additional water distribution infrastructure; however, such infrastructures were not considered in all these studies. Hence, standard protocol needs to be developed for water reuse life cycle studies. Moreover, all these life cycle studies are based on certain cases, which can hardly be generalized to other cases based on the climate and geographical differences over different regions. There is also a lack of studies looking at the contribution of each unit process involved in water reclamation and the impact of scale on environmental loads of water use. Most importantly, these studies do not link the technologies with the quality and applications of the reclaimed water. As a result, these life cycle studies cannot be used as general guidance for the future application of water reclamation, which however, is urgently needed in the area.

5.5 Integrated Resource Recovery

Onsite energy generation, nutrient recycling and water reuse can be integrated in wastewater treatment plants to achieve maximal resource recovery as shown in Figure 5.4. Although there is integrated resource recovery in practice currently, the related studies are rare. In Florida, a state-of-art municipal wastewater treatment plant combines onsite energy generation, nutrient recycling and water reuse. Sludge is first dewatered and digested in the anaerobic digester. CHP is then used to generate electricity from the digested gases. Biosolids from the digestion is heat dried using residual heat from a nearby power plant and sold for land application. Part of the treated water is used for agricultural and landscape irrigation. The integrated resource recovery reduces both material uses in the wastewater treatment plants, and the energy consumption. As a result, the sustainability of the wastewater treatment plants is greatly improved.

At this individual utility scale, there are tradeoffs among resource recovery methods. For instance, when more biogas is generated from the anaerobic digestion, the amount of nutrients that can be recovered through land application is reduced. However, there are no studies optimizing the resource recovery via multiple approaches.

On a community scale, more resource recovery technologies can be applied, but the alternatives must be carefully evaluated in order to achieve maximal recovery. For instance, it would be beneficial to install heat pump systems when the demand is located close to the wastewater treatment plant, but not when the demand is far away. The onsite wind energy generation systems might be better located away from the local residents. Besides, urine separation systems can only be installed on community scale for nutrient recycling. Reclaimed water has to be delivered to the community for toilet flushing, or landscape irrigation. Thus, distances between WWTPs and end users have to be considered. The up-concentration technique is another example of combining onsite energy generation, nutrient recycling and water reclamation on community scales. In this technique, wastewater is first up-concentrated through dynamic sand filtration, dissolved

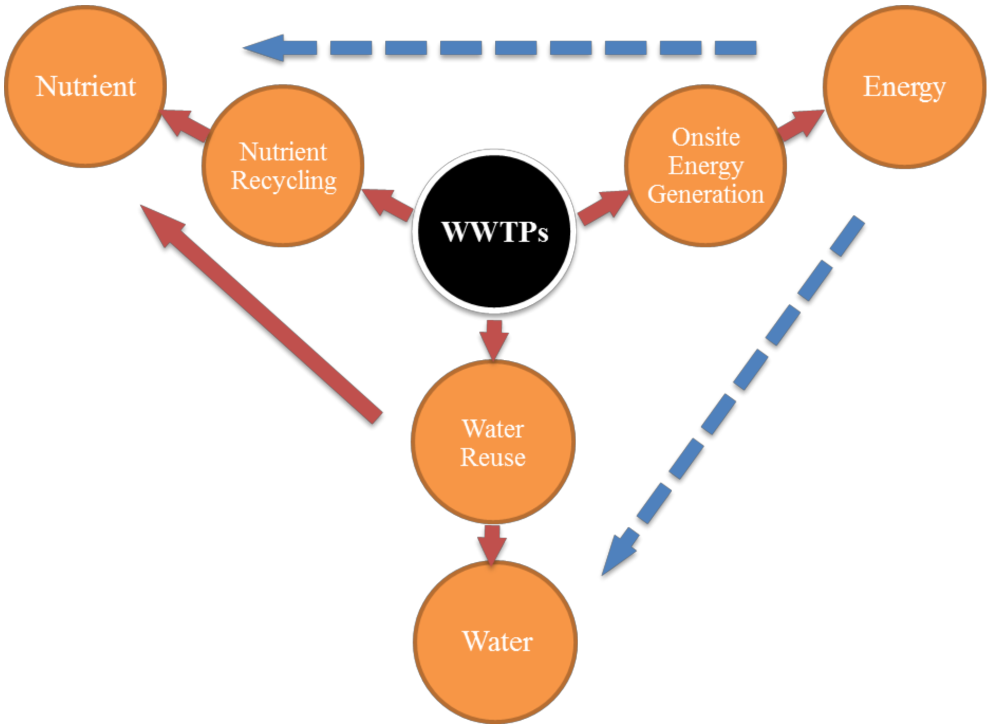


Figure 5.4 Integrated energy, nutrients and water recovery from wastewater treatment plants. (The red solid arrows show the systems, processes or resources needed for or can be generated through a certain product or process. The blue dashed arrows show that energy can be saved from fossil chemicals based fertilizer production through nutrient recycling and from potable water production through water reuse.)

air flotation, membrane filtration, biological sorption or a combination thereof. Then the water is treated with reverse osmosis or ultra-filtration for reuse. On the other hand, the concentrated liquid can be digested for energy recovery as well as nutrient recovery (Verstraete et al., 2009). Through the above examples, integral design combining onsite energy generation, nutrient recycling, and water reuse needs to be carefully evaluated in terms of economic and environmental aspects (e.g., carbon footprint) before implementation.

On a national scale, research and practices on integrated resource recovery in WWTPs need to be encouraged through funding, policy instruments, and regulations.

5.6 Conclusions

This paper reviewed the three approaches of resource recovery in wastewater treatment plants: onsite energy generation, nutrient recycling and water reuse. The available technologies and applications, life cycle studies, and challenges of each one were closely examined.

Onsite energy generation has been widely recognized and studied. It provides electricity or other forms of energy for convenient onsite use. Some onsite energy generation technologies have side benefits such as reducing the organic and inorganic loads of wastewater. The major challenges of onsite energy generation technologies are large capital costs, lack of reliability and specific requirements for climate conditions and locations. Most studies recommending onsite energy generation evaluated the economic benefit of the technologies. There is a lack of studies assessing each technology through environmental perspective. Future studies on onsite energy generation may seek for low cost technologies, easy integration to existing small plants, and integration of different energy generation technologies. Moreover, careful feasibility and life cycle studies have to be carried out before the implementation of each technology.

Nutrient recycling are not widely applied except land application. The most common problems for nutrient recycling lie on safety and the technology imperfection. Biosolids land application is by far the most widely studied nutrient recycling method. However, due to the lack of standard protocols of conducting life cycle studies on biosolids management, these studies render very different results. For the other nutrient recycling technologies, there is a lack of life cycle studies. Future studies on nutrient recycling should focus on public acceptance, the tradeoffs between different technologies over different scales, technology integration for maximal nutrient recovery, as well as consistent LCA framework for technology comparison.

Water reuse has attracted academic and industrial attentions for a long time. Few studies, however, have linked the treatment technology with the desired water quality associated with certain applications. Other challenges of water reuse technologies include the high cost and energy consumption associated with tertiary treatment, and the variability of the effluent quality. Furthermore, there are not many life cycle studies even water reuse has been widely implemented. Although the current life cycle studies are uniformly in support of water reuse, these studies have very different scales, boundaries, and evaluation categories. Future studies on water reuse may pair technologies with water quality and applications. Standard requirements on system boundaries, functional unit and impact categories have to be established for conducting life cycle assessments on water reuse.

5.7 References

ACUA, 2011. Atlantic County Utilities Authority, Green Initiatives, http://www.acua.com/acua//content.aspx?id=474 (last accessed on 8.21.2012).

Alaerts, G., Mahbubar, R., Kelderman, P., 1996. Performance analysis of a full-scale duckweed-covered sewage lagoon, Water Research 30, 843-852.

Allen, R.M., Bennetto, H.P., 1993. Microbial fuel cells: electricity production from carbohydrates, Applied Biochemistry and Biotechnology 39/40, 27-40.

Anderson, J., 1996. The potential for water recycling in Australia--expanding our horizons, Desalination 106, 151-156.

Ardente, F., Beccali, M., Cellura, M., Lo Brano, V., 2008. Energy performances and life cycle assessment of an Italian wind farm, Renewable and Sustainable Energy Reviews 12, 200-217.

Aresta, M., Dibenedetto, A., Barberio, G., 2005. Utilization of macro-algae for enhanced CO2 fixation and biofuels production: Development of a computing software for an LCA study, Fuel Processing Technology 86, 1679-1693.

Asano, T., 2007. Water Reuse: Issues, Technologies and Applications. McGraw-Hill Professional, New York.

Banar, M., Cokaygil, Z., Ozkan, A., 2009. Life cycle assessment of solid waste management options for Eskisehir, Turkey, Waste Management 29, 54-62.

Battistoni, P., Fava, G., Pavan, P., Musacco, A., Cecchi, F., 1997. Phosphate removal in anaerobic liquors by struvite crystallization without addition of chemicals: preliminary results, Water Research 31, 2925-2929.

Benetto, E., Nguyen, D., Lohmann, T., Schmitt, B., Schosseler, P., 2009. Life cycle assessment of ecological sanitation system for small-scale wastewater treatment, Science of the Total Environment 407, 1506-1516.

Björklund, J., Geber, U., Rydberg, T., 2001. Emergy analysis of municipal wastewater treatment and generation of electricity by digestion of sewage sludge, Resources, Conservation and Recycling 31, 293-316.

Boulder, 2012. City of Boulder, Colorado, wastewater facility solar electric system, http://www.bouldercolorado.gov/index.php?option=com_content&view=article&id=8763&Itemid=3482 (last accessed on 6.1.2012).

Boyden, B.H., Rababah, A.A., 1996. Recycling nutrients from municipal wastewater, Desalination 106, 241-246.

Britton, A., Sacluti, F., Oldham, W., Mohammed, A., Mavinic, D., Koch, F., 2007. Value from waste–struvite recovery at the City of Edmonton's Gold Bar WWTP, Proceedings of the IWA Specialist Conference, Moncton, New Brunswick, Canada.

Brown, R., 2009. Energy Efficiency and Renewable Energy Technologies in Wastewater Management, Testimony for a hearing on "Sustainable Wastewater Management" Before the Subcommittee On Water Resources And Environment House Committee On Transportation And Infrastructure.

Brown, S., Beecher, N., Carpenter, A., 2010. Calculator Tool for Determining Greenhouse Gas Emissions for Biosolids Processing and End Use, Environmental Science and Technology 44, 9509-9515.

Browning, 2001. Wind power for the wastewater treatment plant, http://www.browningmontana.com/wind.html (last accessed on 8.15.2012).

Burton, F.L., 1996. Water and wastewater industries: characteristics and energy management opportunities, Burton Engineering, prepared for the Electric Power Research Institute, Palo Alto, CA.

Cartmell, E., Gostelow, P., Riddell-Black, D., Simms, N., Oakey, J., Morris, J., Jeffrey, P., Howsam, P., Pollard, S.J., 2006. Biosolids A Fuel or a Waste? An Integrated Appraisal of Five Co-combustion Scenarios with Policy Analysis, Environmental Science and Technology 40, 649-658.

CEC, 2005. California Energy Commission, Integrated Energy Policy Report, CEC-100-2005-005-CTF.

Çelen, I., Türker, M., 2001. Recovery of ammonia as struvite from anaerobic digester effluents, Environmental Technology 22, 1263-1272.

Cheng, J., Bergmann, B.A., Classen, J.J., Stomp, A.M., Howard, J.W., 2002. Nutrient recovery from swine lagoon water by Spirodela punctata, Bioresource Technology 81, 81-85.

Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration, Energy 34, 2116-2123.

Clarens, A.F., Resurreccion, E.P., White, M.A., Colosi, L.M., 2010. Environmental life cycle comparison of algae to other bioenergy feedstocks, Environmental Science and Technology 44, 1813-1819.

Cleary, J., 2009. Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature, Environment International 35, 1256-1266.

Coltro, L., Garcia, E.E.C., Queiroz, G.C., 2003. Life cycle inventory for electric energy system in Brazil, The International Journal of Life Cycle Assessment 8, 290-296.

Cronk, J.K., Fennessy, M.S., 2001. Wetland Plants: Biology and Ecology. CRC Press.

CSS, 2009. Center for Sustainable systems, U.S. Wastewater Treatment Factsheet, University of Michigan Pub No. CSS04-14.

Culley Jr, D.D., Rejmánková, E., Květ, J., Frye, J., 1981. Production, chemical quality and use of duckweeds (Lemnaceae) in aquaculture, waste management, and animal feeds, Journal of the world mariculture society 12, 27-49.

Cusick, R.D., Bryan, B., Parker, D.S., Merrill, M.D., Mehanna, M., Kiely, P.D., Liu, G., Logan, B.E., 2011. Performance of a pilot-scale continuous flow microbial electrolysis cell fed winery wastewater, Applied Microbiology and Biotechnology 89, 2053-2063.

Ditzig, J., Liu, H., Logan, B.E., 2007. Production of hydrogen from domestic wastewater using a bioelectrochemically assisted microbial reactor (BEAMR), International Journal of Hydrogen Energy 32, 2296-2304.

Dixon, A., Simon, M., Burkitt, T., 2003. Assessing the environmental impact of two options for small-scale wastewater treatment: comparing a reedbed and an aerated biological filter using a life cycle approach, Ecological Engineering 20, 297-308.

DOE, February, 2010. New Wind Resource Maps and Wind Potential Estimates for the United States, June, http://www.windpoweringamerica.gov/filter_detail.asp?itemid=2542 (last accessed on 5.26.2012).

DOE, National Renewal Energy Laboratory, Solar Energy Potential, June, http://energy.gov/maps/solar-energy-potential (last accessed on 8.15.2012).

El-Shafai, S.A., El-Gohary, F.A., Nasr, F.A., Peter van der Steen, N., Gijzen, H.J., 2007. Nutrient recovery from domestic wastewater using a UASB-duckweed ponds system, Bioresource Technology 98, 798-807.

El-Shafai, S.A., El-Gohary, F.A., Nasr, F.A., van der Steen, N.P., Gijzen, H.J., 2004a. Chronic ammonia toxicity to duckweed-fed tilapia (Oreochromis niloticus), Aquaculture 232, 117-127.

El-Shafai, S.A., Gijzen, H.J., Nasr, F.A., El-Gohary, F.A., 2004b. Microbial quality of tilapia reared in fecal-contaminated ponds, Environmental Research 95, 231-238.

EPA, 2008. Clean Watersheds Needs Survey 2008 Report to Congress, CWNS EPA-832-R-10-002.

EPA, 2007. Opportunities for and benefits of combined heat and power at wastewater treatment facilities, EPA-430-R-07-003.

EPA, 2004. Guidelines for Water Reuse, EPA/625/R-04/108.

EPA, 1999. Biosolids Generation, Use and Disposal in the United States, EPA530-R-99-009.

ESMAP, 2008. Good practices in city energy efficiency: Eco2 cities: Integrated resource management in Stockholm, http://www.esmap.org/esmap/sites/esmap.org/files/CS_Stockholm.pdf (last accessed on 8.20.2012).

Etter, B., Tilley, E., Khadka, R., Udert, K., 2011. Low-cost struvite production using source-separated urine in Nepal, Water Research 45, 852-862.

Flores, A., Buckley, C., Fenner, R., 2009. Selecting wastewater systems for sustainability in developing countries, Proceedings of 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Foley, J.M., Rozendal, R.A., Hertle, C.K., Lant, P.A., Rabaey, K., 2010. Life cycle assessment of high-rate anaerobic treatment, microbial fuel cells, and microbial electrolysis cells, Environmental Science and Technology 44, 3629-3637.

Foley, K.J., 2010. Wastewater treatment and energy: an analysis on the feasibility of using renewable energy to power wastewater treatment plants in Singapore, MS Thesis, Massachusetts Institute of Technology.

Forrest, A., Fattah, K., Mavinic, D., Koch, F., 2008. Optimizing struvite production for phosphate recovery in WWTP, Journal of Environmental Engineering 134, 395.

Friotherm, Energy from sewage water – District heating and district cooling in Sandvika, with 2 Unitop 28C heat pump units, http://www.friotherm.com/downloads/sandvika_e005_uk.pdf (last accessed on 6.15.2012).

Frischknecht, R., Jungbluth, N., Althaus, H., Bauer, C., Doka, G., Dones, R., Hischier, R., Hellweg, S., Humbert, S., Köllner, T., 2007. Implementation of life cycle impact assessment methods, ecoinvent report No.3, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf.

Fuchs, V.J., Mihelcic, J.R., Gierke, J.S., 2011. Life cycle assessment of vertical and horizontal flow constructed wetlands for wastewater treatment considering nitrogen and carbon greenhouse gas emissions, Water Research 45, 2073-2081.

Gagnon, L., Belanger, C., Uchiyama, Y., 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001, Energy Policy 30, 1267-1278.

Gaiusobaseki, T., 2010. Hydropower opportunities in the water industry, International Journal of Environmental Sciences 1, 392-402.

Gaterell, M., Gay, R., Wilson, R., Gochin, R., Lester, J., 2000. An economic and environmental evaluation of the opportunities for substituting phosphorus recovered from wastewater treatment works in existing UK fertiliser markets, Environmental Technology 21, 1067-1084.

Genchi, Y., Kikegawa, Y., Inaba, A., 2002. CO2 payback-time assessment of a regional-scale heating and cooling system using a ground source heat-pump in a high energy-consumption area in Tokyo, Applied Energy 71, 147-160.

Granovskii, M., Dincer, I., Rosen, M.A., 2007. Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: Economic factors, International Journal of Hydrogen Energy 32, 927-931.

Groom, M.J., Gray, E.M., Townsend, P.A., 2008. Biofuels and biodiversity: principles for creating better policies for biofuel production, Conservation Biology 22, 602-609.

Guest, G., Bright, R.M., Cherubini, F., Michelsen, O., Strømman, A.H., 2011. Life Cycle Assessment of Biomass-based Combined Heat and Power Plants, Journal of Industrial Ecology 15, 908-921.

Hays, S., Zhang, F., Logan, B.E., 2011. Performance of two different types of anodes in membrane electrode assembly microbial fuel cells for power generation from domestic wastewater, Journal of Power Sources 196, 8293-8300.

Hellstrom, D., 1997. An exergy analysis for a wastewater treatment plantan estimation of the consumption of physical resources, Water Environment Research 69, 44-51.

Hong, J., Hong, J., Otaki, M., Jolliet, O., 2009. Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan, Waste Management 29, 696-703.

Hospido, A., Moreira, T., Martín, M., Rigola, M., Feijoo, G., 2005. Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes The International Journal of Life Cycle Assessment 10, 336-345.

Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis, Journal of Cleaner Production 13, 287-299.

Jaffer, Y., Clark, T., Pearce, P., Parsons, S., 2002. Potential phosphorus recovery by struvite formation, Water Research 36, 1834-1842.

Jönsson, H., 2001. Source separation of human urine–separation efficiency and effects on water emissions, crop yield, energy usage and reliability, Proceedings of First International Conference on Ecological Sanitation, Nining, China .

Khoo, H.H., 2009. Life cycle impact assessment of various waste conversion technologies, Waste Management 29, 1892-1900.

Kim, B.H., 2009. Microbial fuel cell, KISToday 2, 4-8.

Kimming, M., Sundberg, C., Nordberg, A., Baky, A., Bernesson, S., Norén, O., Hansson, P.A., 2011. Biomass from agriculture in small-scale combined heat and power plants-A comparative life cycle assessment, Biomass Bioenergy 35, 1572-1581.

Kroiss, H., Zessner, M., 2010. Wastewater treatment and sludge disposal - what are the challenges? http://netedu.xauat.edu.cn/jpkc/netedu/jpkc2009/szylyybh/content/wlzy/7/6/3%20Kroiss.pdf (last accessed on 6.20.2012).

Kumar, A., Ergas, S., Yuan, X., Sahu, A., Zhang, Q., Dewulf, J., Malcata, F.X., Van Langenhove, H., 2010. Enhanced CO2 fixation and biofuel production via microalgae: recent developments and future directions, Trends in Biotechnology 28, 371-380.

Larsen, T.A., Alder, A.C., Eggen, R.I.L., Maurer, M., Lienert, J., 2009. Source Separation: Will We See a Paradigm Shift in Wastewater Handling? Environmental Science and Technology 43, 6121-6125.

Larsen, T.A., Gujer, W., 1996. Separate management of anthropogenic nutrient solutions (human urine), Water Science and Technology 34, 87-94.

Leverenz, H.L., Tchobanoglous, G., Asano, T., 2011. Direct potable reuse: a future imperative, Journal of Water Reuse and Desalination 1, 2-10.

Li, H., Chien, S.H., Hsieh, M.K., Dzombak, D.A., Vidic, R.D., 2011. Escalating Water Demands for Energy Production and the Potential for Use of Treated Municipal Wastewater, Environmental Science and Technology 45:4195-4200.

Li, Z., Songtao, H., 2006. Research on the Heat Pump System Using Seawater as Heat Source or Sink, Building Energy & Environment 3, DOI: cnki: ISSN:1003-0344.0.2006-03-008.

Liu, H., Grot, S., Logan, B.E., 2005. Electrochemically assisted microbial production of hydrogen from acetate, Environmental Science and Technology 39, 4317-4320.

Liu, H., Logan, B.E., 2004. Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane, Environmental Science and Technology 38, 4040-4046.

Liu, H., Ramnarayanan, R., Logan, B.E., 2004. Production of electricity during wastewater treatment using a single chamber microbial fuel cell, Environmental Science and Technology 38, 2281-2285.

Logan, B.E., Rabaey, K., 2012. Conversion of Wastes into Bioelectricity and Chemicals by Using Microbial Electrochemical Technologies, Science 337, 686-690.

Lundin, M., Bengtsson, M., Molander, S., 2000. Life cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads, Environmental Science and Technology 34, 180-186.

Lundin, M., Morrison, G.M., 2002. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems, Urban Water 4, 145-152.

Lundin, M., Olofsson, M., Pettersson, G., Zetterlund, H., 2004. Environmental and economic assessment of sewage sludge handling options, Resources, Conservation and Recycling 41, 255-278.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M., Chen, Y., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination, Water science and technology: water supply 9, 439-448.

Machado, A.P., Urbano, L., Brito, A., Janknecht, P., Salas, J., Nogueira, R., 2007. Life cycle assessment of wastewater treatment options for small and decentralized communities, Water science and technology 56, 15-22.

Mahmood, T., Elliott, A., 2006. A review of secondary sludge reduction technologies for the pulp and paper industry, Water Research 40, 2093-2112.

Maine DEP, 2002. A monthly newsletter for wastewater discharge licensees, treatment facility operators andassociated persons, Department of Environmental Protection.

Martí, N., Pastor, L., Bouzas, A., Ferrer, J., Seco, A., 2010. Phosphorus recovery by struvite crystallization in WWTPs: Influence of the sludge treatment line operation, Water Research 44, 2371-2379.

Maurer, M., Schwegler, P., Larsen, T., 2003. Nutrients in urine: energetic aspects of removal and recovery, From Nutrient Removal to Recovery 48, 37-46.

McCarty, P.L., Kim, J., Bae, J., 2011. Domestic wastewater treatment as a net energy producer - Can this be achieved? Environmental Science and Technology 45, 7100-7106.

Means, E., 2004. Water and wastewater industry energy efficiency: a research roadmap, Awwa Research Foundation CEC-500-2004-901.

Mels, A.R., van Nieuwenhuijzen, A.F., van der Graaf, J.H.J.M., Klapwijk, B., Koning, J., Rulkens, W.H., 1999. Sustainability criteria as a tool in the development of new sewage treatment methods, Water science and technology 39, 243-250.

Memon, F., Zheng, Z., Butler, D., Shirley-Smith, C., Lui, S., Makropoulos, C., Avery, L., 2007. Life cycle impact assessment of greywater recycling technologies for new developments, Environmental Monitoring and Assessment 129, 27-35.

Meneses, M., Pasqualino, J.C., Castells, F., 2010. Environmental assessment of urban wastewater reuse: Treatment alternatives and applications, Chemosphere 81, 266-272.

Mo, W., Nasiri, F., Eckelman, M.J., Zhang, Q., Zimmerman, J.B., 2010. Measuring the embodied energy in drinking water supply systems: a case study in The Great Lakes region, Environmental Science and Technology 44, 9516-9521.

Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D., 2009. Development and application of an embodied energy model for individual water supply systems in Great Lakes Region, Proceedings of the Water Environment Federation 2009, 5482-5496.

Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options, Water Research 45, 5577-5586.

Münch, E.V., Barr, K., 2001. Controlled struvite crystallisation for removing phosphorus from anaerobic digester sidestreams, Water Research 35, 151-159.

Muñoz, I., Milà-i-Canals, L., Fernández-Alba, A.R., 2010. Life Cycle Assessment of Water Supply Plans in Mediterranean Spain, Journal of Industrial Ecology 14, 902-918.

Nagano, K., Katsura, T., Takeda, S., 2006. Development of a design and performance prediction tool for the ground source heat pump system, Applied Thermal Engineering 26, 1578-1592.

Neave, A., September, 2010. An Introduction to Heat Pumps, http://www.heatpumps.org.uk/ (last accessed on 6.15.2012).

NEBRA, 2007. A national biosolids regulation, quality, end use & disposal survey, Tamworth, NH.

Nichols, D.S., 1983. Capacity of natural wetlands to remove nutrients from wastewater, Journal (Water Pollution Control Federation) 55, 495-505.

Nouri, J., Jafarinia, M., Naddafi, K., Nabizadeh, R., Mahvi, A., Nouri, N., 2006. Energy recovery from wastewater treatment plant, Pakistan Journal of Biological Sciences 9, 3-6.

Novotny, V., 2010. Urban Water and Energy Use From Current US Use to Cities of the Future, Proceedings of the Water Environment Federation 2010, 118-140.

Oron, G., 1990. Economic considerations in wastewater treatment with duckweed for effluent and nitrogen renovation, Journal of the Water Pollution Control Federation, 62, 692-696.

Ortiz, M., Raluy, R., Serra, L., 2007. Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town, Desalination 204, 121-131.

Ostara, 2012. Nutrient management solutions: installations, http://www.ostara.com/nutrient-management-solutions/installations (last accessed on 10.24.2012).

Pant, D., Singh, A., Van Bogaert, G., Gallego, Y.A., Diels, L., Vanbroekhoven, K., 2011. An introduction to the life cycle assessment (LCA) of bioelectrochemical systems (BES) for sustainable energy and product generation: Relevance and key aspects, Renewable and Sustainable Energy Reviews 15, 1305-1313.

Park, D.H., Zeikus, J.G., 2000. Electricity generation in microbial fuel cells using neutral red as an electronophore, Applied and Environmental Microbiology 66, 1292-1297.

Pascale, A., 2010. Life cycle analysis of a community hydroelectric system in rural Thailand, MS Thesis, Murdoch University.

Pasqualino, J.C., Meneses, M., Abella, M., Castells, F., 2009. LCA as a decision support tool for the environmental improvement of the operation of a municipal wastewater treatment plant, Environmental Science and Technology 43, 3300-3307.

Pasqualino, J.C., Meneses, M., Castells, F., 2011. Life Cycle Assessment of Urban Wastewater Reclamation and Reuse Alternatives, Journal of Industrial Ecology 15, 49-63.

Pastor, L., Mangin, D., Ferrer, J., Seco, A., 2010. Struvite formation from the supernatants of an anaerobic digestion pilot plant, Bioresource Technology 101, 118-125.

Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies, Renewable Energy 31, 55-71.

Peters, G.M., Lundie, S., 2001. Life-Cycle Assessment of Biosolids Processing Options, Journal of Industrial Ecology 5, 103-121.

Peters, G.M., Rowley, H.V., 2009. Environmental comparison of biosolids management systems using life cycle assessment, Environmental Science and Technology 43, 2674-2679.

PUB, 2011. Water for all: NeWater, http://www.pub.gov.sg/water/newater/NEWaterOverview/Pages/default.aspx (last accessed on 9.7.2012).

Rabaey, K., Lissens, G., Siciliano, S.D., Verstraete, W., 2003. A microbial fuel cell capable of converting glucose to electricity at high rate and efficiency, Biotechnology Letters 25, 1531-1535.

Rectenwald, L.L., Drenner, R.W., 2000. Nutrient removal from wastewater effluent using an ecological water treatment system, Environmental Science and Technology 34, 522-526.

Rey, F., Martin-Gil, J., Velasco, E., Pérez, D., Varela, F., Palomar, J., Dorado, M., 2004. Life cycle assessment and external environmental cost analysis of heat pumps, Environmental Engineering Science 21, 591-605.

Riber, C., Bhander, G.S., Christensen, T.H., 2008. Environmental assessment of waste incineration in a life-cycle-perspective (EASEWASTE), Waste Management & Research 26, 96-103.

Roller, S.D., Bennetto, H.P., Delaney, G.M., Mason, J.R., Stirling, J.L., Thurston, C.F., 1984. Electron-transfer coupling in microbial fuel cells: 1. comparison of redox-mediator reduction rates and respiratory rates of bacteria, Journal of Chemical Technology and Biotechnology.Biotechnology 34, 3-12.

Rossi, L., Lienert, J., Larsen, T., 2009. Real-life efficiency of urine source separation, Journal of Environmental Management 90, 1909-1917.

Roux, P., Boutin, C., Risch, E., Heduit, A., 2010. Life Cycle environmental Assessment (LCA) of sanitation systems including sewerage: Case of Vertical Flow Constructed Wetlands versus activated sludge, Proceedings of 12th IWA International Conference on Wetland Systems for Water Pollution Control, Venise, Italy.

Rozendal, R.A., Jeremiasse, A.W., Hamelers, H.V.M., Buisman, C.J.N., 2007. Hydrogen production with a microbial biocathode, Environmental Science and Technology 42, 629-634.

Sablayrolles, C., Gabrielle, B., Montrejaud-Vignoles, M., 2010. Life cycle assessment of biosolids land application and evaluation of the factors impacting human toxicity through plant uptake, Journal of Industrial Ecology 14, 231-241.

Sander, K., Murthy, G.S., 2010. Life cycle analysis of algae biodiesel, The International Journal of Life Cycle Assessment 15, 1-11.

Schmid, F., 2008. Sewage water: interesting heat source for heat pumps and chillers, www. bfe. admin. ch/php/modules/publikationen (last accessed on 8.15.2012).

Siracusa, G., La Rosa, A., 2006. Design of a constructed wetland for wastewater treatment in a Sicilian town and environmental evaluation using the emergy analysis, Ecological Modelling 197, 490-497.

Slater, S., 2009. Resources from Waste: A Guide to Integrated Resource Recovery, Victoria, BC: Ministry of Community Development.

Soratana, K., Landis, A.E., 2011. Evaluating Industrial Symbiosis and Algae Cultivation from a Life Cycle Perspective, Bioresource Technology 102, 6892-6901.

SPGSolar, Sewerage commission - Oroville region, http://www.spgsolar.com/markets-served/government-and-education/water-and-sanitation/sewerage-commission-oroville-region/ (last accessed on 8.21.2012).

Stillwell, A.S., Hoppock, D.C., Webber, M.E., 2010. Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus, Sustainability 2, 945-962.

Stokes, J., Horvath, A., 2006. Life cycle energy assessment of alternative water supply systems, The International Journal of Life Cycle Assessment 11, 335-343.

Sturm, B.S.M., Lamer, S.L., 2011. An energy evaluation of coupling nutrient removal from wastewater with algal biomass production, Applied Energy 88, 3499-3506.

Suh, Y.J., Rousseaux, P., 2002. An LCA of alternative wastewater sludge treatment scenarios, Resources, Conservation and Recycling 35, 191-200.

Svanström, M., Fröling, M., Olofsson, M., Lundin, M., 2005. Environmental assessment of supercritical water oxidation and other sewage sludge handling options, Waste Management & Research 23, 356.

Tchobanoglous, G., Leverenz, H., Nellor, M., Crook, J., 2011. Direct Potable Reuse: A Path Forward, WateReuse Research Foundation and WaterReuse California.

Tillman, A.M., Svingby, M., Lundström, H., 1998. Life cycle assessment of municipal waste water systems, The International Journal of Life Cycle Assessment 3, 145-157.

Tripanagnostopoulos, Y., Souliotis, M., Battisti, R., Corrado, A., 2005. Energy, cost and LCA results of PV and hybrid PV/T solar systems, Progress in Photovoltaics: Research and Applications 13, 235-250.

Türker, M., Çelen, I., 2007. Removal of ammonia as struvite from anaerobic digester effluents and recycling of magnesium and phosphate, Bioresource Technology 98, 1529-1534.

Turku Energia, September, 2009. The wastewater utilization in Kakola heat pump plant, http://www.districtenergyaward.org/download/awards2011/New_scheme_Finland_Turku.pdf (last accessed on 6.10. 2012).

Ueno, Y., Fujii, M., 2001. Three years experience of operating and selling recovered struvite from full-scale plant, Environmental Technology 22, 1373-1381.

Umble, A., Ketchum, L., 1997. A strategy for coupling municipal wastewater treatment using the sequencing batch reactor with effluent nutrient recovery through aquaculture, Water Science and Technology 35, 177-184.

USGS, 2009. Estimated use of Water in the United States in 2005. US Geological Survey, Reston, VA.

Van der Bruggen, B., 2010. The Global Water Recycling Situation, Sustainability Science and Engineering 2, 41-62.

Varun, Prakash, R., Bhat, I., 2010. Life Cycle Energy and GHG Analysis of Hydroelectric Power Development in India, International Journal of Green Energy 7, 361-375.

Verstraete, W., Van de Caveye, P., Diamantis, V., 2009. Maximum use of resources present in domestic, Bioresource Technology 100, 5537-5545.

Voltolina, D., Gómez-Villa, H., Correa, G., 2005. Nitrogen removal and recycling by Scenedesmus obliquus in semicontinuous cultures using artificial wastewater and a simulated light and temperature cycle, Bioresource Technology 96, 359-362.

Wang, H., Brown, S.L., Magesan, G.N., Slade, A.H., Quintern, M., Clinton, P.W., Payn, T.W., 2008. Technological options for the management of biosolids, Environmental Science and Pollution Research 15, 308-317.

Werther, J., Ogada, T., 1999. Sewage sludge combustion, Progress in energy and combustion science 25, 55-116.

Wett, B., Buchauer, K., Fimml, C., 2007. Energy self-sufficiency as a feasible concept for wastewater treatment systems, IWA Leading Edge Technology Conference, Asian Water, Singapore , 21-24.

Wilkie, A.C., Mulbry, W.W., 2002. Recovery of dairy manure nutrients by benthic freshwater algae, Bioresource Technology 84, 81-91.

Yang, J., Xu, M., Zhang, X., Hu, Q., Sommerfeld, M., Chen, Y., 2011. Life-cycle analysis on biodiesel production from microalgae: Water footprint and nutrients balance, Bioresource Technology 102, 159-165.

Zakkour, P., Gaterell, M., Griffin, P., Gochin, R., Lester, J., 2002. Developing a sustainable energy strategy for a water utility. Part II: a review of potential technologies and approaches, Journal of Environmental Management 66, 115-125.

Zhao, W., der Voet, E., Zhang, Y., Huppes, G., 2009. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: Case study of Tianjin, China, Science of the Total Environment 407, 1517-1526.

Zhou, J., Jiang, M., Chen, B., Chen, G., 2009. Emergy evaluations for constructed wetland and conventional wastewater treatments, Communications in Nonlinear Science and Numerical Simulation 14, 1781-1789.

Zhu, H., Zhou, Y., 2006. Technological and economic comparison between a ground-source heat pump and an air-source heat pump [J], Renewable Energy 5, DOI: cnki:ISSN:1671-5292.0.2006-05-026.

CHAPTER 6: CARBON NEUTRALITY IN MUNICIPAL WASTEWATER TREATMENT SYSTEMS

6.1 Introduction

Currently, there are around 15,000 wastewater treatment plants (WWTPs) operating in the US (EPA, 2008a). These systems use around 3% of the US electricity for their operation and maintenance (EPA, 2006). Meanwhile, large amounts of chemicals are consumed by these systems to treat the wastewater to the required standards. It has been estimated that energy used in the WWTPs comprises around one fifth of a municipality's total energy use by public utilities, and it will continue to rise by 20% in the next 15 years with the increasing water consumption and more stringent regulations (Means, 2004). Similarly, more materials and chemicals are expected to be consumed in the future for WWTPs construction and operation. Because of the large resource consumptions in the WWTPs, it is very important to manage the WWTPs in a way that can reduce the consumption of finite resources and minimize the environmental loads (Lundin and Morrison, 2002).

To achieve the new management goals, environmental impacts of the WWTPs have to be quantified. Traditionally, researchers evaluate the performance of the WWTPs based on treated water quality and costs (Hellström et al., 2000). While such information

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satisfies the basic health and economic evaluation needs, it provides insufficient information on the environmental impacts associated with constructing and operating the WWTPs over their life time. As a result, life cycle assessment, which enables a more thorough evaluation of the life cycle environmental impacts, has been adopted during the past 15 years for evaluating wastewater infrastructures (Foley et al., 2010; Herz and Lipkow, 2002; Lassaux et al., 2007; Lyons et al., 2009; Roeleveld et al., 1997; Stokes and Horvath, 2006). Among all the life cycle impact indicators, the embodied energy and the associated carbon footprint have been frequently used and shown to be important by previous studies (Lundin and Morrison, 2002; Mels et al., 1999). The embodied energy indicates the life cycle energy consumption in the WWTPs. It includes the energy used onsite of the WWTPs (direct energy), and the energy used indirectly to provide the materials, chemicals and services to the WWTPs (indirect energy). The carbon footprint includes all the greenhouse gas (GHG) emissions associated with energy and material consumptions during the life time of a WWTP.

In order to improve sustainability of WWTPs, various researches have been done to recover resources in wastewater for secondary uses (Hospido et al., 2005; Houillon and Jolliet, 2005; Meneses et al., 2010; Muñoz et al., 2010; Nouri et al., 2006; Ortiz et al., 2007; Pasqualino et al., 2009; Peters and Lundie, 2001; Suh and Rousseaux, 2002; Wett et al., 2007). There are three common ways to recover resources from wastewater: (1) onsite energy generation through Combined Heat and Power systems (CHPs), (2) land application of the digested sludge, and (3) water reuse for residential irrigation. Studies have been carried out to evaluate the environmental benefits of the three methods separately. Nouri et al. (2006) and Wett et al. (2007) studied the onsite energy generation of the WWTPs in Iran and Austria. They suggested that the CHPs alone can offset all the direct energy use in the WWTPs. Land application of the digested sludge is another way of offsetting embodied energy through recovering the wastewater nutrients because it reduces the energy needed for producing fossil fuel-based fertilizers (Hospido et al., 2005; Houillon and Jolliet, 2005; Peters and Lundie, 2001; Suh and Rousseaux, 2002). WWTPs can also offset embodied energy through water reuse because reusing water can save the electricity and chemicals needed for supplying water from the raw water sources (Meneses et al., 2010; Muñoz et al., 2010; Ortiz et al., 2007; Pasqualino et al., 2009). However, the previous studies did not integrate the three methods together to explore the potential of integrated resource recovery to offset embodied energy and achieve carbon neutrality in the WWTPs from the life cycle perspective. The carbon neutrality hereby refers to achieving net zero GHG emissions over the life time of a WWTP.

Questions remain to be answered: What is the potential of offsetting embodied energy through integrated resource recovery? Can municipal WWTPs be carbon neutral? These questions define the goal of this study, which is to evaluate the potential of embodied energy offset and the possibility of carbon neutrality in WWTPs through the integrated resource (energy, nutrient and water) recovery.

6.2 Methodology

This section introduces the methods for calculating the embodied energy, the carbon footprint associated with the embodied energy, and the offset of embodied energy and carbon footprint through different resource recovery options.

6.2.1 Embodied Energy

In this study, embodied energy was calculated for: (1) a whole WWTP; (2) resource recovery systems, including CHPs for onsite energy generation, heat drying systems for biosolids land application, and water delivery systems for reclaimed water; and (3) the resources recovered, including the equivalent value of energy generated from CHPs, and equivalent amount of energy saved through biosolids land application and water reuse. The operation and the construction phases of all infrastructures were considered in the embodied energy calculation. In general, the embodied energy is calculated using Equation 6-1.

$$E = \varepsilon C \tag{6-1}$$

where

E = embodied energy of the system evaluated, TJ;

ε = embodied energy intensity of the system evaluated, TJ/$ million or TJ/MG;

C = expense of the system evaluated, $ million; or output of the system evaluated, MG.

Table 6.1 provides the equations used for calculating the embodied energy associated with operating or constructing each resource recovery system as well as the embodied energy that can be saved through resources recovered from these systems. The embodied energy was reported in primary energy forms, which includes all the losses during the energy production and transmission. The primary energy factors were specifically adjusted for Florida following the method provided by the U.S. Energy Information Administration (EIA, 1995), and are provided in Table 6.2. The embodied energy intensities for the construction and operation of the whole WWTP, the construction of CHP systems (ε_1), heat drying systems (ε_4), and reclaimed water pipeline systems (ε_7) and for recovered nutrient (ε_6) were calculated using Equations 6-2 and 6-3 based on a hybrid input-output method (Mo et al., 2010; Mo et al., 2011). A commodity-by-commodity input-output table containing 424 sectors derived from the 2002 make table and use table provided by the Bureau of Economic Analysis (BEA, 2011) was used in this study.

$$\varepsilon = r \cdot \sum_{k=1}^{\infty}\left(\sum_{i,j=1}^{N} d_{i^{k-1},j^{k}}\,\varepsilon_{i^{k-1}}\right) \tag{6-2}$$

$$\varepsilon_{i^0} = \sum_{n} d_{n,i^0} \times tariff_n \times a_n \tag{6-3}$$

In Equations 6-2 and 6-3,

ε = total embodied energy intensity of the target sector "*t*" as indicated in Table 6.1, TJ/$ output of sector "*t*";

r = adjustment factor for the total embodied energy intensity of the target sector "t" based on site specific data (Mo et al., 2011);

k = stage index;

N = number of sectors in stage k;

$d_{i^{k-1},j^{k}}$ = direct coefficient from sector "*i*" at stage k-1 to sector "*j*" at stage k from the commodity-by-commodity input-output table;

$\varepsilon_{i^{k-1}}$ = energy intensity of sector "*i*" at k-1 stage, TJ/$ output of sector "*i*";

ε_{i^0} = direct energy intensity of sector "*i*" at stage 0, TJ/$ output of sector "*i*";

n = energy supply sector index;

d_{n,i^0} = direct coefficient from energy supply sector n into sector "*i*";

$tariff_n$ = energy tariff of the energy supply sector n as listed in Table 6.2, TJ/$

energy;

a_n = primary energy factor of energy supply sector n as listed in Table 6.2.

Table 6.1 Methods and equations used for the embodied energy calculation of different resource recovery methods

	Onsite energy generation	Nutrient recycling	Water reuse
Construction	$E_c = P \times Q \times C_c \times f \times \varepsilon_1$ (6-4) Where E_c = Embodied energy in constructional phase, TJ; P = Power generation potential of CHPs, 22.2 kW/MGD (EPA, 2007); Q = Wastewater flow capacity, MGD; C_c = Unit constructional cost, $2039/kW (EPA, 2007); f = Conversion factor, 10^{-6}; ε_1 = Embodied energy intensity of the "other engine equipment manufacturing" sector, 13.3 TJ/$ million.	$E_c = K \times (Q \times S \times f_1)^m \times f_2 \times \varepsilon_4$ (6-7) Where K = Economy of scales factor, $14738.5 (Hendrickson, 2008); Q = Wastewater flow capacity, MGD; S = Wastewater solid content, kg/MG; f_1 = Conversion factor, 0.092; f_2 = Conversion factor, 10^{-6}; m = Economy of scales factor, 0.81; ε_4 = Embodied energy intensity of the "other nonresidential construction" sector adapted for wastewater systems, 12.7 TJ/$ million.	$E_c = Q \times C_c \times \varepsilon_7$ (6-10) Where Q = Reclaimed water flow capacity, MGD; C_c = Unit constructional cost of pipeline obtained from City of Tampa Water Department, $3.85 million/MGD; ε_7 = Embodied energy intensity of the "other nonresidential construction" sector adapted for water supply systems, 10.9 TJ/$ million.
Operation	$E_o = Q \times T \times a \times f \times \varepsilon_2$ (6-5) Where E_o = Embodied energy in operational phase, TJ/year; Q = Wastewater flow capacity, MGD; T = Operating days per year, days; α = Primary energy factor for electricity; f = Conversion factor, 10^{-3}; ε_2 = Energy intensity for operating and maintaining digesters, 0.76 GJ/MG for mesophilic digesters, 1.4 GJ/MG for thermophilic digesters (EPA, 2007).	$E_o = Q \times S \times T \times C_o \times f \times \varepsilon_5$ (6-8) Where Q = Wastewater flow capacity, MGD; S = Wastewater solid content, kg/MG; T = Operating days per year, days; C_o = Unit operational cost, $96/ton (EPA, 2012); f = Conversion factor, 10^{-6}; ε_5 = Energy intensity for operating the heat drying system adapted from Florida natural gas heat value, 0.12 GJ/$.	$E_o = Q \times T \times f \times \varepsilon_8$ (6-11) Where Q = Reclaimed water flow capacity, MGD; T = Operating days per year, days; f = Conversion factor, 10^{-3}; ε_8 = The operational embodied energy intensity for supplying reclaimed water, adapted from Mo et al. (2011), 16.1 GJ/MG.
Saving	$E_a = Q \times T \times a \times f \times \varepsilon_3$ (6-6) Where E_a = Embodied energy saved, TJ/year; Q = Wastewater flow capacity, MGD; T = Operating days per year, days; α = Primary energy factor for electricity; f = Conversion factor, 10^{-3}; ε_3 = Energy intensity of energy generation, 3.0 GJ/MG (EPA, 2007).	$E_a = Q \times S \times T \times Y \times f \times \varepsilon_6$ (6-9) Where Q = Wastewater flow capacity, MGD; S = Wastewater solid content, kg/MG; T = Operating days per year, days; Y = Current price of biosolids, $50/dry ton (EPA, 2012); f = Conversion factor, 10^{-9}; ε_6 = Embodied energy intensity of the "fertilizer manufacturing" sector, 76.2 TJ/$ million.	$E_a = Q \times T \times f \times \varepsilon_9$ (6-12) Where Q = Reclaimed water flow capacity, MGD; T = Operating days per year, days; f = Conversion factor, 10^{-3}; ε_9 = The embodied energy intensity for supplying freshwater from local sources, adapted from Mo et al. (2011), 40.6 GJ/MG.

The energy intensities for operating the CHP systems (ε_2), the heat drying systems (ε_5) and the reclaimed water systems (ε_8) as well as for energy generated from the CHP systems (ε_3) include direct energy only. ε_2 and ε_3 were obtained from the US Environmental Protection Agency (EPA, 2007), ε_5 was adapted from the Florida natural gas heat value (EIA, 2012) and ε_8 were adapted from Mo et al. (2011). The embodied energy intensity for reclaimed water, ε_9, was also obtained from Mo et al. (2011). It considers the embodied energy required for supplying one million gallons of water from a surface water source.

6.2.2 Carbon Footprint

There are three types of GHG emissions associated with WWTPs: (1) direct GHG emissions from all the processes in the plant, such as carbon dioxide emission from the activated sludge process; (2) indirect GHG emissions associated with the direct energy consumption of the WWTPs; and (3) indirect GHG emissions associated with the indirect energy consumption of the WWTPs (Ranganathan et al., 2004). Most of the GHG emission protocols do not include the direct GHG emissions because this part of greenhouse gases would have been emitted to the atmosphere through the natural process of decay anyway (Crawford et al., 2011). Hence, this study only considers indirect GHG emissions for the carbon footprint calculation. Four types of energy were considered: coal, natural gas, petroleum and electricity. The amount of each type of energy was calculated using Equations 6-1, 6-2 and 6-3 for each energy supply sector and adjusted by site specific data when available. The carbon emission factor for electricity was calculated based on 2005 Florida eGRID data (EPA, 2008b), which includes emissions of carbon dioxide, methane and nitrous oxide. 100-year global warming potentials were used for methane and nitrous oxide, which are 25 and 298 separately (Forster et al., 2007). The carbon emission factors for coal, natural gas and petroleum were calculated based on national average values (EPA, 2004). Since the embodied energy calculated was in primary energy forms, the carbon emission factors were also adapted to represent the GHG emissions per unit of primary energy. Table 6.2 provides the carbon emission factors of the four types of energy. Carbon footprint can be calculated using Equation 6-13.

$$CF = \sum_{i=1}^{4} E_i \times f_{C,i} \quad (6\text{-}13)$$

where

E_i = The embodied energy amount of energy type i in primary energy form, TJ;

$f_{C,i}$ = The carbon emission factor of energy type i, kg CO_2e/GJ of primary energy;

CF = Total carbon footprint, Mg.

Table 6.2 Primary energy factors and carbon emission factors for four energy types in Florida

Energy types	Primary energy factor	Energy tariff (10^{-3} TJ/$)	Carbon emission factor (Kg CO_2e/GJ of primary energy)
coal	1.13	0.86	78.1
power	3.45	0.09	48.4
gas	1.05	0.25	47.7
petroleum	1.42	0.17	48.6

6.2.3 Embodied Energy and Carbon Footprint Offset

The embodied energy offset is the net embodied energy saving after extracting the amount of embodied energy used for constructing and operating a system from the amount of energy that can be produced or saved. In order to combine the constructional energy with the operational energy and the saved energy, the life span of each system was incorporated. The life span of the WWTP was assumed to be 100 years (Dixon et al., 2003; Machado et al., 2007); the life span of the CHP system was assumed to be 5 years according to the manufacture quote; the life span of the heat drying system was assumed to be 30 years (Gebhart, 1995); and the life span of the reclaimed water pipeline was assumed to be 100 years (Mo et al., 2011; Stokes and Horvath, 2006). Similarly, the carbon footprint offset is the net GHG emission reduction through the implementation of resource recovery systems. The embodied energy and carbon footprint offset were calculated using Equation 6-14.

$$I_b = I_a - I_c / T - I_o \tag{6-14}$$

where

I_b = Embodied energy or carbon footprint offset, TJ/year for embodied energy or Gg/year for carbon footprint;

I_a = Energy or carbon footprint saved by resource recovery, TJ/year for embodied energy or Gg/year for carbon footprint;

I_c = Embodied energy or carbon footprint of system construction, TJ for embodied energy or Gg for carbon footprint;

T = lifetime of the system, years;

I_o = Embodied energy or carbon footprint of system operation, TJ/year for embodied energy or Gg/year for carbon footprint.

The maximal embodied energy or carbon footprint offset is the net embodied energy or carbon footprint saving when the largest potential of onsite energy generation, nutrient recycling or water reuse is achieved. The maximal energy produced or saved ($I_{a,max}$) was estimated using Equation 15. Under maximal recovery condition, I_c and I_o in terms of embodied energy were estimated based on the ratio between I_a and $I_{a,max}$ for each recovery method and the associated carbon footprints were estimated using Equation 6-15.

$$I_{a,max} = \begin{cases} e_m \times \gamma \times Q \times F & \textit{for onsite energy generation} \\ I_{na} \times (n_m / n_c) & \textit{for nutrient recycling} \\ I_{wa} \times (w_m / w_c) & \textit{for water reuse} \end{cases} \quad (6\text{-}15)$$

where

e_m = The energy content in primary energy form, 14.67 KJ/g of COD (Shizas, 2004);

γ = The COD reduction in the selected wastewater treatment plant, g of COD/L of wastewater;

Q = Wastewater flow in the selected wastewater treatment plant, MGD;

F = Conversion factor, 1.39 (L·days·TJ)/(MG·year·KJ)

I_{na} = The embodied energy saved by replacing fossil fuel-based fertilizers under current condition, TJ/year;

n_m = The typical solid content of digested sludge, 100 kg/10^3 m^3 (Asano, 2007);

n_c = The solid content used for nutrient recycling currently in the selected wastewater treatment plant, kg/10^3 m^3;

I_{wa} = The embodied energy saved by water reuse under current condition, TJ/year;

w_m = the total amount of water treated in the selected wastewater treatment plant, MGD;

w_c = The amount of water reclaimed currently in the selected wastewater treatment plant, MGD.

6.3 Howard Curren Wastewater Treatment Plant

The Howard F. Curren Advanced Wastewater Treatment System (HCWTP) is a state-of-art facility located in the city of Tampa, Florida. It has a design capacity of 96 million gallons per day (MGD). The average daily flow in the system is 54.2 MGD. Figure 6.1 provides the treatment processes included in the system. After the treatment, the effluent is suitable not only for discharging directly, but also for public-access reuse. The HCWTP involves three recovery processes as shown in Figure 6.2. Electricity is generated onsite by burning biogas from anaerobic digester in five 500 kW engine generators. After digestion, part of the sludge is heat dried to produce a fertilizer product, which then goes to distribution and marketing. The HCWTP has a sludge drying capacity of 59 dry tons per day. The biosolids that are not heat dried are applied to agriculture land as a soil amendment, but this part of biosolids was not counted for energy offset in this study because of the negligible amount and the generation inconsistency. Additionally, part of the effluent is reused within the plant and provided to outside customers for irrigation or industrial purposes. Current operational and constructional details of the HCWTP are provided in Table 6.3.

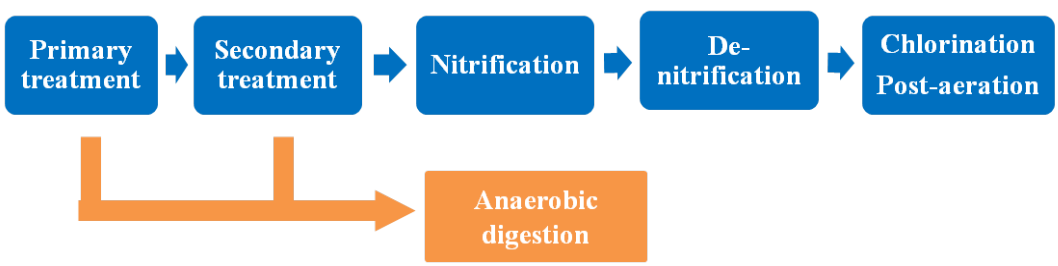


Figure 6.1 Treatment processes in the Howard Curren Wastewater Treatment Plant

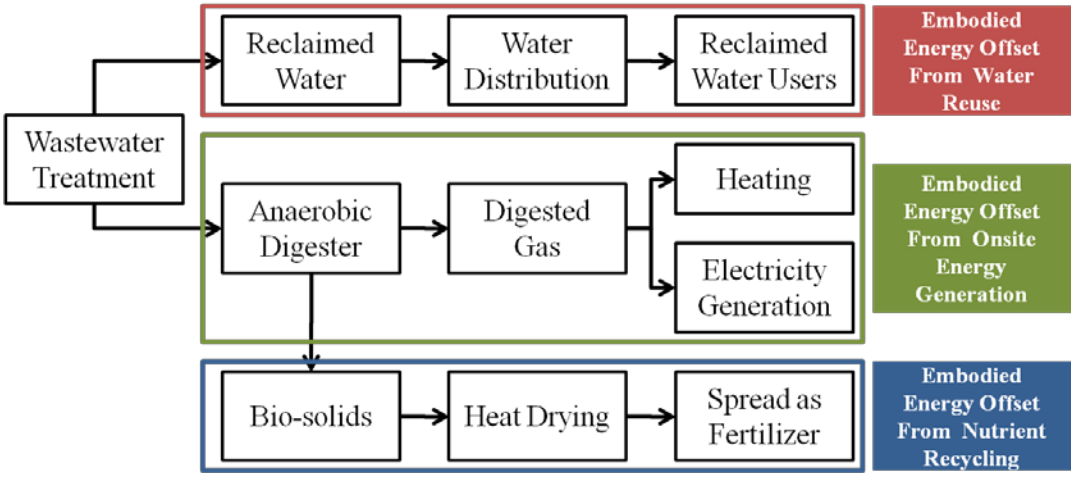


Figure 6.2 Embodied energy recovery methods in municipal sewage systems

Table 6.3 Current operational and constructional details in the Howard F. Curren Advanced Wastewater Treatment Plant

Parameter	Value
Annual total O&M cost	$33.4 million
Annual electricity cost	$5.3 million
Annual natural gas cost	$0.07 million
Total constructional cost	$1.0 billion
Unit natural gas price (EIA, 2012)	$8.7/GJ
Unit electricity price	10.1 cents/kWh
COD reduction	275.3 mg/L
Energy generation from anaerobic digestion	36,025 kWh/day
Dried sludge production rate	2989 tons/year
Water reuse rate	12.1 MGD

6.4 Results and Discussion

6.4.1 Embodied Energy of the Current Howard Curren Wastewater Treatment Plant

The embodied energy was calculated for two phases: the operation (maintenance included) phase and the construction phase. The annual operational embodied energy of the HCWTP was calculated to be 1079 TJ. The percentages of direct energy and indirect energy for the operation phase are 61% and 39% respectively. The annual carbon footprint of the operation phase is 53.0 Gg CO_2e. The annual constructional energy embodiment was calculated to be 114.0 TJ/year. The percentages of direct energy and indirect energy for the construction phase are 52% and 48% respectively. The annual carbon footprint of the construction phase is 5.7 Gg CO_2e. Combining the operation phase and the construction phase, the annual total embodied energy of the HCWTP is 1193 TJ, and the total carbon footprint of the HCWTP is 58.7 Gg CO_2e per year.

For both embodied energy and carbon footprint, the contribution from the operation phase (90%) is significantly higher than the construction phase (10%) from a life cycle perspective. Figure 6.3 provides the energy split for the operational and constructional embodied energy as well as the associated carbon footprint of each type of energy for the HCWTP. Electricity (power) and petroleum represent the largest portion of direct energy in the operation phase and construction phase separately. Power and petroleum have comparable contribution to indirect energy in both the operation phase and the construction phase.

6.4.2 Onsite Energy Generation

The constructional and operational embodied energy of onsite energy generation as well as its annual energy recovery and offset were calculated and provided in Table 6.4. Combining the operation phase and the construction phase, a total embodied energy of 58.4 TJ/year is required to run the CHP system in the HCWTP (91% direct energy and 9% indirect energy) which is relatively low compared with the amount of energy generated by the CHP system. The embodied energy offset through onsite energy

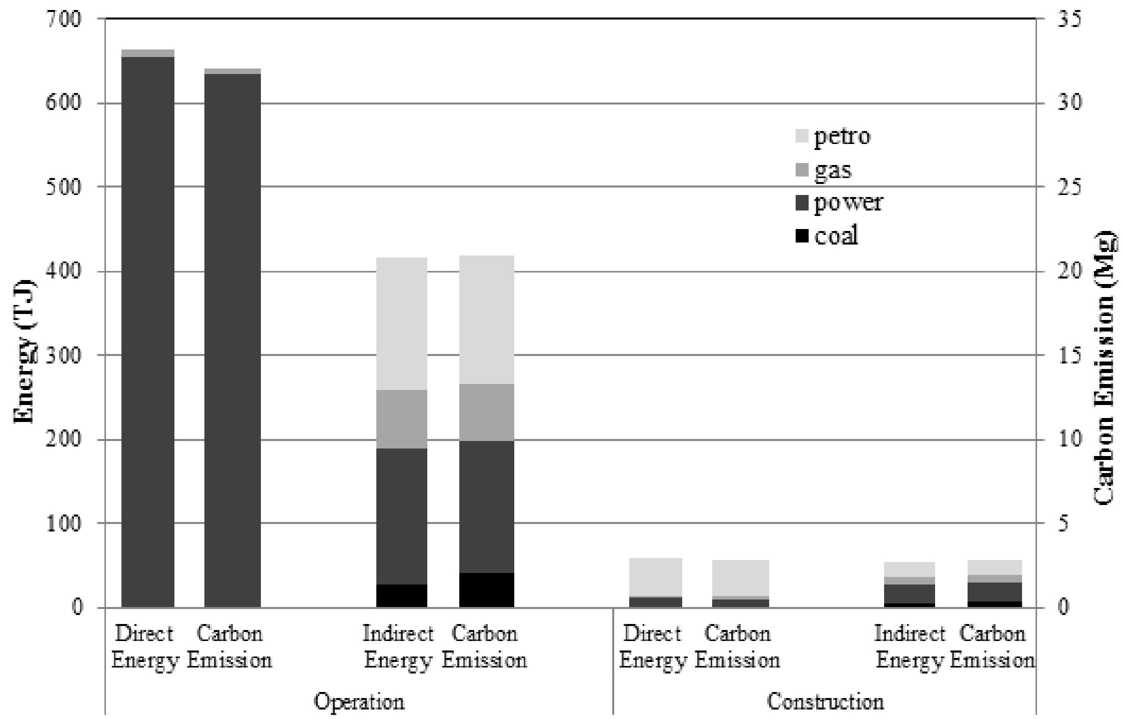


Figure 6.3 The energy and carbon emission splits for the operational and constructional phases of the Howard F. Curren Advanced Wastewater Treatment Plant

generation is around 22% of the current electricity use during the O&M phase in the HCWTP, which is consistent with the percentage provided by the HCWTP. This offset accounts for approximately 12% of the total embodied energy of the current HCWTP. The carbon footprint offset through onsite energy generation accounts for 8% of the total carbon footprint of the HCWTP. Therefore, onsite energy generation is not able to completely offset the total embodied energy and the carbon footprint of the HCWTP under the current condition.

Table 6.4 Embodied energy and associated carbon emission for constructing and operating the resource recovery systems, recovery/saving from the recovery systems and offsets

Resource recovery methods	Onsite energy generation		Nutrient recycling		Water reuse	
	Embodied energy (TJ)	Carbon emission (Gg of CO2e)	Embodied energy (TJ)	Carbon emission (Gg of CO2e)	Embodied energy (TJ)	Carbon emission (Gg of CO2e)
Construction total	32.6	1.7	183	9	509.2	25.3
Construction annual	6.5	0.34	6.1	0.3	5.1	0.25
Operation annual	51.9	2.51	0	0	71.1	3.44
Recovery/saving annual	-204.8	-9.91	-11.4	-0.55	-179.3	-8.86
Offset annual	-146.3	-7.06	-5.3	-0.25	-103.1	-5.16

According to Equation 6-15, the maximal recoverable energy was estimated to be 302.2 TJ/year, and the associated carbon footprint saving is around 14.6 Gg of CO_2e/year. Extracting the constructional and operational energy requirements from the recoverable energy, the maximal embodied energy offset per year is around 219.1 TJ, with an associated carbon footprint offset of 10.6 Gg of CO_2e. Under the maximal onsite energy generation scenario, the embodied energy offset is around 33% of the direct energy use in the operational phase, and 18% of the total embodied energy. The carbon footprint offset is around 12% of the total carbon footprint of the HCWTP. Unlike as estimated by Nouri et al. (2006) and Wett et al. (2007), the maximal onsite energy generation, however, is not able to offset the direct operational energy of the HCWTP. The influent organic loads, flow rate and treatment technologies affect the offset potentials of onsite energy generation. Under current flow rate and treatment technology, it would require at least 3 times of the current organic load in order to completely offset the direct operational energy of the HCWTP.

The potentials to offset embodied energy and carbon footprint through onsite energy generation under different wastewater flow capacities were calculated and shown in Figure 6.4. Since the embodied energy needed for constructing and operating the CHPs is lower than the amount of energy that can be recovered when the flow capacity is above 5 MGD according to the EPA (2004), it will always be beneficial to implement CHPs for embodied energy and carbon footprint offsets. The larger the wastewater flow capacity, the higher embodied energy offset can be achieved, but the increase of the offset potentials with the increase of water flow capacities are not significant. Generally, for WWTPs with similar treatment technology and organic removal rate as the HCWTP, the CHPs have the potential to offset around 18% of the total embodied energy and 12% of the total carbon footprint.

Overall, onsite energy generation provides the most direct way for energy recovery under current condition; however, the embodied energy and carbon footprint offsets that can be achieved are limited. It is not able to completely offset the direct energy use in the HCWTP, not saying the total embodied energy and the associated carbon footprint.

6.4.3 Nutrient Recycling

The constructional and operational embodied energy of the nutrient recycling as well as its annual energy saving and offset were calculated and provided in Table 6.4.

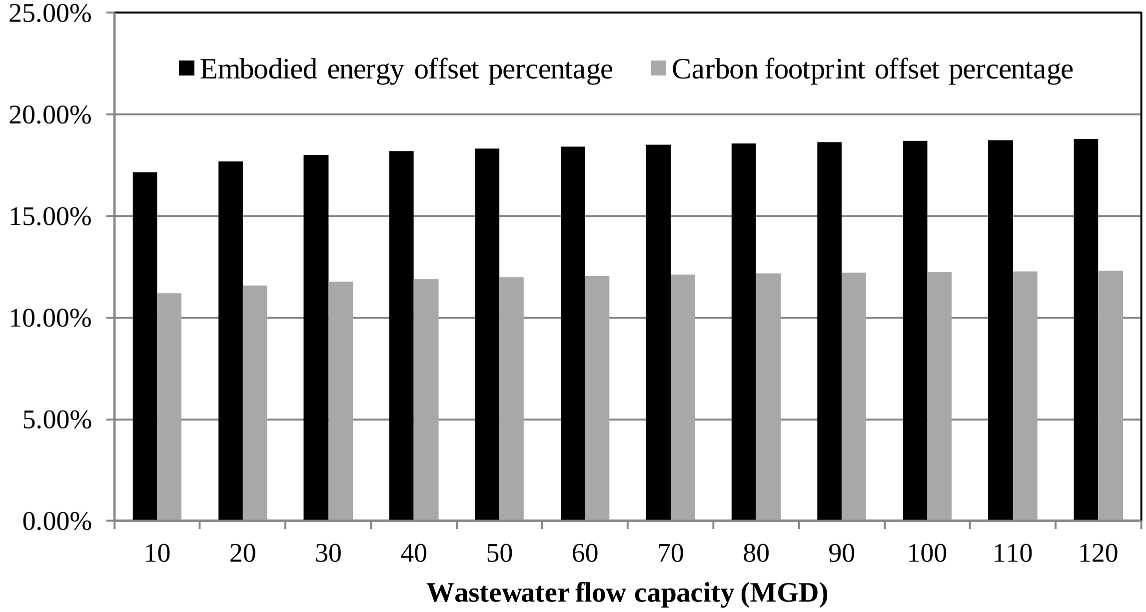


Figure 6.4 The percentages of embodied energy and carbon footprint offsets of onsite energy generation under different wastewater flow capacities

One thing to be noted, according to Equation 6-8, the HCWTP needs an annual operational energy of around 33.0 TJ to fire the heat drying system and the associated carbon footprint is around 1.57 Gg of CO_2e. The operation of the heat drying system has a higher embodied energy compared with the construction. Running a heat drying system yields an annual total embodied energy requirement of 39.1 TJ (92% direct energy and 8% indirect energy), and an annual carbon footprint of 1.87 Gg of CO_2e, which would be greater than the energy that can be saved from land application of the dried sludge. In reality, however, the HCWTP utilizes exhaust heat from a power generation plant for heat drying the digested sludge. As a result, the operational energy of the heat drying system and the associated carbon footprint render zero. Under such condition, nutrient recycling has the potential to offset embodied energy and carbon footprint; however, such offsets are not onsite. Hence, the benefit of nutrient recycling is on a broader scale and is less realized by the WWTPs especially without proper policy and strategies to encourage such practices. The embodied energy offset through nutrient recycling is around 0.4% of the total embodied energy of the HCWTP, which is much lower than onsite energy generation. The carbon footprint offset through nutrient recycling is also around 0.4% of the total carbon footprint of the HCWTP.

According to Equation 6-15, the maximal amount of energy that can be saved from nutrient recycling was calculated to be 28.5 TJ/year, with an associated carbon footprint saving of 1.38 Gg of CO_2e. Considering the constructional embodied energy under this scenario, the embodied energy offset is around 22.4 TJ/year, which is 2% of the total embodied energy of the current HCWTP. The carbon footprint offset could be 1.08 Gg of CO_2, which is also around 2% of the carbon footprint of the current HCWTP. Under the maximal recycling condition and using exhaust heat for the heat drying, the offset potential of nutrient recycling is still very low.

The potentials to offset embodied energy and carbon footprint through nutrient recycling under different wastewater flow capacities were calculated. Without residue heat available, the embodied energy that can be saved from replacing fossil fuel-based fertilizers is not able to offset the total embodied energy under all flow capacities. Even when residue heat is available, the embodied energy and carbon footprint offset potentials are very low as shown in Figure 6.5. The variance of the offset potentials under different flow capacities is very small.

Overall, nutrient recycling through heat dried sludge has very limited benefits and very low potential to offset the total embodied energy and the associated carbon footprint.

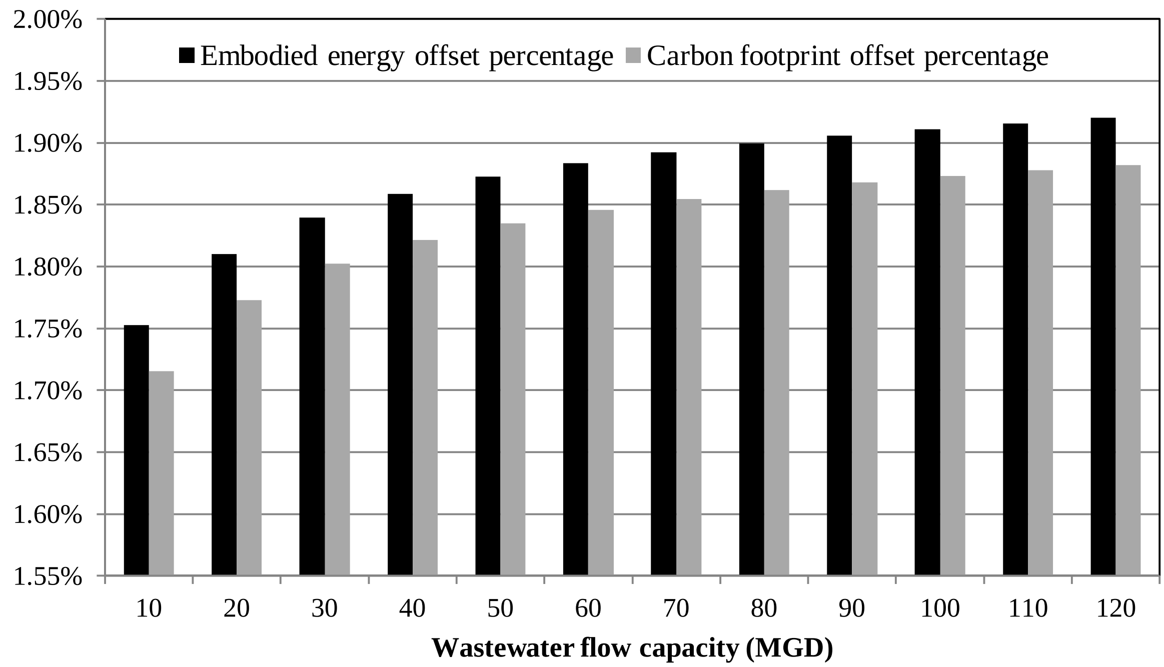


Figure 6.5 The percentages of embodied energy and carbon footprint offsets of nutrient recycling under different wastewater flow capacities

6.4.4 Water Reuse

The constructional and operational embodied energy of water reuse as well as its annual energy saving and offset were calculated and provided in Table 6.4. The embodied energy saved through water reuse is also offsite. Through reusing water, the HCWTP offsets around 9% of its total embodied energy. The carbon footprint offset through water reuse is also around 9% of the total carbon footprint of the HCWTP. The current embodied energy and carbon footprint offset potentials of water reuse in the HCWTP are lower than onsite energy generation, but higher than nutrient recycling.

According to Equation 6-15, the maximal amount of energy that can be saved from water reuse was calculated to be 803.2 TJ/year, and the associated carbon footprint saving is around 39.7 Gg of CO_2e. The embodied energy offset per year is 461.9 TJ/year, and the associated carbon footprint offset is 23.1 Gg of CO_2e. Under the maximal reuse condition, the embodied energy offset accounts for 70% of the HCWTP's direct operational energy, and 39% of the total embodied energy. The maximal embodied energy and carbon footprint offsets of water reuse are higher than that of onsite energy generation and nutrient recycling. However, it is still not able to offset even half of the total embodied energy of the HCWTP.

The potentials to offset embodied energy and carbon footprint through water reuse under different wastewater flow capacities were calculated and shown in Figure 6.6. The embodied energy associated with purple pipeline system construction per year is relatively low when compared with the embodied energy associated with the system operation. The energy needed for operating the water reuse systems is around 40% of the energy that can be saved from reusing water. The offset potential of water reuse increases with the water reuse capacity, but water reuse alone can never offset either direct operational energy or total embodied energy regardless of the flow capacities. Generally, for WWTPs with similar reuse applications as the HCWTP, water reuse has the potential to offset around 37~41% of the total embodied energy and 36~40% of the total carbon footprint.

Overall, water reuse has the highest offset potential, but it is not able to completely offset the total embodied energy and associated carbon footprint under different flow capacities.

6.4.5 Integrated Resource Recovery

In sum, the HCWTP currently has a total embodied energy of 1193 TJ/year, and an annual carbon footprint of 58.7 Gg of CO_2e. If the HCWTP does not have any of the

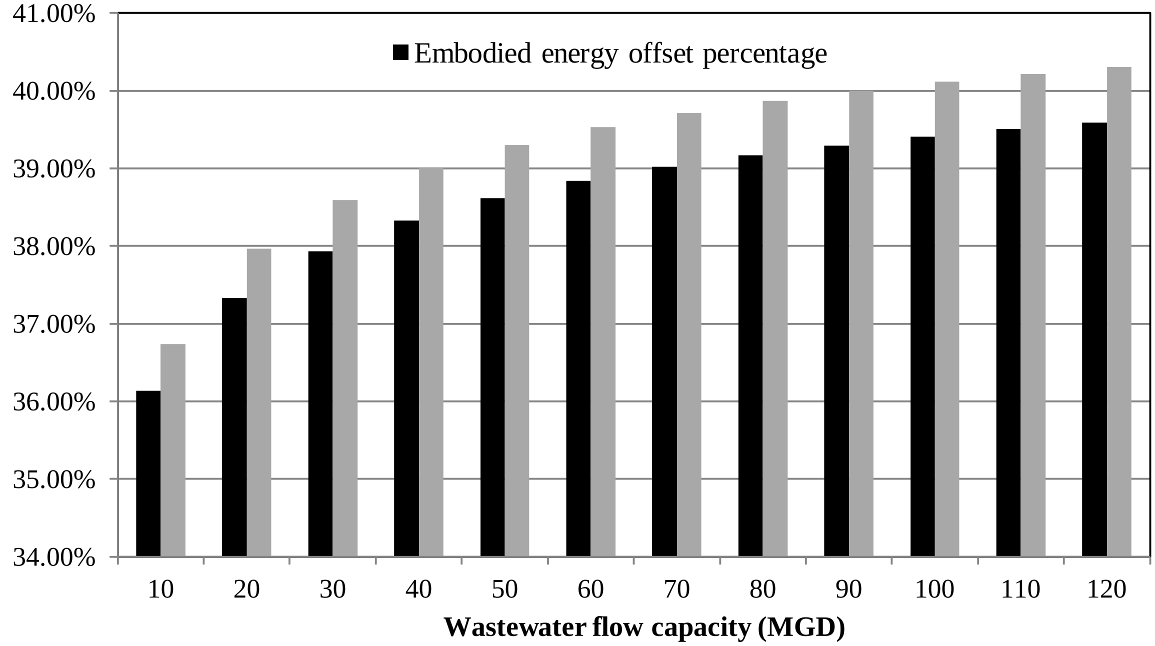


Figure 6.6 The percentages of embodied energy and carbon footprint offsets of water reuse under different wastewater flow capacities

current recovery practices, it will have an annual embodied energy of 1319 TJ, with an associated carbon footprint of 64.8 Gg of CO_2e.

Under the maximal energy recovery/saving condition, the total embodied energy offset is 729.8 TJ/year, which is around 110% of the direct operational energy and 61% of the total embodied energy of the current HCWTP. The integrated resource recovery (combining all three resource recovery methods) is able to offset all the direct operational energy, but not able to offset the total embodied energy of the current HCWTP. The total carbon footprint offsets would be 35.1 Gg of CO_2e, which can offset all the GHG emissions associated with the direct energy use in the operational phase, and 57% of the total carbon footprint of the current HCWTP. Overall, WWTPs can be carbon neutral under integrated resource recovery condition if only direct operational energy is considered; however, they may not be able to achieve carbon neutrality with the three energy recovery methods studied in this paper if the GHG emissions associated with materials and chemicals are also included.

6.5 Conclusions

From the case of the HCWTP in this study, the energy produced onsite through the CHPs alone is not able to supply all the direct operational energy even under the maximal energy generation. On the other hand, if nutrient recycling and water reuse are both integrated, the combined benefits of the three resource recovery methods have the potential to offset the direct operational energy and the associated carbon footprint. The total embodied energy and the associated carbon footprint, however, still cannot be offset by combining these three methods even under maximal recovery condition.

Onsite energy generation has the highest offset for the HCWTP currently, followed by water reuse and nutrient recycling. Under the maximal recovery scenario, however, water reuse has the highest potential to offset the embodied energy and the associated carbon footprint, while onsite energy generation comes to the second and nutrient recycling as the last.

Generally, nutrient recycling through heat dried sludge does not have embodied energy and carbon offsets because of the large operational energy consumption. If residue heat is available for heat drying, nutrient recycling through sludge land application might be beneficial. Thus, complete and comprehensive studies have to be carried out before using heat drying for nutrient recycling.

The amount of energy that can be generated onsite is highly dependent on the organic load of the wastewater, the embodied energy that can be saved through nutrient recycling is highly dependent on the nutrient loads of the wastewater and the embodied energy that can be saved through water reuse is highly dependent on the reclaimed water flow. The current organic, nutrients loads and the reclaimed water flow in the HCWTP are not high enough to offset the total carbon footprint through integrating onsite energy generation, nutrient recycling and water reuse. However, it is still possible to achieve carbon neutrality in wastewater systems through other supplementary strategies, such as reducing energy and material uses onsite, implementing other technologies such as onsite wind and solar power generation.

6.6 References

Asano, T., 2007. Water Reuse: Issues, Technologies and Applications. McGraw-Hill Professional, New York.

BEA, 2011. Benchmark input-output data, http://www.bea.gov/industry/io_annual.htm (Last accessed on 04.10.12.).

Crawford, G., Johnson, T.D., Johnson, B.R., Krause, T., Wilner, H., 2011. CHEApet Users Manual, OWSO4R07c, Water Environment Research Foundation, Virginia.

Dixon, A, Simon, M., Burkitt, T., 2003. Assessing the environmental impact of two options for small-scale wastewater treatment: comparing a reedbed and an aerated biological filter using a life cycle approach. Ecological Engineering, 20, 297-308.

EIA, 2012. Natural gas prices, http://www.eia.gov/dnav/ng/NG_PRI_SUM_DCU_SFL_A.htm (Last accessed on 05.22.12.).

EIA, 1995. Measuring energy efficiency in the United States' economy: A beginning, DOE/EIA-0555(95)/2, National Energy Information Center, Washington DC.

EPA, 2012. Biosolids Technology Fact Sheet Heat Drying, http://water.epa.gov/scitech/wastetech/mtbfact.cfm (Last accessed on 05.10.12.).

EPA, 2008a. Clean Watersheds Needs Survey 2008 Report to Congress, CWNS EPA-832-R-10-002, U.S. Environmental Protection Agency, Washington DC.

EPA, 2008b. eGRID2007 Version1.1 Year 2005 GHG Annual Output Emission Rates, http://cfpub.epa.gov/egridweb/ghg.cfm (Last accessed on 05.10.12.).

EPA, 2007. Opportunities for and benefits of combined heat and power at wastewater treatment facilities, EPA-430-R-07-003, U.S. Environmental Protection Agency, Washington DC.

EPA, 2006. Wastewater management fact sheet-heat drying, EPA 832-F-06-024, http://water.epa.gov/scitech/wastetech/upload/2006_10_16_mtb_heat-drying.pdf (Last accessed on 05.10.12.).

EPA, 2004. Unit conversions, emissions factors, and other reference data, http://www.epa.gov/appdstar/pdf/brochure.pdf (Last accessed on 05.22.12.).

Foley, J., De Haas, D., Hartley, K., Lant, P., 2010. Comprehensive life cycle inventories of alternative wastewater treatment systems, Water Research 44, 1654-1666.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., 2007. Changes in atmospheric constituents and in radiative forcing, Climate change 2007: The Physical Science Basis, 130-234.

Gebhart, W., 1995. Rotating kiln tyres: lubricating between the tyre and shell, World Cement 26, 59-61.

Hellström, D., Jeppsson, U., Kärrman, E., 2000. A framework for systems analysis of sustainable urban water management, Environmental Impact Assessment Review 20, 311-321.

Herz, R., Lipkow, A., 2002. Life cycle assessment of water mains and sewers, Water science and technology: water supply 2, 51-58.

Hospido, A., Moreira, T., Martín, M., Rigola, M., Feijoo, G., 2005. Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes, The International Journal of Life Cycle Assessment 10, 336-345.

Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis, Journal of Cleaner Production 13, 287-299.

Lassaux, S., Renzoni, R., Germain, A., 2007. LCA Case Studies Life Cycle Assessment of Water: From the Pumping Station to the Wastewater Treatment Plant, The International Journal of Life Cycle Assessment 12, 118-126.

Hendrickson, C., 2008. Project Management in Construction, Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA, web published.

Lundin, M., Morrison, G.M., 2002. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems, Urban Water 4, 145-152.

Lyons, E., Zhang, P., Benn, T., Sharif, F., Li, K., Crittenden, J., Costanza, M., Chen, Y., 2009. Life cycle assessment of three water supply systems: importation, reclamation and desalination, Water science and technology: water supply 9, 439-448.

Machado, A.P., Urbano, L., Brito, A.G., Janknecht, P., Salas, J.J., Nogueira, R., 2007. Life cycle assessment of wastewater treatment options for small and decentralized communities, Water Science and Technology 56, 15-22.

Means, E., 2004. Water and wastewater industry energy efficiency: a research roadmap, Awwa Research Foundation .

Mels, A.R., van Nieuwenhuijzen, A.F., van der Graaf, J.H.J.M., Klapwijk, B., Koning, J., Rulkens, W.H., 1999. Sustainability criteria as a tool in the development of new sewage treatment methods, Water science and technology 39, 243-250.

Meneses, M., Pasqualino, J.C., Castells, F., 2010. Environmental assessment of urban wastewater reuse: Treatment alternatives and applications, Chemosphere 81, 266-272.

Mo, W., Nasiri, F., Eckelman, M.J., Zhang, Q., Zimmerman, J.B., 2010. Measuring the embodied energy in drinking water supply systems: a case study in The Great Lakes region, Environmental Science and Technology 44, 9516-9521.

Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options, Water Research 45, 5577-5586.

Muñoz, I., Milà-i-Canals, L., Fernández-Alba, A.R., 2010. Life Cycle Assessment of Water Supply Plans in Mediterranean Spain, Journal of Industrial Ecology 14, 902-918.

Nouri, J., Jafarinia, M., Naddafi, K., Nabizadeh, R., Mahvi, A., Nouri, N., 2006. Energy recovery from wastewater treatment plant, Pakistan Journal of Biological Sciences 9, 3-6.

Ortiz, M., Raluy, R., Serra, L., 2007. Life cycle assessment of water treatment technologies: wastewater and water-reuse in a small town, Desalination 204, 121-131.

Pasqualino, J.C., Meneses, M., Abella, M., Castells, F., 2009. LCA as a decision support tool for the environmental improvement of the operation of a municipal wastewater treatment plant, Environmental Science and Technology 43, 3300-3307.

Peters, G.M., Lundie, S., 2001. Life Cycle Assessment of Biosolids Processing Options, Journal of Industrial Ecology 5, 103-121.

Ranganathan, J., Corbier, L., Bhatia, P., Schmitz, S., Gage, P., Oren, K., 2004. The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard (Revised Edition), Washington, DC: World Resources Institute and World Business Council for Sustainable Development.

Roeleveld, P., Klapwijk, A., Eggels, P., Rulkens, W., Van Starkenburg, W., 1997. Sustainability of municipal wastewater treatment, Water science and technology 35, 221-228.

Shizas, I., 2004. Experimental determination of energy content of unknown organics in municipal wastewater streams, Journal of Energy Engineering 130, 45-53.

Stokes, J., Horvath, A., 2006. Life cycle energy assessment of alternative water supply systems, The International Journal of Life Cycle Assessment 11, 335-343.

Suh, Y.J., Rousseaux, P., 2002. An LCA of alternative wastewater sludge treatment scenarios, Resources, Conservation and Recycling 35, 191-200.

Wett, B., Buchauer, K., Fimml, C., 2007. Energy self-sufficiency as a feasible concept for wastewater treatment systems, IWA Leading Edge Technology Conference, Asian Water, Singapore, pp. 21-24.

CHPATER 7: REGIONAL EMBODIED ENERGY IN WATER SUPPLY: THE IMPACTS OF WATER SOURCE, LAND USE AND POPULATION

7.1 Introduction

Water and energy are two interrelated resources. Providing water and wastewater treatment services consumes a large amount of energy (4% of the US electricity directly used for pumping and treating water), and providing energy requires a large amount of water for cooling (39% of the US freshwater withdrawal) and processing. Because of the reinforcing relationship between water and energy, water stressors do not only impact water resources but also energy resources.

Not only the amount of water withdrawn but also the quality of water will affect energy use in water supply. When water demand increases, more energy is needed to pump and treat the larger quantity of water to meet the demand. Capacity expansion might be necessary or new systems have to be constructed. On the other hand, when water quality decreases, more energy is needed for treating the lower quality water. Sometimes, a water source shift is necessary when the available freshwater quantity or quality is improper for potable water supply. A previous study has shown that energy requirement generally differs for different water sources (Mo et al., 2011). Desalination is the most energy intensive water supply option, while surface water supply and groundwater supply are comparatively less energy intensive (Mo et al., 2011).

Water quantity and quality are further affected by water stressors, such as population, economic development, land use change and climate change. Many studies have projected the correlations between the water stressors and water quantity and quality. Population growth, especially in the urban areas, is shown to have a significant impact on water demand and intensify local water stress (Arnell, 2004; Meigh et al., 1999; Sun et al., 2008; Vörösmarty et al., 2000). Population growth also impacts water quality by diminishing the return flow to the water body and impairing the self-cleaning abilities of the water bodies (Ehrlich and Holdren, 1971). Population distribution, on the other hand, affects the distribution of water pipeline networks. When population is more distributed, pipeline intensity for supplying the same amount of water would be higher and vice versa.

Economic development introduces new technologies and products, which could potentially change the physical and chemical characteristics of water. For example, water discharge from the power plants changes the temperature of local water body. Disposal of pharmaceuticals and pesticides changes the chemical composition of water bodies. Economic development also induces uneven resource distribution and overconsumption in the well-developed regions, which also increases the stress on water quantity.

Climate change is shown to have impact on both water quantity (Arnell, 2004; Meigh et al., 1999; Sun et al., 2008; Vörösmarty et al., 2000) and quality (Whitehead et al., 2009). It affects water resources mainly through changes of precipitation, evaporation, flows, runoff, temperature and ability of watersheds to assimilate pollutants (Gleick, 2000). Arnell (2004) and Vorosmarty et al. (2000) stated minor impact of climate change on water quantity and quality globally compared with population growth. On the other hand, Sun et al. (2008) reported that climate change has the major impact on regional water demand and supply in the southeastern US.

Studies have also shown a significant relationship between land use and water quality (Johnes and Heathwaite, 1997; Lenat and Crawford, 1994; Sliva and Dudley Williams, 2001; Tong and Chen, 2002) and quantity (Claessens et al., 2006; Foley et al., 2005). Theoretically, land use would affect water quantity and quality because runoffs from the agricultural land use would have higher nutrient contents while runoffs from the urban land use normally have higher organic and inorganic contents. It has been proven that agricultural and impervious urban lands produce a much higher level of nitrogen and phosphorus than other land surfaces (Lenat and Crawford, 1994; Tong and Chen, 2002). On the other hand, one study has shown that impacts of land use are less significant than population and climate change (Sun et al., 2008).

Although the relationships between the water stressors and water quantity and quality have been widely studied, there have been very limited studies linking the water stressors to the water-related energy consumption. Studies have mentioned the increase in energy use of water supply due to population growth and climate change (Dinar, 1994; Vieira and Ramos, 2009), but no researches have been carried out to quantify the relationship between the water stressors and energy use in water supply. While these water stressors have changed at an accelerating rate over the past 100-150 years and will continue to change rapidly in future (Zimmerman et al., 2008), it is important to understand water-related energy consumption on regional scales in order to provide guidance for future planning.

Hence, this study aims at quantifying the relationship between the water stressors and the energy use in water supply. The concept of "embodied energy" or "life cycle energy" has been used to indicate energy used both directly for pumping and treatment processes, and indirectly for providing the materials over the life time of a water infrastructure.

7.2 Methodology

7.2.1 Indicator Selection

In this study, the correlations between water stressors and energy use in water supply were studied on county level for a selected state in the US. Among the major water stressors, population and land use were selected for this study. Water source was also selected as an indicator because it impacts the amount of energy needed for water treatment and delivery. Climate change and economic development were not considered in this study because these two stressors do not vary significantly in the selected state. For each selected water stressor, specific indicators were chosen for quantitative analysis. Table 7.1 provides the indicators selected for each water stressor as well as their data sources for the selected state.

Total population (P) and population density (P_d) were used to indicate population growth and population distribution respectively. Percentages of both urban land (L_u) and agricultural land (L_a) were selected to represent the land use situation of each county. Land cover in the selected state was classified into 19 categories (NCCGIA, 1997a). Among the 19 categories, the "high intensity developed land" and the "low intensity developed land" were included as urban land, while the "cultivated land" and the "managed herbaceous cover" were included as agricultural land. To indicate the differences of water source among each county, only the percentage of surface water supply (w_s) was used as an indicator in this study because the selected state only has two main water sources: groundwater and surface water.

Table 7.1 Indicators and sources for population, land use and water source

Category	Population	Land use	Water source
Indicators	Total population (P) (Number)	Percentage of urban land (L_u) (%)	Percentage of groundwater supply (w_g) (%)
	Population density (P_d) (Number·acre^{-1})	Percentage of agricultural land (L_a) (%)	Percentage of surface water supply (w_s) (%)
			Percentage of desalinated water supply (w_d) (%)
			Percentage of reclaimed water supply (w_r) (%)
Data source	US Census (USCB, 2012)	NC Land Cover Data (NCCGIA, 1997b)	NC GIS Database (NCREDC, 2000)

7.2.2 Application of Geographical Information System

The Geographical Information System (GIS) was used in this study to show the distribution of water stressors, provide land use and water infrastructure information, and assist embodied energy calculation. GIS is a computer system capable of storing and providing data describing the earth's surface (Juahir et al., 2010). It provides spatial information describing location and shape of structures and landscapes. It also stores other descriptive information relating each feature and each object on the map. Studies have revealed that for a large geographic area, a GIS might be the only tool that has the ability to handle the different subsystems and their physical traits (Bakhshi and deMonsabert, 2009).

In this study, the land use and water infrastructure information were originally obtained for the whole state. In order to extract data and calculate indicator values for each county, a layer of county boundary was obtained from the US census TIGER database (USCB, 2012) and the function of “split” was used in the ArcMap 10. After the land use indicators and embodied energy were calculated for each county, they were added to the attribute table of the county boundary layer along with the population and water source indicators. As a result, all information can be visually displayed in GIS for comparison and further calculation.

7.2.3 Embodied Energy Calculation

Embodied energy in this study was calculated as the product of embodied energy intensity (TJ of embodied energy in primary energy form/$ million) and the associated cost as shown in Equation 7-1. This study incorporated the embodied energy intensities estimated in Chapter 4 instead of the national averaged energy intensities for the economic sectors. Chapter 4 provided the embodied energy intensities of a groundwater supply systems and a surface water supply system through an input-output based hybrid analysis approach. Most of the North Carolina groundwater supply systems apply simple disinfection for treatment, which is the same as the groundwater supply system studied in Chapter 4. Moreover, most of the North Carolina surface water supply systems use conventional treatment process, including coagulation, sedimentation, filtration and disinfection, which is also very similar as the surface water supply system studied in Chapter 4. Hence, although these two systems were located in different geographical places, embodied energy intensities calculated in Chapter 4 were considered more accurate than national averaged energy intensities because they better represents the differences between the two types of water systems. Table 7.2 provides values of the energy intensities used in this study. Embodied energy of the operation phase and the construction phase was calculated separately. A life span of 100 years was applied regarding the construction phase.

$$E = \sum C_i \times e_i \tag{7-1}$$

where

E = The total embodied energy of the water supply systems of a selected county per year, TJ/year;

C_i = The cost of the construction phase or the operation phase on year basis; $ million/year;

e_i = The embodied energy intensity of the construction phase or the operation phase in primary energy forms; TJ/$ million.

Table 7.2 The energy intensities for operating and constructing the groundwater and surface water supply systems

Water source	Operation and Maintenance (TJ/$ million)	Construction (TJ/$ million)
Groundwater supply	24.8	11.1
Surface water supply	15.8	10.9

Constructional and operational costs were calculated for different types of water supply infrastructures, including water intake infrastructures (wells for groundwater supply and exposed tower for surface water supply), pumping stations, pipelines, water treatment plants and storage tanks. Cost equations and their sources were provided in Table 2.4 in Chapter 2. The operational cost for water delivery was included as the operation of pipeline instead of pumping stations. Operational costs for the storage tanks were neglected.

7.2.4 Correlation Analysis

A correlation analysis was performed to determine if and to what degree the indicators are linearly related with each other. This study utilizes Pearson correlation coefficients to indicate the strength and direction of the correlations between the indicators. Unlike other correlation coefficients, the Pearson correlation coefficient is sensitive only to the linear relationship between two variables; even they are non-linearly related with each other (Aitken, 1957; Croxton and Cowden, 1939; Dietrich, 1991). The Pearson coefficients range from -1 to 1. Values closer to 1 indicate stronger positive correlation, while values closer to -1 indicate stronger negative correlation. Values closer to 0 indicate weaker correlation. The Pearson correlation coefficients were calculated using the open sourced R software through Equation (7-2).

$$r = (\sum v_i v_j - (\sum v_i \sum v_j / n)) / \sqrt{(\sum v_i^2 - (\sum v_i)^2 / n)(\sum v_j^2 - (\sum v_j)^2 / n)} \qquad (7\text{-}2)$$

where

v_i, v_j = Any two indicators of the five selected indicators: P, P_d, L_u, L_a and w_s;

n = Number of total datasets;

r = the calculated Pearson correlation coefficient.

As there are no hard rules to determine the strength of the Pearson correlation, this study adopts the following guidelines (Shortell, 2001): $0 \le |r| \le 0.45$ weak correlation; $0.45 < |r| \le 0.75$ fair correlation; and $0.75 < |r| \le 1$ strong correlation.

7.2.5 Regression Analysis

In order to establish a regression model between the indicators and the embodied energy of water supply, the R software was used. Initial values of the variables (the indicator values) were normalized in order to avoid bias associated with the scale differences among the datasets. Equation 7-3 was used for the normalization.

$$f(x) = (x - \overline{X}) / s \qquad (7\text{-}3)$$

where,

x = Original data;

$f(x)$ = Transformed data after normalization;

$\overline{X}$ = Average of the original dataset;

s = Standard deviation of the original dataset.

The first attempt was to establish a linear regression model. If the linear regression did not work, then non-linear regression would be applied. In order to establish a linear regression model, the variables have to be selected based on their significance. There are two kinds of stepwise selection, forward selection and backward selection. In forward selection, one variable is included at each step; but it has drawbacks. One important drawback of this approach is that in the process, one or more of already included variables may become non-significant (Myers, 1990). Hence, backward selection was used in this study. The backward selection started with fitting a model with all the variables. Then the least significant variable is dropped if it does not meet the chosen critical level (smallest Akaike Information Criterion (AIC) value of all variables). The same rule was applied until all remaining variables are statistically significant. AIC is generally used as a measure of the relative goodness of fit of a regression model

(Akaike, 1974). It can be interpreted using Equation 7-4. In this study, the stepwise selection stops when AIC value is equal to Mallow's Cp. Mallow's Cp is commonly served as the stopping rule for the stepwise regression. Equation 7-5 explains the calculation of Mallow's Cp (Mallows, 1973).

$$AIC = 2p - 2\ln(L) \qquad (7\text{-}4)$$

where

AIC = Akaike Information Criterion value;

p = Number of free variables in the regression model;

L = The maximized value of the likelihood function for the regression model.

$$Cp = SS_{res} / MS_{res} - n + 2(p+1) \qquad (7\text{-}5)$$

where

C_p = Value of Mallow's Cp;

SS_{res} = The residual sum of squares for the model with p variables;

MS_{res} = The residual mean square when using all available variables.

After the regression model was established, a leave-one-out cross validation was carried out to test the model's capability of embodied energy prediction. The leave-one-out cross validation was also performed in the R software. Leave-one-out cross validation is usually used for validating small datasets (Cawley and Talbot, 2003). It involves using one observation as the validation data and the rest as the training data each time. This process was repeated for all the observations. The leave-one-out cross validation uses data most efficiently, but it can be computationally expensive for large datasets. Sum square, mean square, F value and Pr value were given to interpret the variance and significance of each variable. Pr values especially show the probability that an effect at least as extreme as the current observation has occurred by chance (Hennekens et al., 1987). Pr values smaller than 0.05 were considered as significant in this study. Additionally, a figure was drawn with predicted embodied energy value as x-axis and actual embodied energy value as y-axis for all the observations. The fitness of all observation points to the line of y=x (actual embodied energy values = predicted embodied energy values) was examined. The R squared value was calculated and used to show the regression model's capability of prediction. The R squared value above 0.7 was considered to indicate a strong prediction capability of the regression model.

7.3 Case Study

The state of North Carolina was selected for this study because it has the most sufficient water supply infrastructure data which are required for the embodied energy estimation. North Carolina belongs to the southeast climate region (Karl et al., 1984). Climate of this region is uniquely warm and wet, with mild winters and high humidity, compared with the rest of the continental United States (Karl and Melillo, 2009). Geographical Information System (GIS) data on water supply infrastructures were complete for 77 counties out of 100 counties in North Carolina. Some counties in mid-North Carolina and east North Carolina, such as Rockingham, Guilford, Alamance, Person, Orange, Wake, Pamlico do not have (complete) data. Figure 7.1 shows the distributions of water infrastructure among the counties in North Carolina, as well as the counties lack of or without infrastructure data.

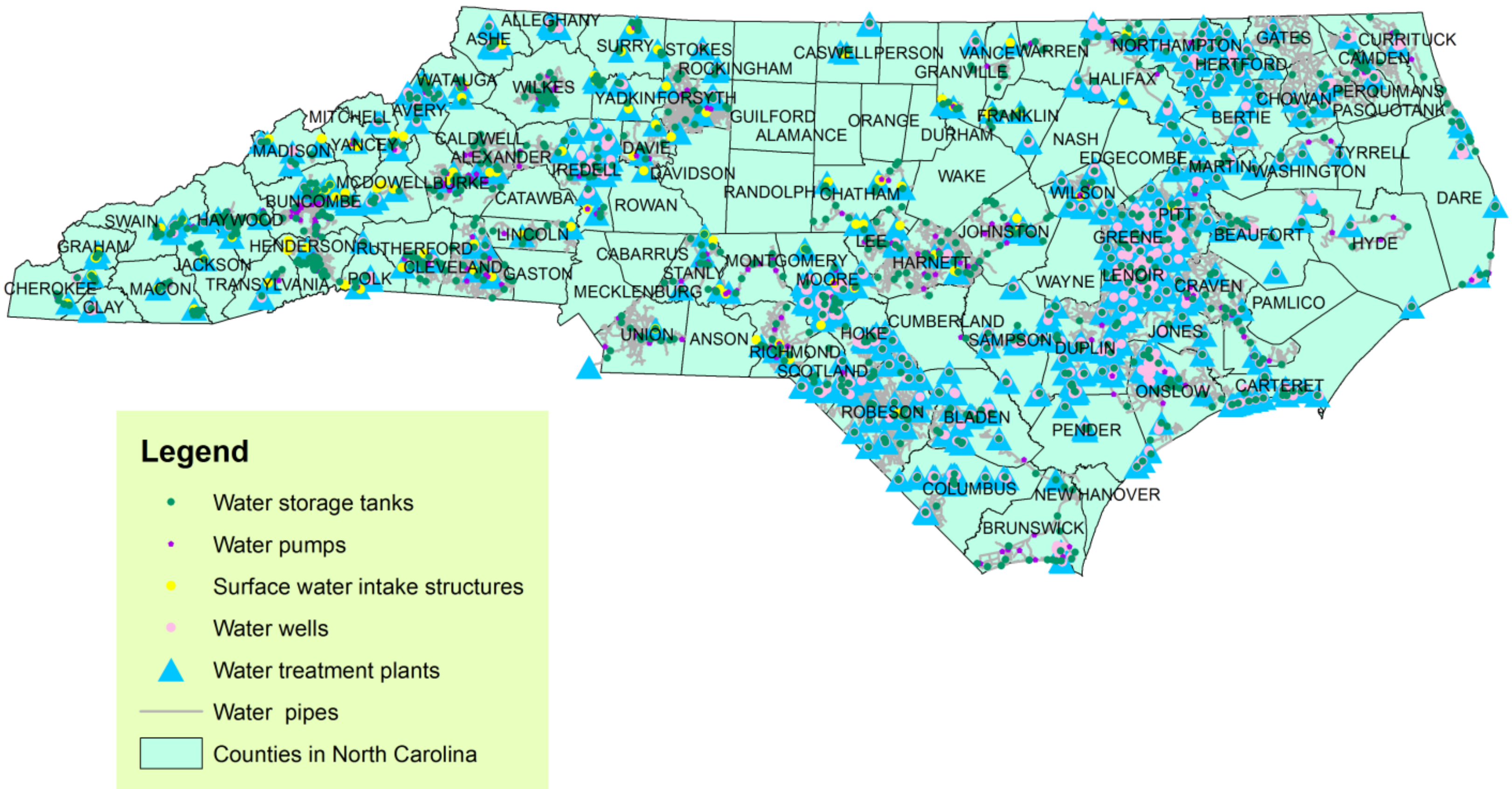
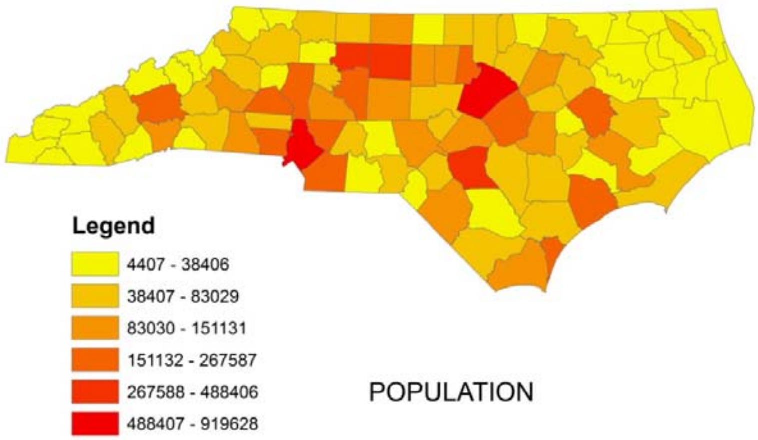
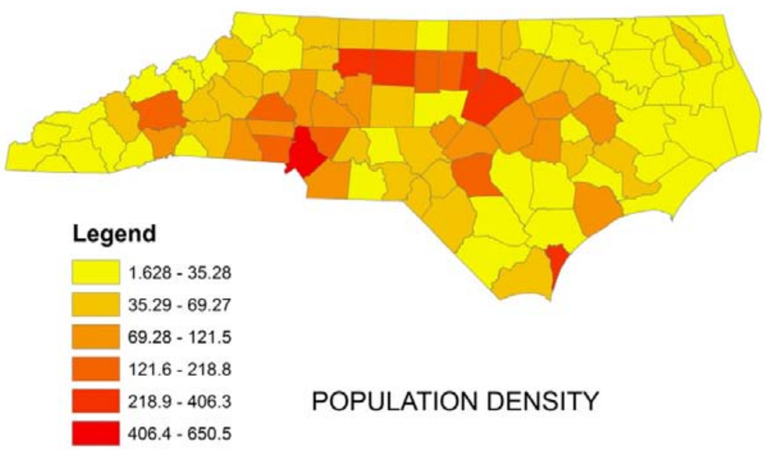


Figure 7.1 The distribution of water infrastructure among the counties in North Carolina

Figure 7.2 provides the total population and population density distributions in North Carolina. Distributions of population and population density are slightly different, especially in the southeast part of the state. Overall, population is more concentrated in the counties at the middle of the state than the east or west part of the state.



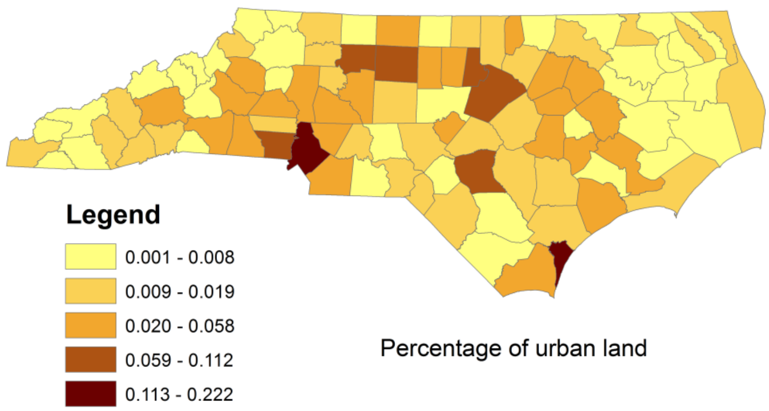
(a)



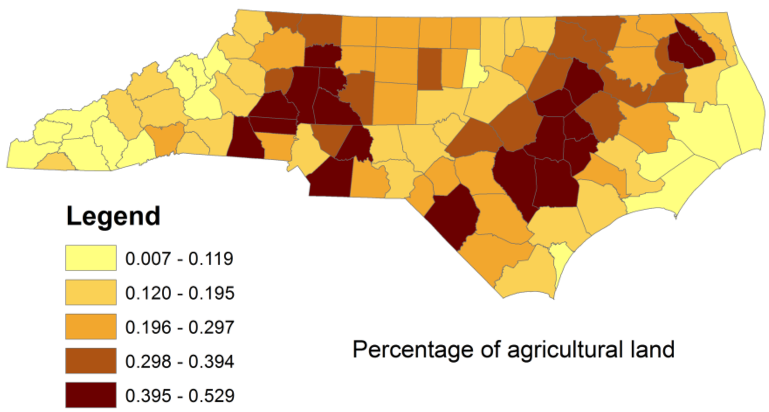
(b)

Figure 7.2 The total population and population density distribution in North Carolina. (a) distribution of population among the counties in North Carolina, and (b) distribution of population among the counties in North Carolina in unit of acre^{-1}

Figure 7.3 provides the distributions of percentages of urban land and percentages of agricultural land among the counties in North Carolina. Counties in the middle of the state have more urban land, and counties surrounding these highly urbanized counties have more agricultural land.



(a)



(b)

Figure 7.3 The percentage of urban land and the percentage of agricultural land of the North Carolina. (a) distribution of urban land percentage among the counties of North Carolina, and (b) distribution of agricultural land percentage among the counties of North Carolina

Figure 7.4 provides the distribution of surface water percentages in North Carolina. The figure shows that west of the state is dominated by surface water sources, while southeast of the state is dominated by groundwater sources. This is consistent with Figure 7.1, which shows the surface water intake structures are mostly concentrated in west North Carolina while the groundwater wells are more concentrated in east North Carolina.

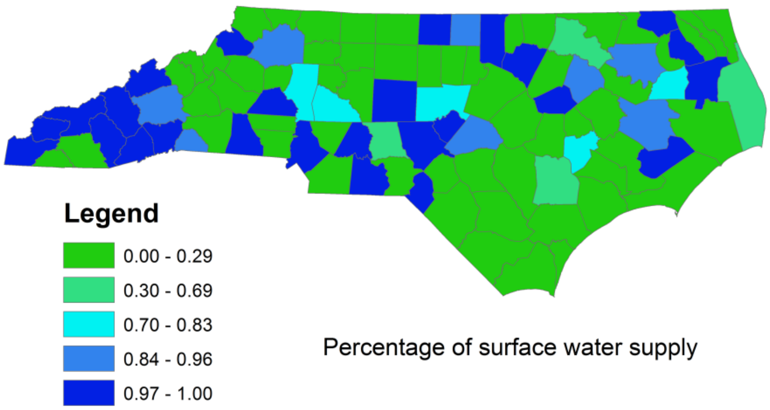


Figure 7.4 The distribution of surface water percentages in North Carolina.

7.4 Results and Discussion

7.4.1 Embodied Energy of Different Water Supply Infrastructures

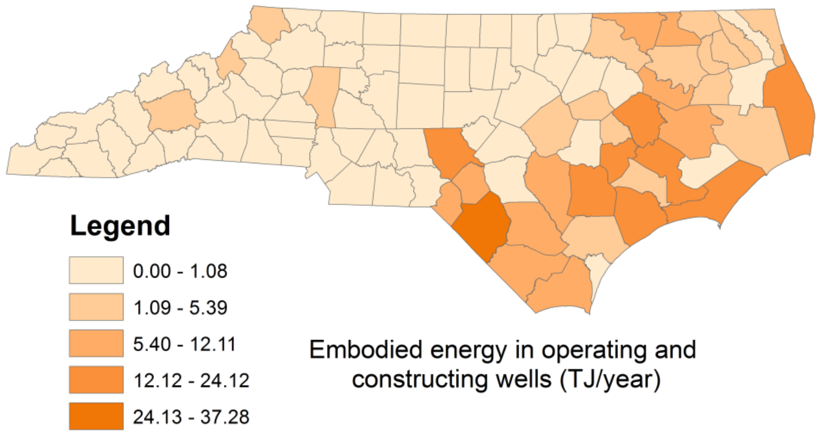
Embodied energy for each type of water supply infrastructure was calculated for each county and provided in Figure 7.5. Figure 7.5(a) provides the distribution of embodied energy in well construction and operation. Embodied energy in operating and constructing wells is concentrated in the east North Carolina, which is consistent with the water source distribution. Counties with high embodied energy in operating and constructing wells include Robeson, Craven, Moore, Pitt, Lenoir, Duplin, Onslow, Carteret and Dare.

Figure 7.5(b) provides the distribution of embodied energy in surface water intake infrastructure construction and operation. Unlike the distribution of embodied energy in well construction and operation, embodied energy in surface water intake infrastructure construction and operation is mainly concentrated in the west North Carolina. This is also consistent with water source distributions as shown in Figure 7.4. Counties with high embodied energy in surface water intake infrastructure construction and operation include Surry, Forsyth, Davie, Chatham, Haywood, Rutherford, Cleveland and Harnett.

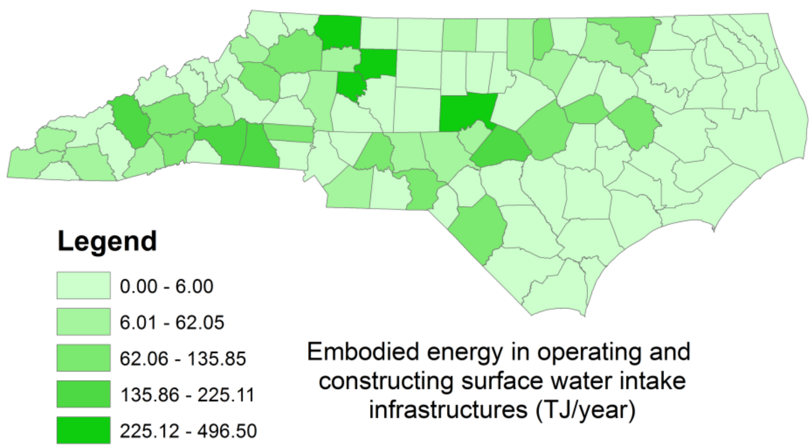
Figure 7.5(c) provides the distribution of embodied energy in operating and constructing pumping stations, pipes and water storage tanks. Embodied energy is more evenly distributed among the counties compared with wells and surface water intake infrastructures. It shows that water demand is more evenly distributed among the counties in North Carolina. Moreover, the result is also consistent with the population and land use patterns in North Carolina. Counties with high embodied energy in constructing and operating pumping station, pipes and water storage tanks include Burke, Forsyth, Robeson and Brunswick.

Figure 7.5(d) provides the distribution of embodied energy in treatment plant construction and operation. The distribution of embodied energy in treatment plant construction and operation is also very evenly distributed among the counties in North Carolina, but the distribution pattern is different from the distribution of embodied energy in pumping stations, pipes and water storage tanks. Counties with high embodied energy in treatment plant construction and operation include Forsyth, Mitchell and Stokes.

According to the ranges of embodied energy in different water infrastructure types, water distribution has the highest embodied energy followed by water treatment. Water intake infrastructures have the lowest embodied energy. Surface water intake infrastructures have a wider range of embodied energy consumption than wells in North Carolina, because they are more concentrated in certain counties, and the capacity of surface water intake infrastructures is much higher compared with wells.

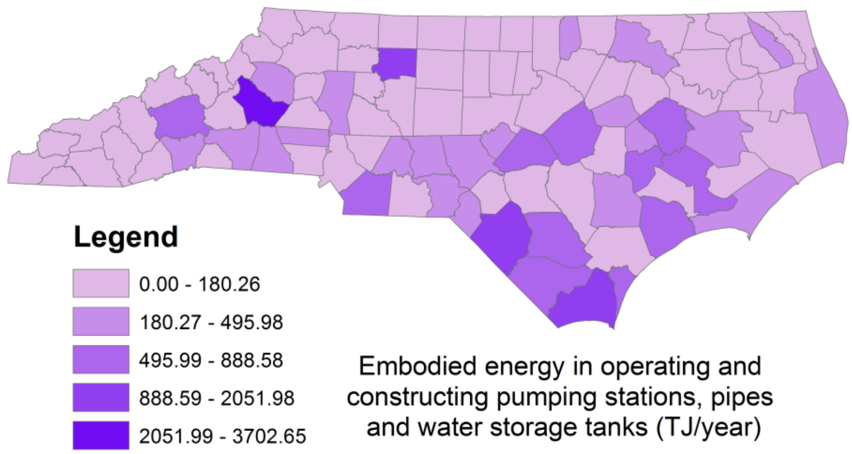


(a)

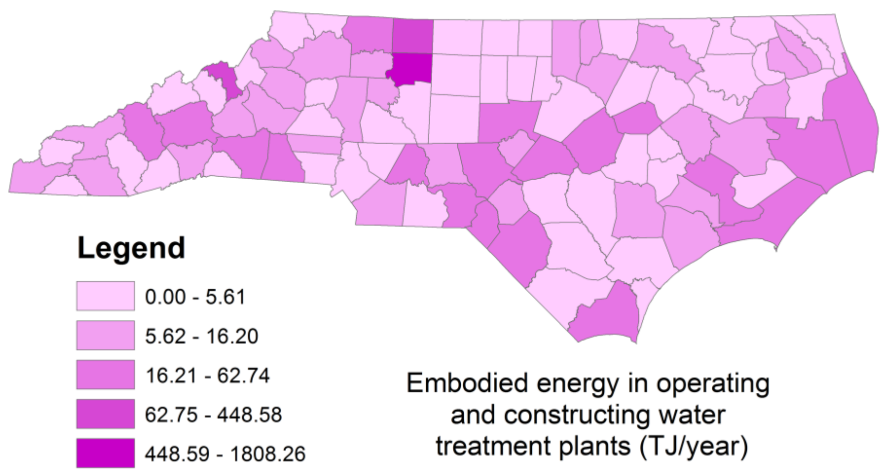


(b)

Figure 7.5 Distribution of annual embodied energy in operating and constructing wells, surface water intake infrastructures, pumping stations, pipes, water storage tanks and water treatment systems. (a) distribution of embodied energy in operating and constructing wells among the counties in North Carolina in unit of TJ/year; (b) distribution of embodied energy in operating and constructing surface water intake infrastructures among the counties in North Carolina in unit of TJ/year; (c) distribution of embodied energy in operating and constructing pumping stations, pipes and water storage tanks among the counties in North Carolina in unit of TJ/year; and (d) distribution of embodied energy in operating and constructing water treatment plants among the counties in North Carolina in unit of TJ/year.



(c)



(d)

Figure 7.5 (continued).

At last, embodied energy in different types of water infrastructures as listed in Figure 7.5 was combined. Figure 7.6 provides the distribution of total embodied energy of water supply in North Carolina. According to Figure 7.6, counties with the highest total embodied energy are Forsyth and Burke, while Buncombe, Johnston, Pitt, Craven, Brunswick and Robeson come to the next. The infrastructures contributed to high total embodied energy in water supply in Forsyth are water treatment plants and water distribution networks. This is consistent with the high total population, population density and urban land percentage in Forsyth. On the other hand, Burke has a high embodied energy mainly because of pipeline operation and construction. Total population, population density, and percentage of urban land in Burke are not very high. Hence, the extremely large pipeline operation and construction might be caused by its specific geographical conditions. Burke has large elevation variances within the county because it is on the edge of the Appalachian Mountains (Geology, 2012). Hence, this extreme case is eliminated in correlation analysis and regression analysis.

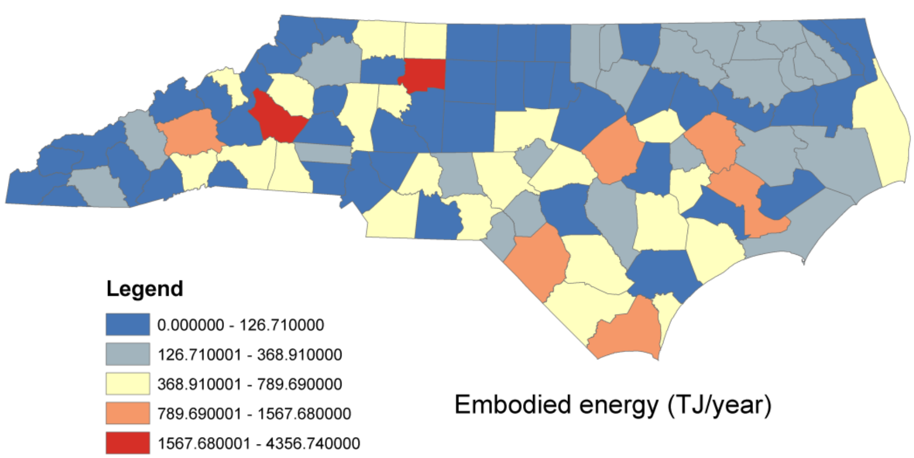


Figure 7.6 Distribution of embodied energy in North Carolina

7.4.2 Correlation Analysis

Table 7.3 provides the Pearson correlation coefficients between the five indicators. According to Table 7.3, coefficients between total population, population density and percentage of urban land are larger than 0.75. Thus, they have strong positive correlations between each other. Both percentage of agricultural land and percentage of surface water supply, on the other hand, show weak correlations with other indicators. The correlation analysis shows that not all the selected indicators are independent. Hence, a further selection process is needed when doing the regression analysis.

Table 7.3 Pearson correlations between the indicators of total population, population density, percentage of urban land, percentage of agricultural land and percentage of surface water supply

Pearson correlation coefficient	P	P_d	L_u	L_a	w_s
P	1.000	0.892	0.805	0.229	0.265
P_d	0.892	1.000	0.896	0.249	0.375
L_u	0.805	0.896	1.000	0.179	0.324
L_a	0.229	0.249	0.179	1.000	-0.178
w_s	0.265	0.375	0.324	-0.178	1.000

Indicators with strong correlations are highlighted in green.

7.4.3 Regression Analysis

Table 7.4 provides the mean and standard deviation values for all the indicators and the embodied energy of water supply datasets. Total population has the highest standard deviation, and embodied energy comes to the next. It indicates that total population and embodied energy datasets have large variances from the means. On the other hand, population density, percentage of urban land, percentage of agricultural land and percentage of surface water only have small variances from the means.

Table 7.4 Mean and standard deviation of all the indicator datasets and the embodied energy of water supply dataset

Variables	P	P_d	L_u	L_a	w_s	ee
Mean	60602.9	1.9E-01	1.2E-02	2.5E-01	5.3E-01	404.8
Stdev	58481.4	1.8E-01	1.3E-02	1.3E-01	4.7E-01	564.7

Means and standard deviations listed in Table 7.4 were used to normalize the datasets using Equation 7-3. After all datasets were normalized, a backward selection was applied. After the backward selection, population density and percentage of agricultural land were eliminated from the linear regression model. The elimination of population density can be explained by the correlation analysis that it is highly correlated with total population and percentage of urban land. On the other hand, percentage of agricultural land is eliminated because it is not strongly correlated with embodied energy. Agriculture irrigation mainly relies on freshwater withdrawal; hence, it does not directly impact the embodied energy of water supply. The water quality deterioration resulted from fertilizer and pesticides use may not impact the water treatment to an extent to change the treatment technologies. The function of natural environmental buffer might have also reduced the impacts of agriculture on water quality. According to Table 7.3, percentage of surface water supply also has a weak correlation with the embodied energy; however, theoretically water source is correlated with the embodied energy of water supply because it determines the treatment technologies. This theoretical correlation was proven to be true in the regression model, although the impact of the water source is small compared with total population and percentage of urban land. Part of the reason is that embodied energy intensities in supplying groundwater and surface water do not vary a lot on volumetric basis.

After the backward selection, a linear regression model was established, and it is provided in Equation 7-6.

$$f(ee) = a \cdot f(P) + b \cdot f(L_u) + c \cdot f(w_s) + d \qquad (7\text{-}6)$$

where,

$f(ee)$ = Normalized embodied energy of water supply data;

$f(P)$ = Normalized total population data;

$f(L_u)$ = Normalized percentage of urban land data;

$f(w_s)$ = Normalized percentage of surface water supply data;

a = Linear regression factor a, 4.18×10^{-1};

b = Linear regression factor b, 5.36×10^{-1};

c = Linear regression factor c, -1.48×10^{-1};

d = Linear regression factor d, -1.65×10^{-5}.

7.5 Model Validation

After the regression model was established, leave-one-out cross validation was carried out in the R software. Table 7.5 provides the sum square, mean square, F value and Pr value for all the selected indicators and residuals during the leave-one-out cross validation. Total population has the largest variance, while percentage of surface water supply has the smallest variance according the sum square and mean square values. The Pr values of all the selected indicators are smaller than 0.05, which shows all the selected indicators are statistically significant. Figure 7.7 further provides the comparison between actual embodied energy and predicted embodied energy for all the observations. All the data points falling on the line as shown in Figure 7.7 are with equal x-axis and y-axis values, which mean the predicted embodied energy values equal the actual embodied energy values. The R squared value was calculated to be 0.76. It shows that the regression model has a good prediction capability.

Table 7.5 Sum square, mean square, F value and Pr value for all the selected indicators and residuals during the leave-one-out cross validation

Variables	Sum Square	Mean Square	F value	Pr(>F)
P	49.1	49.1	195.59	< 2e-16
L_u	6.3	6.3	25.2	3.60E-06
w_s	1.5	1.5	5.84	0.018
residuals	18.1	0.3		

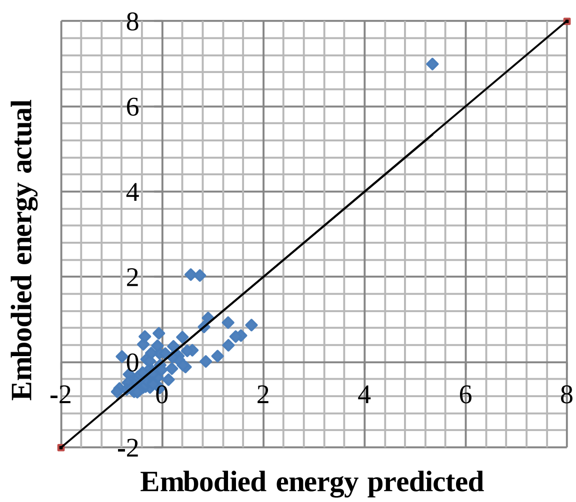


Figure 7.7 Comparison between actual embodied energy and predicted embodied energy for all the observations

7.6 Conclusions

This study examined the correlations between population, land use and water source indicators and the embodied energy of water supply in North Carolina. Embodied energy of well construction and operation is concentrated in east North Carolina, while embodied energy of surface water intake infrastructure construction and operation is concentrated in west North Carolina. This is consistent with water source distribution. Other types of water infrastructure are more evenly distributed. Overall, water distribution consumes the highest amount of embodied energy, while water treatment plant comes to the next. Water intake infrastructures consume least embodied energy, while surface water intake infrastructures consume more energy than wells. Counties with the highest total embodied energy are Forsyth and Burke, while Buncombe, Johnston, Pitt, Craven, Brunswick and Robeson come to the next.

In the correlation analysis, it was found that total population, population density and percentage of urban land have strong correlations between each other, but percentage of agricultural land and percentage of surface water supply do not have strong correlations with the rest of the indicators.

In the regression analysis, total population, percentage of urban land and percentage of surface water supply were selected through a backward selection process as statistically significant. A linear regression model was established after the backward selection. The cross validation of the model shows that the model has a good prediction capability.

This study is a preliminary attempt to describe the embodied energy of water supply by indicators of population, percentage of urban land, and percentage of surface water supply. This study might have not exhaust all the possible impact factors of embodied energy, but the regression model gives a good embodied energy prediction capability based on selected indicators. Often, data for these three indicators are easy to obtain, while estimating embodied energy for a region would be very time consuming and data intensive. Hence, this model provides an alternative way to quickly estimate embodied energy of water supply in a region and can be used as a supporting tool for decision making and urban planning.

Future studies may focus on including more impact factors, such climate change on temporal scale for model perfection. Moreover, this model need to be further adjusted for application in other areas other than North Carolina.

7.7 References

Aitken, A.C., 1957. Statistical Mathematics. Oliver and Boyd.

Akaike, H., 1974. A new look at the statistical model identification, Automatic Control 19, 716-723.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environ. Change 14, 31-52.

Bakhshi, A.A., deMonsabert, S.M., 2009. A GIS Methodology for Estimating the Carbon Footprint in Municipal Water and Wastewater in Fairfax County, Virginia, Energy Engineering 106, 7-24.

Cawley, G.C., Talbot, N.L.C., 2003. Efficient leave-one-out cross-validation of kernel Fisher discriminant classifiers, Pattern Recognit 36, 2585-2592.

Claessens, L., Hopkinson, C.S., Rastetter, E.B., Vallino, J.J., 2006. Effect of historical changes in land use and climate on the water budget of an urbanizing watershed, Water Resources Research, 42, W03426, doi:10.1029/2005WR004131.

Croxton, F.E., Cowden, D.J., 1939. Applied general statistics, Prentice-Hall, Inc. New York.

Dietrich, C.F., 1991. Uncertainty, Calibration, and Probability: The Statistics of Scientific and Industrial Measurement. Taylor & Francis.

Dinar, A., 1994. Impact of energy cost and water resource availability on agriculture and ground water quality in California, Resource and energy economics 16, 47-66.

Ehrlich, P.R., Holdren, J.P., 1971. Impact of population growth, Science 171, 1212-1217.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., 2005. Global consequences of land use, Science 309, 570-574.

Geology, 2012. North Carolina Physical Map, http://geology.com/topographic-physical-map/north-carolina.shtml (last accessed on 9/13/2012).

Gleick, P.H., 2000. Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. Pacific Institute for Studies in Development, Environment, and Security.

Hennekens, C.H., Buring, J.E., Mayrent, S.L., 1987. Epidemiology in Medicine. Lippincott Williams & Wilkins.

Johnes, P., Heathwaite, A., 1997. Modelling the impact of land use change on water quality in agricultural catchments, Hydrological Processes 11, 269-286.

Juahir, H., Zain, S.M., Aris, A.Z., Yusoff, M.K., Mokhtar, M.B., 2010. Spatial assessment of Langat river water quality using chemometrics, Journal of Environmental Monitoring 12, 287-295.

Karl, T., Koss, W.J., National Climatic Data Center (US), 1984. Regional and National Monthly, Seasonal, and Annual Temperature Weighted by Area, 1895-1983. National Climatic Data Center.

Karl, T.R., Melillo, J.M., 2009. Global Climate Change Impacts in the United States. Cambridge University Press.

Lenat, D.R., Crawford, J.K., 1994. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams, Hydrobiologia 294, 185-199.

Mallows, C.L., 1973. Some comments on Cp, Technometrics , 661-675.

Meigh, J., McKenzie, A., Sene, K., 1999. A grid-based approach to water scarcity estimates for eastern and southern Africa, Water Resources Management 13, 85-115.

Mo, W., Zhang, Q., Mihelcic, J.R., Hokanson, D.R., 2011. Embodied energy comparison of surface water and groundwater supply options, Water Research 45, 5577-5586.

Myers, R.H., 1990. Classical and Modern Regression with Applications. Duxbury Press Belmont, California.

NCCGIA, 1997a. North Carolina Corporate Geographic Database, Comprehensive land cover mapping for the State of North Carolina, 2012.

NCCGIA, 1997b. The source of the Land Cover - 1996, Raster data is the North Carolina Corporate Geographic Database, 2012.

NCREDC, 2000. The source of the Water Systems - water treatment plant data is the North Carolina Corporate Geographic Database, 2012.

Shortell, T., 2001. An introduction to data analysis & presentation, 2012.

Sliva, L., Dudley Williams, D., 2001. Buffer zone versus whole catchment approaches to studying land use impact on river water quality, Water Research 35, 3462-3472.

Sun, G., McNulty, S.G., Moore Myers, J.A., Cohen, E.C., 2008. Impacts of Multiple Stresses on Water Demand and Supply Across the Southeastern United States1, JAWRA Journal of the American Water Resources Association 44, 1441-1457.

Tong, S.T.Y., Chen, W., 2002. Modeling the relationship between land use and surface water quality, Journal of Environmental Management 66, 377-393.

USCB, 2012. US Census TIGER/Line Shapefiles, 2012.

Vieira, F., Ramos, H.M., 2009. Optimization of operational planning for wind/hydro hybrid water supply systems, Renewable Energy 34, 928-936.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth, Science 289, 284-288.

Whitehead, P., Wilby, R., Battarbee, R., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality, Hydrological Sciences Journal 54, 101-123.

Zimmerman, J.B., Mihelcic, J.R., Smith, J., 2008. Global stressors on water quality and quantity, Environmental Science and Technology 42, 4247-4254.

CHAPTER 8: CONCLUSIONS AND FUTURE STUDY

8.1 Conclusions

In this dissertation study, an input-output-based hybrid embodied energy model was developed. This model was used in three different applications for analyzing the energy burden on the existed water infrastructures. The correlation between embodied energy in regional water supply systems and demographic and environmental characteristics were also investigated. The following are the major research contributions of this dissertation.

An input-output-based hybrid embodied energy model under the US context which improved the previous life cycle embodied energy model and process-based hybrid embodied energy model, was developed in this study (Chapter 2). This model is flexible in terms of data availability. It can give a rough estimation of embodied energy in water systems with limited data input such as system capacity or capital and O&M cost of the system. Given more site specific data, the model can modify the embodied energy of different energy paths involved in water related sectors. The results can be more accurate and specific for the system evaluated. Overall, the model is easy to be applied for estimating either individual or regional embodied energy of water systems, and can be used to assist local and regional water and energy management. Furthermore, the methodology behind this model can also be used to assess embodied energy of other economic sectors in the US.

The importance of indirect energy was demonstrated by this study. Through applying the input-output-based hybrid embodied energy model on both water supply systems and wastewater treatment systems (Chapters 3, 4 and 6), it was shown that indirect energy accounts for a significant proportion (around 50% for both system construction and operation phases) of the total embodied energy of water systems. Hence, the indirect energy should not be simply neglected when estimating the energy burden of water systems, especially when optimizing existed and planned water infrastructures.

A comparison of estimated embodied energy among different water sources was conducted, with a focus on embodied energy of surface water supply and groundwater supply (Chapter 4). The comparison shows that different water sources have different embodied energy intensities. Desalination is the most energy intensive option among all the water sources. Surface and groundwater supply have comparable volumetric embodied energy intensities, but surface water supply has higher indirect energy intensity, while the groundwater supply has higher direct energy intensity. The embodied energy and benefits of reclaimed water depend on local situations and additional treatment needed to ensure treated wastewater suitable for the desired application.

A comparison of estimated embodied energy of similar water supply systems in the US and China reveals differences in direct and indirect energy compositions under different economic context (Chapter 4). It also points out the different aspects that each system can focus on in order to improve embodied energy efficiency. The China system can focus on improving its direct energy efficiency by conducting energy budgets and adopting energy saving technologies, while the US system can focus on improving its indirect energy efficiency by minimizing material and labor consumptions and shortening project timelines.

A review on the current resource recovery technologies in wastewater treatment systems reveals that there are very limited life cycle studies on the resource recovery technologies applied in the municipal wastewater treatment systems (Chapter 5). Furthermore, there has not been any life cycle studies or embodied energy analysis for the integrated resource recovery in wastewater treatment systems while some technologies apparently have trade-offs between the resource investments and resource recovery benefits. This review shows that there is a need for the integrated resource recovery analysis in order to evaluate the sustainability and resource recovery potential of municipal wastewater treatment systems.

An integrated resource recovery study was carried out for a large scale advanced municipal wastewater treatment system to determine the potential of this system to achieve carbon neutrality (Chapter 6). This study evaluated the resource recovery potentials of onsite energy generation through combined heat and power systems, nutrient recycling through heat dried biosolids land application and water reuse for residential irrigation. This study also revealed that the integration of the above three resource recovery methods has the potential to offset the direct operational energy and the associated carbon footprint of the selected wastewater treatment system, but it cannot offset the total embodied energy to achieve carbon neutrality even under maximal recovery conditions. This study provides insights into the current resource recovery practices in wastewater treatment systems beyond traditional financial analysis. It also shows other resource recovery strategies have to be incorporated to improve the sustainability of large scale wastewater treatment systems

A study on the correlation between embodied energy in regional water supply systems and demographic and environmental characteristics shows that energy embodied in water supply systems in a region is related to population growth, land use patterns, especially percentage of urban land, and water sources (Chapter 7). This part of study is a preliminary attempt to describe the embodied energy of water supply by demographic and environmental indicators. This study does not exhaust all the possible impact factors of embodied energy, while the regression model developed gives a good prediction capability. Hence, this model provides an alternative way to quickly estimate embodied energy of water supply in a region and can be used as a supporting tool for decision making and planning.

8.2 Future Study

8.2.1 Improve Model Applicability with User Interface

The model was developed using Matlab and difficult to be accessed by general public users. To improve the applicability of the model, a user interface can be developed so that general public or utilities without detailed knowledge of the model can easily apply it. The model should include user friendly input interface and visual output interface. The input interface should be flexible by defining mandatory and optional user inputs and providing default values and estimation equations so the users can apply the model with limited data availability. Accordingly, the embodied energy estimation can have different degrees of accuracy depending on methods used to determine the input parameters.

For the water-energy model, the mandatory user inputs shall include, but are not limited to source of water, total operational and constructional cost either directly obtained from utilities or estimated with system parameters. The optional user inputs include operational and constructional direct energy consumptions (e.g., electricity for pumping, natural gas for heating), costs of different types of materials, costs of administrative and labor services and so on. Outputs from the model, including direct, indirect and total embodied energy of systems, top sectors and energy paths contributing to the embodied energy of the system, can be presented in tabular or graphical format. Furthermore, the model shall be able to provide information such as which process or part of the water/wastewater treatment system is the most embodied energy intensive, how is the energy intensity of an individual system compared with the US or world average values, and how can a system reduce its embodied energy. Hence, this interactive embodied energy model would serve as a useful management tool for water systems planning and administration.

8.2.2 Link Water Quality with Embodied Energy of Water Supply through Unit Treatment Processes

This dissertation study compared the embodied energy of water supply with different raw water sources, but it did not link to water quality. Future study should explore the relationship between water quality and embodied energy in water supply.

In order to achieve this goal, the following research tasks have to be carried out: (a) Select indicators that can be best used to represent water quality; (b) Compile most commonly used treatment trains for different water quality through literature review and expert consultation; (c) Investigate the relationship between water indicators and energy and material consumption of each unit process in different treatment trains; (d) Analyze the embodied energy of each unit process based on energy and material consumption; (e) Establish the relationship between raw water quality and the estimated embodied energy of unit processes. This information will be useful for water utilities in evaluating existing treatment trains and planning for system expansion or new system adoption.

8.2.3 Further Explore Resource Recovery in Wastewater Treatment Systems

This dissertation study mainly examined the resource recovery potential of onsite energy generation through CHPs, nutrient recycling through biosolids land application, and water reuse for residential irrigation through a case study in Florida. Further studies can be carried out to (a) include other resource recovery technologies, such as onsite wind and solar energy and effluent hydropower, or substitute the existing resource recovery methods with other methods in the Howard Curren wastewater treatment plant to examine the potential of resource recovery in the plant; (b) expand the study to systems with capacities and treatment technologies different from the Howard Curren wastewater treatment plant, and examine the benefits and limitations of resource recovery technologies under different capacities and technologies; (c) study the tradeoffs between different resource recovery methods, and between different technologies.

8.2.4 Embodied Energy of Water/Wastewater Systems under Climate Change

This dissertation study explored the embodied energy of water supply systems with different water sources and under different economic context, but the geographical and climate differences among these water systems were not considered. On spatial scale, climate differs considerably both globally and nationally. In the US, specifically, the west part of the country is drier while the east part of the country is more humid. On temporal scale, the impacts of climate change on the environment and society have been observed and attracted much attention.

Climate impacts water/wastewater treatment systems mainly through changes of precipitation and temperature. For example, water conveyance systems would be very energy intensive under desert climate. Energy consumption on water conveyance in South California is 8.28 J/m3 of raw water, much higher than other regions in the US (Olsson, 2011). Increased precipitation may cause flooding and increase the urban runoff, which further impact water quality. While studies in this dissertation have addressed problems such as energy burden of different water sources and economic structures, it can be very important and also interesting to incorporate climate change as a stressor for further studies.

When incorporating climate changes, the study should be able to answer the following questions: (a) How significant can climate change impact on energy burdens of water supply systems and wastewater systems? (b) How will spatial and temporal climate changes impact the resource recovery strategies in wastewater treatment systems, especially the water reuse strategies?

The first question can be addressed by analyzing similar water/wastewater systems under different climate conditions to establish an empirical correlation between climate change and embodied energy of water systems. The second question can be achieved by analyzing the impact of climate conditions on resource recovery technologies and the climate-related limitations of each technology. This study will provide basis for further study on policy and management implications of resource recovery under different climate conditions.

8.2.5 Further Explore the Correlation between Embodied Energy of Water Systems and Water Stressors

The last chapter of the dissertation was a preliminary attempt to describe the embodied energy of water supply by demographic and environmental indicators. A linear regression model was developed to describe the embodied energy of water supply as a function of population, land use and water source. Although the linear regression model has a capability of roughly predicting the embodied energy based on these indicators, water stressors and associated indicators considered by this study are very limited, and thus, the accuracy of the model can be further improved. Moreover, the regression model was only developed for North Carolina based on county scale; however, the applicability of the model to other geographical areas and/or other scales was not evaluated.

Future studies may focus on: (a) a more thorough search of impact factors, such as climate change, economic development, water quality and so on; (b) model calibration for different scales and geographical locations; (c) model expansion to further include energy associated water-related end use and wastewater systems.

To carry on the above proposed studies, extensive data are needed. Possible data sources include state or county GIS databases, US Bureau of Census, Department of Energy, state or county government agencies. A similar statistical analysis as described in Chapter 7 can be carried out, and the regression model can be calibrated for other scales and geographical locations with the required data.

8.3 References

Olsson, G., 2011. Water and Energy Nexus, Encyclopedia of Sustainability Science and Technology, Springer Verlag.

APPENDICES

Appendix A Additional Tables

Table A.1 Direct, indirect and total embodied energy intensities of the non-energy commodity sectors in the US input-output tables

NAICS IO code	Name of the Commodity Sector	Direct Energy Intensity (GJ/$)	Indirect Energy Intensity (GJ/$)	Total Embodied Energy Intensity (GJ/$)
1111A0	Oilseed farming	1.16E-02	8.43E-03	2.00E-02
1111B0	Grain farming	1.63E-02	1.31E-02	2.94E-02
111200	Vegetable and melon farming	1.43E-02	7.01E-03	2.13E-02
1113A0	Fruit farming	1.38E-02	6.56E-03	2.04E-02
111335	Tree nut farming	1.47E-02	6.22E-03	2.09E-02
111400	Greenhouse, nursery, and floriculture production	1.68E-02	5.26E-03	2.21E-02
111910	Tobacco farming	2.35E-02	1.17E-02	3.52E-02
111920	Cotton farming	2.11E-02	1.79E-02	3.90E-02
1119A0	Sugarcane and sugar beet farming	2.01E-02	8.43E-03	2.86E-02
1119B0	All other crop farming	2.63E-02	9.73E-03	3.61E-02
1121A0	Cattle ranching and farming	9.64E-03	1.95E-02	2.92E-02
112120	Dairy cattle and milk production	1.32E-02	1.22E-02	2.54E-02
112A00	Animal production, except cattle and poultry and eggs	1.04E-02	8.97E-03	1.94E-02
112300	Poultry and egg production	1.51E-02	1.84E-02	3.36E-02
113A00	Forest nurseries, forest products, and timber tracts	7.85E-03	8.02E-03	1.59E-02
113300	Logging	1.63E-03	7.75E-03	9.38E-03
114100	Fishing	2.10E-02	4.90E-03	2.59E-02
114200	Hunting and trapping	7.58E-03	5.84E-03	1.34E-02
115000	Support activities for agriculture and forestry	4.14E-03	1.16E-02	1.57E-02
212210	Iron ore mining	5.41E-02	9.76E-03	6.39E-02
2122A0	Gold, silver, and other metal ore mining	2.83E-02	7.29E-03	3.56E-02

Appendix A (continued)

Table A.1 (continued)

212230	Copper, nickel, lead, and zinc mining	3.48E-02	4.58E-03	3.94E-02
212310	Stone mining and quarrying	1.95E-02	5.52E-03	2.50E-02
212320	Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	2.51E-02	5.54E-03	3.06E-02
212390	Other nonmetallic mineral mining and quarrying	3.29E-02	5.63E-03	3.85E-02
213111	Drilling oil and gas wells	5.40E-03	1.07E-02	1.61E-02
213112	Support activities for oil and gas operations	5.76E-03	6.78E-03	1.25E-02
21311A	Support activities for other mining	1.04E-02	9.04E-03	1.94E-02
221300	Water, sewage and other systems	8.96E-03	5.28E-03	1.42E-02
230101	Nonresidential commercial and health care structures	3.68E-03	5.62E-03	9.29E-03
230102	Nonresidential manufacturing structures	3.42E-03	4.39E-03	7.81E-03
230103	Other nonresidential structures	5.87E-03	5.85E-03	1.17E-02
230201	Residential permanent site single- and multi-family structures	3.56E-03	8.13E-03	1.17E-02
230202	Other residential structures	3.42E-03	7.71E-03	1.11E-02
230301	Nonresidential maintenance and repair	4.94E-03	5.97E-03	1.09E-02
230302	Residential maintenance and repair	2.31E-03	8.42E-03	1.07E-02
311111	Dog and cat food manufacturing	5.90E-03	1.35E-02	1.94E-02
311119	Other animal food manufacturing	6.54E-03	1.76E-02	2.42E-02
311210	Flour milling and malt manufacturing	1.20E-02	1.49E-02	2.68E-02
311221	Wet corn milling	3.26E-02	1.60E-02	4.86E-02
31122A	Soybean and other oilseed processing	8.59E-03	1.78E-02	2.64E-02
311225	Fats and oils refining and blending	7.76E-03	1.85E-02	2.62E-02
311230	Breakfast cereal manufacturing	5.58E-03	9.73E-03	1.53E-02
31131A	Sugar cane mills and refining	1.23E-02	2.08E-02	3.32E-02
311313	Beet sugar manufacturing	1.95E-02	1.77E-02	3.71E-02

Appendix A (continued)

Table A.1 (continued)

311320	Chocolate and confectionery manufacturing from cacao beans	4.64E-03	1.57E-02	2.04E-02
311330	Confectionery manufacturing from purchased chocolate	4.59E-03	1.29E-02	1.75E-02
311340	Nonchocolate confectionery manufacturing	5.06E-03	1.42E-02	1.93E-02
311410	Frozen food manufacturing	7.87E-03	1.30E-02	2.09E-02
311420	Fruit and vegetable canning, pickling, and drying	6.87E-03	1.22E-02	1.90E-02
31151A	Fluid milk and butter manufacturing	5.82E-03	1.66E-02	2.24E-02
311513	Cheese manufacturing	5.12E-03	1.86E-02	2.37E-02
311514	Dry, condensed, and evaporated dairy product manufacturing	6.22E-03	1.67E-02	2.30E-02
311520	Ice cream and frozen dessert manufacturing	5.06E-03	1.39E-02	1.89E-02
31161A	Animal (except poultry) slaughtering, rendering, and processing	4.82E-03	1.91E-02	2.40E-02
311615	Poultry processing	5.25E-03	1.86E-02	2.39E-02
311700	Seafood product preparation and packaging	7.93E-03	1.50E-02	2.29E-02
311810	Bread and bakery product manufacturing	6.88E-03	9.33E-03	1.62E-02
311820	Cookie, cracker and pasta manufacturing	5.15E-03	1.22E-02	1.74E-02
311830	Tortilla manufacturing	1.05E-02	1.02E-02	2.06E-02
311910	Snack food manufacturing	5.15E-03	1.31E-02	1.82E-02
311920	Coffee and tea manufacturing	3.97E-03	1.35E-02	1.75E-02
311930	Flavoring syrup and concentrate manufacturing	1.79E-03	6.08E-03	7.86E-03
311940	Seasoning and dressing manufacturing	3.70E-03	1.46E-02	1.83E-02
311990	All other food manufacturing	7.27E-03	1.19E-02	1.92E-02
312110	Soft drink and ice manufacturing	3.77E-03	1.53E-02	1.90E-02
312120	Breweries	4.79E-03	1.21E-02	1.69E-02
312130	Wineries	3.51E-03	9.99E-03	1.35E-02
312140	Distilleries	2.62E-03	4.89E-03	7.50E-03

Appendix A (continued)

Table A.1 (continued)

3122A0	Tobacco product manufacturing	1.87E-03	4.23E-03	6.10E-03
313100	Fiber, yarn, and thread mills	1.15E-02	2.16E-02	3.31E-02
313210	Broadwoven fabric mills	1.10E-02	1.51E-02	2.62E-02
313220	Narrow fabric mills and schiffli machine embroidery	6.65E-03	1.32E-02	1.98E-02
313230	Nonwoven fabric mills	9.75E-03	1.57E-02	2.55E-02
313240	Knit fabric mills	9.52E-03	1.59E-02	2.54E-02
313310	Textile and fabric finishing mills	9.78E-03	1.41E-02	2.39E-02
313320	Fabric coating mills	7.27E-03	1.57E-02	2.30E-02
314110	Carpet and rug mills	4.50E-03	1.99E-02	2.44E-02
314120	Curtain and linen mills	3.82E-03	1.30E-02	1.68E-02
314910	Textile bag and canvas mills	1.97E-03	1.04E-02	1.23E-02
314990	All other textile product mills	5.89E-03	1.39E-02	1.97E-02
315100	Apparel knitting mills	5.65E-03	1.08E-02	1.64E-02
315210	Cut and sew apparel contractors	5.37E-03	5.16E-03	1.05E-02
315220	Men's and boys' cut and sew apparel manufacturing	2.53E-03	8.97E-03	1.15E-02
315230	Women's and girls' cut and sew apparel manufacturing	3.25E-03	1.04E-02	1.36E-02
315290	Other cut and sew apparel manufacturing	2.66E-03	8.95E-03	1.16E-02
315900	Apparel accessories and other apparel manufacturing	1.08E-02	9.25E-03	2.00E-02
316100	Leather and hide tanning and finishing	3.72E-03	1.68E-02	2.05E-02
316200	Footwear manufacturing	3.33E-03	1.04E-02	1.37E-02
316900	Other leather and allied product manufacturing	3.26E-03	8.54E-03	1.18E-02
321100	Sawmills and wood preservation	6.04E-03	8.72E-03	1.48E-02
32121A	Veneer and plywood manufacturing	8.09E-03	8.71E-03	1.68E-02
32121B	Engineered wood member and truss manufacturing	2.67E-03	8.53E-03	1.12E-02
321219	Reconstituted wood product manufacturing	2.19E-02	1.08E-02	3.27E-02
321910	Wood windows and doors and millwork	3.54E-03	9.62E-03	1.32E-02
321920	Wood container and pallet manufacturing	5.94E-03	8.64E-03	1.46E-02

Appendix A (continued)

Table A.1 (continued)

321991	Manufactured home (mobile home) manufacturing	1.27E-03	1.16E-02	1.29E-02
321992	Prefabricated wood building manufacturing	1.46E-03	9.38E-03	1.08E-02
321999	All other miscellaneous wood product manufacturing	5.67E-03	8.34E-03	1.40E-02
322110	Pulp mills	2.41E-02	9.89E-03	3.40E-02
322120	Paper mills	2.00E-02	9.90E-03	2.98E-02
322130	Paperboard mills	3.10E-02	8.50E-03	3.95E-02
322210	Paperboard container manufacturing	5.21E-03	1.75E-02	2.27E-02
32222A	Coated and laminated paper, packaging paper and plastics film manufacturing	5.31E-03	1.47E-02	2.00E-02
32222B	All other paper bag and coated and treated paper manufacturing	4.34E-03	1.68E-02	2.11E-02
322230	Stationery product manufacturing	3.33E-03	1.47E-02	1.80E-02
322291	Sanitary paper product manufacturing	1.04E-02	9.77E-03	2.01E-02
322299	All other converted paper product manufacturing	6.24E-03	1.33E-02	1.95E-02
323110	Printing	4.46E-03	8.73E-03	1.32E-02
323120	Support activities for printing	3.20E-03	5.47E-03	8.67E-03
324121	Asphalt paving mixture and block manufacturing	7.85E-02	6.73E-03	8.52E-02
324122	Asphalt shingle and coating materials manufacturing	4.58E-02	8.61E-03	5.44E-02
324191	Petroleum lubricating oil and grease manufacturing	7.94E-02	6.93E-03	8.64E-02
324199	All other petroleum and coal products manufacturing	7.12E-02	4.76E-03	7.59E-02
325110	Petrochemical manufacturing	2.88E-02	1.58E-02	4.46E-02
325120	Industrial gas manufacturing	5.28E-02	7.64E-03	6.04E-02
325130	Synthetic dye and pigment manufacturing	3.12E-02	1.34E-02	4.46E-02
325181	Alkalies and chlorine manufacturing	5.97E-02	1.01E-02	6.99E-02
325182	Carbon black manufacturing	1.11E-01	2.76E-03	1.14E-01
325188	All other basic inorganic chemical manufacturing	3.23E-02	1.17E-02	4.40E-02

Appendix A (continued)

Table A.1 (continued)

325190	Other basic organic chemical manufacturing	3.11E-02	2.05E-02	5.17E-02
325211	Plastics material and resin manufacturing	2.20E-02	2.43E-02	4.64E-02
325212	Synthetic rubber manufacturing	1.76E-02	1.99E-02	3.75E-02
325220	Artificial and synthetic fibers and filaments manufacturing	1.71E-02	2.09E-02	3.80E-02
325310	Fertilizer manufacturing	5.61E-02	2.01E-02	7.63E-02
325320	Pesticide and other agricultural chemical manufacturing	6.40E-03	1.40E-02	2.04E-02
325411	Medicinal and botanical manufacturing	5.28E-03	5.23E-03	1.05E-02
325412	Pharmaceutical preparation manufacturing	2.03E-03	5.25E-03	7.29E-03
325413	In-vitro diagnostic substance manufacturing	3.06E-03	5.23E-03	8.29E-03
325414	Biological product (except diagnostic) manufacturing	2.84E-03	4.28E-03	7.12E-03
325510	Paint and coating manufacturing	3.73E-03	1.87E-02	2.24E-02
325520	Adhesive manufacturing	2.34E-02	1.45E-02	3.80E-02
325610	Soap and cleaning compound manufacturing	7.35E-03	1.04E-02	1.77E-02
325620	Toilet preparation manufacturing	6.22E-03	7.68E-03	1.39E-02
325910	Printing ink manufacturing	2.29E-02	1.81E-02	4.11E-02
3259A0	All other chemical product and preparation manufacturing	1.08E-02	1.49E-02	2.58E-02
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	8.25E-03	1.89E-02	2.72E-02
326121	Unlaminated plastics profile shape manufacturing	7.67E-03	1.55E-02	2.32E-02
326122	Plastic pipe and pipe fitting manufacturing	7.24E-03	2.22E-02	2.94E-02
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	7.68E-03	1.51E-02	2.28E-02
326140	Polystyrene foam product manufacturing	9.74E-03	1.67E-02	2.65E-02

Appendix A (continued)

Table A.1 (continued)

326150	Urethane and other foam product (except polystyrene) manufacturing	5.81E-03	1.79E-02	2.37E-02
326160	Plastics bottle manufacturing	1.20E-02	1.92E-02	3.12E-02
32619A	Other plastics product manufacturing	7.23E-03	1.30E-02	2.03E-02
326210	Tire manufacturing	6.82E-03	1.62E-02	2.30E-02
326220	Rubber and plastics hoses and belting manufacturing	5.53E-03	1.40E-02	1.95E-02
326290	Other rubber product manufacturing	6.42E-03	1.38E-02	2.02E-02
32711A	Pottery, ceramics, and plumbing fixture manufacturing	1.34E-02	7.66E-03	2.11E-02
32712A	Brick, tile, and other structural clay product manufacturing	3.29E-02	4.48E-03	3.74E-02
32712B	Clay and nonclay refractory manufacturing	1.45E-02	1.02E-02	2.47E-02
327211	Flat glass manufacturing	3.86E-02	8.18E-03	4.68E-02
327212	Other pressed and blown glass and glassware manufacturing	1.55E-02	1.01E-02	2.56E-02
327213	Glass container manufacturing	3.14E-02	7.72E-03	3.92E-02
327215	Glass product manufacturing made of purchased glass	1.01E-02	1.12E-02	2.13E-02
327310	Cement manufacturing	4.78E-02	7.10E-03	5.49E-02
327320	Ready-mix concrete manufacturing	4.29E-03	1.86E-02	2.28E-02
327330	Concrete pipe, brick and block manufacturing	4.84E-03	1.28E-02	1.77E-02
327390	Other concrete product manufacturing	4.09E-03	1.02E-02	1.43E-02
3274A0	Lime and gypsum product manufacturing	3.84E-02	1.14E-02	4.98E-02
327910	Abrasive product manufacturing	7.87E-03	7.10E-03	1.50E-02
327991	Cut stone and stone product manufacturing	5.21E-03	7.60E-03	1.28E-02
327992	Ground or treated mineral and earth manufacturing	1.95E-02	7.51E-03	2.70E-02
327993	Mineral wool manufacturing	2.22E-02	9.22E-03	3.14E-02
327999	Miscellaneous nonmetallic mineral products	8.71E-03	1.38E-02	2.25E-02

Appendix A (continued)

Table A.1 (continued)

331110	Iron and steel mills and ferroalloy manufacturing	3.81E-02	1.73E-02	5.54E-02
331200	Steel product manufacturing from purchased steel	1.76E-02	1.54E-02	3.30E-02
33131A	Alumina refining and primary aluminum production	4.07E-02	1.79E-02	5.86E-02
331314	Secondary smelting and alloying of aluminum	4.31E-02	1.77E-02	6.08E-02
33131B	Aluminum product manufacturing from purchased aluminum	9.01E-03	2.24E-02	3.14E-02
331411	Primary smelting and refining of copper	8.93E-03	1.75E-02	2.65E-02
331419	Primary smelting and refining of nonferrous metal (except copper and aluminum)	1.46E-02	1.47E-02	2.92E-02
331420	Copper rolling, drawing, extruding and alloying	6.33E-03	1.39E-02	2.03E-02
331490	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	8.13E-03	1.23E-02	2.04E-02
331510	Ferrous metal foundries	1.53E-02	8.30E-03	2.36E-02
331520	Nonferrous metal foundries	1.06E-02	1.32E-02	2.38E-02
33211A	All other forging, stamping, and sintering	1.29E-02	1.58E-02	2.86E-02
332114	Custom roll forming	3.84E-03	2.20E-02	2.58E-02
33211B	Crown and closure manufacturing and metal stamping	4.46E-03	1.47E-02	1.91E-02
33221A	Cutlery, utensil, pot, and pan manufacturing	3.61E-03	1.04E-02	1.40E-02
33221B	Handtool manufacturing	4.24E-03	1.11E-02	1.53E-02
332310	Plate work and fabricated structural product manufacturing	2.81E-03	1.44E-02	1.72E-02
332320	Ornamental and architectural metal products manufacturing	2.68E-03	1.38E-02	1.64E-02
332410	Power boiler and heat exchanger manufacturing	3.97E-03	1.15E-02	1.55E-02
332420	Metal tank (heavy gauge) manufacturing	3.72E-03	1.36E-02	1.73E-02

Appendix A (continued)

Table A.1 (continued)

332430	Metal can, box, and other metal container (light gauge) manufacturing	5.24E-03	1.87E-02	2.40E-02
33299A	Ammunition manufacturing	6.40E-03	6.51E-03	1.29E-02
33299B	Arms, ordnance, and accessories manufacturing	3.35E-03	6.52E-03	9.87E-03
332500	Hardware manufacturing	2.79E-03	9.94E-03	1.27E-02
332600	Spring and wire product manufacturing	4.57E-03	1.30E-02	1.76E-02
332710	Machine shops	4.25E-03	7.39E-03	1.16E-02
332720	Turned product and screw, nut, and bolt manufacturing	4.63E-03	9.69E-03	1.43E-02
332800	Coating, engraving, heat treating and allied activities	1.27E-02	1.22E-02	2.49E-02
33291A	Valve and fittings other than plumbing	3.37E-03	9.02E-03	1.24E-02
332913	Plumbing fixture fitting and trim manufacturing	3.31E-03	9.33E-03	1.26E-02
332991	Ball and roller bearing manufacturing	6.06E-03	9.20E-03	1.53E-02
332996	Fabricated pipe and pipe fitting manufacturing	3.52E-03	1.35E-02	1.71E-02
33299C	Other fabricated metal manufacturing	5.74E-03	1.17E-02	1.74E-02
333111	Farm machinery and equipment manufacturing	2.07E-03	1.08E-02	1.29E-02
333112	Lawn and garden equipment manufacturing	1.66E-03	1.08E-02	1.25E-02
333120	Construction machinery manufacturing	4.35E-03	1.05E-02	1.49E-02
333130	Mining and oil and gas field machinery manufacturing	3.13E-03	1.16E-02	1.48E-02
33329A	Other industrial machinery manufacturing	3.20E-03	9.68E-03	1.29E-02
333220	Plastics and rubber industry machinery manufacturing	2.65E-03	9.38E-03	1.20E-02
333295	Semiconductor machinery manufacturing	2.68E-03	7.80E-03	1.05E-02
33331A	Vending, commercial, industrial, and office machinery manufacturing	2.74E-03	9.86E-03	1.26E-02

Appendix A (continued)

Table A.1 (continued)

333314	Optical instrument and lens manufacturing	2.95E-03	7.38E-03	1.03E-02
333315	Photographic and photocopying equipment manufacturing	4.27E-03	9.72E-03	1.40E-02
333319	Other commercial and service industry machinery manufacturing	4.09E-03	8.61E-03	1.27E-02
33341A	Air purification and ventilation equipment manufacturing	2.71E-03	1.04E-02	1.31E-02
333414	Heating equipment, except warm air furnaces	3.05E-03	1.04E-02	1.34E-02
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	1.99E-03	9.76E-03	1.17E-02
333511	Industrial mold manufacturing	5.06E-03	8.93E-03	1.40E-02
33351A	Metal cutting and forming machine tool manufacturing	3.05E-03	8.37E-03	1.14E-02
333514	Special tool, die, jig, and fixture manufacturing	3.59E-03	9.14E-03	1.27E-02
333515	Cutting tool and machine tool accessory manufacturing	4.58E-03	7.84E-03	1.24E-02
33351B	Rolling mill and other metalworking machinery manufacturing	2.74E-03	7.78E-03	1.05E-02
333611	Turbine and turbine generator set units manufacturing	1.13E-03	6.99E-03	8.13E-03
333612	Speed changer, industrial high-speed drive, and gear manufacturing	4.53E-03	7.66E-03	1.22E-02
333613	Mechanical power transmission equipment manufacturing	4.74E-03	9.47E-03	1.42E-02
333618	Other engine equipment manufacturing	2.60E-03	1.07E-02	1.33E-02
333911	Pump and pumping equipment manufacturing	2.78E-03	9.30E-03	1.21E-02
333912	Air and gas compressor manufacturing	2.65E-03	9.43E-03	1.21E-02
333920	Material handling equipment manufacturing	2.37E-03	1.20E-02	1.44E-02
333991	Power-driven handtool manufacturing	2.02E-03	1.00E-02	1.20E-02

Appendix A (continued)

Table A.1 (continued)

33399A	Other general purpose machinery manufacturing	3.04E-03	9.45E-03	1.25E-02
333993	Packaging machinery manufacturing	1.94E-03	7.83E-03	9.78E-03
333994	Industrial process furnace and oven manufacturing	3.19E-03	7.52E-03	1.07E-02
33399B	Fluid power process machinery	3.47E-03	9.74E-03	1.32E-02
334111	Electronic computer manufacturing	5.66E-04	5.84E-03	6.41E-03
334112	Computer storage device manufacturing	2.66E-03	6.24E-03	8.89E-03
33411A	Computer terminals and other computer peripheral equipment manufacturing	1.65E-03	6.61E-03	8.26E-03
334210	Telephone apparatus manufacturing	1.19E-03	5.93E-03	7.12E-03
334220	Broadcast and wireless communications equipment	1.15E-03	6.15E-03	7.30E-03
334290	Other communications equipment manufacturing	2.08E-03	5.91E-03	7.99E-03
334300	Audio and video equipment manufacturing	1.80E-03	9.96E-03	1.18E-02
334411	Electron tube manufacturing	4.95E-03	1.14E-02	1.63E-02
334412	Bare printed circuit board manufacturing	5.84E-03	7.84E-03	1.37E-02
334413	Semiconductor and related device manufacturing	4.50E-03	6.94E-03	1.14E-02
33441A	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing	5.09E-03	8.33E-03	1.34E-02
334417	Electronic connector manufacturing	3.90E-03	8.89E-03	1.28E-02
334418	Printed circuit assembly (electronic assembly) manufacturing	1.81E-03	7.12E-03	8.93E-03
334419	Other electronic component manufacturing	3.23E-03	7.23E-03	1.05E-02
334510	Electromedical and electrotherapeutic apparatus manufacturing	1.13E-03	6.82E-03	7.95E-03

Appendix A (continued)

Table A.1 (continued)

334511	Search, detection, and navigation instruments manufacturing	2.58E-03	4.92E-03	7.49E-03
334512	Automatic environmental control manufacturing	2.28E-03	7.58E-03	9.87E-03
334513	Industrial process variable instruments manufacturing	2.12E-03	7.53E-03	9.65E-03
334514	Totalizing fluid meters and counting devices manufacturing	1.63E-03	8.39E-03	1.00E-02
334515	Electricity and signal testing instruments manufacturing	1.89E-03	4.93E-03	6.82E-03
334516	Analytical laboratory instrument manufacturing	1.52E-03	6.21E-03	7.72E-03
334517	Irradiation apparatus manufacturing	1.39E-03	7.05E-03	8.44E-03
33451A	Other Measuring and Controlling Device Manufacturing	1.98E-03	6.37E-03	8.36E-03
33461A	Software, audio, and video media reproducing	4.20E-03	9.11E-03	1.33E-02
334613	Magnetic and optical recording media manufacturing	3.67E-03	8.71E-03	1.24E-02
335110	Electric lamp bulb and part manufacturing	4.61E-03	6.76E-03	1.14E-02
335120	Lighting fixture manufacturing	2.38E-03	9.42E-03	1.18E-02
335210	Small electrical appliance manufacturing	2.07E-03	9.83E-03	1.19E-02
335221	Household cooking appliance manufacturing	2.12E-03	1.33E-02	1.54E-02
335222	Household refrigerator and home freezer manufacturing	1.91E-03	1.33E-02	1.52E-02
335224	Household laundry equipment manufacturing	1.83E-03	1.16E-02	1.35E-02
335228	Other major household appliance manufacturing	2.13E-03	1.08E-02	1.29E-02
335311	Power, distribution, and specialty transformer manufacturing	2.73E-03	1.34E-02	1.61E-02
335312	Motor and generator manufacturing	2.84E-03	1.02E-02	1.31E-02
335313	Switchgear and switchboard apparatus manufacturing	1.85E-03	6.97E-03	8.81E-03

Appendix A (continued)

Table A.1 (continued)

335314	Relay and industrial control manufacturing	1.51E-03	5.81E-03	7.32E-03
335911	Storage battery manufacturing	7.81E-03	1.19E-02	1.97E-02
335912	Primary battery manufacturing	2.29E-03	9.01E-03	1.13E-02
335920	Communication and energy wire and cable manufacturing	3.76E-03	1.28E-02	1.66E-02
335930	Wiring device manufacturing	3.68E-03	1.01E-02	1.38E-02
335991	Carbon and graphite product manufacturing	1.41E-02	1.37E-02	2.78E-02
335999	All other miscellaneous electrical equipment and component manufacturing	2.18E-03	6.36E-03	8.54E-03
336111	Automobile Manufacturing	1.00E-03	1.04E-02	1.14E-02
336112	Light truck and utility vehicle manufacturing	1.01E-03	1.12E-02	1.22E-02
336120	Heavy duty truck manufacturing	3.16E-03	1.12E-02	1.43E-02
336211	Motor vehicle body manufacturing	1.67E-03	9.88E-03	1.16E-02
336212	Truck trailer manufacturing	2.12E-03	1.31E-02	1.53E-02
336213	Motor home manufacturing	8.35E-04	1.10E-02	1.18E-02
336214	Travel trailer and camper manufacturing	1.54E-03	1.32E-02	1.48E-02
336300	Motor vehicle parts manufacturing	2.74E-03	1.23E-02	1.50E-02
336411	Aircraft manufacturing	1.22E-03	6.82E-03	8.04E-03
336412	Aircraft engine and engine parts manufacturing	2.40E-03	5.72E-03	8.12E-03
336413	Other aircraft parts and auxiliary equipment manufacturing	4.12E-03	7.28E-03	1.14E-02
336414	Guided missile and space vehicle manufacturing	1.69E-03	5.23E-03	6.92E-03
33641A	Propulsion units and parts for space vehicles and guided missiles	3.29E-03	4.92E-03	8.20E-03
336500	Railroad rolling stock manufacturing	1.75E-03	8.48E-03	1.02E-02
336611	Ship building and repairing	2.43E-03	6.79E-03	9.22E-03
336612	Boat building	1.76E-03	9.53E-03	1.13E-02
336991	Motorcycle, bicycle, and parts manufacturing	1.74E-03	1.27E-02	1.45E-02

Appendix A (continued)

Table A.1 (continued)

336992	Military armored vehicle, tank, and tank component manufacturing	2.53E-03	8.58E-03	1.11E-02
336999	All other transportation equipment manufacturing	1.26E-03	1.16E-02	1.28E-02
337110	Wood kitchen cabinet and countertop manufacturing	2.79E-03	8.73E-03	1.15E-02
337121	Upholstered household furniture manufacturing	1.78E-03	1.05E-02	1.23E-02
337122	Nonupholstered wood household furniture manufacturing	3.86E-03	7.83E-03	1.17E-02
33712A	Metal and other household furniture (except wood) manufacturing	3.67E-03	1.30E-02	1.67E-02
337127	Institutional furniture manufacturing	3.28E-03	1.00E-02	1.33E-02
33721A	Wood television, radio, and sewing machine cabinet manufacturing	2.83E-03	8.31E-03	1.11E-02
337212	Office furniture and custom architectural woodwork and millwork manufacturing	2.68E-03	8.89E-03	1.16E-02
337215	Showcase, partition, shelving, and locker manufacturing	4.16E-03	1.34E-02	1.76E-02
337910	Mattress manufacturing	1.34E-03	9.96E-03	1.13E-02
337920	Blind and shade manufacturing	2.29E-03	1.27E-02	1.50E-02
339111	Laboratory apparatus and furniture manufacturing	1.74E-03	7.30E-03	9.04E-03
339112	Surgical and medical instrument manufacturing	1.71E-03	5.35E-03	7.06E-03
339113	Surgical appliance and supplies manufacturing	1.78E-03	6.49E-03	8.26E-03
339114	Dental equipment and supplies manufacturing	1.61E-03	8.61E-03	1.02E-02
339115	Ophthalmic goods manufacturing	2.64E-03	5.05E-03	7.69E-03
339116	Dental laboratories	1.53E-03	3.78E-03	5.31E-03
339910	Jewelry and silverware manufacturing	1.13E-03	1.05E-02	1.17E-02

Appendix A (continued)

Table A.1 (continued)

339920	Sporting and athletic goods manufacturing	2.35E-03	1.02E-02	1.25E-02
339930	Doll, toy, and game manufacturing	2.40E-03	1.02E-02	1.26E-02
339940	Office supplies (except paper) manufacturing	2.79E-03	9.06E-03	1.18E-02
339950	Sign manufacturing	2.58E-03	9.64E-03	1.22E-02
339991	Gasket, packing, and sealing device manufacturing	5.08E-03	1.01E-02	1.51E-02
339992	Musical instrument manufacturing	2.79E-03	4.50E-03	7.29E-03
33999A	All other miscellaneous manufacturing	2.75E-03	1.00E-02	1.28E-02
339994	Broom, brush, and mop manufacturing	2.67E-03	8.87E-03	1.15E-02
420000	Wholesale trade	2.44E-03	2.31E-03	4.75E-03
4A0000	Retail trade	4.58E-03	2.45E-03	7.03E-03
481000	Air transportation	2.58E-02	3.03E-03	2.89E-02
482000	Rail transportation	8.43E-03	4.09E-03	1.25E-02
483000	Water transportation	2.52E-03	5.58E-03	8.10E-03
484000	Truck transportation	1.49E-02	5.31E-03	2.03E-02
485000	Transit and ground passenger transportation	3.59E-02	5.63E-03	4.15E-02
486000	Pipeline transportation	5.31E-02	4.32E-03	5.74E-02
48A000	Scenic and sightseeing transportation and support activities for transportation	5.91E-03	4.80E-03	1.07E-02
492000	Couriers and messengers	1.90E-02	3.07E-03	2.20E-02
493000	Warehousing and storage	9.56E-03	3.45E-03	1.30E-02
511110	Newspaper publishers	2.14E-03	5.18E-03	7.32E-03
511120	Periodical publishers	9.15E-04	5.49E-03	6.41E-03
511130	Book publishers	8.69E-04	4.10E-03	4.97E-03
5111A0	Directory, mailing list, and other publishers	9.13E-04	4.76E-03	5.67E-03
511200	Software publishers	1.27E-04	2.32E-03	2.45E-03
512100	Motion picture and video industries	1.69E-03	2.12E-03	3.81E-03
512200	Sound recording industries	1.30E-03	4.49E-03	5.80E-03

Appendix A (continued)

Table A.1 (continued)

515100	Radio and television broadcasting	1.29E-03	2.97E-03	4.26E-03
515200	Cable and other subscription programming	1.07E-03	3.23E-03	4.30E-03
516110	Internet publishing and broadcasting	5.40E-04	5.00E-03	5.54E-03
517000	Telecommunications	2.24E-03	2.79E-03	5.03E-03
518100	Internet service providers and web search portals	1.23E-03	2.81E-03	4.05E-03
518200	Data processing, hosting, and related services	5.33E-04	3.03E-03	3.56E-03
519100	Other information services	3.15E-03	2.41E-03	5.55E-03
52A000	Monetary authorities and depository credit intermediation	1.98E-04	1.53E-03	1.73E-03
522A00	Nondepository credit intermediation and related activities	9.01E-04	1.85E-03	2.75E-03
523000	Securities, commodity contracts, investments, and related activities	6.88E-04	1.83E-03	2.51E-03
524100	Insurance carriers	5.49E-05	1.62E-03	1.67E-03
524200	Insurance agencies, brokerages, and related activities	9.28E-04	2.12E-03	3.05E-03
525000	Funds, trusts, and other financial vehicles	2.77E-04	2.23E-03	2.51E-03
531000	Real estate	5.77E-03	1.61E-03	7.38E-03
S00800	Owner-occupied dwellings	1.13E-06	1.82E-03	1.82E-03
532100	Automotive equipment rental and leasing	9.64E-04	2.40E-03	3.36E-03
532A00	General and consumer goods rental except video tapes and discs	3.16E-03	2.66E-03	5.82E-03
532230	Video tape and disc rental	8.25E-03	3.81E-03	1.21E-02
532400	Commercial and industrial machinery and equipment rental and leasing	1.57E-03	3.01E-03	4.57E-03
533000	Lessors of nonfinancial intangible assets	4.02E-03	9.95E-04	5.01E-03
541100	Legal services	7.32E-04	1.72E-03	2.45E-03

Appendix A (continued)

Table A.1 (continued)

541200	Accounting, tax preparation, bookkeeping, and payroll services	1.08E-03	1.77E-03	2.85E-03
541300	Architectural, engineering, and related services	1.50E-03	2.63E-03	4.14E-03
541400	Specialized design services	1.12E-03	2.70E-03	3.82E-03
541511	Custom computer programming services	3.67E-03	1.65E-03	5.33E-03
541512	Computer systems design services	1.07E-03	3.00E-03	4.07E-03
54151A	Other computer related services, including facilities management	8.68E-04	2.31E-03	3.18E-03
541610	Management, scientific, and technical consulting services	5.13E-04	2.37E-03	2.88E-03
5416A0	Environmental and other technical consulting services	8.89E-04	2.20E-03	3.09E-03
541700	Scientific research and development services	3.37E-03	3.74E-03	7.11E-03
541800	Advertising and related services	1.68E-03	4.04E-03	5.72E-03
5419A0	All other miscellaneous professional, scientific, and technical services	1.22E-03	1.74E-03	2.96E-03
541920	Photographic services	2.36E-03	3.49E-03	5.85E-03
541940	Veterinary services	1.44E-03	4.72E-03	6.16E-03
550000	Management of companies and enterprises	2.33E-03	2.10E-03	4.43E-03
561300	Employment services	9.56E-04	1.26E-03	2.21E-03
561500	Travel arrangement and reservation services	2.81E-03	2.90E-03	5.71E-03
561100	Office administrative services	1.37E-03	2.52E-03	3.89E-03
561200	Facilities support services	2.12E-03	2.86E-03	4.98E-03
561400	Business support services	1.64E-03	2.91E-03	4.55E-03
561600	Investigation and security services	1.42E-03	2.32E-03	3.75E-03
561700	Services to buildings and dwellings	2.43E-02	2.91E-03	2.72E-02
561900	Other support services	2.96E-03	3.06E-03	6.02E-03
562000	Waste management and remediation services	3.76E-03	3.86E-03	7.62E-03

Appendix A (continued)

Table A.1 (continued)

611100	Elementary and secondary schools	5.22E-03	3.79E-03	9.00E-03
611A00	Junior colleges, colleges, universities, and professional schools	1.40E-02	3.90E-03	1.79E-02
611B00	Other educational services	1.51E-03	2.98E-03	4.50E-03
621A00	Offices of physicians, dentists, and other health practitioners	1.18E-03	2.53E-03	3.70E-03
621B00	Medical and diagnostic labs and outpatient and other ambulatory care services	2.22E-03	3.33E-03	5.56E-03
621600	Home health care services	2.55E-03	2.56E-03	5.12E-03
622000	Hospitals	4.40E-03	3.74E-03	8.14E-03
623000	Nursing and residential care facilities	5.45E-03	2.92E-03	8.37E-03
624A00	Individual and family services	1.96E-03	3.40E-03	5.36E-03
624200	Community food, housing, and other relief services, including rehabilitation services	3.64E-03	4.03E-03	7.66E-03
624400	Child day care services	3.49E-03	3.49E-03	6.98E-03
711100	Performing arts companies	1.39E-03	2.64E-03	4.03E-03
711200	Spectator sports	2.54E-03	2.91E-03	5.45E-03
711A00	Promoters of performing arts and sports and agents for public figures	2.45E-03	4.39E-03	6.84E-03
711500	Independent artists, writers, and performers	3.89E-04	1.88E-03	2.27E-03
712000	Museums, historical sites, zoos, and parks	9.88E-03	3.24E-03	1.31E-02
713A00	Amusement parks, arcades, and gambling industries	6.10E-03	2.86E-03	8.96E-03
713B00	Other amusement and recreation industries	8.60E-03	4.29E-03	1.29E-02
713940	Fitness and recreational sports centers	1.16E-02	3.57E-03	1.52E-02
713950	Bowling centers	1.83E-02	3.69E-03	2.20E-02
7211A0	Hotels and motels, including casino hotels	1.17E-02	3.28E-03	1.50E-02
721A00	Other accommodations	1.17E-02	3.18E-03	1.48E-02

Appendix A (continued)

Table A.1 (continued)

722000	Food services and drinking places	6.97E-03	5.30E-03	1.23E-02
8111A0	Automotive repair and maintenance, except car washes	2.85E-03	4.87E-03	7.72E-03
811192	Car washes	1.11E-02	3.17E-03	1.43E-02
811200	Electronic and precision equipment repair and maintenance	1.75E-03	2.86E-03	4.61E-03
811300	Commercial and industrial machinery and equipment repair and maintenance	2.57E-03	3.52E-03	6.08E-03
811400	Personal and household goods repair and maintenance	2.90E-03	4.08E-03	6.98E-03
812100	Personal care services	4.85E-03	2.74E-03	7.58E-03
812200	Death care services	5.00E-03	5.22E-03	1.02E-02
812300	Dry-cleaning and laundry services	6.52E-03	2.00E-03	8.51E-03
812900	Other personal services	2.39E-03	3.05E-03	5.44E-03
813100	Religious organizations	8.30E-04	3.26E-03	4.09E-03
813A00	Grantmaking, giving, and social advocacy organizations	1.35E-03	4.29E-03	5.64E-03
813B00	Civic, social, professional, and similar organizations	5.61E-03	4.08E-03	9.69E-03
814000	Private households	0.00E+00	0.00E+00	0.00E+00
491000	Postal service	3.58E-03	1.99E-03	5.56E-03
S00102	Other Federal Government enterprises	4.91E-03	1.65E-03	6.56E-03
S00203	Other State and local government enterprises	1.05E-02	5.95E-03	1.64E-02
S00500	General Federal defense government services	3.46E-03	2.91E-03	6.37E-03
S00600	General Federal nondefense government services	3.27E-03	3.28E-03	6.56E-03
S00700	General state and local government services	7.20E-03	3.69E-03	1.09E-02
S00401	Scrap	7.05E-03	8.29E-03	1.53E-02

Appendix A (continued)

Table A.2 Original and modified direct energy intensities for the 25 sectors with available data

Sector	Total energy use (GJ)	Industry output from Input-Output tables (Million $)	Direct energy intensity from process analysis (DEI1) (GJ/100$)	Direct energy intensity from input-output analysis (DEI2)(GJ /100$)	Change rate (DEI1/DEI2)
Wet Corn Milling	228947119	8231.1	2.78	4.86	0.57
Sugar	118166255	4211.6	2.81	3.32	0.85
Tobacco	21101117	47464.7	0.04	0.61	0.07
Pulp Mills	236332510	3509	6.74	3.40	1.98
Paper Mills	1156341212	45350.2	2.55	2.98	0.85
Paperboard Mills	957990712	21101.3	4.54	3.95	1.15
Petrochemicals	937944651	18693.8	5.02	4.46	1.12
Industrial Gases	215231393	5856.8	3.67	6.04	0.61
Alkalies and Chlorine	201515667	2751.9	7.32	6.99	1.05
Carbon Black	92844915	1032	9.00	11.37	0.79
Other Basic Inorganic Chemicals	230002175	15680.3	1.47	4.40	0.33
Other Basic Organic Chemicals	2101671253	54946.8	3.82	5.17	0.74
Plastics Materials and Resins	1921256703	46537.1	4.13	4.64	0.89
Synthetic Rubber	60138183	5341.9	1.13	3.75	0.30
Fertilizers	564454880	9911.9	5.69	7.63	0.75
Pharmaceutical Preparation	88624691	108636.9	0.08	0.73	0.11
Flat Glass	66468519	2648.6	2.51	4.68	0.54
Glass Containers	69633686	4364	1.60	3.92	0.41
Cements	431517843	7310.7	5.90	5.49	1.07
Lime	111835920	4885.9	2.29	4.98	0.46
Mineral Wool	54862904	4812.1	1.14	3.14	0.36
Iron and Steel Mills	1408499560	46570	3.02	5.54	0.55
Steel Products from Purchased Steel	47477513	14826.4	0.32	3.30	0.10
Semiconductors and Related Devices	70688742	60832.7	0.12	1.14	0.10
Light Trucks and Utility Vehicles	60138183	134261.3	0.04	1.22	0.04

Appendix A (continued)

Table A.3 Detailed annual expenses in the Kalamazoo Public Water Supply System

Phase	Items	Annual Expense (Million Dollars)	Related Original Total Energy (TJ)	Total Energy Modified (TJ)
Operation	Real Estate	0.88	2.94	7.50
	Water and Sewer	0.04	0.85	0.67
	Disinfectants	0.20	0.78	15.56
	Organic Chemicals	0.00	0.86	0.00
	Maintenance	1.90	6.10	35.37
	Telecommunication	0.10	0.08	0.62
	Postal Services	0.09	0.02	0.51
	Training and Education	0.01	0.02	0.12
	Engineering Services	0.24	1.50	1.85
Construction	Asphalt	0.30	53.02	18.21

Table A.4 Detailed annual expenses in the City of Tampa Waterworks

Phase	Items	Annual Expense (Million Dollars)	Related Original Total Energy (TJ)	Total Energy Modified (TJ)
Operation	Inorganic Chemicals	8.06	0.35	45.54
	Disinfectants	0.75	4.81	58.04
	Organic Chemicals	0.00	5.26	0.00
	Water	5.48	5.25	97.97
	Telecommunication	0.34	0.52	2.11
	Postal service	0.34	0.12	1.87
	Maintenance	8.22	37.55	153.09
	Engineering Service	4.48	9.23	34.51
Construction	Asphalt	0.00	186.32	0.00

Appendix A (continued)

Table A.5 Direct and total coal intensities of the non-energy sectors in the US input-output tables

NAICS IO code	Name of the Commodity Sector	Direct Coal Intensity(GJ/$)	Total Coal Intensity(GJ/$)
1111A0	Oilseed farming	0.00E+00	1.76E-04
1111B0	Grain farming	0.00E+00	2.75E-04
111200	Vegetable and melon farming	0.00E+00	1.62E-04
1113A0	Fruit farming	0.00E+00	1.64E-04
111335	Tree nut farming	0.00E+00	1.44E-04
111400	Greenhouse, nursery, and floriculture production	0.00E+00	9.39E-05
111910	Tobacco farming	0.00E+00	2.64E-04
111920	Cotton farming	0.00E+00	4.05E-04
1119A0	Sugarcane and sugar beet farming	0.00E+00	2.06E-04
1119B0	All other crop farming	0.00E+00	2.42E-04
1121A0	Cattle ranching and farming	0.00E+00	2.17E-04
112120	Dairy cattle and milk production	0.00E+00	3.31E-04
112A00	Animal production, except cattle and poultry and eggs	5.21E-07	1.89E-04
112300	Poultry and egg production	5.42E-03	6.88E-03
113A00	Forest nurseries, forest products, and timber tracts	2.57E-06	2.75E-04
113300	Logging	1.54E-05	1.47E-04
114100	Fishing	0.00E+00	1.44E-04
114200	Hunting and trapping	2.87E-06	4.11E-04
115000	Support activities for agriculture and forestry	2.74E-05	2.71E-04
212210	Iron ore mining	5.95E-03	7.71E-03
2122A0	Gold, silver, and other metal ore mining	3.66E-03	4.68E-03
212230	Copper, nickel, lead, and zinc mining	3.56E-03	4.16E-03
212310	Stone mining and quarrying	2.94E-03	3.55E-03
212320	Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	3.84E-03	4.60E-03
212390	Other nonmetallic mineral mining and quarrying	4.93E-03	5.66E-03

Appendix A (continued)

Table A.5 (continued)

213111	Drilling oil and gas wells	1.23E-03	2.66E-03
213112	Support activities for oil and gas operations	1.56E-03	2.41E-03
21311A	Support activities for other mining	2.06E-03	4.19E-03
221300	Water, sewage and other systems	1.18E-06	3.37E-04
230101	Nonresidential commercial and health care structures	0.00E+00	6.57E-04
230102	Nonresidential manufacturing structures	0.00E+00	5.13E-04
230103	Other nonresidential structures	0.00E+00	5.56E-04
230201	Residential permanent site single- and multi-family structures	0.00E+00	6.73E-04
230202	Other residential structures	0.00E+00	6.32E-04
230301	Nonresidential maintenance and repair	0.00E+00	5.01E-04
230302	Residential maintenance and repair	0.00E+00	6.21E-04
311111	Dog and cat food manufacturing	5.83E-04	1.29E-03
311119	Other animal food manufacturing	5.44E-04	1.10E-03
311210	Flour milling and malt manufacturing	6.94E-04	9.21E-04
311221	Wet corn milling	3.83E-03	4.11E-03
31122A	Soybean and other oilseed processing	1.05E-03	1.42E-03
311225	Fats and oils refining and blending	9.21E-04	1.72E-03
311230	Breakfast cereal manufacturing	5.06E-04	1.05E-03
31131A	Sugar cane mills and refining	1.72E-03	2.94E-03
311313	Beet sugar manufacturing	3.13E-03	3.46E-03
311320	Chocolate and confectionery manufacturing from cacao beans	2.83E-04	1.05E-03
311330	Confectionery manufacturing from purchased chocolate	2.86E-04	9.81E-04
311340	Nonchocolate confectionery manufacturing	4.00E-04	1.24E-03
311410	Frozen food manufacturing	6.12E-04	1.22E-03
311420	Fruit and vegetable canning, pickling, and drying	7.79E-04	1.67E-03

Appendix A (continued)

Table A.5 (continued)

31151A	Fluid milk and butter manufacturing	4.18E-04	8.69E-04
311513	Cheese manufacturing	4.64E-04	9.78E-04
311514	Dry, condensed, and evaporated dairy product manufacturing	6.42E-04	1.25E-03
311520	Ice cream and frozen dessert manufacturing	1.71E-04	9.18E-04
31161A	Animal (except poultry) slaughtering, rendering, and processing	4.14E-04	7.74E-04
311615	Poultry processing	3.46E-04	3.31E-03
311700	Seafood product preparation and packaging	7.52E-04	9.99E-04
311810	Bread and bakery product manufacturing	5.57E-04	1.07E-03
311820	Cookie, cracker and pasta manufacturing	3.98E-04	1.10E-03
311830	Tortilla manufacturing	9.49E-04	1.31E-03
311910	Snack food manufacturing	5.83E-04	1.06E-03
311920	Coffee and tea manufacturing	3.45E-04	9.72E-04
311930	Flavoring syrup and concentrate manufacturing	1.54E-04	4.81E-04
311940	Seasoning and dressing manufacturing	2.68E-04	1.05E-03
311990	All other food manufacturing	5.45E-04	1.14E-03
312110	Soft drink and ice manufacturing	2.52E-04	1.39E-03
312120	Breweries	5.03E-04	2.00E-03
312130	Wineries	1.67E-04	9.60E-04
312140	Distilleries	1.85E-04	5.40E-04
3122A0	Tobacco product manufacturing	1.18E-04	3.40E-04
313100	Fiber, yarn, and thread mills	2.34E-04	7.24E-04
313210	Broadwoven fabric mills	4.56E-04	9.71E-04
313220	Narrow fabric mills and schiffli machine embroidery	4.11E-04	7.49E-04
313230	Nonwoven fabric mills	5.51E-04	1.08E-03
313240	Knit fabric mills	7.28E-04	1.17E-03
313310	Textile and fabric finishing mills	8.74E-04	1.37E-03
313320	Fabric coating mills	4.92E-04	1.10E-03
314110	Carpet and rug mills	1.55E-04	6.89E-04

Appendix A (continued)

Table A.5 (continued)

314120	Curtain and linen mills	1.29E-04	6.29E-04
314910	Textile bag and canvas mills	4.27E-05	5.19E-04
314990	All other textile product mills	1.68E-04	8.55E-04
315100	Apparel knitting mills	8.18E-05	4.57E-04
315210	Cut and sew apparel contractors	6.79E-05	2.28E-04
315220	Men's and boys' cut and sew apparel manufacturing	5.14E-05	4.35E-04
315230	Women's and girls' cut and sew apparel manufacturing	3.32E-05	4.70E-04
315290	Other cut and sew apparel manufacturing	4.05E-06	3.33E-04
315900	Apparel accessories and other apparel manufacturing	3.91E-05	3.63E-04
316100	Leather and hide tanning and finishing	0.00E+00	5.05E-04
316200	Footwear manufacturing	8.39E-07	3.45E-04
316900	Other leather and allied product manufacturing	2.10E-09	3.61E-04
321100	Sawmills and wood preservation	3.14E-05	2.15E-04
32121A	Veneer and plywood manufacturing	9.04E-05	2.49E-04
32121B	Engineered wood member and truss manufacturing	1.57E-05	3.12E-04
321219	Reconstituted wood product manufacturing	1.76E-04	4.23E-04
321910	Wood windows and doors and millwork	2.30E-05	4.91E-04
321920	Wood container and pallet manufacturing	2.06E-05	5.12E-04
321991	Manufactured home (mobile home) manufacturing	0.00E+00	1.11E-03
321992	Prefabricated wood building manufacturing	1.49E-06	5.89E-04
321999	All other miscellaneous wood product manufacturing	8.67E-05	4.03E-04
322110	Pulp mills	3.94E-03	4.40E-03
322120	Paper mills	2.58E-03	3.24E-03
322130	Paperboard mills	4.69E-03	5.12E-03
322210	Paperboard container manufacturing	3.85E-04	2.20E-03

Appendix A (continued)

Table A.5 (continued)

32222A	Coated and laminated paper, packaging paper and plastics film manufacturing	5.49E-04	1.63E-03
32222B	All other paper bag and coated and treated paper manufacturing	3.05E-04	1.55E-03
322230	Stationery product manufacturing	1.12E-04	1.53E-03
322291	Sanitary paper product manufacturing	1.20E-03	1.94E-03
322299	All other converted paper product manufacturing	5.98E-04	1.89E-03
323110	Printing	4.59E-06	6.07E-04
323120	Support activities for printing	7.59E-07	3.92E-04
324121	Asphalt paving mixture and block manufacturing	8.16E-04	1.31E-03
324122	Asphalt shingle and coating materials manufacturing	2.26E-04	1.02E-03
324191	Petroleum lubricating oil and grease manufacturing	2.13E-04	4.49E-04
324199	All other petroleum and coal products manufacturing	5.53E-04	7.15E-04
325110	Petrochemical manufacturing	6.86E-04	1.10E-03
325120	Industrial gas manufacturing	5.17E-04	8.32E-04
325130	Synthetic dye and pigment manufacturing	3.73E-04	1.28E-03
325181	Alkalies and chlorine manufacturing	1.84E-03	2.35E-03
325182	Carbon black manufacturing	2.82E-04	3.78E-04
325188	All other basic inorganic chemical manufacturing	6.17E-04	1.43E-03
325190	Other basic organic chemical manufacturing	7.43E-04	1.34E-03
325211	Plastics material and resin manufacturing	4.62E-04	1.14E-03
325212	Synthetic rubber manufacturing	3.95E-04	9.44E-04
325220	Artificial and synthetic fibers and filaments manufacturing	3.05E-04	8.76E-04
325310	Fertilizer manufacturing	5.84E-04	1.30E-03
325320	Pesticide and other agricultural chemical manufacturing	8.82E-05	5.07E-04
325411	Medicinal and botanical manufacturing	9.58E-05	2.52E-04

Appendix A (continued)

Table A.5 (continued)

325412	Pharmaceutical preparation manufacturing	3.12E-05	1.90E-04
325413	In-vitro diagnostic substance manufacturing	1.95E-05	1.96E-04
325414	Biological product (except diagnostic) manufacturing	4.52E-05	1.81E-04
325510	Paint and coating manufacturing	3.34E-05	8.08E-04
325520	Adhesive manufacturing	8.87E-05	6.36E-04
325610	Soap and cleaning compound manufacturing	1.10E-04	4.82E-04
325620	Toilet preparation manufacturing	1.31E-04	4.95E-04
325910	Printing ink manufacturing	2.52E-05	5.40E-04
3259A0	All other chemical product and preparation manufacturing	1.13E-04	6.54E-04
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	1.98E-04	7.93E-04
326121	Unlaminated plastics profile shape manufacturing	1.54E-04	6.67E-04
326122	Plastic pipe and pipe fitting manufacturing	5.45E-05	7.15E-04
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	3.62E-04	1.10E-03
326140	Polystyrene foam product manufacturing	3.98E-04	1.01E-03
326150	Urethane and other foam product (except polystyrene) manufacturing	1.34E-04	7.94E-04
326160	Plastics bottle manufacturing	6.91E-05	6.60E-04
32619A	Other plastics product manufacturing	1.05E-04	6.75E-04
326210	Tire manufacturing	2.79E-04	8.67E-04
326220	Rubber and plastics hoses and belting manufacturing	1.93E-04	9.76E-04
326290	Other rubber product manufacturing	1.87E-04	1.03E-03
32711A	Pottery, ceramics, and plumbing fixture manufacturing	3.02E-03	3.86E-03
32712A	Brick, tile, and other structural clay product manufacturing	8.70E-03	8.96E-03

Appendix A (continued)

Table A.5 (continued)

32712B	Clay and nonclay refractory manufacturing	3.03E-03	4.17E-03
327211	Flat glass manufacturing	9.80E-03	1.03E-02
327212	Other pressed and blown glass and glassware manufacturing	2.78E-03	3.89E-03
327213	Glass container manufacturing	6.76E-03	7.36E-03
327215	Glass product manufacturing made of purchased glass	1.64E-03	3.11E-03
327310	Cement manufacturing	8.90E-03	9.78E-03
327320	Ready-mix concrete manufacturing	9.02E-04	3.32E-03
327330	Concrete pipe, brick and block manufacturing	7.96E-04	2.79E-03
327390	Other concrete product manufacturing	7.02E-04	2.50E-03
3274A0	Lime and gypsum product manufacturing	9.76E-03	1.09E-02
327910	Abrasive product manufacturing	9.05E-04	1.40E-03
327991	Cut stone and stone product manufacturing	5.86E-04	1.17E-03
327992	Ground or treated mineral and earth manufacturing	4.00E-03	5.09E-03
327993	Mineral wool manufacturing	4.20E-03	4.96E-03
327999	Miscellaneous nonmetallic mineral products	1.33E-03	3.06E-03
331110	Iron and steel mills and ferroalloy manufacturing	2.06E-02	2.56E-02
331200	Steel product manufacturing from purchased steel	8.04E-03	1.27E-02
33131A	Alumina refining and primary aluminum production	3.62E-03	5.24E-03
331314	Secondary smelting and alloying of aluminum	3.76E-03	5.35E-03
33131B	Aluminum product manufacturing from purchased aluminum	1.66E-03	3.83E-03
331411	Primary smelting and refining of copper	1.50E-03	3.63E-03
331419	Primary smelting and refining of nonferrous metal (except copper and aluminum)	2.07E-03	4.17E-03

Appendix A (continued)

Table A.5 (continued)

331420	Copper rolling, drawing, extruding and alloying	6.59E-04	2.17E-03
331490	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	1.09E-03	3.13E-03
331510	Ferrous metal foundries	1.73E-03	3.72E-03
331520	Nonferrous metal foundries	1.61E-03	2.89E-03
33211A	All other forging, stamping, and sintering	1.19E-03	6.20E-03
332114	Custom roll forming	1.24E-06	7.94E-03
33211B	Crown and closure manufacturing and metal stamping	3.00E-05	4.30E-03
33221A	Cutlery, utensil, pot, and pan manufacturing	1.40E-05	1.91E-03
33221B	Handtool manufacturing	1.48E-05	2.98E-03
332310	Plate work and fabricated structural product manufacturing	9.37E-06	4.80E-03
332320	Ornamental and architectural metal products manufacturing	1.77E-05	3.65E-03
332410	Power boiler and heat exchanger manufacturing	2.62E-05	3.06E-03
332420	Metal tank (heavy gauge) manufacturing	2.03E-05	4.48E-03
332430	Metal can, box, and other metal container (light gauge) manufacturing	1.20E-05	4.15E-03
33299A	Ammunition manufacturing	3.24E-06	7.61E-04
33299B	Arms, ordnance, and accessories manufacturing	2.31E-06	9.85E-04
332500	Hardware manufacturing	1.04E-05	2.22E-03
332600	Spring and wire product manufacturing	4.10E-05	3.95E-03
332710	Machine shops	2.22E-05	1.34E-03
332720	Turned product and screw, nut, and bolt manufacturing	1.57E-05	2.66E-03
332800	Coating, engraving, heat treating and allied activities	4.14E-05	2.92E-03

Appendix A (continued)

Table A.5 (continued)

33291A	Valve and fittings other than plumbing	1.45E-05	1.65E-03
332913	Plumbing fixture fitting and trim manufacturing	2.85E-06	1.08E-03
332991	Ball and roller bearing manufacturing	1.72E-05	2.36E-03
332996	Fabricated pipe and pipe fitting manufacturing	2.50E-05	4.44E-03
33299C	Other fabricated metal manufacturing	7.13E-05	2.56E-03
333111	Farm machinery and equipment manufacturing	1.49E-05	2.19E-03
333112	Lawn and garden equipment manufacturing	1.54E-05	1.81E-03
333120	Construction machinery manufacturing	5.81E-06	1.93E-03
333130	Mining and oil and gas field machinery manufacturing	2.63E-05	2.64E-03
33329A	Other industrial machinery manufacturing	3.51E-05	2.08E-03
333220	Plastics and rubber industry machinery manufacturing	3.67E-05	2.11E-03
333295	Semiconductor machinery manufacturing	1.74E-05	7.09E-04
33331A	Vending, commercial, industrial, and office machinery manufacturing	7.67E-07	1.49E-03
333314	Optical instrument and lens manufacturing	3.11E-05	6.62E-04
333315	Photographic and photocopying equipment manufacturing	1.54E-05	6.84E-04
333319	Other commercial and service industry machinery manufacturing	1.36E-05	1.26E-03
33341A	Air purification and ventilation equipment manufacturing	4.74E-05	2.01E-03
333414	Heating equipment, except warm air furnaces	3.49E-05	2.13E-03
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	4.61E-06	1.90E-03

Appendix A (continued)

Table A.5 (continued)

333511	Industrial mold manufacturing	7.64E-05	1.95E-03
33351A	Metal cutting and forming machine tool manufacturing	4.60E-05	1.81E-03
333514	Special tool, die, jig, and fixture manufacturing	1.47E-05	2.40E-03
333515	Cutting tool and machine tool accessory manufacturing	3.03E-05	1.74E-03
33351B	Rolling mill and other metalworking machinery manufacturing	1.19E-06	1.53E-03
333611	Turbine and turbine generator set units manufacturing	1.65E-05	1.35E-03
333612	Speed changer, industrial high-speed drive, and gear manufacturing	3.82E-06	1.61E-03
333613	Mechanical power transmission equipment manufacturing	3.13E-05	2.28E-03
333618	Other engine equipment manufacturing	1.62E-05	1.52E-03
333911	Pump and pumping equipment manufacturing	1.29E-05	1.54E-03
333912	Air and gas compressor manufacturing	2.33E-05	1.47E-03
333920	Material handling equipment manufacturing	2.00E-05	2.93E-03
333991	Power-driven handtool manufacturing	2.18E-06	1.56E-03
33399A	Other general purpose machinery manufacturing	9.52E-05	1.71E-03
333993	Packaging machinery manufacturing	2.42E-05	1.13E-03
333994	Industrial process furnace and oven manufacturing	5.92E-05	1.45E-03
33399B	Fluid power process machinery	1.72E-05	2.19E-03
334111	Electronic computer manufacturing	0.00E+00	3.17E-04
334112	Computer storage device manufacturing	5.67E-08	4.82E-04
33411A	Computer terminals and other computer peripheral equipment manufacturing	2.90E-07	5.10E-04

Appendix A (continued)

Table A.5 (continued)

334210	Telephone apparatus manufacturing	6.01E-09	3.52E-04
334220	Broadcast and wireless communications equipment	2.23E-06	3.73E-04
334290	Other communications equipment manufacturing	5.66E-07	4.85E-04
334300	Audio and video equipment manufacturing	7.24E-06	1.19E-03
334411	Electron tube manufacturing	6.53E-07	1.31E-03
334412	Bare printed circuit board manufacturing	0.00E+00	5.87E-04
334413	Semiconductor and related device manufacturing	9.02E-08	4.46E-04
33441A	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing	4.29E-06	1.26E-03
334417	Electronic connector manufacturing	8.28E-06	8.54E-04
334418	Printed circuit assembly (electronic assembly) manufacturing	8.70E-07	4.08E-04
334419	Other electronic component manufacturing	6.87E-07	6.73E-04
334510	Electromedical and electrotherapeutic apparatus manufacturing	6.37E-07	5.66E-04
334511	Search, detection, and navigation instruments manufacturing	5.94E-07	3.41E-04
334512	Automatic environmental control manufacturing	8.95E-06	9.02E-04
334513	Industrial process variable instruments manufacturing	2.56E-06	9.61E-04
334514	Totalizing fluid meters and counting devices manufacturing	2.70E-05	8.42E-04
334515	Electricity and signal testing instruments manufacturing	6.90E-07	3.54E-04
334516	Analytical laboratory instrument manufacturing	1.33E-06	4.93E-04

Appendix A (continued)

Table A.5 (continued)

334517	Irradiation apparatus manufacturing	4.61E-06	8.39E-04
33451A	Other Measuring and Controlling Device Manufacturing	4.33E-07	6.89E-04
33461A	Software, audio, and video media reproducing	1.02E-07	4.86E-04
334613	Magnetic and optical recording media manufacturing	3.85E-06	6.20E-04
335110	Electric lamp bulb and part manufacturing	5.88E-05	7.71E-04
335120	Lighting fixture manufacturing	2.50E-05	1.45E-03
335210	Small electrical appliance manufacturing	2.32E-05	1.02E-03
335221	Household cooking appliance manufacturing	2.28E-05	2.56E-03
335222	Household refrigerator and home freezer manufacturing	1.72E-05	2.27E-03
335224	Household laundry equipment manufacturing	2.60E-05	2.45E-03
335228	Other major household appliance manufacturing	2.76E-05	1.84E-03
335311	Power, distribution, and specialty transformer manufacturing	2.32E-05	3.38E-03
335312	Motor and generator manufacturing	1.12E-05	2.23E-03
335313	Switchgear and switchboard apparatus manufacturing	1.27E-05	1.11E-03
335314	Relay and industrial control manufacturing	2.27E-05	7.48E-04
335911	Storage battery manufacturing	2.70E-05	1.32E-03
335912	Primary battery manufacturing	3.10E-06	1.47E-03
335920	Communication and energy wire and cable manufacturing	2.45E-05	1.15E-03
335930	Wiring device manufacturing	4.35E-05	1.80E-03
335991	Carbon and graphite product manufacturing	5.75E-05	5.62E-04
335999	All other miscellaneous electrical equipment and component manufacturing	1.70E-05	6.99E-04
336111	Automobile Manufacturing	1.10E-05	1.36E-03
336112	Light truck and utility vehicle manufacturing	1.06E-05	1.48E-03

Appendix A (continued)

Table A.5 (continued)

336120	Heavy duty truck manufacturing	7.21E-05	1.55E-03
336211	Motor vehicle body manufacturing	1.69E-05	1.71E-03
336212	Truck trailer manufacturing	2.39E-05	2.37E-03
336213	Motor home manufacturing	1.73E-05	1.13E-03
336214	Travel trailer and camper manufacturing	1.44E-05	1.86E-03
336300	Motor vehicle parts manufacturing	2.09E-05	2.33E-03
336411	Aircraft manufacturing	8.46E-06	8.13E-04
336412	Aircraft engine and engine parts manufacturing	2.20E-05	6.11E-04
336413	Other aircraft parts and auxiliary equipment manufacturing	2.64E-05	8.16E-04
336414	Guided missile and space vehicle manufacturing	6.19E-06	3.84E-04
33641A	Propulsion units and parts for space vehicles and guided missiles	2.68E-05	4.12E-04
336500	Railroad rolling stock manufacturing	1.41E-05	1.61E-03
336611	Ship building and repairing	1.50E-05	1.08E-03
336612	Boat building	1.25E-05	8.95E-04
336991	Motorcycle, bicycle, and parts manufacturing	2.15E-05	2.86E-03
336992	Military armored vehicle, tank, and tank component manufacturing	3.28E-05	1.51E-03
336999	All other transportation equipment manufacturing	1.40E-05	1.87E-03
337110	Wood kitchen cabinet and countertop manufacturing	2.26E-05	3.58E-04
337121	Upholstered household furniture manufacturing	1.04E-05	7.42E-04
337122	Nonupholstered wood household furniture manufacturing	2.73E-05	3.72E-04
33712A	Metal and other household furniture (except wood) manufacturing	6.99E-05	1.67E-03
337127	Institutional furniture manufacturing	6.41E-05	1.75E-03

Appendix A (continued)

Table A.5 (continued)

33721A	Wood television, radio, and sewing machine cabinet manufacturing	1.26E-06	2.08E-04
337212	Office furniture and custom architectural woodwork and millwork manufacturing	2.70E-05	1.27E-03
337215	Showcase, partition, shelving, and locker manufacturing	3.42E-05	3.07E-03
337910	Mattress manufacturing	2.03E-05	7.82E-04
337920	Blind and shade manufacturing	6.85E-05	1.19E-03
339111	Laboratory apparatus and furniture manufacturing	2.88E-07	6.26E-04
339112	Surgical and medical instrument manufacturing	1.07E-07	3.29E-04
339113	Surgical appliance and supplies manufacturing	9.57E-06	5.90E-04
339114	Dental equipment and supplies manufacturing	1.68E-06	1.02E-03
339115	Ophthalmic goods manufacturing	0.00E+00	2.17E-04
339116	Dental laboratories	4.94E-07	3.12E-04
339910	Jewelry and silverware manufacturing	8.81E-09	1.22E-03
339920	Sporting and athletic goods manufacturing	2.38E-06	1.24E-03
339930	Doll, toy, and game manufacturing	1.40E-06	5.80E-04
339940	Office supplies (except paper) manufacturing	2.79E-06	5.06E-04
339950	Sign manufacturing	3.38E-07	9.55E-04
339991	Gasket, packing, and sealing device manufacturing	9.22E-06	1.13E-03
339992	Musical instrument manufacturing	0.00E+00	1.85E-04
33999A	All other miscellaneous manufacturing	1.06E-05	1.27E-03
339994	Broom, brush, and mop manufacturing	2.11E-05	4.94E-04
420000	Wholesale trade	4.55E-06	7.58E-05
4A0000	Retail trade	7.03E-06	8.27E-05

Appendix A (continued)

Table A.5 (continued)

481000	Air transportation	2.74E-07	7.89E-05
482000	Rail transportation	3.00E-07	2.66E-04
483000	Water transportation	3.24E-04	7.23E-04
484000	Truck transportation	3.03E-07	1.44E-04
485000	Transit and ground passenger transportation	7.89E-09	3.71E-04
486000	Pipeline transportation	0.00E+00	3.45E-04
48A000	Scenic and sightseeing transportation and support activities for transportation	6.78E-06	1.47E-04
492000	Couriers and messengers	0.00E+00	6.72E-05
493000	Warehousing and storage	5.89E-05	1.70E-04
511110	Newspaper publishers	2.07E-06	3.46E-04
511120	Periodical publishers	0.00E+00	1.86E-04
511130	Book publishers	3.50E-06	1.74E-04
5111A0	Directory, mailing list, and other publishers	2.00E-07	1.86E-04
511200	Software publishers	0.00E+00	5.63E-05
512100	Motion picture and video industries	1.42E-06	5.53E-05
512200	Sound recording industries	2.65E-09	1.39E-04
515100	Radio and television broadcasting	5.07E-06	1.00E-04
515200	Cable and other subscription programming	3.77E-06	1.57E-04
516110	Internet publishing and broadcasting	3.94E-08	2.54E-04
517000	Telecommunications	1.05E-05	1.16E-04
518100	Internet service providers and web search portals	5.08E-06	1.07E-04
518200	Data processing, hosting, and related services	0.00E+00	1.01E-04
519100	Other information services	4.12E-06	8.39E-05
52A000	Monetary authorities and depository credit intermediation	8.99E-07	3.32E-05
522A00	Nondepository credit intermediation and related activities	4.71E-08	3.80E-05
523000	Securities, commodity contracts, investments, and related activities	7.02E-07	3.64E-05

Appendix A (continued)

Table A.5 (continued)

524100	Insurance carriers	2.25E-12	3.19E-05
524200	Insurance agencies, brokerages, and related activities	2.35E-06	4.01E-05
525000	Funds, trusts, and other financial vehicles	0.00E+00	3.43E-05
531000	Real estate	5.44E-05	9.44E-05
S00800	Owner-occupied dwellings	0.00E+00	6.50E-05
532100	Automotive equipment rental and leasing	1.10E-06	7.13E-05
532A00	General and consumer goods rental except video tapes and discs	7.47E-08	1.24E-04
532230	Video tape and disc rental	1.21E-05	2.33E-04
532400	Commercial and industrial machinery and equipment rental and leasing	5.78E-06	1.20E-04
533000	Lessors of nonfinancial intangible assets	0.00E+00	2.96E-05
541100	Legal services	1.41E-06	3.96E-05
541200	Accounting, tax preparation, bookkeeping, and payroll services	2.81E-06	5.71E-05
541300	Architectural, engineering, and related services	3.76E-05	1.53E-04
541400	Specialized design services	1.50E-06	9.07E-05
541511	Custom computer programming services	6.08E-07	3.25E-05
541512	Computer systems design services	4.85E-07	1.00E-04
54151A	Other computer related services, including facilities management	6.69E-08	6.09E-05
541610	Management, scientific, and technical consulting services	2.79E-06	5.64E-05
5416A0	Environmental and other technical consulting services	4.92E-07	9.71E-05
541700	Scientific research and development services	3.76E-04	5.35E-04
541800	Advertising and related services	2.55E-06	1.91E-04
5419A0	All other miscellaneous professional, scientific, and technical services	3.90E-06	5.64E-05

Appendix A (continued)

Table A.5 (continued)

541920	Photographic services	1.04E-05	9.47E-05
541940	Veterinary services	6.55E-06	1.40E-04
550000	Management of companies and enterprises	6.36E-06	7.06E-05
561300	Employment services	2.10E-06	2.73E-05
561500	Travel arrangement and reservation services	2.07E-05	9.34E-05
561100	Office administrative services	2.66E-06	6.07E-05
561200	Facilities support services	6.87E-06	1.93E-04
561400	Business support services	2.17E-06	7.93E-05
561600	Investigation and security services	1.55E-06	1.08E-04
561700	Services to buildings and dwellings	3.88E-06	1.06E-04
561900	Other support services	4.95E-06	9.90E-05
562000	Waste management and remediation services	1.35E-05	2.06E-04
611100	Elementary and secondary schools	5.41E-06	1.25E-04
611A00	Junior colleges, colleges, universities, and professional schools	1.72E-05	1.55E-04
611B00	Other educational services	3.38E-06	1.36E-04
621A00	Offices of physicians, dentists, and other health practitioners	2.02E-06	8.01E-05
621B00	Medical and diagnostic labs and outpatient and other ambulatory care services	6.61E-06	1.19E-04
621600	Home health care services	1.06E-05	9.82E-05
622000	Hospitals	9.53E-06	1.31E-04
623000	Nursing and residential care facilities	1.40E-05	1.25E-04
624A00	Individual and family services	1.19E-05	1.44E-04
624200	Community food, housing, and other relief services, including rehabilitation services	4.65E-06	2.31E-04
624400	Child day care services	8.18E-06	1.40E-04
711100	Performing arts companies	0.00E+00	5.02E-05
711200	Spectator sports	4.30E-06	9.12E-05

Appendix A (continued)

Table A.5 (continued)

711A00	Promoters of performing arts and sports and agents for public figures	7.51E-07	7.97E-05
711500	Independent artists, writers, and performers	0.00E+00	5.41E-05
712000	Museums, historical sites, zoos, and parks	1.93E-05	9.63E-05
713A00	Amusement parks, arcades, and gambling industries	1.62E-06	1.40E-04
713B00	Other amusement and recreation industries	2.99E-05	2.46E-04
713940	Fitness and recreational sports centers	2.62E-05	1.95E-04
713950	Bowling centers	4.19E-05	2.02E-04
7211A0	Hotels and motels, including casino hotels	2.26E-05	1.36E-04
721A00	Other accommodations	3.34E-05	1.38E-04
722000	Food services and drinking places	3.45E-05	3.18E-04
8111A0	Automotive repair and maintenance, except car washes	3.45E-06	4.19E-04
811192	Car washes	2.36E-05	2.24E-04
811200	Electronic and precision equipment repair and maintenance	6.04E-06	1.45E-04
811300	Commercial and industrial machinery and equipment repair and maintenance	2.83E-06	3.10E-04
811400	Personal and household goods repair and maintenance	3.32E-06	3.42E-04
812100	Personal care services	2.49E-06	9.04E-05
812200	Death care services	1.39E-05	3.92E-04
812300	Dry-cleaning and laundry services	1.23E-05	8.59E-05
812900	Other personal services	3.72E-06	1.13E-04
813100	Religious organizations	0.00E+00	6.79E-05
813A00	Grantmaking, giving, and social advocacy organizations	3.50E-06	1.20E-04
813B00	Civic, social, professional, and similar organizations	1.68E-05	1.50E-04
814000	Private households	0.00E+00	0.00E+00
491000	Postal service	0.00E+00	9.51E-05

Appendix A (continued)

Table A.5 (continued)

S00102	Other Federal Government enterprises	0.00E+00	6.52E-05
S00203	Other State and local government enterprises	7.26E-07	3.94E-04
S00500	General Federal defense government services	0.00E+00	1.50E-04
S00600	General Federal nondefense government services	3.11E-04	4.41E-04
S00700	General state and local government services	3.95E-05	1.70E-04
S00401	Scrap	6.58E-04	1.77E-03

Appendix A (continued)

Table A.6 Direct and total electricity intensities of the non-energy sectors in the US input-output tables

NAICS IO code	Name of the Commodity Sector	Direct Electricity Intensity (GJ/$)	Total Electricity Intensity (GJ/$)
1111A0	Oilseed farming	4.33E-03	7.65E-03
1111B0	Grain farming	3.62E-03	7.98E-03
111200	Vegetable and melon farming	8.40E-03	1.10E-02
1113A0	Fruit farming	8.88E-03	1.11E-02
111335	Tree nut farming	9.38E-03	1.15E-02
111400	Greenhouse, nursery, and floriculture production	3.55E-03	5.16E-03
111910	Tobacco farming	8.13E-03	1.27E-02
111920	Cotton farming	7.45E-03	1.29E-02
1119A0	Sugarcane and sugar beet farming	9.13E-03	1.23E-02
1119B0	All other crop farming	1.13E-02	1.46E-02
1121A0	Cattle ranching and farming	3.44E-03	1.09E-02
112120	Dairy cattle and milk production	7.55E-03	1.23E-02
112A00	Animal production, except cattle and poultry and eggs	5.26E-03	8.86E-03
112300	Poultry and egg production	4.84E-03	1.13E-02
113A00	Forest nurseries, forest products, and timber tracts	2.98E-03	5.79E-03
113300	Logging	1.15E-04	2.75E-03
114100	Fishing	0.00E+00	1.81E-03
114200	Hunting and trapping	6.29E-04	2.93E-03
115000	Support activities for agriculture and forestry	1.82E-03	4.80E-03
212210	Iron ore mining	3.62E-02	3.99E-02
2122A0	Gold, silver, and other metal ore mining	1.78E-02	2.10E-02
212230	Copper, nickel, lead, and zinc mining	2.48E-02	2.72E-02
212310	Stone mining and quarrying	9.97E-03	1.21E-02
212320	Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	1.22E-02	1.43E-02
212390	Other nonmetallic mineral mining and quarrying	1.76E-02	1.97E-02
213111	Drilling oil and gas wells	1.23E-03	4.80E-03

Appendix A (continued)

Table A.6 (continued)

213112	Support activities for oil and gas operations	9.87E-04	3.49E-03
21311A	Support activities for other mining	1.74E-03	5.12E-03
221300	Water, sewage and other systems	2.19E-03	4.25E-03
230101	Nonresidential commercial and health care structures	1.13E-03	3.48E-03
230102	Nonresidential manufacturing structures	9.17E-04	2.93E-03
230103	Other nonresidential structures	1.08E-03	3.34E-03
230201	Residential permanent site single- and multi-family structures	9.70E-04	4.39E-03
230202	Other residential structures	9.82E-04	4.12E-03
230301	Nonresidential maintenance and repair	9.11E-04	3.20E-03
230302	Residential maintenance and repair	5.12E-04	3.95E-03
311111	Dog and cat food manufacturing	2.94E-03	8.03E-03
311119	Other animal food manufacturing	3.38E-03	9.52E-03
311210	Flour milling and malt manufacturing	8.45E-03	1.29E-02
311221	Wet corn milling	1.13E-02	1.60E-02
31122A	Soybean and other oilseed processing	3.08E-03	9.60E-03
311225	Fats and oils refining and blending	3.11E-03	9.96E-03
311230	Breakfast cereal manufacturing	3.06E-03	6.72E-03
31131A	Sugar cane mills and refining	3.81E-03	1.14E-02
311313	Beet sugar manufacturing	3.83E-03	1.10E-02
311320	Chocolate and confectionery manufacturing from cacao beans	3.21E-03	9.68E-03
311330	Confectionery manufacturing from purchased chocolate	3.11E-03	8.47E-03
311340	Nonchocolate confectionery manufacturing	2.99E-03	8.31E-03
311410	Frozen food manufacturing	4.82E-03	1.03E-02
311420	Fruit and vegetable canning, pickling, and drying	2.98E-03	8.31E-03
31151A	Fluid milk and butter manufacturing	3.76E-03	1.14E-02

Appendix A (continued)

Table A.6 (continued)

311513	Cheese manufacturing	2.79E-03	1.14E-02
311514	Dry, condensed, and evaporated dairy product manufacturing	3.04E-03	1.06E-02
311520	Ice cream and frozen dessert manufacturing	4.25E-03	1.03E-02
31161A	Animal (except poultry) slaughtering, rendering, and processing	2.74E-03	1.03E-02
311615	Poultry processing	3.49E-03	1.03E-02
311700	Seafood product preparation and packaging	4.19E-03	7.14E-03
311810	Bread and bakery product manufacturing	3.89E-03	7.83E-03
311820	Cookie, cracker and pasta manufacturing	3.18E-03	8.18E-03
311830	Tortilla manufacturing	5.67E-03	1.00E-02
311910	Snack food manufacturing	2.23E-03	7.79E-03
311920	Coffee and tea manufacturing	2.16E-03	8.51E-03
311930	Flavoring syrup and concentrate manufacturing	1.07E-03	3.58E-03
311940	Seasoning and dressing manufacturing	2.21E-03	8.35E-03
311990	All other food manufacturing	4.50E-03	9.63E-03
312110	Soft drink and ice manufacturing	2.63E-03	1.00E-02
312120	Breweries	2.51E-03	7.69E-03
312130	Wineries	2.77E-03	7.61E-03
312140	Distilleries	7.90E-04	2.62E-03
3122A0	Tobacco product manufacturing	7.53E-04	2.48E-03
313100	Fiber, yarn, and thread mills	1.02E-02	1.86E-02
313210	Broadwoven fabric mills	8.57E-03	1.49E-02
313220	Narrow fabric mills and schiffli machine embroidery	4.61E-03	1.07E-02
313230	Nonwoven fabric mills	6.79E-03	1.25E-02
313240	Knit fabric mills	5.36E-03	1.31E-02
313310	Textile and fabric finishing mills	4.93E-03	1.13E-02
313320	Fabric coating mills	3.49E-03	9.51E-03
314110	Carpet and rug mills	2.26E-03	1.10E-02
314120	Curtain and linen mills	2.68E-03	9.05E-03
314910	Textile bag and canvas mills	1.29E-03	6.15E-03
314990	All other textile product mills	4.16E-03	9.94E-03

Appendix A (continued)

Table A.6 (continued)

315100	Apparel knitting mills	3.67E-03	9.18E-03
315210	Cut and sew apparel contractors	2.76E-03	5.41E-03
315220	Men's and boys' cut and sew apparel manufacturing	1.51E-03	5.87E-03
315230	Women's and girls' cut and sew apparel manufacturing	1.20E-03	6.38E-03
315290	Other cut and sew apparel manufacturing	1.87E-03	6.31E-03
315900	Apparel accessories and other apparel manufacturing	1.99E-03	6.36E-03
316100	Leather and hide tanning and finishing	2.28E-03	9.12E-03
316200	Footwear manufacturing	2.22E-03	6.85E-03
316900	Other leather and allied product manufacturing	1.59E-03	5.38E-03
321100	Sawmills and wood preservation	4.60E-03	7.87E-03
32121A	Veneer and plywood manufacturing	5.86E-03	9.34E-03
32121B	Engineered wood member and truss manufacturing	1.97E-03	6.09E-03
321219	Reconstituted wood product manufacturing	1.23E-02	1.63E-02
321910	Wood windows and doors and millwork	2.81E-03	7.18E-03
321920	Wood container and pallet manufacturing	2.88E-03	6.85E-03
321991	Manufactured home (mobile home) manufacturing	9.46E-04	6.09E-03
321992	Prefabricated wood building manufacturing	1.02E-03	5.43E-03
321999	All other miscellaneous wood product manufacturing	4.03E-03	7.74E-03
322110	Pulp mills	7.99E-03	1.19E-02
322120	Paper mills	8.73E-03	1.25E-02
322130	Paperboard mills	1.20E-02	1.53E-02
322210	Paperboard container manufacturing	2.95E-03	9.86E-03
32222A	Coated and laminated paper, packaging paper and plastics film manufacturing	3.02E-03	8.42E-03
32222B	All other paper bag and coated and treated paper manufacturing	2.98E-03	9.43E-03

Appendix A (continued)

Table A.6 (continued)

322230	Stationery product manufacturing	2.79E-03	8.68E-03
322291	Sanitary paper product manufacturing	5.13E-03	8.86E-03
322299	All other converted paper product manufacturing	3.86E-03	9.09E-03
323110	Printing	3.02E-03	6.52E-03
323120	Support activities for printing	2.49E-03	4.89E-03
324121	Asphalt paving mixture and block manufacturing	3.97E-03	6.47E-03
324122	Asphalt shingle and coating materials manufacturing	2.24E-03	5.40E-03
324191	Petroleum lubricating oil and grease manufacturing	1.60E-03	3.98E-03
324199	All other petroleum and coal products manufacturing	3.79E-03	5.22E-03
325110	Petrochemical manufacturing	3.62E-03	7.38E-03
325120	Industrial gas manufacturing	3.66E-02	4.00E-02
325130	Synthetic dye and pigment manufacturing	6.63E-03	1.17E-02
325181	Alkalies and chlorine manufacturing	2.97E-02	3.32E-02
325182	Carbon black manufacturing	9.04E-03	1.01E-02
325188	All other basic inorganic chemical manufacturing	2.03E-02	2.54E-02
325190	Other basic organic chemical manufacturing	6.30E-03	1.20E-02
325211	Plastics material and resin manufacturing	5.78E-03	1.20E-02
325212	Synthetic rubber manufacturing	5.25E-03	1.03E-02
325220	Artificial and synthetic fibers and filaments manufacturing	7.82E-03	1.46E-02
325310	Fertilizer manufacturing	7.13E-03	1.21E-02
325320	Pesticide and other agricultural chemical manufacturing	2.11E-03	6.50E-03
325411	Medicinal and botanical manufacturing	2.05E-03	4.20E-03
325412	Pharmaceutical preparation manufacturing	1.13E-03	3.17E-03
325413	In-vitro diagnostic substance manufacturing	2.33E-03	4.77E-03

Appendix A (continued)

Table A.6 (continued)

325414	Biological product (except diagnostic) manufacturing	1.99E-03	4.05E-03
325510	Paint and coating manufacturing	1.66E-03	7.46E-03
325520	Adhesive manufacturing	2.47E-03	7.82E-03
325610	Soap and cleaning compound manufacturing	1.89E-03	5.88E-03
325620	Toilet preparation manufacturing	8.56E-04	3.94E-03
325910	Printing ink manufacturing	1.51E-03	6.53E-03
3259A0	All other chemical product and preparation manufacturing	2.89E-03	8.48E-03
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	5.91E-03	1.16E-02
326121	Unlaminated plastics profile shape manufacturing	6.36E-03	1.13E-02
326122	Plastic pipe and pipe fitting manufacturing	6.74E-03	1.29E-02
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	4.57E-03	1.02E-02
326140	Polystyrene foam product manufacturing	5.77E-03	1.10E-02
326150	Urethane and other foam product (except polystyrene) manufacturing	2.77E-03	8.76E-03
326160	Plastics bottle manufacturing	1.14E-02	1.68E-02
32619A	Other plastics product manufacturing	5.08E-03	9.62E-03
326210	Tire manufacturing	4.33E-03	8.86E-03
326220	Rubber and plastics hoses and belting manufacturing	3.74E-03	8.56E-03
326290	Other rubber product manufacturing	4.68E-03	9.15E-03
32711A	Pottery, ceramics, and plumbing fixture manufacturing	5.71E-03	8.99E-03
32712A	Brick, tile, and other structural clay product manufacturing	8.20E-03	1.00E-02
32712B	Clay and nonclay refractory manufacturing	6.03E-03	1.02E-02
327211	Flat glass manufacturing	1.08E-02	1.42E-02

Appendix A (continued)

Table A.6 (continued)

327212	Other pressed and blown glass and glassware manufacturing	7.57E-03	1.17E-02
327213	Glass container manufacturing	1.23E-02	1.55E-02
327215	Glass product manufacturing made of purchased glass	5.15E-03	9.71E-03
327310	Cement manufacturing	2.26E-02	2.56E-02
327320	Ready-mix concrete manufacturing	1.53E-03	9.28E-03
327330	Concrete pipe, brick and block manufacturing	2.62E-03	8.10E-03
327390	Other concrete product manufacturing	2.13E-03	6.48E-03
3274A0	Lime and gypsum product manufacturing	1.03E-02	1.46E-02
327910	Abrasive product manufacturing	5.07E-03	8.22E-03
327991	Cut stone and stone product manufacturing	3.40E-03	6.57E-03
327992	Ground or treated mineral and earth manufacturing	8.23E-03	1.11E-02
327993	Mineral wool manufacturing	1.03E-02	1.39E-02
327999	Miscellaneous nonmetallic mineral products	3.33E-03	9.05E-03
331110	Iron and steel mills and ferroalloy manufacturing	1.02E-02	1.68E-02
331200	Steel product manufacturing from purchased steel	6.07E-03	1.19E-02
33131A	Alumina refining and primary aluminum production	3.06E-02	4.14E-02
331314	Secondary smelting and alloying of aluminum	3.27E-02	4.33E-02
33131B	Aluminum product manufacturing from purchased aluminum	4.38E-03	1.85E-02
331411	Primary smelting and refining of copper	4.79E-03	1.46E-02
331419	Primary smelting and refining of nonferrous metal (except copper and aluminum)	9.41E-03	1.72E-02
331420	Copper rolling, drawing, extruding and alloying	4.43E-03	1.16E-02
331490	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	5.07E-03	1.11E-02

Appendix A (continued)

Table A.6 (continued)

331510	Ferrous metal foundries	1.05E-02	1.39E-02
331520	Nonferrous metal foundries	6.09E-03	1.41E-02
33211A	All other forging, stamping, and sintering	7.12E-03	1.32E-02
332114	Custom roll forming	2.26E-03	1.03E-02
33211B	Crown and closure manufacturing and metal stamping	3.19E-03	8.84E-03
33221A	Cutlery, utensil, pot, and pan manufacturing	2.09E-03	6.95E-03
33221B	Handtool manufacturing	3.21E-03	7.65E-03
332310	Plate work and fabricated structural product manufacturing	1.98E-03	7.23E-03
332320	Ornamental and architectural metal products manufacturing	1.90E-03	7.43E-03
332410	Power boiler and heat exchanger manufacturing	2.64E-03	7.36E-03
332420	Metal tank (heavy gauge) manufacturing	2.53E-03	7.54E-03
332430	Metal can, box, and other metal container (light gauge) manufacturing	3.74E-03	1.26E-02
33299A	Ammunition manufacturing	4.43E-03	7.38E-03
33299B	Arms, ordnance, and accessories manufacturing	2.56E-03	5.78E-03
332500	Hardware manufacturing	2.04E-03	6.27E-03
332600	Spring and wire product manufacturing	3.12E-03	8.04E-03
332710	Machine shops	3.19E-03	6.66E-03
332720	Turned product and screw, nut, and bolt manufacturing	3.69E-03	7.71E-03
332800	Coating, engraving, heat treating and allied activities	6.21E-03	1.08E-02
33291A	Valve and fittings other than plumbing	2.74E-03	7.08E-03
332913	Plumbing fixture fitting and trim manufacturing	2.29E-03	6.85E-03
332991	Ball and roller bearing manufacturing	4.73E-03	8.63E-03

Appendix A (continued)

Table A.6 (continued)

332996	Fabricated pipe and pipe fitting manufacturing	2.61E-03	7.74E-03
33299C	Other fabricated metal manufacturing	3.39E-03	8.40E-03
333111	Farm machinery and equipment manufacturing	1.26E-03	5.99E-03
333112	Lawn and garden equipment manufacturing	1.20E-03	6.19E-03
333120	Construction machinery manufacturing	1.33E-03	6.12E-03
333130	Mining and oil and gas field machinery manufacturing	2.41E-03	7.45E-03
33329A	Other industrial machinery manufacturing	2.44E-03	6.82E-03
333220	Plastics and rubber industry machinery manufacturing	2.08E-03	6.38E-03
333295	Semiconductor machinery manufacturing	2.22E-03	6.12E-03
33331A	Vending, commercial, industrial, and office machinery manufacturing	1.05E-03	5.49E-03
333314	Optical instrument and lens manufacturing	2.67E-03	6.18E-03
333315	Photographic and photocopying equipment manufacturing	2.72E-03	6.81E-03
333319	Other commercial and service industry machinery manufacturing	1.26E-03	5.18E-03
33341A	Air purification and ventilation equipment manufacturing	1.98E-03	6.79E-03
333414	Heating equipment, except warm air furnaces	2.09E-03	6.42E-03
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	1.56E-03	5.91E-03
333511	Industrial mold manufacturing	4.13E-03	7.96E-03
33351A	Metal cutting and forming machine tool manufacturing	2.45E-03	6.21E-03
333514	Special tool, die, jig, and fixture manufacturing	2.96E-03	6.79E-03
333515	Cutting tool and machine tool accessory manufacturing	3.99E-03	7.36E-03
33351B	Rolling mill and other metalworking machinery manufacturing	2.01E-03	5.65E-03

Appendix A (continued)

Table A.6 (continued)

333611	Turbine and turbine generator set units manufacturing	8.51E-04	4.17E-03
333612	Speed changer, industrial high-speed drive, and gear manufacturing	3.18E-03	6.73E-03
333613	Mechanical power transmission equipment manufacturing	3.64E-03	7.79E-03
333618	Other engine equipment manufacturing	1.71E-03	6.85E-03
333911	Pump and pumping equipment manufacturing	2.26E-03	6.77E-03
333912	Air and gas compressor manufacturing	2.03E-03	6.60E-03
333920	Material handling equipment manufacturing	1.44E-03	6.67E-03
333991	Power-driven handtool manufacturing	1.64E-03	6.42E-03
33399A	Other general purpose machinery manufacturing	2.27E-03	6.63E-03
333993	Packaging machinery manufacturing	1.56E-03	5.49E-03
333994	Industrial process furnace and oven manufacturing	2.42E-03	5.96E-03
33399B	Fluid power process machinery	2.90E-03	7.18E-03
334111	Electronic computer manufacturing	3.35E-04	3.69E-03
334112	Computer storage device manufacturing	2.42E-03	5.77E-03
33411A	Computer terminals and other computer peripheral equipment manufacturing	7.93E-04	4.32E-03
334210	Telephone apparatus manufacturing	5.01E-04	3.81E-03
334220	Broadcast and wireless communications equipment	9.84E-04	4.49E-03
334290	Other communications equipment manufacturing	1.54E-03	4.66E-03
334300	Audio and video equipment manufacturing	1.45E-03	6.43E-03
334411	Electron tube manufacturing	3.68E-03	9.15E-03

Appendix A (continued)

Table A.6 (continued)

334412	Bare printed circuit board manufacturing	4.79E-03	8.95E-03
334413	Semiconductor and related device manufacturing	3.74E-03	7.53E-03
33441A	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing	4.39E-03	8.36E-03
334417	Electronic connector manufacturing	3.33E-03	7.86E-03
334418	Printed circuit assembly (electronic assembly) manufacturing	1.59E-03	5.71E-03
334419	Other electronic component manufacturing	2.77E-03	6.57E-03
334510	Electromedical and electrotherapeutic apparatus manufacturing	9.31E-04	4.15E-03
334511	Search, detection, and navigation instruments manufacturing	2.08E-03	4.76E-03
334512	Automatic environmental control manufacturing	1.78E-03	5.49E-03
334513	Industrial process variable instruments manufacturing	1.73E-03	5.51E-03
334514	Totalizing fluid meters and counting devices manufacturing	1.22E-03	5.53E-03
334515	Electricity and signal testing instruments manufacturing	1.61E-03	4.32E-03
334516	Analytical laboratory instrument manufacturing	1.19E-03	4.32E-03
334517	Irradiation apparatus manufacturing	9.12E-04	4.40E-03
33451A	Other Measuring and Controlling Device Manufacturing	1.68E-03	4.91E-03
33461A	Software, audio, and video media reproducing	3.63E-03	7.64E-03
334613	Magnetic and optical recording media manufacturing	2.70E-03	6.68E-03
335110	Electric lamp bulb and part manufacturing	3.49E-03	6.61E-03
335120	Lighting fixture manufacturing	1.69E-03	5.81E-03
335210	Small electrical appliance manufacturing	1.64E-03	5.71E-03

Appendix A (continued)

Table A.6 (continued)

335221	Household cooking appliance manufacturing	1.31E-03	7.15E-03
335222	Household refrigerator and home freezer manufacturing	1.50E-03	6.90E-03
335224	Household laundry equipment manufacturing	1.19E-03	6.10E-03
335228	Other major household appliance manufacturing	1.41E-03	5.85E-03
335311	Power, distribution, and specialty transformer manufacturing	2.04E-03	6.91E-03
335312	Motor and generator manufacturing	2.02E-03	6.57E-03
335313	Switchgear and switchboard apparatus manufacturing	1.47E-03	4.74E-03
335314	Relay and industrial control manufacturing	1.24E-03	4.15E-03
335911	Storage battery manufacturing	6.31E-03	1.24E-02
335912	Primary battery manufacturing	1.86E-03	5.70E-03
335920	Communication and energy wire and cable manufacturing	3.00E-03	9.00E-03
335930	Wiring device manufacturing	3.07E-03	7.31E-03
335991	Carbon and graphite product manufacturing	8.99E-03	1.19E-02
335999	All other miscellaneous electrical equipment and component manufacturing	1.73E-03	5.12E-03
336111	Automobile Manufacturing	6.22E-04	5.77E-03
336112	Light truck and utility vehicle manufacturing	6.27E-04	6.10E-03
336120	Heavy duty truck manufacturing	6.95E-04	6.15E-03
336211	Motor vehicle body manufacturing	1.02E-03	5.57E-03
336212	Truck trailer manufacturing	1.56E-03	7.66E-03
336213	Motor home manufacturing	5.69E-04	5.72E-03
336214	Travel trailer and camper manufacturing	9.89E-04	7.37E-03
336300	Motor vehicle parts manufacturing	2.08E-03	7.61E-03
336411	Aircraft manufacturing	9.58E-04	4.51E-03
336412	Aircraft engine and engine parts manufacturing	1.68E-03	4.73E-03
336413	Other aircraft parts and auxiliary equipment manufacturing	3.01E-03	6.55E-03

Appendix A (continued)

Table A.6 (continued)

336414	Guided missile and space vehicle manufacturing	1.38E-03	4.22E-03
33641A	Propulsion units and parts for space vehicles and guided missiles	2.63E-03	5.20E-03
336500	Railroad rolling stock manufacturing	1.09E-03	4.94E-03
336611	Ship building and repairing	2.02E-03	5.15E-03
336612	Boat building	1.22E-03	5.79E-03
336991	Motorcycle, bicycle, and parts manufacturing	1.16E-03	6.95E-03
336992	Military armored vehicle, tank, and tank component manufacturing	1.98E-03	6.01E-03
336999	All other transportation equipment manufacturing	7.93E-04	6.07E-03
337110	Wood kitchen cabinet and countertop manufacturing	2.02E-03	6.04E-03
337121	Upholstered household furniture manufacturing	1.46E-03	6.34E-03
337122	Nonupholstered wood household furniture manufacturing	3.19E-03	6.80E-03
33712A	Metal and other household furniture (except wood) manufacturing	2.60E-03	7.87E-03
337127	Institutional furniture manufacturing	2.32E-03	6.63E-03
33721A	Wood television, radio, and sewing machine cabinet manufacturing	2.48E-03	6.53E-03
337212	Office furniture and custom architectural woodwork and millwork manufacturing	1.92E-03	5.80E-03
337215	Showcase, partition, shelving, and locker manufacturing	2.91E-03	8.11E-03
337910	Mattress manufacturing	1.00E-03	5.43E-03
337920	Blind and shade manufacturing	1.78E-03	7.93E-03
339111	Laboratory apparatus and furniture manufacturing	1.23E-03	4.65E-03
339112	Surgical and medical instrument manufacturing	1.49E-03	3.85E-03

Appendix A (continued)

Table A.6 (continued)

339113	Surgical appliance and supplies manufacturing	1.39E-03	4.13E-03
339114	Dental equipment and supplies manufacturing	1.37E-03	5.31E-03
339115	Ophthalmic goods manufacturing	2.45E-03	4.66E-03
339116	Dental laboratories	1.29E-03	3.21E-03
339910	Jewelry and silverware manufacturing	8.06E-04	6.42E-03
339920	Sporting and athletic goods manufacturing	1.68E-03	5.84E-03
339930	Doll, toy, and game manufacturing	1.82E-03	5.76E-03
339940	Office supplies (except paper) manufacturing	2.21E-03	5.71E-03
339950	Sign manufacturing	1.87E-03	5.99E-03
339991	Gasket, packing, and sealing device manufacturing	3.89E-03	7.74E-03
339992	Musical instrument manufacturing	2.13E-03	4.41E-03
33999A	All other miscellaneous manufacturing	2.04E-03	6.18E-03
339994	Broom, brush, and mop manufacturing	1.95E-03	5.10E-03
420000	Wholesale trade	1.35E-03	2.39E-03
4A0000	Retail trade	3.97E-03	5.20E-03
481000	Air transportation	2.98E-04	1.59E-03
482000	Rail transportation	2.10E-04	1.82E-03
483000	Water transportation	1.54E-03	3.64E-03
484000	Truck transportation	7.76E-04	2.30E-03
485000	Transit and ground passenger transportation	4.57E-03	6.89E-03
486000	Pipeline transportation	3.37E-03	5.19E-03
48A000	Scenic and sightseeing transportation and support activities for transportation	1.60E-03	3.16E-03
492000	Couriers and messengers	1.39E-03	2.48E-03
493000	Warehousing and storage	7.80E-03	9.56E-03
511110	Newspaper publishers	1.91E-03	4.13E-03
511120	Periodical publishers	7.28E-04	3.15E-03
511130	Book publishers	6.88E-04	2.57E-03
5111A0	Directory, mailing list, and other publishers	7.81E-04	3.00E-03

Appendix A (continued)

Table A.6 (continued)

511200	Software publishers	3.38E-05	1.21E-03
512100	Motion picture and video industries	1.52E-03	2.68E-03
512200	Sound recording industries	1.17E-03	3.49E-03
515100	Radio and television broadcasting	5.70E-04	2.25E-03
515200	Cable and other subscription programming	4.63E-04	2.20E-03
516110	Internet publishing and broadcasting	3.51E-04	2.45E-03
517000	Telecommunications	9.98E-04	2.35E-03
518100	Internet service providers and web search portals	5.80E-04	1.96E-03
518200	Data processing, hosting, and related services	3.82E-04	1.77E-03
519100	Other information services	2.25E-03	3.41E-03
52A000	Monetary authorities and depository credit intermediation	5.73E-05	7.70E-04
522A00	Nondepository credit intermediation and related activities	6.59E-04	1.64E-03
523000	Securities, commodity contracts, investments, and related activities	5.63E-04	1.53E-03
524100	Insurance carriers	4.85E-05	9.40E-04
524200	Insurance agencies, brokerages, and related activities	6.71E-04	1.76E-03
525000	Funds, trusts, and other financial vehicles	2.64E-04	1.57E-03
531000	Real estate	5.31E-03	6.07E-03
S00800	Owner-occupied dwellings	0.00E+00	8.48E-04
532100	Automotive equipment rental and leasing	7.45E-04	1.93E-03
532A00	General and consumer goods rental except video tapes and discs	2.34E-03	3.70E-03
532230	Video tape and disc rental	7.62E-03	9.72E-03
532400	Commercial and industrial machinery and equipment rental and leasing	8.74E-04	2.30E-03
533000	Lessors of nonfinancial intangible assets	3.35E-03	3.87E-03

Appendix A (continued)

Table A.6 (continued)

541100	Legal services	5.57E-04	1.50E-03
541200	Accounting, tax preparation, bookkeeping, and payroll services	8.46E-04	1.72E-03
541300	Architectural, engineering, and related services	5.87E-04	1.86E-03
541400	Specialized design services	9.29E-04	2.19E-03
541511	Custom computer programming services	3.60E-03	4.54E-03
541512	Computer systems design services	8.10E-04	2.31E-03
54151A	Other computer related services, including facilities management	6.99E-04	1.85E-03
541610	Management, scientific, and technical consulting services	3.53E-04	1.42E-03
5416A0	Environmental and other technical consulting services	5.59E-04	1.61E-03
541700	Scientific research and development services	1.81E-03	3.32E-03
541800	Advertising and related services	1.22E-03	3.09E-03
5419A0	All other miscellaneous professional, scientific, and technical services	9.11E-04	1.78E-03
541920	Photographic services	1.94E-03	3.60E-03
541940	Veterinary services	5.73E-04	2.75E-03
550000	Management of companies and enterprises	1.80E-03	2.93E-03
561300	Employment services	7.06E-04	1.31E-03
561500	Travel arrangement and reservation services	6.67E-04	2.11E-03
561100	Office administrative services	1.00E-03	2.20E-03
561200	Facilities support services	1.74E-03	3.03E-03
561400	Business support services	1.25E-03	2.51E-03
561600	Investigation and security services	9.39E-04	2.06E-03
561700	Services to buildings and dwellings	6.22E-04	1.91E-03
561900	Other support services	2.34E-03	3.77E-03
562000	Waste management and remediation services	1.14E-03	2.77E-03
611100	Elementary and secondary schools	2.34E-03	4.22E-03

Appendix A (continued)

Table A.6 (continued)

611A00	Junior colleges, colleges, universities, and professional schools	7.39E-03	9.20E-03
611B00	Other educational services	6.23E-04	2.04E-03
621A00	Offices of physicians, dentists, and other health practitioners	9.85E-04	2.23E-03
621B00	Medical and diagnostic labs and outpatient and other ambulatory care services	1.48E-03	3.08E-03
621600	Home health care services	9.96E-04	2.15E-03
622000	Hospitals	3.07E-03	4.98E-03
623000	Nursing and residential care facilities	4.13E-03	5.58E-03
624A00	Individual and family services	9.09E-04	2.58E-03
624200	Community food, housing, and other relief services, including rehabilitation services	2.90E-03	4.93E-03
624400	Child day care services	2.82E-03	4.50E-03
711100	Performing arts companies	1.17E-03	2.43E-03
711200	Spectator sports	2.11E-03	3.67E-03
711A00	Promoters of performing arts and sports and agents for public figures	2.03E-03	3.85E-03
711500	Independent artists, writers, and performers	3.01E-04	1.32E-03
712000	Museums, historical sites, zoos, and parks	7.56E-03	9.22E-03
713A00	Amusement parks, arcades, and gambling industries	3.64E-03	4.85E-03
713B00	Other amusement and recreation industries	6.17E-03	8.09E-03
713940	Fitness and recreational sports centers	9.32E-03	1.11E-02
713950	Bowling centers	1.66E-02	1.82E-02
7211A0	Hotels and motels, including casino hotels	9.43E-03	1.09E-02
721A00	Other accommodations	9.01E-03	1.04E-02
722000	Food services and drinking places	5.66E-03	8.08E-03
8111A0	Automotive repair and maintenance, except car washes	2.36E-03	4.70E-03
811192	Car washes	7.57E-03	9.06E-03
811200	Electronic and precision equipment repair and maintenance	1.43E-03	2.92E-03

Appendix A (continued)

Table A.6 (continued)

811300	Commercial and industrial machinery and equipment repair and maintenance	2.06E-03	3.70E-03
811400	Personal and household goods repair and maintenance	2.38E-03	4.30E-03
812100	Personal care services	4.47E-03	5.92E-03
812200	Death care services	3.42E-03	5.75E-03
812300	Dry-cleaning and laundry services	5.23E-03	6.14E-03
812900	Other personal services	1.67E-03	3.10E-03
813100	Religious organizations	4.66E-04	2.06E-03
813A00	Grantmaking, giving, and social advocacy organizations	9.03E-04	2.93E-03
813B00	Civic, social, professional, and similar organizations	4.04E-03	6.00E-03
814000	Private households	0.00E+00	0.00E+00
491000	Postal service	9.10E-04	1.65E-03
S00102	Other Federal Government enterprises	2.48E-03	3.21E-03
S00203	Other State and local government enterprises	2.55E-03	4.89E-03
S00500	General Federal defense government services	1.22E-03	2.56E-03
S00600	General Federal nondefense government services	9.40E-04	2.45E-03
S00700	General state and local government services	1.77E-03	3.22E-03
S00401	Scrap	2.74E-03	6.37E-03

Appendix A (continued)

Table A.7 Direct and total petroleum intensities of the non-energy sectors in the US input-output tables

NAICS IO code	Name of the Commodity Sector	Direct Petroleum Intensity (GJ/$)	Total Petroluem Intensity (GJ/$)
1111A0	Oilseed farming	6.96E-03	9.76E-03
1111B0	Grain farming	1.02E-02	1.42E-02
111200	Vegetable and melon farming	5.60E-03	7.85E-03
1113A0	Fruit farming	4.28E-03	6.42E-03
111335	Tree nut farming	4.59E-03	6.63E-03
111400	Greenhouse, nursery, and floriculture production	9.71E-03	1.19E-02
111910	Tobacco farming	1.44E-02	1.84E-02
111920	Cotton farming	1.14E-02	1.80E-02
1119A0	Sugarcane and sugar beet farming	1.01E-02	1.30E-02
1119B0	All other crop farming	1.39E-02	1.72E-02
1121A0	Cattle ranching and farming	5.07E-03	1.42E-02
112120	Dairy cattle and milk production	5.46E-03	1.02E-02
112A00	Animal production, except cattle and poultry and eggs	4.66E-03	8.38E-03
112300	Poultry and egg production	3.29E-03	9.80E-03
113A00	Forest nurseries, forest products, and timber tracts	4.46E-03	7.14E-03
113300	Logging	1.49E-03	5.29E-03
114100	Fishing	2.10E-02	2.29E-02
114200	Hunting and trapping	5.99E-03	8.19E-03
115000	Support activities for agriculture and forestry	2.02E-03	5.30E-03
212210	Iron ore mining	2.04E-03	4.60E-03
2122A0	Gold, silver, and other metal ore mining	8.71E-04	2.35E-03
212230	Copper, nickel, lead, and zinc mining	5.19E-04	1.23E-03
212310	Stone mining and quarrying	1.55E-03	3.34E-03
212320	Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	2.22E-03	3.86E-03
212390	Other nonmetallic mineral mining and quarrying	1.75E-03	3.63E-03
213111	Drilling oil and gas wells	5.83E-04	4.41E-03

Appendix A (continued)

Table A.7 (continued)

213112	Support activities for oil and gas operations	4.28E-04	2.74E-03
21311A	Support activities for other mining	3.46E-03	5.42E-03
221300	Water, sewage and other systems	3.03E-03	4.96E-03
230101	Nonresidential commercial and health care structures	2.35E-03	3.85E-03
230102	Nonresidential manufacturing structures	2.31E-03	3.33E-03
230103	Other nonresidential structures	4.53E-03	6.51E-03
230201	Residential permanent site single- and multi-family structures	2.39E-03	4.89E-03
230202	Other residential structures	2.25E-03	4.81E-03
230301	Nonresidential maintenance and repair	3.76E-03	5.94E-03
230302	Residential maintenance and repair	1.68E-03	4.49E-03
311111	Dog and cat food manufacturing	1.41E-04	4.83E-03
311119	Other animal food manufacturing	3.36E-04	7.36E-03
311210	Flour milling and malt manufacturing	1.82E-04	7.39E-03
311221	Wet corn milling	2.17E-03	9.81E-03
31122A	Soybean and other oilseed processing	3.94E-04	8.59E-03
311225	Fats and oils refining and blending	2.26E-04	7.02E-03
311230	Breakfast cereal manufacturing	1.49E-04	3.35E-03
31131A	Sugar cane mills and refining	4.55E-04	7.14E-03
311313	Beet sugar manufacturing	7.30E-04	8.64E-03
311320	Chocolate and confectionery manufacturing from cacao beans	7.04E-05	5.08E-03
311330	Confectionery manufacturing from purchased chocolate	8.70E-05	3.97E-03
311340	Nonchocolate confectionery manufacturing	1.45E-04	4.56E-03
311410	Frozen food manufacturing	1.46E-04	4.70E-03
311420	Fruit and vegetable canning, pickling, and drying	1.96E-04	3.73E-03
31151A	Fluid milk and butter manufacturing	1.11E-04	6.37E-03

Appendix A (continued)

Table A.7 (continued)

311513	Cheese manufacturing	1.16E-04	6.99E-03
311514	Dry, condensed, and evaporated dairy product manufacturing	1.58E-04	6.03E-03
311520	Ice cream and frozen dessert manufacturing	4.40E-05	4.53E-03
31161A	Animal (except poultry) slaughtering, rendering, and processing	1.17E-04	8.68E-03
311615	Poultry processing	9.59E-05	5.84E-03
311700	Seafood product preparation and packaging	2.03E-04	1.08E-02
311810	Bread and bakery product manufacturing	1.77E-04	2.86E-03
311820	Cookie, cracker and pasta manufacturing	1.10E-04	3.86E-03
311830	Tortilla manufacturing	3.20E-04	3.81E-03
311910	Snack food manufacturing	1.43E-04	4.82E-03
311920	Coffee and tea manufacturing	1.06E-04	4.37E-03
311930	Flavoring syrup and concentrate manufacturing	3.87E-05	1.88E-03
311940	Seasoning and dressing manufacturing	1.91E-04	4.96E-03
311990	All other food manufacturing	1.99E-04	4.08E-03
312110	Soft drink and ice manufacturing	8.08E-05	3.39E-03
312120	Breweries	1.53E-04	2.70E-03
312130	Wineries	5.51E-05	2.49E-03
312140	Distilleries	6.94E-04	2.21E-03
3122A0	Tobacco product manufacturing	6.16E-04	2.17E-03
313100	Fiber, yarn, and thread mills	1.07E-04	8.46E-03
313210	Broadwoven fabric mills	1.68E-04	5.32E-03
313220	Narrow fabric mills and schiffli machine embroidery	1.62E-04	4.48E-03
313230	Nonwoven fabric mills	2.59E-04	6.25E-03
313240	Knit fabric mills	3.03E-04	5.13E-03
313310	Textile and fabric finishing mills	3.32E-04	4.80E-03
313320	Fabric coating mills	1.25E-03	6.84E-03
314110	Carpet and rug mills	3.26E-04	7.05E-03
314120	Curtain and linen mills	1.30E-04	3.73E-03

Appendix A (continued)

Table A.7 (continued)

314910	Textile bag and canvas mills	9.82E-05	3.01E-03
314990	All other textile product mills	2.60E-04	4.80E-03
315100	Apparel knitting mills	1.27E-04	3.06E-03
315210	Cut and sew apparel contractors	1.76E-04	1.50E-03
315220	Men's and boys' cut and sew apparel manufacturing	6.77E-05	2.21E-03
315230	Women's and girls' cut and sew apparel manufacturing	1.45E-04	2.62E-03
315290	Other cut and sew apparel manufacturing	5.80E-05	2.20E-03
315900	Apparel accessories and other apparel manufacturing	5.85E-04	2.96E-03
316100	Leather and hide tanning and finishing	0.00E+00	6.32E-03
316200	Footwear manufacturing	1.64E-05	3.24E-03
316900	Other leather and allied product manufacturing	4.09E-05	2.71E-03
321100	Sawmills and wood preservation	3.09E-04	4.32E-03
32121A	Veneer and plywood manufacturing	4.49E-04	4.20E-03
32121B	Engineered wood member and truss manufacturing	1.85E-04	2.97E-03
321219	Reconstituted wood product manufacturing	4.39E-03	8.83E-03
321910	Wood windows and doors and millwork	1.81E-04	3.26E-03
321920	Wood container and pallet manufacturing	2.21E-03	4.86E-03
321991	Manufactured home (mobile home) manufacturing	1.23E-04	3.04E-03
321992	Prefabricated wood building manufacturing	1.18E-04	2.79E-03
321999	All other miscellaneous wood product manufacturing	4.69E-04	3.47E-03
322110	Pulp mills	1.98E-03	5.42E-03
322120	Paper mills	1.93E-03	5.03E-03
322130	Paperboard mills	2.11E-03	5.19E-03
322210	Paperboard container manufacturing	8.84E-04	4.57E-03
32222A	Coated and laminated paper, packaging paper and plastics film manufacturing	2.94E-04	4.82E-03

Appendix A (continued)

Table A.7 (continued)

32222B	All other paper bag and coated and treated paper manufacturing	1.93E-04	5.09E-03
322230	Stationery product manufacturing	9.75E-05	3.39E-03
322291	Sanitary paper product manufacturing	8.98E-04	3.67E-03
322299	All other converted paper product manufacturing	2.97E-04	3.31E-03
323110	Printing	6.47E-04	3.33E-03
323120	Support activities for printing	1.74E-04	1.75E-03
324121	Asphalt paving mixture and block manufacturing	6.68E-02	6.92E-02
324122	Asphalt shingle and coating materials manufacturing	4.12E-02	4.41E-02
324191	Petroleum lubricating oil and grease manufacturing	6.85E-02	7.12E-02
324199	All other petroleum and coal products manufacturing	5.35E-02	5.55E-02
325110	Petrochemical manufacturing	1.49E-02	2.19E-02
325120	Industrial gas manufacturing	1.02E-02	1.26E-02
325130	Synthetic dye and pigment manufacturing	1.93E-02	2.38E-02
325181	Alkalies and chlorine manufacturing	1.46E-02	1.83E-02
325182	Carbon black manufacturing	8.18E-02	8.29E-02
325188	All other basic inorganic chemical manufacturing	5.20E-03	8.40E-03
325190	Other basic organic chemical manufacturing	1.36E-02	2.23E-02
325211	Plastics material and resin manufacturing	9.58E-03	2.00E-02
325212	Synthetic rubber manufacturing	7.09E-03	1.59E-02
325220	Artificial and synthetic fibers and filaments manufacturing	6.01E-03	1.45E-02
325310	Fertilizer manufacturing	9.67E-03	1.51E-02
325320	Pesticide and other agricultural chemical manufacturing	3.16E-03	8.61E-03
325411	Medicinal and botanical manufacturing	2.12E-03	3.99E-03
325412	Pharmaceutical preparation manufacturing	5.68E-04	2.48E-03
325413	In-vitro diagnostic substance manufacturing	4.98E-04	2.14E-03
325414	Biological product (except diagnostic) manufacturing	3.82E-04	1.72E-03

Appendix A (continued)

Table A.7 (continued)

325510	Paint and coating manufacturing	1.71E-03	9.42E-03
325520	Adhesive manufacturing	2.00E-02	2.53E-02
325610	Soap and cleaning compound manufacturing	4.06E-03	7.82E-03
325620	Toilet preparation manufacturing	3.85E-03	6.41E-03
325910	Printing ink manufacturing	2.12E-02	3.02E-02
3259A0	All other chemical product and preparation manufacturing	6.64E-03	1.20E-02
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	7.37E-04	8.52E-03
326121	Unlaminated plastics profile shape manufacturing	1.79E-04	6.34E-03
326122	Plastic pipe and pipe fitting manufacturing	6.61E-05	9.44E-03
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	3.06E-04	5.30E-03
326140	Polystyrene foam product manufacturing	8.16E-04	7.40E-03
326150	Urethane and other foam product (except polystyrene) manufacturing	2.00E-03	8.71E-03
326160	Plastics bottle manufacturing	1.13E-04	8.12E-03
32619A	Other plastics product manufacturing	1.33E-03	6.15E-03
326210	Tire manufacturing	2.28E-04	7.86E-03
326220	Rubber and plastics hoses and belting manufacturing	2.79E-04	5.41E-03
326290	Other rubber product manufacturing	2.69E-04	5.67E-03
32711A	Pottery, ceramics, and plumbing fixture manufacturing	4.66E-04	2.42E-03
32712A	Brick, tile, and other structural clay product manufacturing	1.51E-03	3.01E-03
32712B	Clay and nonclay refractory manufacturing	5.24E-04	2.95E-03
327211	Flat glass manufacturing	1.66E-03	4.13E-03
327212	Other pressed and blown glass and glassware manufacturing	4.89E-04	2.87E-03
327213	Glass container manufacturing	1.13E-03	3.40E-03

Appendix A (continued)

Table A.7 (continued)

327215	Glass product manufacturing made of purchased glass	5.44E-04	2.77E-03
327310	Cement manufacturing	1.49E-03	3.08E-03
327320	Ready-mix concrete manufacturing	3.36E-04	4.14E-03
327330	Concrete pipe, brick and block manufacturing	1.39E-04	2.42E-03
327390	Other concrete product manufacturing	1.30E-04	2.04E-03
3274A0	Lime and gypsum product manufacturing	1.91E-03	5.02E-03
327910	Abrasive product manufacturing	3.69E-04	2.43E-03
327991	Cut stone and stone product manufacturing	2.11E-04	2.70E-03
327992	Ground or treated mineral and earth manufacturing	7.14E-04	2.93E-03
327993	Mineral wool manufacturing	7.37E-04	3.65E-03
327999	Miscellaneous nonmetallic mineral products	1.74E-03	4.70E-03
331110	Iron and steel mills and ferroalloy manufacturing	1.56E-03	4.50E-03
331200	Steel product manufacturing from purchased steel	5.18E-04	2.92E-03
33131A	Alumina refining and primary aluminum production	3.66E-04	2.88E-03
331314	Secondary smelting and alloying of aluminum	3.60E-04	2.87E-03
33131B	Aluminum product manufacturing from purchased aluminum	1.61E-04	2.46E-03
331411	Primary smelting and refining of copper	1.51E-04	2.15E-03
331419	Primary smelting and refining of nonferrous metal (except copper and aluminum)	1.79E-04	2.18E-03
331420	Copper rolling, drawing, extruding and alloying	8.18E-05	2.51E-03
331490	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	1.14E-04	2.11E-03
331510	Ferrous metal foundries	1.65E-04	1.76E-03
331520	Nonferrous metal foundries	1.70E-04	1.96E-03

Appendix A (continued)

Table A.7 (continued)

33211A	All other forging, stamping, and sintering	2.91E-04	2.46E-03
332114	Custom roll forming	1.42E-04	2.75E-03
33211B	Crown and closure manufacturing and metal stamping	1.11E-04	2.43E-03
33221A	Cutlery, utensil, pot, and pan manufacturing	2.38E-04	1.97E-03
33221B	Handtool manufacturing	1.38E-04	1.94E-03
332310	Plate work and fabricated structural product manufacturing	7.84E-05	2.14E-03
332320	Ornamental and architectural metal products manufacturing	7.10E-05	2.29E-03
332410	Power boiler and heat exchanger manufacturing	8.04E-05	1.85E-03
332420	Metal tank (heavy gauge) manufacturing	9.33E-05	2.04E-03
332430	Metal can, box, and other metal container (light gauge) manufacturing	9.74E-05	2.56E-03
33299A	Ammunition manufacturing	2.34E-04	1.81E-03
33299B	Arms, ordnance, and accessories manufacturing	4.34E-05	1.23E-03
332500	Hardware manufacturing	6.62E-05	1.83E-03
332600	Spring and wire product manufacturing	1.43E-04	2.16E-03
332710	Machine shops	4.15E-04	1.80E-03
332720	Turned product and screw, nut, and bolt manufacturing	8.55E-05	1.53E-03
332800	Coating, engraving, heat treating and allied activities	2.18E-03	4.84E-03
33291A	Valve and fittings other than plumbing	4.56E-05	1.51E-03
332913	Plumbing fixture fitting and trim manufacturing	1.10E-04	1.99E-03
332991	Ball and roller bearing manufacturing	7.81E-05	1.49E-03
332996	Fabricated pipe and pipe fitting manufacturing	6.82E-05	1.84E-03
33299C	Other fabricated metal manufacturing	6.32E-04	2.69E-03
333111	Farm machinery and equipment manufacturing	1.07E-04	2.13E-03
333112	Lawn and garden equipment manufacturing	5.04E-05	2.13E-03
333120	Construction machinery manufacturing	2.30E-03	4.25E-03

Appendix A (continued)

Table A.7 (continued)

333130	Mining and oil and gas field machinery manufacturing	1.63E-04	2.15E-03
33329A	Other industrial machinery manufacturing	1.60E-04	1.76E-03
333220	Plastics and rubber industry machinery manufacturing	5.37E-05	1.52E-03
333295	Semiconductor machinery manufacturing	1.91E-04	2.02E-03
33331A	Vending, commercial, industrial, and office machinery manufacturing	1.42E-03	3.58E-03
333314	Optical instrument and lens manufacturing	6.60E-05	1.87E-03
333315	Photographic and photocopying equipment manufacturing	1.01E-03	3.88E-03
333319	Other commercial and service industry machinery manufacturing	2.45E-03	4.32E-03
33341A	Air purification and ventilation equipment manufacturing	5.62E-05	1.91E-03
333414	Heating equipment, except warm air furnaces	1.57E-04	2.29E-03
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	4.27E-05	1.84E-03
333511	Industrial mold manufacturing	1.57E-04	1.88E-03
33351A	Metal cutting and forming machine tool manufacturing	5.25E-05	1.52E-03
333514	Special tool, die, jig, and fixture manufacturing	6.75E-05	1.53E-03
333515	Cutting tool and machine tool accessory manufacturing	5.39E-05	1.54E-03
33351B	Rolling mill and other metalworking machinery manufacturing	1.04E-04	1.43E-03
333611	Turbine and turbine generator set units manufacturing	2.56E-05	1.07E-03
333612	Speed changer, industrial high-speed drive, and gear manufacturing	9.89E-05	1.27E-03
333613	Mechanical power transmission equipment manufacturing	9.63E-05	1.58E-03
333618	Other engine equipment manufacturing	3.26E-04	2.38E-03
333911	Pump and pumping equipment manufacturing	7.18E-05	1.70E-03

Appendix A (continued)

Table A.7 (continued)

333912	Air and gas compressor manufacturing	6.43E-05	1.84E-03
333920	Material handling equipment manufacturing	1.03E-04	1.95E-03
333991	Power-driven handtool manufacturing	8.44E-05	1.92E-03
33399A	Other general purpose machinery manufacturing	8.84E-05	1.90E-03
333993	Packaging machinery manufacturing	5.52E-05	1.53E-03
333994	Industrial process furnace and oven manufacturing	1.03E-04	1.43E-03
33399B	Fluid power process machinery	6.23E-05	1.71E-03
334111	Electronic computer manufacturing	9.25E-05	1.38E-03
334112	Computer storage device manufacturing	6.24E-05	1.47E-03
33411A	Computer terminals and other computer peripheral equipment manufacturing	5.60E-04	2.02E-03
334210	Telephone apparatus manufacturing	3.54E-05	1.37E-03
334220	Broadcast and wireless communications equipment	1.68E-05	1.37E-03
334290	Other communications equipment manufacturing	6.26E-05	1.42E-03
334300	Audio and video equipment manufacturing	3.17E-05	2.03E-03
334411	Electron tube manufacturing	7.59E-05	2.14E-03
334412	Bare printed circuit board manufacturing	1.14E-04	1.86E-03
334413	Semiconductor and related device manufacturing	3.08E-04	1.81E-03
33441A	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing	2.81E-05	1.70E-03
334417	Electronic connector manufacturing	2.85E-05	1.95E-03
334418	Printed circuit assembly (electronic assembly) manufacturing	2.28E-05	1.54E-03
334419	Other electronic component manufacturing	5.95E-05	1.61E-03
334510	Electromedical and electrotherapeutic apparatus manufacturing	2.11E-05	1.85E-03
334511	Search, detection, and navigation instruments manufacturing	4.68E-05	1.16E-03

Appendix A (continued)

Table A.7 (continued)

334512	Automatic environmental control manufacturing	9.43E-05	1.72E-03
334513	Industrial process variable instruments manufacturing	7.43E-05	1.63E-03
334514	Totalizing fluid meters and counting devices manufacturing	3.69E-05	1.86E-03
334515	Electricity and signal testing instruments manufacturing	1.17E-04	1.24E-03
334516	Analytical laboratory instrument manufacturing	6.91E-05	1.63E-03
334517	Irradiation apparatus manufacturing	3.11E-04	1.74E-03
33451A	Other Measuring and Controlling Device Manufacturing	4.20E-05	1.46E-03
33461A	Software, audio, and video media reproducing	3.07E-05	2.58E-03
334613	Magnetic and optical recording media manufacturing	5.63E-05	2.51E-03
335110	Electric lamp bulb and part manufacturing	5.21E-05	1.42E-03
335120	Lighting fixture manufacturing	1.50E-04	2.27E-03
335210	Small electrical appliance manufacturing	4.60E-05	2.78E-03
335221	Household cooking appliance manufacturing	3.56E-05	2.47E-03
335222	Household refrigerator and home freezer manufacturing	1.93E-05	3.05E-03
335224	Household laundry equipment manufacturing	2.78E-05	2.19E-03
335228	Other major household appliance manufacturing	3.57E-05	2.54E-03
335311	Power, distribution, and specialty transformer manufacturing	4.65E-05	3.00E-03
335312	Motor and generator manufacturing	4.00E-05	1.73E-03
335313	Switchgear and switchboard apparatus manufacturing	1.62E-05	1.33E-03
335314	Relay and industrial control manufacturing	6.28E-06	1.19E-03
335911	Storage battery manufacturing	8.31E-05	2.40E-03
335912	Primary battery manufacturing	1.69E-04	2.15E-03

Appendix A (continued)

Table A.7 (continued)

335920	Communication and energy wire and cable manufacturing	4.27E-05	2.97E-03
335930	Wiring device manufacturing	6.50E-05	2.26E-03
335991	Carbon and graphite product manufacturing	2.34E-04	7.71E-03
335999	All other miscellaneous electrical equipment and component manufacturing	1.72E-04	1.40E-03
336111	Automobile Manufacturing	2.42E-05	2.03E-03
336112	Light truck and utility vehicle manufacturing	3.66E-05	2.24E-03
336120	Heavy duty truck manufacturing	1.57E-04	2.32E-03
336211	Motor vehicle body manufacturing	7.50E-05	1.84E-03
336212	Truck trailer manufacturing	3.52E-05	2.35E-03
336213	Motor home manufacturing	1.47E-05	2.43E-03
336214	Travel trailer and camper manufacturing	4.68E-05	2.58E-03
336300	Motor vehicle parts manufacturing	6.12E-05	2.29E-03
336411	Aircraft manufacturing	4.06E-05	1.35E-03
336412	Aircraft engine and engine parts manufacturing	1.27E-04	1.20E-03
336413	Other aircraft parts and auxiliary equipment manufacturing	2.59E-04	1.94E-03
336414	Guided missile and space vehicle manufacturing	3.07E-05	1.18E-03
33641A	Propulsion units and parts for space vehicles and guided missiles	4.70E-05	1.16E-03
336500	Railroad rolling stock manufacturing	4.86E-05	1.56E-03
336611	Ship building and repairing	5.72E-05	1.50E-03
336612	Boat building	4.85E-05	2.26E-03
336991	Motorcycle, bicycle, and parts manufacturing	4.99E-05	1.81E-03
336992	Military armored vehicle, tank, and tank component manufacturing	4.81E-05	1.60E-03
336999	All other transportation equipment manufacturing	3.44E-05	2.31E-03
337110	Wood kitchen cabinet and countertop manufacturing	1.54E-04	3.08E-03

Appendix A (continued)

Table A.7 (continued)

337121	Upholstered household furniture manufacturing	2.60E-05	2.88E-03
337122	Nonupholstered wood household furniture manufacturing	6.66E-05	2.51E-03
33712A	Metal and other household furniture (except wood) manufacturing	1.03E-04	3.58E-03
337127	Institutional furniture manufacturing	1.22E-04	2.42E-03
33721A	Wood television, radio, and sewing machine cabinet manufacturing	3.20E-06	2.46E-03
337212	Office furniture and custom architectural woodwork and millwork manufacturing	7.26E-05	2.25E-03
337215	Showcase, partition, shelving, and locker manufacturing	1.56E-04	2.98E-03
337910	Mattress manufacturing	4.59E-05	2.91E-03
337920	Blind and shade manufacturing	5.85E-05	2.98E-03
339111	Laboratory apparatus and furniture manufacturing	1.70E-04	2.18E-03
339112	Surgical and medical instrument manufacturing	2.62E-05	1.68E-03
339113	Surgical appliance and supplies manufacturing	5.73E-05	1.90E-03
339114	Dental equipment and supplies manufacturing	7.19E-05	1.81E-03
339115	Ophthalmic goods manufacturing	1.12E-05	1.67E-03
339116	Dental laboratories	4.08E-05	9.52E-04
339910	Jewelry and silverware manufacturing	3.76E-05	1.84E-03
339920	Sporting and athletic goods manufacturing	8.79E-05	2.85E-03
339930	Doll, toy, and game manufacturing	4.83E-05	3.29E-03
339940	Office supplies (except paper) manufacturing	7.30E-05	3.26E-03
339950	Sign manufacturing	9.03E-05	2.82E-03
339991	Gasket, packing, and sealing device manufacturing	2.55E-04	3.22E-03
339992	Musical instrument manufacturing	5.51E-05	1.39E-03
33999A	All other miscellaneous manufacturing	6.81E-05	2.72E-03

Appendix A (continued)

Table A.7 (continued)

339994	Broom, brush, and mop manufacturing	1.70E-04	3.98E-03
420000	Wholesale trade	7.93E-04	1.69E-03
4A0000	Retail trade	3.35E-04	1.16E-03
481000	Air transportation	2.55E-02	2.66E-02
482000	Rail transportation	8.15E-03	9.77E-03
483000	Water transportation	9.65E-05	2.32E-03
484000	Truck transportation	1.39E-02	1.71E-02
485000	Transit and ground passenger transportation	3.08E-02	3.29E-02
486000	Pipeline transportation	3.33E-02	3.48E-02
48A000	Scenic and sightseeing transportation and support activities for transportation	2.38E-03	4.90E-03
492000	Couriers and messengers	1.76E-02	1.91E-02
493000	Warehousing and storage	1.10E-03	2.30E-03
511110	Newspaper publishers	8.51E-05	1.60E-03
511120	Periodical publishers	1.53E-04	2.20E-03
511130	Book publishers	7.48E-05	1.47E-03
5111A0	Directory, mailing list, and other publishers	8.10E-05	1.67E-03
511200	Software publishers	7.67E-05	8.80E-04
512100	Motion picture and video industries	5.77E-05	6.98E-04
512200	Sound recording industries	1.07E-04	1.57E-03
515100	Radio and television broadcasting	2.43E-04	1.01E-03
515200	Cable and other subscription programming	2.06E-04	1.04E-03
516110	Internet publishing and broadcasting	1.52E-04	2.08E-03
517000	Telecommunications	3.98E-04	1.23E-03
518100	Internet service providers and web search portals	2.38E-04	1.13E-03
518200	Data processing, hosting, and related services	1.04E-04	1.26E-03
519100	Other information services	5.16E-04	1.36E-03
52A000	Monetary authorities and depository credit intermediation	9.10E-05	7.05E-04
522A00	Nondepository credit intermediation and related activities	1.42E-04	7.37E-04

Appendix A (continued)

Table A.7 (continued)

523000	Securities, commodity contracts, investments, and related activities	9.35E-05	6.97E-04
524100	Insurance carriers	2.88E-06	4.77E-04
524200	Insurance agencies, brokerages, and related activities	1.20E-04	8.80E-04
525000	Funds, trusts, and other financial vehicles	1.28E-05	6.83E-04
531000	Real estate	9.97E-05	7.37E-04
S00800	Owner-occupied dwellings	1.10E-06	6.78E-04
532100	Automotive equipment rental and leasing	1.22E-04	9.46E-04
532A00	General and consumer goods rental except video tapes and discs	3.22E-04	1.15E-03
532230	Video tape and disc rental	2.15E-04	1.20E-03
532400	Commercial and industrial machinery and equipment rental and leasing	3.00E-04	1.37E-03
533000	Lessors of nonfinancial intangible assets	1.30E-04	4.49E-04
541100	Legal services	1.01E-04	6.27E-04
541200	Accounting, tax preparation, bookkeeping, and payroll services	1.23E-04	7.57E-04
541300	Architectural, engineering, and related services	6.00E-04	1.49E-03
541400	Specialized design services	1.11E-04	1.07E-03
541511	Custom computer programming services	5.06E-05	5.30E-04
541512	Computer systems design services	2.17E-04	1.24E-03
54151A	Other computer related services, including facilities management	1.42E-04	9.57E-04
541610	Management, scientific, and technical consulting services	1.12E-04	1.08E-03
5416A0	Environmental and other technical consulting services	1.87E-04	9.07E-04
541700	Scientific research and development services	6.92E-04	2.26E-03
541800	Advertising and related services	1.96E-04	1.46E-03
5419A0	All other miscellaneous professional, scientific, and technical services	1.27E-04	7.03E-04

Appendix A (continued)

Table A.7 (continued)

541920	Photographic services	2.07E-04	1.46E-03
541940	Veterinary services	3.63E-04	2.01E-03
550000	Management of companies and enterprises	1.80E-04	7.89E-04
561300	Employment services	1.71E-04	6.60E-04
561500	Travel arrangement and reservation services	8.25E-04	1.82E-03
561100	Office administrative services	1.79E-04	1.11E-03
561200	Facilities support services	1.57E-04	1.09E-03
561400	Business support services	2.30E-04	1.43E-03
561600	Investigation and security services	3.18E-04	1.10E-03
561700	Services to buildings and dwellings	2.34E-02	2.45E-02
561900	Other support services	2.89E-04	1.37E-03
562000	Waste management and remediation services	1.94E-03	3.38E-03
611100	Elementary and secondary schools	5.15E-04	1.83E-03
611A00	Junior colleges, colleges, universities, and professional schools	1.52E-03	2.86E-03
611B00	Other educational services	3.90E-04	1.43E-03
621A00	Offices of physicians, dentists, and other health practitioners	8.29E-05	9.13E-04
621B00	Medical and diagnostic labs and outpatient and other ambulatory care services	4.42E-04	1.55E-03
621600	Home health care services	1.04E-03	1.97E-03
622000	Hospitals	9.17E-04	2.06E-03
623000	Nursing and residential care facilities	4.61E-04	1.39E-03
624A00	Individual and family services	4.32E-04	1.50E-03
624200	Community food, housing, and other relief services, including rehabilitation services	2.84E-04	1.51E-03
624400	Child day care services	2.51E-04	1.37E-03
711100	Performing arts companies	8.58E-05	1.12E-03
711200	Spectator sports	1.99E-04	1.05E-03
711A00	Promoters of performing arts and sports and agents for public figures	1.96E-04	2.27E-03

Appendix A (continued)

Table A.7 (continued)

711500	Independent artists, writers, and performers	4.29E-05	6.37E-04
712000	Museums, historical sites, zoos, and parks	1.14E-03	2.26E-03
713A00	Amusement parks, arcades, and gambling industries	9.60E-04	1.99E-03
713B00	Other amusement and recreation industries	1.30E-03	2.75E-03
713940	Fitness and recreational sports centers	9.49E-04	2.08E-03
713950	Bowling centers	5.96E-04	1.88E-03
7211A0	Hotels and motels, including casino hotels	8.12E-04	2.06E-03
721A00	Other accommodations	8.76E-04	2.17E-03
722000	Food services and drinking places	4.96E-04	2.14E-03
8111A0	Automotive repair and maintenance, except car washes	1.81E-04	1.53E-03
811192	Car washes	1.39E-03	2.37E-03
811200	Electronic and precision equipment repair and maintenance	1.23E-04	9.50E-04
811300	Commercial and industrial machinery and equipment repair and maintenance	2.51E-04	1.22E-03
811400	Personal and household goods repair and maintenance	2.24E-04	1.34E-03
812100	Personal care services	1.38E-04	9.55E-04
812200	Death care services	6.15E-04	2.23E-03
812300	Dry-cleaning and laundry services	4.47E-04	1.13E-03
812900	Other personal services	2.85E-04	1.39E-03
813100	Religious organizations	9.39E-05	1.36E-03
813A00	Grantmaking, giving, and social advocacy organizations	2.95E-04	1.93E-03
813B00	Civic, social, professional, and similar organizations	6.09E-04	2.03E-03
814000	Private households	0.00E+00	0.00E+00
491000	Postal service	1.78E-03	2.67E-03
S00102	Other Federal Government enterprises	4.18E-05	6.31E-04
S00203	Other State and local government enterprises	3.56E-03	5.68E-03

Appendix A (continued)

Table A.7 (continued)

S00500	General Federal defense government services	1.96E-03	2.96E-03
S00600	General Federal nondefense government services	1.48E-03	2.57E-03
S00700	General state and local government services	3.71E-03	5.20E-03
S00401	Scrap	2.12E-03	4.12E-03

Appendix A (continued)

Table A.8 Direct and total oil&gas intensities of the non-energy sectors in the US input-output tables

NAICS IO code	Name of the Commodity Sector	Direct Oil&Gas Intensity (GJ/$)	Total Oil&Gas Intensity (GJ/$)
1111A0	Oilseed farming	3.24E-04	2.45E-03
1111B0	Grain farming	2.52E-03	6.94E-03
111200	Vegetable and melon farming	2.65E-04	2.25E-03
1113A0	Fruit farming	6.87E-04	2.70E-03
111335	Tree nut farming	7.13E-04	2.63E-03
111400	Greenhouse, nursery, and floriculture production	3.57E-03	4.99E-03
111910	Tobacco farming	1.00E-03	3.83E-03
111920	Cotton farming	2.29E-03	7.75E-03
1119A0	Sugarcane and sugar beet farming	8.75E-04	3.07E-03
1119B0	All other crop farming	1.09E-03	3.95E-03
1121A0	Cattle ranching and farming	1.13E-03	3.77E-03
112120	Dairy cattle and milk production	2.26E-04	2.54E-03
112A00	Animal production, except cattle and poultry and eggs	4.75E-04	1.94E-03
112300	Poultry and egg production	1.61E-03	5.60E-03
113A00	Forest nurseries, forest products, and timber tracts	4.05E-04	2.65E-03
113300	Logging	6.38E-06	1.19E-03
114100	Fishing	0.00E+00	1.04E-03
114200	Hunting and trapping	9.50E-04	1.89E-03
115000	Support activities for agriculture and forestry	2.73E-04	5.32E-03
212210	Iron ore mining	9.99E-03	1.17E-02
2122A0	Gold, silver, and other metal ore mining	6.01E-03	7.54E-03
212230	Copper, nickel, lead, and zinc mining	5.97E-03	6.81E-03
212310	Stone mining and quarrying	5.03E-03	6.01E-03
212320	Sand, gravel, clay, and ceramic and refractory minerals mining and quarrying	6.82E-03	7.85E-03
212390	Other nonmetallic mineral mining and quarrying	8.56E-03	9.51E-03
213111	Drilling oil and gas wells	2.36E-03	4.27E-03

Appendix A (continued)

Table A.8 (continued)

213112	Support activities for oil and gas operations	2.79E-03	3.91E-03
21311A	Support activities for other mining	3.12E-03	4.69E-03
221300	Water, sewage and other systems	3.74E-03	4.70E-03
230101	Nonresidential commercial and health care structures	1.96E-04	1.31E-03
230102	Nonresidential manufacturing structures	1.95E-04	1.04E-03
230103	Other nonresidential structures	2.65E-04	1.31E-03
230201	Residential permanent site single- and multi-family structures	1.92E-04	1.72E-03
230202	Other residential structures	1.88E-04	1.57E-03
230301	Nonresidential maintenance and repair	2.68E-04	1.27E-03
230302	Residential maintenance and repair	1.13E-04	1.66E-03
311111	Dog and cat food manufacturing	2.23E-03	5.21E-03
311119	Other animal food manufacturing	2.28E-03	6.21E-03
311210	Flour milling and malt manufacturing	2.63E-03	5.62E-03
311221	Wet corn milling	1.53E-02	1.88E-02
31122A	Soybean and other oilseed processing	4.07E-03	6.78E-03
311225	Fats and oils refining and blending	3.51E-03	7.54E-03
311230	Breakfast cereal manufacturing	1.87E-03	4.20E-03
31131A	Sugar cane mills and refining	6.34E-03	1.17E-02
311313	Beet sugar manufacturing	1.18E-02	1.40E-02
311320	Chocolate and confectionery manufacturing from cacao beans	1.08E-03	4.55E-03
311330	Confectionery manufacturing from purchased chocolate	1.10E-03	4.04E-03
311340	Nonchocolate confectionery manufacturing	1.53E-03	5.16E-03
311410	Frozen food manufacturing	2.30E-03	4.66E-03
311420	Fruit and vegetable canning, pickling, and drying	2.92E-03	5.35E-03
31151A	Fluid milk and butter manufacturing	1.53E-03	3.83E-03

Appendix A (continued)

Table A.8 (continued)

311513	Cheese manufacturing	1.74E-03	4.34E-03
311514	Dry, condensed, and evaporated dairy product manufacturing	2.38E-03	5.05E-03
311520	Ice cream and frozen dessert manufacturing	6.02E-04	3.24E-03
31161A	Animal (except poultry) slaughtering, rendering, and processing	1.55E-03	4.17E-03
311615	Poultry processing	1.32E-03	4.43E-03
311700	Seafood product preparation and packaging	2.79E-03	3.97E-03
311810	Bread and bakery product manufacturing	2.26E-03	4.44E-03
311820	Cookie, cracker and pasta manufacturing	1.46E-03	4.22E-03
311830	Tortilla manufacturing	3.52E-03	5.52E-03
311910	Snack food manufacturing	2.19E-03	4.56E-03
311920	Coffee and tea manufacturing	1.36E-03	3.62E-03
311930	Flavoring syrup and concentrate manufacturing	5.27E-04	1.93E-03
311940	Seasoning and dressing manufacturing	1.04E-03	3.91E-03
311990	All other food manufacturing	2.02E-03	4.31E-03
312110	Soft drink and ice manufacturing	8.09E-04	4.22E-03
312120	Breweries	1.63E-03	4.51E-03
312130	Wineries	5.17E-04	2.44E-03
312140	Distilleries	9.48E-04	2.13E-03
3122A0	Tobacco product manufacturing	3.83E-04	1.11E-03
313100	Fiber, yarn, and thread mills	1.01E-03	5.33E-03
313210	Broadwoven fabric mills	1.84E-03	4.95E-03
313220	Narrow fabric mills and schiffli machine embroidery	1.47E-03	3.87E-03
313230	Nonwoven fabric mills	2.15E-03	5.64E-03
313240	Knit fabric mills	3.13E-03	6.02E-03
313310	Textile and fabric finishing mills	3.64E-03	6.39E-03
313320	Fabric coating mills	2.03E-03	5.55E-03
314110	Carpet and rug mills	1.76E-03	5.61E-03
314120	Curtain and linen mills	8.77E-04	3.43E-03
314910	Textile bag and canvas mills	5.46E-04	2.66E-03
314990	All other textile product mills	1.30E-03	4.14E-03
315100	Apparel knitting mills	1.77E-03	3.72E-03
315210	Cut and sew apparel contractors	2.37E-03	3.40E-03
315220	Men's and boys' cut and sew apparel manufacturing	9.01E-04	2.98E-03

Appendix A (continued)

Table A.8 (continued)

315230	Women's and girls' cut and sew apparel manufacturing	1.87E-03	4.17E-03
315290	Other cut and sew apparel manufacturing	7.29E-04	2.76E-03
315900	Apparel accessories and other apparel manufacturing	8.15E-03	1.03E-02
316100	Leather and hide tanning and finishing	1.44E-03	4.57E-03
316200	Footwear manufacturing	1.09E-03	3.27E-03
316900	Other leather and allied product manufacturing	1.63E-03	3.36E-03
321100	Sawmills and wood preservation	1.10E-03	2.36E-03
32121A	Veneer and plywood manufacturing	1.69E-03	3.02E-03
32121B	Engineered wood member and truss manufacturing	4.95E-04	1.83E-03
321219	Reconstituted wood product manufacturing	4.95E-03	7.11E-03
321910	Wood windows and doors and millwork	5.24E-04	2.23E-03
321920	Wood container and pallet manufacturing	8.33E-04	2.36E-03
321991	Manufactured home (mobile home) manufacturing	1.99E-04	2.60E-03
321992	Prefabricated wood building manufacturing	3.17E-04	2.03E-03
321999	All other miscellaneous wood product manufacturing	1.08E-03	2.40E-03
322110	Pulp mills	1.02E-02	1.22E-02
322120	Paper mills	6.71E-03	9.09E-03
322130	Paperboard mills	1.22E-02	1.39E-02
322210	Paperboard container manufacturing	9.97E-04	6.07E-03
32222A	Coated and laminated paper, packaging paper and plastics film manufacturing	1.45E-03	5.15E-03
32222B	All other paper bag and coated and treated paper manufacturing	8.60E-04	5.07E-03
322230	Stationery product manufacturing	3.22E-04	4.39E-03
322291	Sanitary paper product manufacturing	3.14E-03	5.66E-03
322299	All other converted paper product manufacturing	1.49E-03	5.22E-03
323110	Printing	7.92E-04	2.73E-03
323120	Support activities for printing	5.33E-04	1.63E-03

Appendix A (continued)

Table A.8 (continued)

324121	Asphalt paving mixture and block manufacturing	6.95E-03	8.23E-03
324122	Asphalt shingle and coating materials manufacturing	2.10E-03	3.85E-03
324191	Petroleum lubricating oil and grease manufacturing	9.10E-03	1.07E-02
324199	All other petroleum and coal products manufacturing	1.34E-02	1.45E-02
325110	Petrochemical manufacturing	9.64E-03	1.42E-02
325120	Industrial gas manufacturing	5.40E-03	7.01E-03
325130	Synthetic dye and pigment manufacturing	4.88E-03	7.90E-03
325181	Alkalies and chlorine manufacturing	1.37E-02	1.60E-02
325182	Carbon black manufacturing	1.98E-02	2.03E-02
325188	All other basic inorganic chemical manufacturing	6.22E-03	8.78E-03
325190	Other basic organic chemical manufacturing	1.05E-02	1.61E-02
325211	Plastics material and resin manufacturing	6.22E-03	1.33E-02
325212	Synthetic rubber manufacturing	4.85E-03	1.03E-02
325220	Artificial and synthetic fibers and filaments manufacturing	2.96E-03	8.11E-03
325310	Fertilizer manufacturing	3.88E-02	4.78E-02
325320	Pesticide and other agricultural chemical manufacturing	1.04E-03	4.76E-03
325411	Medicinal and botanical manufacturing	1.01E-03	2.06E-03
325412	Pharmaceutical preparation manufacturing	3.09E-04	1.45E-03
325413	In-vitro diagnostic substance manufacturing	2.12E-04	1.19E-03
325414	Biological product (except diagnostic) manufacturing	4.24E-04	1.17E-03
325510	Paint and coating manufacturing	3.35E-04	4.74E-03
325520	Adhesive manufacturing	8.62E-04	4.24E-03
325610	Soap and cleaning compound manufacturing	1.29E-03	3.56E-03
325620	Toilet preparation manufacturing	1.38E-03	3.05E-03
325910	Printing ink manufacturing	2.57E-04	3.82E-03
3259A0	All other chemical product and preparation manufacturing	1.19E-03	4.69E-03

Appendix A (continued)

Table A.8 (continued)

326110	Plastics packaging materials and unlaminated film and sheet manufacturing	1.40E-03	6.27E-03
326121	Unlaminated plastics profile shape manufacturing	9.70E-04	4.92E-03
326122	Plastic pipe and pipe fitting manufacturing	3.80E-04	6.33E-03
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	2.45E-03	6.17E-03
326140	Polystyrene foam product manufacturing	2.75E-03	7.06E-03
326150	Urethane and other foam product (except polystyrene) manufacturing	9.16E-04	5.46E-03
326160	Plastics bottle manufacturing	4.61E-04	5.60E-03
32619A	Other plastics product manufacturing	7.05E-04	3.82E-03
326210	Tire manufacturing	1.99E-03	5.40E-03
326220	Rubber and plastics hoses and belting manufacturing	1.31E-03	4.57E-03
326290	Other rubber product manufacturing	1.29E-03	4.40E-03
32711A	Pottery, ceramics, and plumbing fixture manufacturing	4.20E-03	5.80E-03
32712A	Brick, tile, and other structural clay product manufacturing	1.45E-02	1.54E-02
32712B	Clay and nonclay refractory manufacturing	4.92E-03	7.29E-03
327211	Flat glass manufacturing	1.63E-02	1.80E-02
327212	Other pressed and blown glass and glassware manufacturing	4.65E-03	7.17E-03
327213	Glass container manufacturing	1.12E-02	1.29E-02
327215	Glass product manufacturing made of purchased glass	2.79E-03	5.73E-03
327310	Cement manufacturing	1.48E-02	1.65E-02
327320	Ready-mix concrete manufacturing	1.52E-03	6.11E-03
327330	Concrete pipe, brick and block manufacturing	1.29E-03	4.35E-03
327390	Other concrete product manufacturing	1.13E-03	3.32E-03
3274A0	Lime and gypsum product manufacturing	1.64E-02	1.92E-02

Appendix A (continued)

Table A.8 (continued)

327910	Abrasive product manufacturing	1.53E-03	2.93E-03
327991	Cut stone and stone product manufacturing	1.02E-03	2.38E-03
327992	Ground or treated mineral and earth manufacturing	6.57E-03	7.94E-03
327993	Mineral wool manufacturing	6.99E-03	8.93E-03
327999	Miscellaneous nonmetallic mineral products	2.32E-03	5.69E-03
331110	Iron and steel mills and ferroalloy manufacturing	5.74E-03	8.56E-03
331200	Steel product manufacturing from purchased steel	3.00E-03	5.50E-03
33131A	Alumina refining and primary aluminum production	6.13E-03	9.08E-03
331314	Secondary smelting and alloying of aluminum	6.35E-03	9.26E-03
33131B	Aluminum product manufacturing from purchased aluminum	2.81E-03	6.59E-03
331411	Primary smelting and refining of copper	2.49E-03	6.08E-03
331419	Primary smelting and refining of nonferrous metal (except copper and aluminum)	2.92E-03	5.67E-03
331420	Copper rolling, drawing, extruding and alloying	1.16E-03	4.00E-03
331490	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	1.85E-03	4.06E-03
331510	Ferrous metal foundries	2.91E-03	4.29E-03
331520	Nonferrous metal foundries	2.70E-03	4.84E-03
33211A	All other forging, stamping, and sintering	4.26E-03	6.82E-03
332114	Custom roll forming	1.44E-03	4.89E-03
33211B	Crown and closure manufacturing and metal stamping	1.12E-03	3.56E-03
33221A	Cutlery, utensil, pot, and pan manufacturing	1.26E-03	3.14E-03
33221B	Handtool manufacturing	8.81E-04	2.75E-03
332310	Plate work and fabricated structural product manufacturing	7.50E-04	3.04E-03

Appendix A (continued)

Table A.8 (continued)

332320	Ornamental and architectural metal products manufacturing	6.95E-04	3.07E-03
332410	Power boiler and heat exchanger manufacturing	1.22E-03	3.18E-03
332420	Metal tank (heavy gauge) manufacturing	1.09E-03	3.27E-03
332430	Metal can, box, and other metal container (light gauge) manufacturing	1.39E-03	4.66E-03
33299A	Ammunition manufacturing	1.74E-03	2.96E-03
33299B	Arms, ordnance, and accessories manufacturing	7.48E-04	1.87E-03
332500	Hardware manufacturing	6.74E-04	2.40E-03
332600	Spring and wire product manufacturing	1.26E-03	3.41E-03
332710	Machine shops	6.18E-04	1.84E-03
332720	Turned product and screw, nut, and bolt manufacturing	8.38E-04	2.41E-03
332800	Coating, engraving, heat treating and allied activities	4.26E-03	6.34E-03
33291A	Valve and fittings other than plumbing	5.64E-04	2.14E-03
332913	Plumbing fixture fitting and trim manufacturing	9.11E-04	2.72E-03
332991	Ball and roller bearing manufacturing	1.23E-03	2.78E-03
332996	Fabricated pipe and pipe fitting manufacturing	8.16E-04	3.03E-03
33299C	Other fabricated metal manufacturing	1.65E-03	3.79E-03
333111	Farm machinery and equipment manufacturing	6.88E-04	2.57E-03
333112	Lawn and garden equipment manufacturing	3.96E-04	2.33E-03
333120	Construction machinery manufacturing	7.14E-04	2.56E-03
333130	Mining and oil and gas field machinery manufacturing	5.32E-04	2.51E-03
33329A	Other industrial machinery manufacturing	5.67E-04	2.22E-03
333220	Plastics and rubber industry machinery manufacturing	4.71E-04	2.02E-03

Appendix A (continued)

Table A.8 (continued)

333295	Semiconductor machinery manufacturing	2.44E-04	1.62E-03
33331A	Vending, commercial, industrial, and office machinery manufacturing	2.72E-04	2.04E-03
333314	Optical instrument and lens manufacturing	1.82E-04	1.61E-03
333315	Photographic and photocopying equipment manufacturing	5.22E-04	2.61E-03
333319	Other commercial and service industry machinery manufacturing	3.68E-04	1.94E-03
33341A	Air purification and ventilation equipment manufacturing	6.32E-04	2.44E-03
333414	Heating equipment, except warm air furnaces	7.73E-04	2.59E-03
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	3.81E-04	2.09E-03
333511	Industrial mold manufacturing	6.96E-04	2.20E-03
33351A	Metal cutting and forming machine tool manufacturing	5.01E-04	1.88E-03
333514	Special tool, die, jig, and fixture manufacturing	5.43E-04	2.00E-03
333515	Cutting tool and machine tool accessory manufacturing	4.97E-04	1.78E-03
33351B	Rolling mill and other metalworking machinery manufacturing	6.17E-04	1.90E-03
333611	Turbine and turbine generator set units manufacturing	2.41E-04	1.53E-03
333612	Speed changer, industrial high-speed drive, and gear manufacturing	1.25E-03	2.57E-03
333613	Mechanical power transmission equipment manufacturing	9.74E-04	2.57E-03
333618	Other engine equipment manufacturing	5.46E-04	2.53E-03
333911	Pump and pumping equipment manufacturing	4.38E-04	2.07E-03

Appendix A (continued)

Table A.8 (continued)

333912	Air and gas compressor manufacturing	5.35E-04	2.18E-03
333920	Material handling equipment manufacturing	8.07E-04	2.83E-03
333991	Power-driven handtool manufacturing	2.91E-04	2.13E-03
33399A	Other general purpose machinery manufacturing	5.87E-04	2.25E-03
333993	Packaging machinery manufacturing	3.01E-04	1.63E-03
333994	Industrial process furnace and oven manufacturing	6.10E-04	1.87E-03
33399B	Fluid power process machinery	4.93E-04	2.13E-03
334111	Electronic computer manufacturing	1.39E-04	1.02E-03
334112	Computer storage device manufacturing	1.73E-04	1.17E-03
33411A	Computer terminals and other computer peripheral equipment manufacturing	2.98E-04	1.41E-03
334210	Telephone apparatus manufacturing	6.49E-04	1.58E-03
334220	Broadcast and wireless communications equipment	1.49E-04	1.07E-03
334290	Other communications equipment manufacturing	4.80E-04	1.43E-03
334300	Audio and video equipment manufacturing	3.17E-04	2.11E-03
334411	Electron tube manufacturing	1.19E-03	3.73E-03
334412	Bare printed circuit board manufacturing	9.40E-04	2.29E-03
334413	Semiconductor and related device manufacturing	4.55E-04	1.66E-03
33441A	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing	6.65E-04	2.10E-03
334417	Electronic connector manufacturing	5.35E-04	2.12E-03
334418	Printed circuit assembly (electronic assembly) manufacturing	1.91E-04	1.28E-03

Appendix A (continued)

Table A.8 (continued)

334419	Other electronic component manufacturing	3.94E-04	1.61E-03
334510	Electromedical and electrotherapeutic apparatus manufacturing	1.74E-04	1.39E-03
334511	Search, detection, and navigation instruments manufacturing	4.53E-04	1.23E-03
334512	Automatic environmental control manufacturing	3.96E-04	1.75E-03
334513	Industrial process variable instruments manufacturing	3.13E-04	1.55E-03
334514	Totalizing fluid meters and counting devices manufacturing	3.52E-04	1.79E-03
334515	Electricity and signal testing instruments manufacturing	1.64E-04	9.10E-04
334516	Analytical laboratory instrument manufacturing	2.53E-04	1.28E-03
334517	Irradiation apparatus manufacturing	1.62E-04	1.46E-03
33451A	Other Measuring and Controlling Device Manufacturing	2.62E-04	1.29E-03
33461A	Software, audio, and video media reproducing	5.35E-04	2.60E-03
334613	Magnetic and optical recording media manufacturing	9.06E-04	2.56E-03
335110	Electric lamp bulb and part manufacturing	1.01E-03	2.58E-03
335120	Lighting fixture manufacturing	5.15E-04	2.28E-03
335210	Small electrical appliance manufacturing	3.64E-04	2.39E-03
335221	Household cooking appliance manufacturing	7.49E-04	3.20E-03
335222	Household refrigerator and home freezer manufacturing	3.79E-04	2.96E-03
335224	Household laundry equipment manufacturing	5.93E-04	2.71E-03
335228	Other major household appliance manufacturing	6.56E-04	2.71E-03
335311	Power, distribution, and specialty transformer manufacturing	6.28E-04	2.84E-03
335312	Motor and generator manufacturing	7.67E-04	2.57E-03

Appendix A (continued)

Table A.8 (continued)

335313	Switchgear and switchboard apparatus manufacturing	3.55E-04	1.64E-03
335314	Relay and industrial control manufacturing	2.42E-04	1.24E-03
335911	Storage battery manufacturing	1.39E-03	3.58E-03
335912	Primary battery manufacturing	2.60E-04	1.97E-03
335920	Communication and energy wire and cable manufacturing	6.94E-04	3.45E-03
335930	Wiring device manufacturing	5.06E-04	2.46E-03
335991	Carbon and graphite product manufacturing	4.80E-03	7.61E-03
335999	All other miscellaneous electrical equipment and component manufacturing	2.70E-04	1.32E-03
336111	Automobile Manufacturing	3.45E-04	2.28E-03
336112	Light truck and utility vehicle manufacturing	3.41E-04	2.41E-03
336120	Heavy duty truck manufacturing	2.24E-03	4.32E-03
336211	Motor vehicle body manufacturing	5.59E-04	2.44E-03
336212	Truck trailer manufacturing	5.04E-04	2.88E-03
336213	Motor home manufacturing	2.35E-04	2.56E-03
336214	Travel trailer and camper manufacturing	4.91E-04	2.94E-03
336300	Motor vehicle parts manufacturing	5.82E-04	2.77E-03
336411	Aircraft manufacturing	2.16E-04	1.37E-03
336412	Aircraft engine and engine parts manufacturing	5.69E-04	1.58E-03
336413	Other aircraft parts and auxiliary equipment manufacturing	8.27E-04	2.09E-03
336414	Guided missile and space vehicle manufacturing	2.72E-04	1.13E-03
33641A	Propulsion units and parts for space vehicles and guided missiles	5.88E-04	1.42E-03
336500	Railroad rolling stock manufacturing	5.96E-04	2.12E-03
336611	Ship building and repairing	3.34E-04	1.50E-03
336612	Boat building	4.80E-04	2.35E-03
336991	Motorcycle, bicycle, and parts manufacturing	5.12E-04	2.85E-03

Appendix A (continued)

Table A.8 (continued)

336992	Military armored vehicle, tank, and tank component manufacturing	4.70E-04	1.99E-03
336999	All other transportation equipment manufacturing	4.15E-04	2.57E-03
337110	Wood kitchen cabinet and countertop manufacturing	5.88E-04	2.05E-03
337121	Upholstered household furniture manufacturing	2.81E-04	2.29E-03
337122	Nonupholstered wood household furniture manufacturing	5.76E-04	2.01E-03
33712A	Metal and other household furniture (except wood) manufacturing	8.97E-04	3.55E-03
337127	Institutional furniture manufacturing	7.77E-04	2.51E-03
33721A	Wood television, radio, and sewing machine cabinet manufacturing	3.48E-04	1.94E-03
337212	Office furniture and custom architectural woodwork and millwork manufacturing	6.54E-04	2.24E-03
337215	Showcase, partition, shelving, and locker manufacturing	1.07E-03	3.44E-03
337910	Mattress manufacturing	2.73E-04	2.19E-03
337920	Blind and shade manufacturing	3.78E-04	2.90E-03
339111	Laboratory apparatus and furniture manufacturing	3.35E-04	1.58E-03
339112	Surgical and medical instrument manufacturing	1.88E-04	1.21E-03
339113	Surgical appliance and supplies manufacturing	3.20E-04	1.65E-03
339114	Dental equipment and supplies manufacturing	1.71E-04	2.08E-03
339115	Ophthalmic goods manufacturing	1.77E-04	1.15E-03
339116	Dental laboratories	2.06E-04	8.33E-04
339910	Jewelry and silverware manufacturing	2.89E-04	2.18E-03
339920	Sporting and athletic goods manufacturing	5.75E-04	2.62E-03
339930	Doll, toy, and game manufacturing	5.32E-04	2.95E-03
339940	Office supplies (except paper) manufacturing	4.98E-04	2.37E-03

Appendix A (continued)

Table A.8 (continued)

339950	Sign manufacturing	6.25E-04	2.46E-03
339991	Gasket, packing, and sealing device manufacturing	9.22E-04	3.05E-03
339992	Musical instrument manufacturing	5.99E-04	1.31E-03
33999A	All other miscellaneous manufacturing	6.32E-04	2.60E-03
339994	Broom, brush, and mop manufacturing	5.28E-04	1.97E-03
420000	Wholesale trade	2.91E-04	5.98E-04
4A0000	Retail trade	2.65E-04	5.81E-04
481000	Air transportation	6.87E-05	6.38E-04
482000	Rail transportation	7.61E-05	6.59E-04
483000	Water transportation	5.58E-04	1.41E-03
484000	Truck transportation	2.42E-04	7.68E-04
485000	Transit and ground passenger transportation	4.81E-04	1.36E-03
486000	Pipeline transportation	1.64E-02	1.71E-02
48A000	Scenic and sightseeing transportation and support activities for transportation	1.93E-03	2.50E-03
492000	Couriers and messengers	3.55E-07	3.65E-04
493000	Warehousing and storage	6.02E-04	9.81E-04
511110	Newspaper publishers	1.35E-04	1.23E-03
511120	Periodical publishers	3.35E-05	8.79E-04
511130	Book publishers	1.03E-04	7.47E-04
5111A0	Directory, mailing list, and other publishers	5.05E-05	8.15E-04
511200	Software publishers	1.61E-05	2.99E-04
512100	Motion picture and video industries	1.04E-04	3.67E-04
512200	Sound recording industries	2.84E-05	5.99E-04
515100	Radio and television broadcasting	4.70E-04	8.97E-04
515200	Cable and other subscription programming	3.96E-04	8.97E-04
516110	Internet publishing and broadcasting	3.68E-05	7.62E-04
517000	Telecommunications	8.34E-04	1.33E-03
518100	Internet service providers and web search portals	4.12E-04	8.55E-04
518200	Data processing, hosting, and related services	4.67E-05	4.32E-04

Appendix A (continued)

Table A.8 (continued)

519100	Other information services	3.72E-04	7.04E-04
52A000	Monetary authorities and depository credit intermediation	4.91E-05	2.21E-04
522A00	Nondepository credit intermediation and related activities	1.01E-04	3.36E-04
523000	Securities, commodity contracts, investments, and related activities	3.13E-05	2.51E-04
524100	Insurance carriers	3.62E-06	2.23E-04
524200	Insurance agencies, brokerages, and related activities	1.35E-04	3.68E-04
525000	Funds, trusts, and other financial vehicles	0.00E+00	2.21E-04
531000	Real estate	3.05E-04	4.77E-04
S00800	Owner-occupied dwellings	2.79E-08	2.30E-04
532100	Automotive equipment rental and leasing	9.60E-05	4.13E-04
532A00	General and consumer goods rental except video tapes and discs	4.93E-04	8.43E-04
532230	Video tape and disc rental	4.05E-04	9.10E-04
532400	Commercial and industrial machinery and equipment rental and leasing	3.88E-04	7.87E-04
533000	Lessors of nonfinancial intangible assets	5.33E-04	6.62E-04
541100	Legal services	7.30E-05	2.77E-04
541200	Accounting, tax preparation, bookkeeping, and payroll services	1.09E-04	3.16E-04
541300	Architectural, engineering, and related services	2.78E-04	6.36E-04
541400	Specialized design services	8.05E-05	4.70E-04
541511	Custom computer programming services	2.65E-05	2.24E-04
541512	Computer systems design services	3.91E-05	4.26E-04
54151A	Other computer related services, including facilities management	2.71E-05	3.06E-04
541610	Management, scientific, and technical consulting services	4.58E-05	3.30E-04

Appendix A (continued)

Table A.8 (continued)

5416A0	Environmental and other technical consulting services	1.42E-04	4.77E-04
541700	Scientific research and development services	4.92E-04	9.91E-04
541800	Advertising and related services	2.66E-04	9.74E-04
5419A0	All other miscellaneous professional, scientific, and technical services	1.81E-04	4.18E-04
541920	Photographic services	2.09E-04	6.93E-04
541940	Veterinary services	5.01E-04	1.26E-03
550000	Management of companies and enterprises	3.37E-04	6.39E-04
561300	Employment services	7.67E-05	2.20E-04
561500	Travel arrangement and reservation services	1.30E-03	1.69E-03
561100	Office administrative services	1.90E-04	5.15E-04
561200	Facilities support services	2.16E-04	6.73E-04
561400	Business support services	1.58E-04	5.30E-04
561600	Investigation and security services	1.63E-04	4.87E-04
561700	Services to buildings and dwellings	2.09E-04	6.73E-04
561900	Other support services	3.23E-04	7.79E-04
562000	Waste management and remediation services	6.56E-04	1.26E-03
611100	Elementary and secondary schools	2.36E-03	2.82E-03
611A00	Junior colleges, colleges, universities, and professional schools	5.05E-03	5.67E-03
611B00	Other educational services	4.97E-04	8.94E-04
621A00	Offices of physicians, dentists, and other health practitioners	1.08E-04	4.78E-04
621B00	Medical and diagnostic labs and outpatient and other ambulatory care services	2.91E-04	8.09E-04
621600	Home health care services	5.06E-04	9.03E-04
622000	Hospitals	4.06E-04	9.71E-04
623000	Nursing and residential care facilities	8.44E-04	1.28E-03
624A00	Individual and family services	6.07E-04	1.12E-03
624200	Community food, housing, and other relief services, including rehabilitation services	4.50E-04	9.89E-04

Appendix A (continued)

Table A.8 (continued)

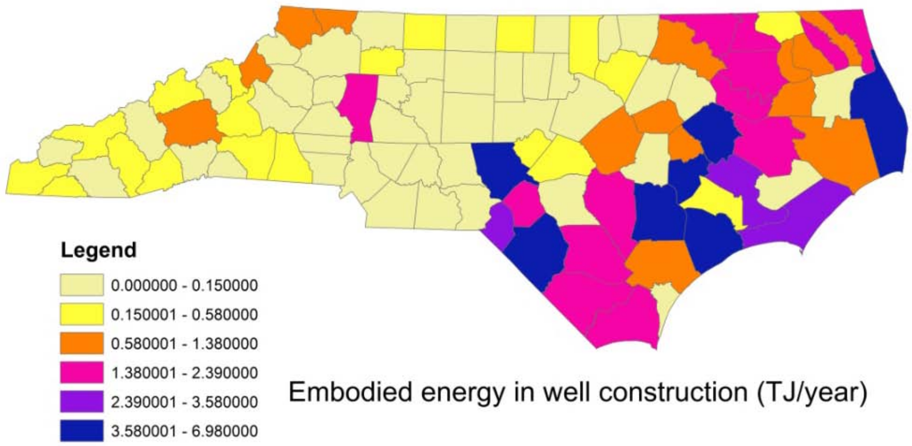
624400	Child day care services	4.12E-04	9.73E-04
711100	Performing arts companies	1.37E-04	4.21E-04
711200	Spectator sports	2.24E-04	6.37E-04
711A00	Promoters of performing arts and sports and agents for public figures	2.24E-04	6.36E-04
711500	Independent artists, writers, and performers	4.55E-05	2.62E-04
712000	Museums, historical sites, zoos, and parks	1.15E-03	1.55E-03
713A00	Amusement parks, arcades, and gambling industries	1.50E-03	1.98E-03
713B00	Other amusement and recreation industries	1.11E-03	1.81E-03
713940	Fitness and recreational sports centers	1.31E-03	1.75E-03
713950	Bowling centers	1.14E-03	1.74E-03
7211A0	Hotels and motels, including casino hotels	1.43E-03	1.92E-03
721A00	Other accommodations	1.74E-03	2.18E-03
722000	Food services and drinking places	7.84E-04	1.73E-03
8111A0	Automotive repair and maintenance, except car washes	3.11E-04	1.08E-03
811192	Car washes	2.10E-03	2.61E-03
811200	Electronic and precision equipment repair and maintenance	1.96E-04	5.95E-04
811300	Commercial and industrial machinery and equipment repair and maintenance	2.57E-04	8.59E-04
811400	Personal and household goods repair and maintenance	2.94E-04	9.98E-04
812100	Personal care services	2.36E-04	6.22E-04
812200	Death care services	9.49E-04	1.85E-03
812300	Dry-cleaning and laundry services	8.27E-04	1.16E-03
812900	Other personal services	4.27E-04	8.35E-04
813100	Religious organizations	2.70E-04	6.01E-04

Appendix A (continued)

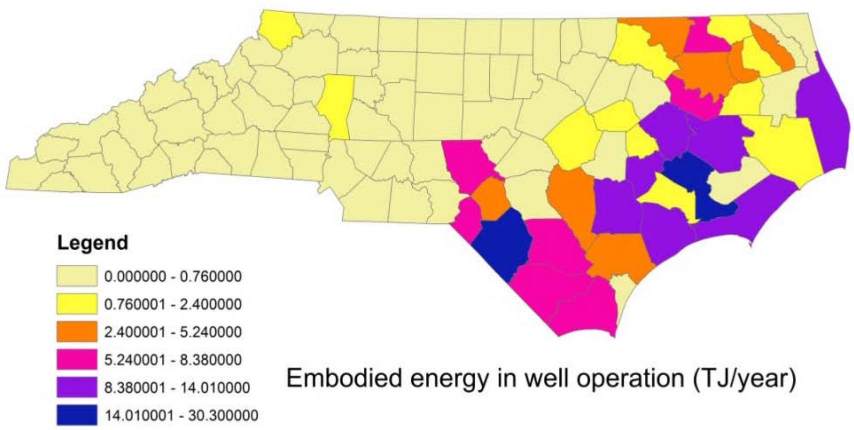
Table A.8 (continued)

813A00	Grantmaking, giving, and social advocacy organizations	1.44E-04	6.60E-04
813B00	Civic, social, professional, and similar organizations	9.40E-04	1.51E-03
814000	Private households	0.00E+00	0.00E+00
491000	Postal service	8.81E-04	1.14E-03
S00102	Other Federal Government enterprises	2.39E-03	2.65E-03
S00203	Other State and local government enterprises	4.38E-03	5.48E-03
S00500	General Federal defense government services	2.83E-04	7.02E-04
S00600	General Federal nondefense government services	5.38E-04	1.10E-03
S00700	General state and local government services	1.68E-03	2.30E-03
S00401	Scrap	1.54E-03	3.08E-03

Appendix B Additional Figures



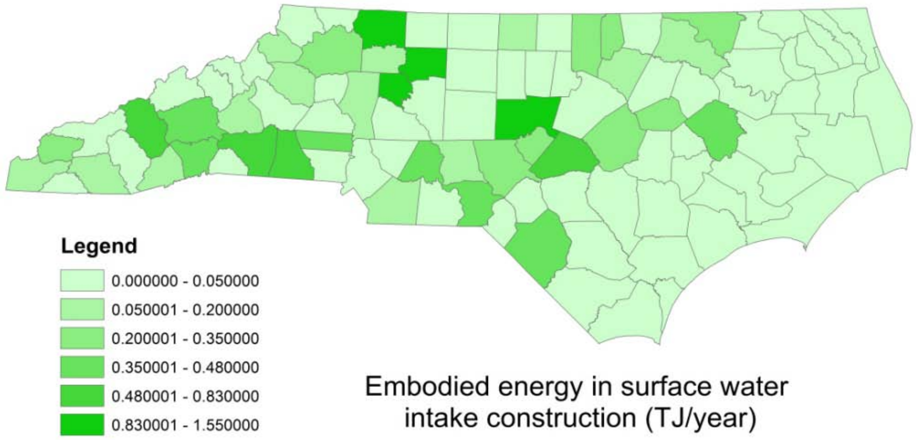
(a)



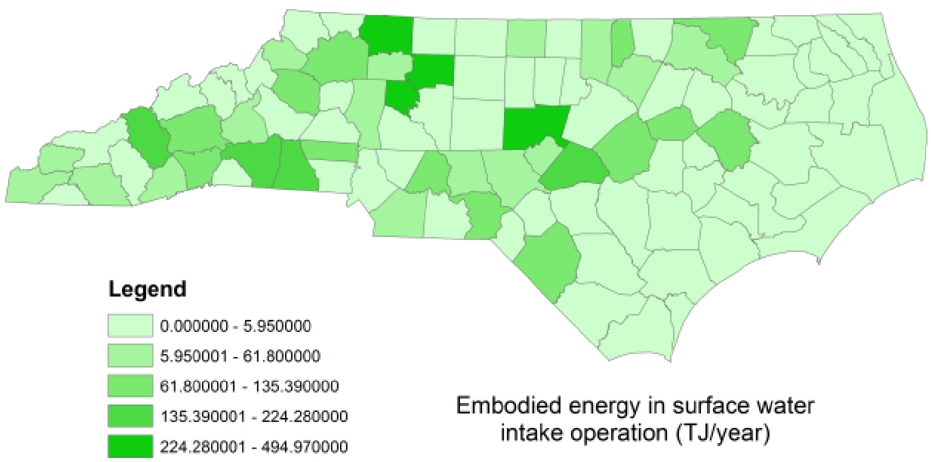
(b)

Figure B.1 Distribution of embodied energy in well construction and operation. (a) distribution of embodied energy in well construction among the counties in North Carolina in unit of TJ/year, and (b) distribution of embodied energy in well operation among the counties in North Carolina in unit of TJ/year

Appendix B (continued)



(a)



(b)

Figure B.2 Distribution of embodied energy in surface water intake infrastructure construction and operation. (a) distribution of embodied energy in surface water intake infrastructure construction among the counties in North Carolina in unit of TJ/year, and (b) distribution of embodied energy in surface water intake infrastructure operation among the counties in North Carolina in unit of TJ/year

Appendix B (continued)

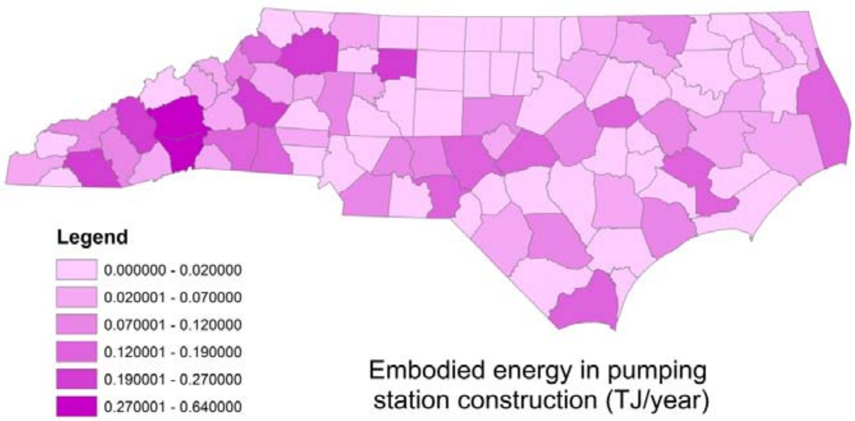
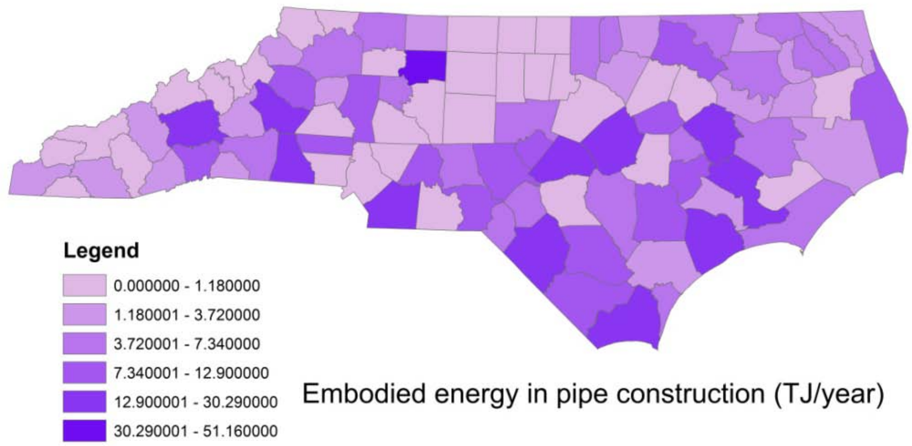
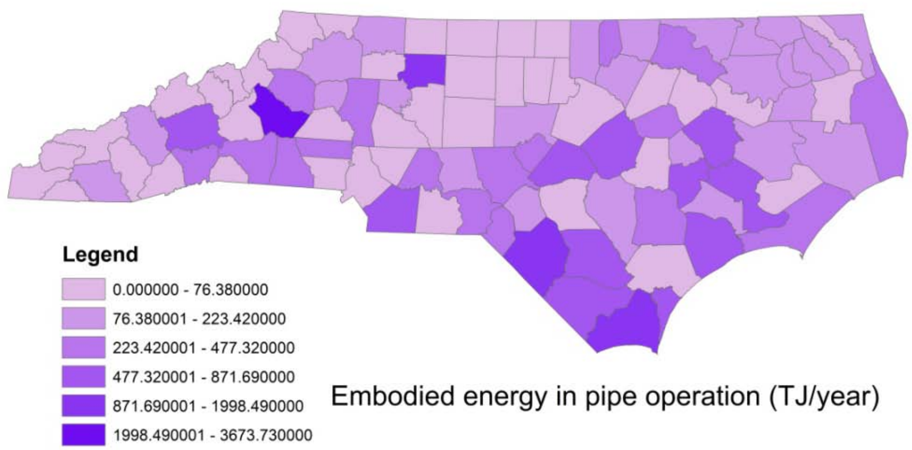


Figure B.3 Distribution of embodied energy in pumping station construction

Appendix B (continued)



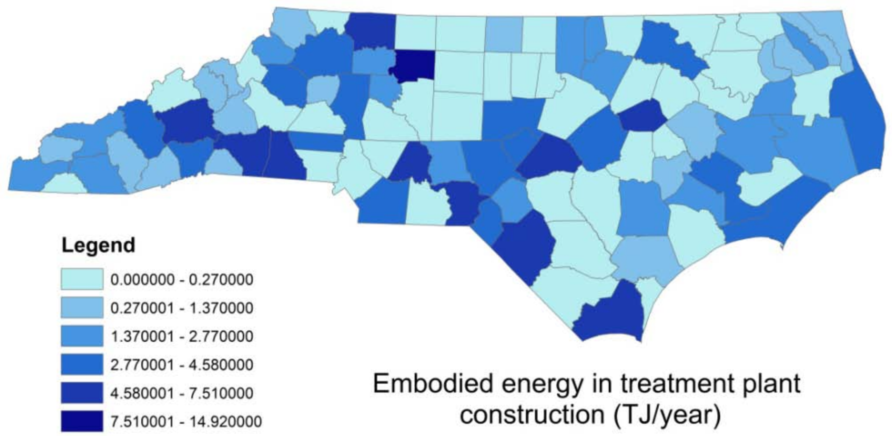
(a)



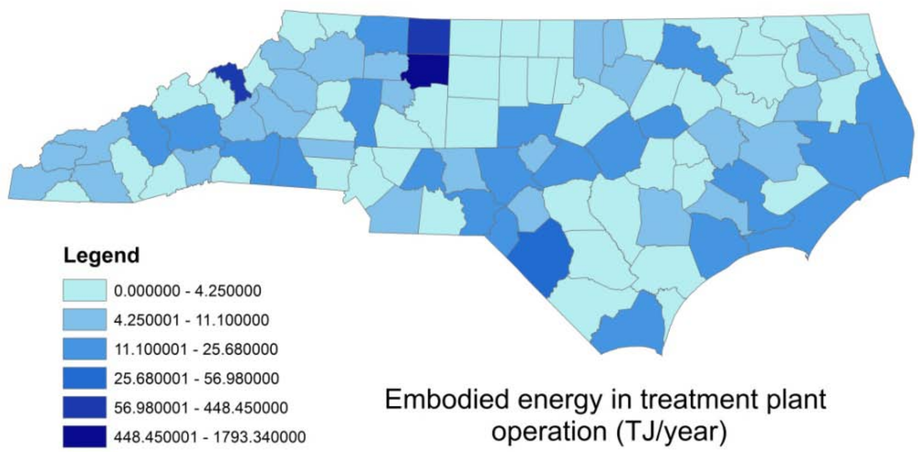
(b)

Figure B.4 Distribution of embodied energy in pipeline construction and operation. (a) distribution of embodied energy in pipeline system construction among the counties in North Carolina in unit of TJ/year, and (b) distribution of embodied energy in water pumping among the counties in North Carolina in unit of TJ/year

Appendix B (continued)



(a)



(b)

Figure B.5 Distribution of embodied energy in water treatment plant construction and operation. (a) distribution of embodied energy in water treatment plant construction among the counties in North Carolina in unit of TJ/year, and (b) distribution of embodied energy in water treatment plant operation among the counties in North Carolina in unit of TJ/year

Appendix B (continued)

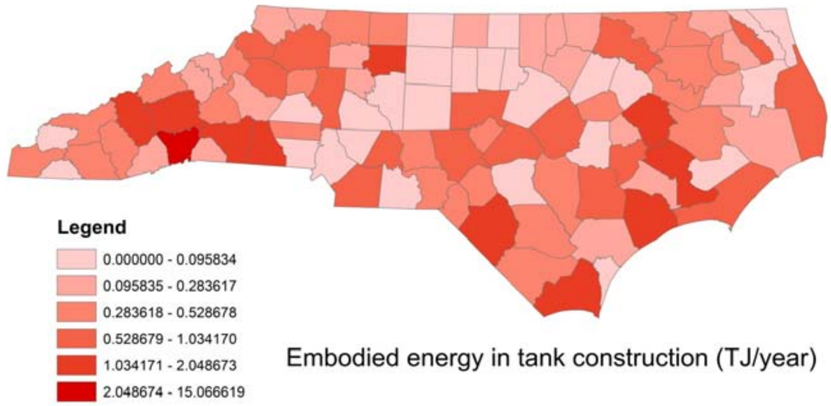


Figure B.6 Distribution of embodied energy in water storage tank construction

Appendix B (continued)

```
Start:  AIC=-98.94
EE ~ POP + POPDEN + URB + AG + SUR

         Df Sum of Sq    RSS      AIC
- POPDEN  1   0.21840 17.873 -100.005
- AG      1   0.30488 17.959  -99.639
<none>                17.655  -98.940
- POP     1   1.85115 19.506  -93.362
- SUR     1   1.87655 19.531  -93.263
- URB     1   3.09106 20.746  -88.678

Step:  AIC=-100.01
EE ~ POP + URB + AG + SUR

       Df Sum of Sq    RSS      AIC
- AG    1    0.2107 18.084 -101.115
<none>              17.873 -100.005
- SUR   1    1.6604 19.533  -95.254
- POP   1    4.8063 22.679  -83.905
- URB   1    7.3994 25.273  -75.677

Step:  AIC=-101.11
EE ~ POP + URB + SUR

       Df Sum of Sq    RSS      AIC
<none>              18.084 -101.115
- SUR   1    1.4669 19.551  -97.187
- POP   1    4.6115 22.695  -85.852
- URB   1    7.3071 25.391  -77.322
```

Figure B.7 Results of backward selection for the linear regression model using the R software

Appendix C Data Acquisition Questionnaire for Water Supply Systems

Questionnaire provided to utilities to obtain data for surface water sourced systems

1. Types of water intake structure: submerged crib or exposed tower?
2. If submerged crib, please provide the maximum flow (MGD) here.
3. If exposed tower, provide maximum flow (MGD) and tower height (ft) here. Besides, provide the height of the cofferdam (ft) here.
4. For raw water pumping, please indicate the number of pumping stations and provide the capacity for each pumping station (MGD).
5. Provide the diameter (inches) and length (mile) of water mains in the whole system.
6. For water treatment, indicate annual average daily water flow (MGD) in the system.
7. What kind of the following treatment technologies are used in your facility
    - Flash Mix + Gravel Bed Filtration + Granular Bed Filtration + Clearwell
    - Flash Mix + Flocculation + Granular Bed Filtration + Clearwell
    - Flash Mix + Flocculation + Sedimentation + Granular Bed Filtration + Clearwell
    - Flash Mix + Flocculation + Dissolved air floatation + Filtration + Clearwell
    - Flash Mix + Solids contact clarifier (lime, soda ash, ferrous sulfate) + CO2 contact tank + Clarifier + Filtration + Clearwell
    - Aeration + Contact Tank + Filtration + Clearwell
    - Micro Screen + Micro Filter + Clearwell
    - Pre-ozonation + Flash Mix + Flocculation + BAF with GAC Bed + Clearwell
    - Pre-ozonation + Flash Mix + Flocculation + Clarifier + Pre-filter ozonation + BAF with GAC bed + Clearwell
8. If your facility is of other combination of technologies, what is it? List the unit processes below please and indicate the volume of each structure.
9. For finished water pumping, indicate the number of pumping stations, and provide the capacity of each pumping stations (MGD).
10. Types of water storage: underground reservoir or uplifted water storage tank
11. If underground reservoir, provide the number of reservoirs and the capacity of each reservoir (cubic meter).
12. If uplifted water storage tank, provide the number of water storage tanks and the capacity of each tank (cubic meter).
13. Please provide the total annual operation and maintenance costs in the system. Add up the following parts:

    Annual labor cost (payroll, administration, supervision)

    Annual maintenance and repair cost (replacement, repair, technology innovation and so on)

    Annual energy (electricity, natural gas) bill

    Annual chemical cost

Appendix C (continued)

14. Please indicate the annual energy bill here
    Electricity
    Natural gas
15. Indicate the amount of asphalt used in the system
16. If available, please provide the total construction cost of the system, and indicate which year's dollar value is it.
17. Please provide the unit electricity price and natural gas price in your area

Appendix C (continued)

Questionnaire provided to utilities to obtain data for ground water sourced systems

1. Well data
   - Design flow of each well
   - Diameter of each well
   - Depth of each well
   - Well head (depth to the water level + head loss)
   - Pump efficiency if available
2. Water main data
   - Length of water mains
   - Diameter of pipes
   - Average uphill/downhill slope (ft/1000ft)
   - Friction loss (ft/1000ft)
3. Storage capacity of each water storage facilities, indicate above ground or underground
4. Pumping station data
   - Capacity of each pumping station
   - Total number of the pumping stations
5. How many gallons of water are actually treated per day (MGD)?
6. What is the maximum and average design flow of each of the treatment facility?
7. Please indicate the annual energy bill here
   - Electricity
   - Natural gas
8. Annual maintenance and repair cost
9. Annual total operation and maintenance cost
10. Amount of asphalt used in the system for construction
11. Total construction cost

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Publication: Environmental Science & Technology

Publisher: American Chemical Society

Date: Dec 1, 2010

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