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# MANAGING CO2 EMISSIONS REGIONALLY USING GEOGRAPHICAL INFORMATION SYSTEM (GIS) SPATIAL MODELING AND PINCH ANALYSIS

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by

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A Research Paper
Submitted in Partial Fulfillment of the Requirements for the
Master of Science

Department of Mechanical Engineering and Energy Processes
in the Graduate School
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RESEARCH PAPER APPROVAL

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Approved by:

Dr. Rasit Koc, Chair

Graduate School
Southern Illinois University Carbondale
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## AN ABSTRACT OF THE RESEARCH PAPER OF

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TITLE: MANAGING $CO_2$ EMISSIONS REGIONALLY USING GEOGRAPHICAL INFORMATION SYSTEM (GIS) SPATIAL MODELING AND PINCH ANALYSIS

MAJOR PROFESSOR: Dr. Kanchan Mondal

Climate change has become the major global challenge of sustainability; among various anthropogenic sources of carbon dioxide ($CO_2$) emissions, the burning of fossil fuels for energy to support commercial, residential, municipal and industrial sectors is considered to be the primary cause of increasing levels of carbon dioxide emissions. However, because climate change is regionally driven with global consequences, to analyze emissions data, energy planning techniques must be developed which are simple, replicable and optimized for maximum benefit. Climate scenarios are continually derived from global models despite these models containing little to no regional or local specificity. Place-based research, well grounded in local experience, offers a more tractable alternative for defining complex interactions among the environmental, economic, and social processes that drive greenhouse gas emissions.

The focus of this study involves the development of a balanced energy supply and demand model under carbon constraints for the Southern Illinois energy sector; this sector represents the local specificity desired to build a carbon emissions pinch analysis model at the local level. This project is intended to formulate a robust methodology for constructing a Geographic Data Base Management System by employing a bottom/up approach to $CO_2$ emissions modeling; the resulting data base can serve as the foundation for an environmental applications model employing pinch analysis techniques to address the allocation of energy resources and technologies to reduce $CO_2$ emissions.

# ACKNOWLEDGMENTS

I would first like to thank my research advisor Dr. Kanchan Mondal at Southern Illinois University from the Department of Mechanical Engineering for introducing me to the weighty and far reaching topic of pinch analysis and its application in the management of carbon dioxide emissions. His continued trust in research areas outside of his core research knowledge allowed me to explore information held in EPA, EIA, and IDOT shapefile databases in the quest for localized emissions data using GIS. A special thanks is due to Dr. Ruopu Li at Southern Illinois University from the Department of Geography for his continued efforts to figure out how GIS could assist in this research initiative as well as his assistance in the development of a geodatabase structure with which to compile the acquired data. Also, my review committee members that include Dr. Rasit Koc and Dr. Emmanuel Nsofor for a timely turnaround on the required review and defense of this research paper submission. And finally, a special shout-out to Tammy K. Hopkins, Office Manager from the Department of Mechanical Engineering for her continued support in providing timely solutions throughout the worthy quest for a master's degree from this reputable institution.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# CHAPTER 1

## INTRODUCTION

Climate change is increasingly becoming the major global challenge of sustainability; because climate change is regionally driven with global consequences, energy planning techniques must be developed that are simple in nature yet optimized for maximum benefit. In order to grasp the liability of human activity on our planet, society as a whole need to comprehend one gigantic measurement, namely "35 GIGATONS"; scientists measure the production of $CO_2$ resulting from anthropogenic activities in a particular unit called a Giga-ton.

In the International System of Units, the prefix "Giga" means $10^9$, or one billion (1,000,000,000), thus, a Giga-ton is the equivalent to a billion metric tons. To put this huge number into perspective, a male African elephant weighs, on average, 6.8 metric tons. So one Giga-ton of $CO_2$ emitted from anthropogenic sources is equivalent to catapulting 100 million elephants into our atmosphere annually. But the actual amount of $CO_2$ is conservatively estimated at 35 times greater; this equates to catapulting one thousand elephants every second into our atmosphere each day. Therefore, instead of counting sheep at night, we ought to be thinking in terms of counting the equivalent weight of the one thousand elephants we place into our own atmosphere, every second of every day. Which comes at a cost. The devastating effect of floods, wildfires, and drought that have been accentuated by climate change; the man-made sources which account for these astronomically large amounts of $CO_2$ emissions include the burning of fossil fuels for energy to support the residential, commercial, industrial and transportation sectors (Figure 1-1). The status quo is no longer sufficient; existing regulations, policies, and procedures that were once effective in protecting lives, property, and prosperity are no longer viable in our rapidly evolving world[1]

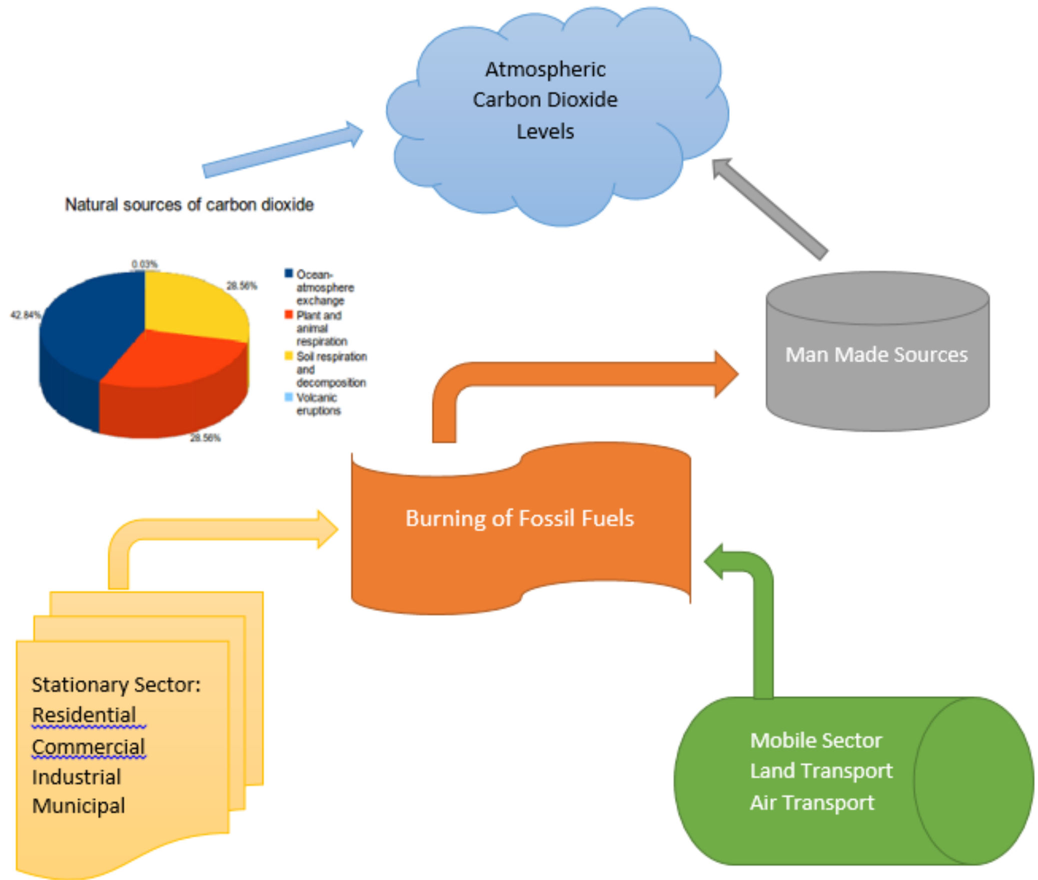



**Figure 1.1: Carbon Dioxide emissions and their sources[2]**

Geographical information systems (GIS) are uniquely suited to address the complex process of assessing risk, while simultaneously fortifying policy makers with reliable information with which to develop strategies for minimizing both present and future risk  Methodologies for sustainable energy planning include pinch analysis, life cycle analysis, and mathematical programming; in terms of technique, graphical, charted and mathematical models have been successfully employed to minimize carbon dioxide ($CO_2$) emissions.

One approach to assessing the relationship between energy supply, demand, and the resulting $CO_2$ emissions is through Carbon Emission Pinch Analysis (CEPA); these techniques are developed by engineers for policymakers as a planning tool by which one investigates the feasibility of reaching future demand for electricity while reducing carbon emissions [3].

**Problem Statement**

A Problem definition of carbon constrained energy planning is stated as follows[4]:

- Given a set of energy demands (regions), designed as DEMANDS = $\{j \mid j = 1, 2, \ldots N_{DEMANDS}\}$. Each demand requires energy consumption of $D_j$ and at the same time, is restricted to a maximum emission time of $E_{D,j}$. Dividing the emission limit by the energy consumption yields the emission factor for each demand $C_{D,j}$.
- Energy streams within a system or region are characterized by a quality index. This index corresponds to a linear mixing rule and follows an inverse scale where zero is the highest quality, while larger positive numerical values indicate lower quality levels.
- Given a set of energy sources, designated as SOURCES = $\{i \mid i = 1, 2, \ldots N_{SOURCES}\}$ to be allocated to energy supply demands. Each source has an available energy of $S_i$ and is characterized by an emission factor $C_{s,i}$. The product of the available energy and the emission factor fives the total emission of the source, Es,i.
- Energy may also be supplied to the system from an external resource whose supply is unlimited. This resource is available at a quality level $Q^{ext}$. The external resource is considered to be a superior quality compared to the internal sources (i.e., $Q^{ext} < Q_i$). It is also assumed that it is desirable to make use of all external resources sparingly.
- The main problem is to target the minimum quantity of external energy resource needed to satisfy both energy quantity and quality requirements of the system sinks. Note: this condition is also equivalent to maximizing the use of the available internal energy sources. The secondary problem is to determine the appropriate allocation of energy streams by matching energy sources. A secondary problem arises in the determination and appropriate allocation of energy streams by matching energy sources and sinks such that the determined target is satisfied.

**Research Issues**

Climate change has increasingly becoming the major global challenge of sustainability; because climate change is regionally driven with global consequences, energy planning techniques must be developed that are simple in nature yet optimized for maximum benefit. Decision makers must intuitively understand the problem structure while being systematically equipped with robust tools to facilitate proper planning for the future. Stern[5] states that “if carbon emissions are to be reduced [….] then policies must encourage the development portfolio of options; this will act both to reduce risks and improve chances of success.”

While energy efficiency is seen as one of the most promising measures for reducing global $CO_2$ emissions[6]; the introduction of low carbon technologies is another. Unfortunately, no current technology for removing $CO_2$ from large sources like coal-fired power plants exist which concurrently satisfy the needs of safety, efficiency and economy. Current technologies are vastly more expensive (as with renewable energy) and controversial (as in the case of nuclear energy or carbon capture and storage)[7].

A carbon footprint is useful in illustrating the extent to which humanity is using nature’s resources faster than they can regenerate the same, otherwise known as sustainability. Environmental sustainability is defined as the rate at which renewable resources, resultant pollution, coupled with non-renewable resource depletion can be continued indefinitely. One’s carbon footprint is historically defined as "the total set of greenhouse gas emissions caused by an organization, event, product or individual[8]. The carbon footprint of a region is defined by the total amount of greenhouse gases produced which either directly or indirectly support human activity, usually expressed in equivalent tons of carbon dioxide ($CO_2$). It is only when the size of a carbon footprint is known, that a strategy can be devised to reduce it, e.g. by technological developments, better process and product management, carbon capture, consumption strategies, and carbon offsetting[9].

*Think globally and act locally* has been a slogan of the environmental movement for decades. This slogan, however, falls short in the area of climate change for it neglects its cause and consequence because global and national emissions are averaged in such a way that they neglect distinct local trajectories of greenhouse gas emissions and their driving forces, while at the same time, over-look opportunities to mitigate emissions. Knowledge held locally is inadequate and rarely leads to action since most decisions that could result in major local emission reductions will not be made "locally". Current ways of relating global climate change to localities are top-down, from the global to the local.[10]

Local governments need to quantify and analyze carbon emissions by implementing sound reduction strategies in order to help nations meet global $CO_2$ reduction goals. Most of the models implemented to perform carbon inventories and assessments at the regional and local level are Microsoft Excel-based and have no GIS or spatial component. To provide a basis for carbon emissions reduction policies, this project proposes to develop an automated $CO_2$ Model by using GIS techniques and various spatial analytical tools. A $CO_2$ Model, when constructed, makes it possible to estimate and analyze the distribution of carbon emissions from residential, commercial, industrial and transportation energy sector land use.

Creating a GIS database can be extremely time-consuming and labor-intensive; locating suitable, workable data for a project can be elusive and problematic because emissions data is often calculated using a top – trickle down methodology; aggregated data is often generalized and based upon regional, national and/or global averages rather than place-based emissions. Successfully applying GIS requires the right data—the data needed to address a specific issue—in a format accessible to tools that can produce meaningful information.

## Proposed Solution

All energy systems resultant of the "industrial revolution" emit greenhouse gases (GHGs) and contribute to anthropogenic climate change. It is now widely recognized that GHG emissions resulting from the use of a particular energy technology need to be quantified over all stages of the technology and its fuel life-cycle. Since the early 1970's, energy modelling has proven itself to be a progressively cutting-edge science for analyzing energy systems, sub-systems and GHG emissions. While energy modelling has a wide variety of application, with the end goal of providing decision makers with a better understanding of current and future supply, demand, fuel pricing and consumption, models have also been developed to facilitate better design of energy supply systems in both the short and long term to ensure sustainable exploitation of available energy resources.

Pinch analysis was originally developed based on thermodynamic principles to identify optimal energy utilization strategies for process plants[11]. More recently, applications of pinch analysis include energy analysis, financial management, production planning, reuse/recycles system design and most recently, this technique has been applied to carbon emission reduction models. Pinch analysis methods repeatedly illustrate their ability to systematically identify minimum quantity zero-emission or low-carbon energy resources and provide an energy allocation scheme needed to meet $CO_2$ emission limits. The use of pinch analysis as a tool for carbon emission reductions and planning began during the last decade with a central focus on the following five areas[12].

(1) Determination of the optimal energy resource mix for national or regional carbon emission planning for the power generating sector;
(2) Power plant retrofit and carbon capture and storage integration;
(3) Screening of potential process changes and cleaner production options within a chemical process;
(4) Carbon emission reduction via optimal heat and renewable energy resource integration within a total site;
(5) Development of targeting and design tools for utility gas networks.

Climate change scenarios, often derived from global models, contain little to no regional or local specificity. Data, whether aggregate (total electricity consumption for commercial, residential, industrial and transportation) or non-aggregate (such as metered data) must be obtained. Place-based research (georeferenced data), well grounded in local experience, offers a more tractable alternative which satisfactorily define complex interactions amidst economic, environmental, and social processes collectively.

## Research Scope

Figure 1.2 geospatially delineates the study area which includes the counties of Franklin, Jackson, and Williamson, Illinois. The map identifies the regional $CO_2$ emission sources that will be quantified in the study.

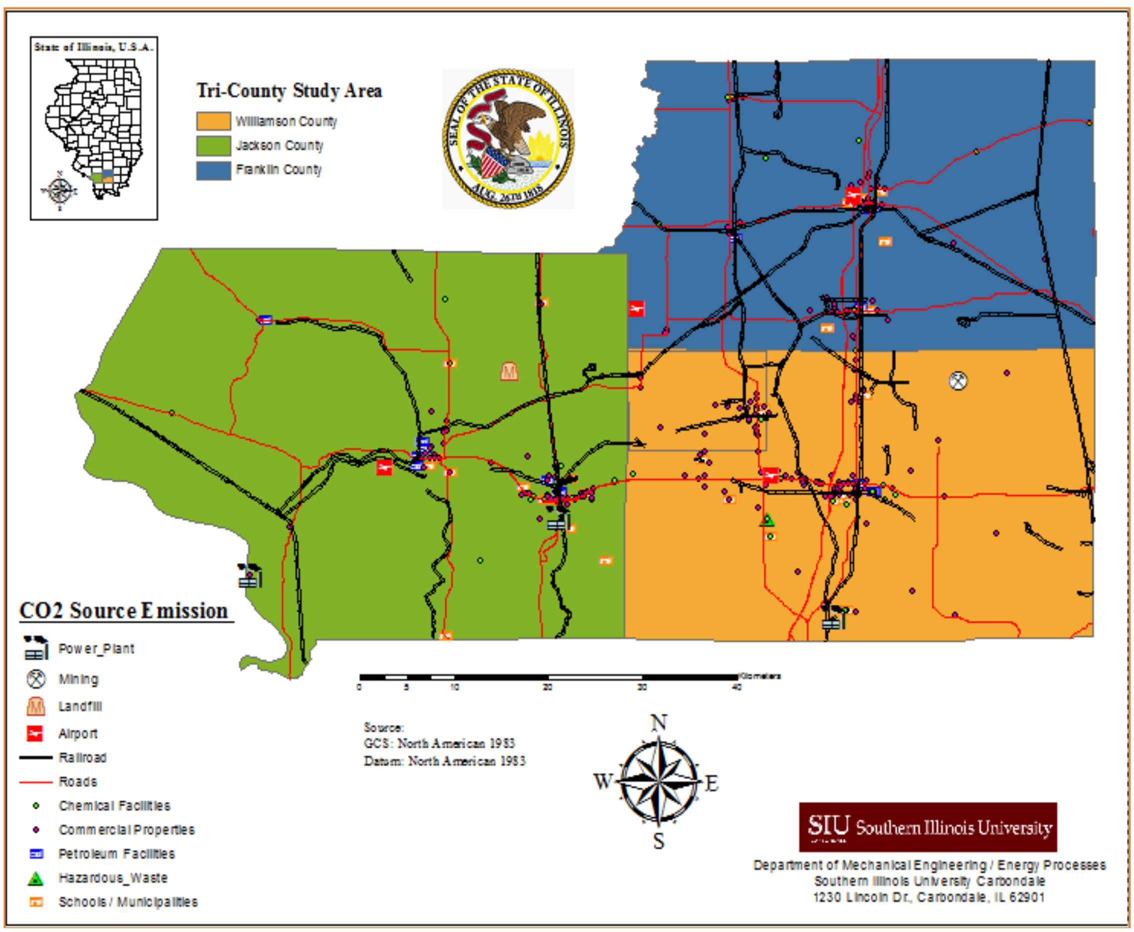



**Figure 1.2: Study Area**

## Model Fabrication

To develop the geographic data base management system, a base map (Figure 1.2) was created to delineate the major sources of $CO_2$ emissions in the tri-county area; geo-referenced data for large stationary sources were sought and anticipated to include data from the residential, commercial and industrial sectors together with the transportation (mobile) energy sector ( local airports, railways, and roads). This data, if available, would then be used to develop a bottom/up methodology for carbon emission pinch analysis (CEPA).

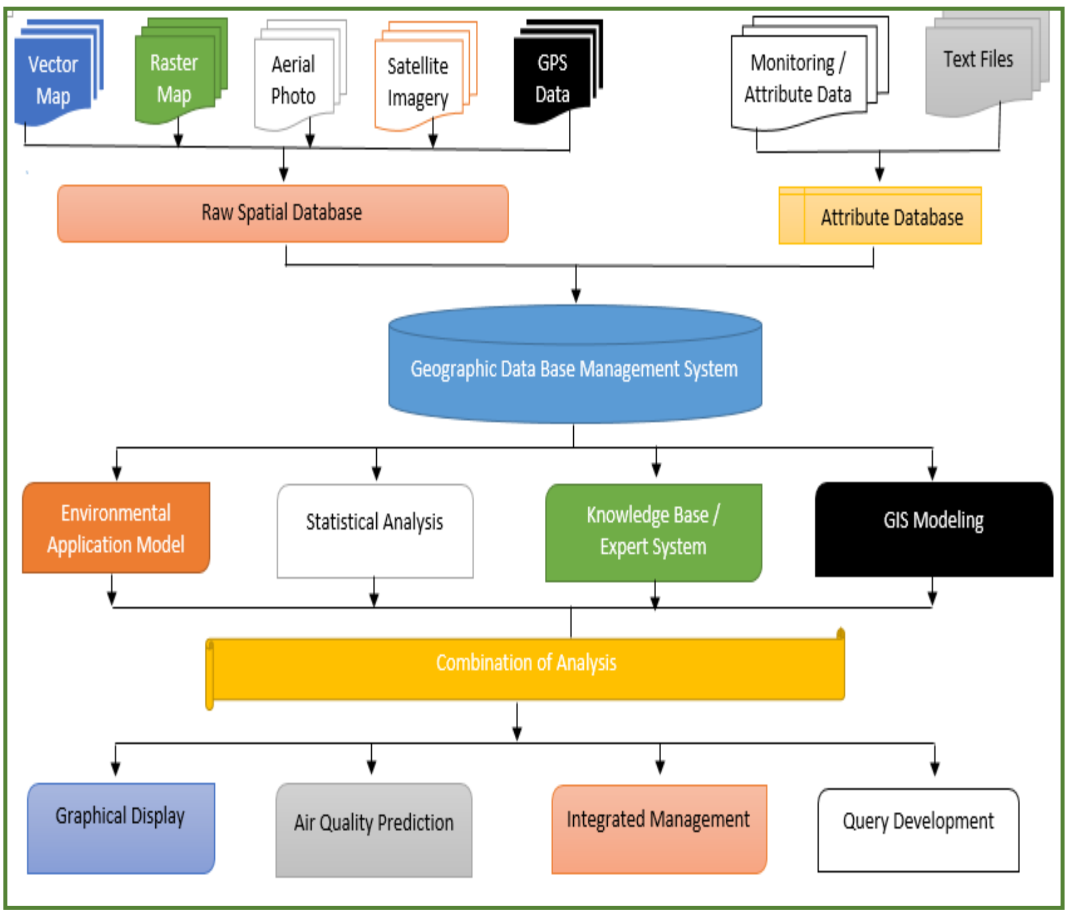



**Figure 1.3: Flow Chart for Constructing $CO_2$ Emissions Model**

Figure 1.3 represents the flow of activities proposed for data base compilation. The integration of digital and attribute (tabular) datasets with geospatial technologies will be used to assess the location and distribution of $CO_2$ emission concentrations.

## Research Goals and Objectives

Research goals include the development of a regional carbon footprint supply and demand chain model through use of GIS spatial modeling, employing Pinch Analysis techniques aimed at the reduction of $CO_2$ emissions at the local level by means of carbon offsetting. An example of carbon offsetting involves using the excess carbon emissions in one county, offset by an adjacent county leading to an overall reduction in emissions. In order to develop a statistically relevant and robust planning tool targeting a 30% reduction in a regions carbon footprint at the local level, the following data must be obtained:

1) Energy demand data from three adjoining Illinois counties, broken down by both the transportation and stationary energy sectors.
2) Energy supply data from the same three counties, including internal fuel sources.
3) $CO_2$ emissions data by energy sector and fuel source.

# CHAPTER 2

## BACKGROUND AND LITERATURE REVIEW

This chapter provides the necessary background composition for $CO_2$ emission modeling and answers questions regarding why estimating $CO_2$ emissions at a local level is important, what kind of estimation methods have been used previously and at what scale, and what policies drive $CO_2$ emissions reduction programs. There are two major sections in this chapter. The first section provides a general overview of different types of research and models that exist for estimating $CO_2$ emissions. The second section explains the policies that mandate emission reductions and speaks to methods recommended at the local level.

### Estimating Carbon Emissions

Carbon dioxide ($CO_2$) is one of the major greenhouse gases and is studied extensively in research related to greenhouse gas emissions, climate change, and global warming. According to the Energy Information Administration (EIA), 80 percent of the U.S. greenhouse gas emissions are energy-related carbon dioxide emissions (EIA, 2007)[2]. Although emission sources are local, research is focused intensively at a global level[13]. The literatures on carbon emissions estimation can be divided into global, national, state, and local levels.

### Global, National and State Level Estimation

Several studies conducted at the national and global levels have associated increases in carbon emissions directly with the economic growth of a region. The EIA states that the energy use in the United States is primarily driven by economic growth in the long term, and is affected by fluctuations in weather patterns (e.g., number of cooling and heating days) and energy generation sources in the short-term (Energy Information Administration, 2007).

The Department of Energy (DOE) has designed an energy indicators system which provides a hierarchal structure to generate indexes that explain the change in energy use over time (U.S. Dept. of Energy, 2003). Three types of indexes are developed in a hierarchical structure to measure the change in energy use: economy-wide energy consumption is in the highest aggregation level, and the unit defined to measure the activity at this level (intensity indicator) is defined by gross domestic product (GDP); the second level of the hierarchical system includes the residential, commercial, industrial, and transportation sectors, and the indicators defined to measure the activity were divided into different categories. The energy intensity indicators for the residential category, which could be further divided into different housing types, are household size and floor space (in square feet); for the commercial category the indicator identified is floor space (in square feet) only.

Other studies conducted to estimate carbon emissions at global and national levels; Stoker and Judson (1998) constructed a carbon emission models using an econometric model to compare the emissions at both national and global levels[14]. Fossil fuel combustion, population growth, and income from 1950 to 1990 were considered in their model.

Researchers at the Massachusetts Institute of Technology developed a system as part of an Integrated Global Systems Model (IGSM) to project the effects of economic growth on man-made greenhouse gas emissions and aerosols. The newer version of the IGSM, the Emission Prediction and Policy Analysis (EPPA) model includes regional and land use to represent energy flow of the earth system as a whole.

The United States Environmental Protection Agency (USEPA) has developed methodologies to compile a comprehensive greenhouse gas inventory at the state level, based upon approaches established by the Intergovernmental Panel on Climate Change (IPCC) to inventory greenhouse gases at the national level[13]. According to Kates, Mayfield, Torrie, and Witcher (1998), the EPA and IPCC-based emissions calculation method is very detail-oriented and may be beneficial and applicable to nations that have consumption or activity level data.

Most of the aforementioned research relates carbon emissions from energy consumption at the global, national, and state levels to economic and demographic patterns. The methods developed to estimate emissions at the global and national level cannot be applied at the local level due to the complexities associated with disaggregated data[13]. The problems related to emissions allocation decrease as spatial aggregation increases; in part it is also because there is more data collected at the national level than the local levels[13].

## Local Level Estimation

Since this project focuses on carbon emissions at a regional (county) scale - or - local level, it is important to understand the complexities associated with carbon emissions estimation methods at the local level. There are several methods for estimating and reporting carbon emissions at local levels. The best methods identified were simple, replicable, and maintainable with the least effort.

There were several top-down and bottom-up approaches identified in the literature. The top-down approaches, developed by the electric utility industry, predict the end-use electricity for buildings based on historical data loads[15]. The bottom-up approaches, in contrast, use individual building energy consumption per hour to estimate city-level consumption. The energy calculations for some of the bottom-up approaches are estimated using pre-existing building simulation software like EQUEST and DOE 2.2, developed by the U.S. Department of Energy. Buildings are divided into different categories based on their characteristics and the simulation software is used to predict the energy consumption for a set of prototype buildings representative of buildings in a particular city[15].

Two organizations have independently developed methods to calculate greenhouse emissions at the local level, though with different objectives: the International Council for Local Environmental Initiatives-Cities for Climate Protection (ICLEI-CCP) campaign, and the Association of American Geographers-Global Change in Local Places (AAG-GCLP)[10]. The objective of AAG-GCLP is to understand the causes of greenhouse gas emissions and their impact at the local level. The ICLEI-CCP method looks at the total fuel and electricity sales per sector to predict total emissions in cities[13]. ICLEI-CCP and AAG-GCLP are not GIS-oriented. Both methods are used to inventory greenhouse gas emissions at the city level.

The University of California at Davis (UC Davis) has developed a GIS-based land use planning and forecasting model for regional or county-level analysis. The model has several components to predict suitable areas for future urban growth. One of the components of the model is a greenhouse gas calculator, which allows users to calculate energy demands and resulting greenhouse gases from new developments. The total energy (electricity and gas) demand in a residential category is calculated by multiplying the number of residential households by an average number of square feet of a building in the residential land use category and by the energy intensity for the residential land use type (University of California at Davis, 2008). The total energy demand in a commercial land use category is calculated by multiplying the number of square feet of a building by the average energy intensity for the land use category. A similar method was developed by the California Climate Action (CCA) Registry for estimating electricity use for commercial sectors. The only difference is that the CCA Registry recommends estimating end-use energy consumption for commercial sectors based on the average electricity intensity of comparable facilities, instead of that for the land use category.

The study recommends deriving the average electricity intensity of comparable facilities from the results of an extensive survey and analysis administered and supported by California Energy Commission (CEC) for forecasting end-use energy demand and assessing energy efficiency market activities (California Energy Commission, 2006). The California Commercial End-Use Survey divided and analyzed end-use energy demand according to CEC forecasting zone (FCZ) and electricity utility region.

As for the residential sector, the CEC commissioned a Unit Energy Consumption (UEC) study by teaming up with the investor owned utilities. UEC is defined as the average energy consumed by a household in a year. The California Statewide Residential Appliance Saturation Study (RASS) was conducted to allow comparison of end-use energy consumption across utilities service regions and climate zones similar to the commercial survey explained above. The results also provide UEC based on variables, such as dwelling type, dwelling vintage, and income for different climate zones and utility regions (California Energy Commission, 2004). Several factors, including economic, demographic, building structure, and weather play weighty roles in assessing unit energy consumption for a building. The level of sophistication used to inventory and calculate emissions depends on the amount of resources local organizations are willing to spend[13]. In addition, these factors may not be equally important in determining the local energy consumption. For example, in a region that has not experienced much economic growth, economic factors may not influence the change in energy consumption when compared to other factors. Therefore, it is possible that factors which need to be considered may vary across different study areas.

## Carbon Constrained Energy Planning

Carbon constrained energy planning is a relatively new area of research dedicated to working with regional carbon dioxide ($CO_2$) emissions limits through the deployment of various low-carbon technologies; research into the development of modeling techniques to analyze and simulate the effects of these technologies on carbon emissions is on the rise to optimize the deployment of appropriate technologies on carbon emissions in order to meet environmental goals in light of both technical and economic constraints[16].

## Pinch Analysis

Tan and Foo[17] were the first to employ pinch analysis techniques for carbon constrained energy sector planning. This methodology assumes that within a given system, there exist a discrete set of energy sources, each with a specific carbon intensity characteristic of the fuel and/or technology. The system was assumed to contain a set of energy demands which have a specified carbon footprint limit; composite curves use energy as the horizontal axis and $CO_2$ emission s as the vertical axis. This is illustrated in Figure 2.1.

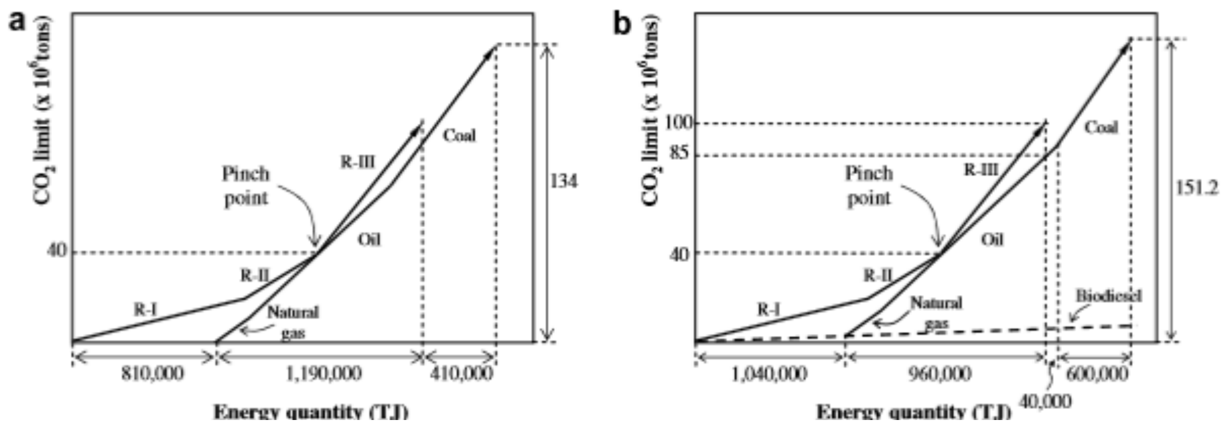



**Figure 2.1: Energy planning targeting (a) $CO_2$ neutral source (b) low-carbon source[17]**

Composite curves are formulated only after a determination of the following[11]:

- The energy demand/sink composite curve (CC) where the recovery of resources is based on the maximum limits of the sinks; the coordinate system in CEPA is the amount of $CO_2$ (or $CO_2$ equivalent) per unit time versus the amount of energy per unit time. This technique provides a slope delineating the amount of $CO_2$ per unit of energy for any line plotted on the system.
- The absolute maximum amount of energy for the matching of the overlapping horizontal (shallow locus) projection of the energy demand CC with that of the shifted energy resource ;
- The absolute minimum amount of energy for renewables is reached through the shifting of the energy resource CC against the energy demand CC to the resulting $CO_2$ pinch point.
- The finalized shift of the energy resource CC is positioned below that of the energy demand CC so that the optimal energy resource (OER) mix is obtained.
- The slope of an individual resource/demand line segment is given by the emission factor (EF) of the respective energy resource/demand.

To develop a better understanding of energy systems, a graphical method has been expanded to include total site, Linnhoff[18]; total site assumption employed by Klemes[16] encompassed regional and national energy sectors. Lee[17] recognized that optimization was possible within regional and national energy sectors covering a broader geographic and temporal scale that include residential consumption, transportation and industry. Crilly and Zhelev[3] later define the methodology of total site assumption on a sector as paramount in the development and implementation of CEPA; total site assumption on a regional and/or national scale guarantees that a region or sector's electricity demand is being met by a network of power producers who feed into the transmission grid – and that this electricity was/will be consumed by being transported to where it was/will be required; composite curves developed to mitigate $CO_2$ emissions regionally are shown in Figure 2.2. At the regional level, a carbon emissions constrained energy planning statement can be expressed as follows[19]:

(1) Identification of the minimum quantity of zero-emission or low-carbon energy resource including nuclear, solar, wind and hydraulic energies needed to meet the total energy supply and $CO_2$ emission limits in a region.

(2) Identification of the energy allocation scheme to meet the specified emissions limits of every region using the minimum quantity of zero-emission or low carbon energy resource in a system of many regions.

(3) Identification of the extent of $CO_2$ emissions reductions to meet emission constrained energy planning targets.

**Carbon Emissions Pinch Analysis (CEPA)**

Linear programming based $CO_2$ emissions pinch analysis (CEPA) methodology involves the graphical plotting of an energy demand (called the total actual demand, TAED) and an equal energy resource (called total actual energy resource, TAER) in the $CO_2$ versus J coordinate system[17]. At the regional level, carbon emissions constrained energy planning looks to delineate the following[19]:

(1) Minimum quantity of zero-emission or low-carbon energy resources including nuclear, solar, wind, geothermal and hydraulic energies necessary to meet total energy supply and $CO_2$ emission limits within a region.

(2) An energy allocation scheme that meets specified emission limits of each region using a minimum quantity of zero-emission or low-carbon energy resources.

(3) The extent of $CO_2$ emissions reduction to meet emission constrained regional energy planning. Zero-emission or low-carbon energy resources has made full use of reaching the aim of reducing $CO_2$ emissions. However, these energy resources are relative expensive, or are not mature compared with conventional fossil fuels in the applied technology. Therefore, pinch analysis method are used systematically to identify of the minimum quantity of zero emission or low-carbon energy resource and the energy allocation scheme needed to meet $CO_2$ emissions limits are important.

In basic CEPA methodology, no adaptations for the baseline are considered, however adaptation may be necessary when CEPA technology is applied to a regional electricity sector. As a result of numerical approaches to the problem of $CO_2$ emissions[20], it became apparent that the assumption of zero-carbon technologies had to be reconciled because of the presence of their small carbon footprint; one of the most important adaptations appears to be in the arena of using non-zero operational weighted average emission factors (WAEF) for each of the constituent wind, hydro, landfill gas, biomass and other gases; non-zero WAEFs reflect the non-green nature of renewables in a more realistic manner[21]. More recently, low carbon technologies shift diagonally along a shallow locus, rather than horizontally[22]. Other adaptations involve forecasting tools linking optimal energy resource mixes (or fuel mix) whose resulting GHG emissions are constrained by $CO_2$ limits imposed by present and future policy which account for the dynamic nature of both energy resources and energy demand[11].

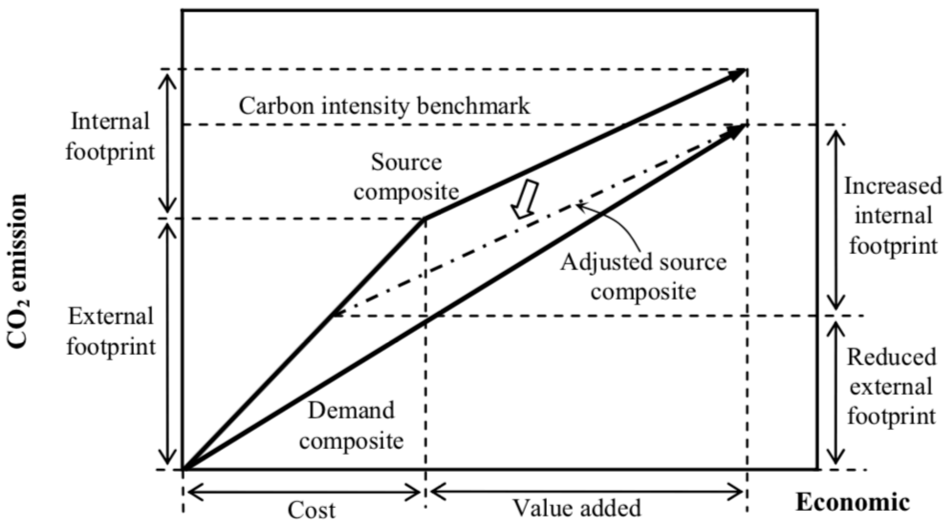



**Figure 2.2: Carbon emissions pinch analysis composite curves[36]**

## Life Cycle Analysis

Life cycle analysis (LCA) is a tool employed to assess the sustainability of various energy sources; over the last thirty years, LCAs have been published for a variety of electricity generation technologies. LCA studies often calculate the environmental impact of energy sources against sustainability criteria. LCA can assist with:

- Identifying opportunities to improve environmental performance of products at various points in their life cycle
- Informing decision makers in industry, government or non-government organizations for the purpose of planning, priority setting, product or process design and retrofit;
- The selection of relevant indicators including measurement techniques.

Life cycle assessment provides a well-established and comprehensive framework to compare renewable energy technologies with fossil-based and nuclear energy technologies.

Life cycle assessment methodologies have been evolving for a few decades now and are supported by international initiatives and governed by standards (Cowle et al, 2006; ISO 1040:2006). A 4-part approach to LCA widely accepted today is as follows:

(1) Stating the purpose of the study and appropriately identifying the boundaries of the study (Goal and Scope definition)

(2) Quantifying the energy use and raw material inputs and environmental releases associated with each stage of the life cycle (Life Cycle Inventory)

(3) Interpreting the results of the inventory to assess the impacts on human health and the environment )Life Cycle Impact Assessment)

(4) Evaluating opportunities to reduce energy, material inputs, or environmental impacts along the life cycle (Improvement Analysis or Interpretation)

### Mathematical Programming and Optimization

Although a pinch analysis approach is sufficient for less complicated planning scenarios, and offers graphical displays that are easy to assimilate, mathematical linear programming (LP) provides an opportunity to integrate more complex, case-specific goal functions; the premise of mathematical programming as applied to pinch analysis is that the pinch approach suffers from inherent simplification and lower expandability than mathematical programming. Equations derived by Tan and Foo[17] are derived directly from pinch approach principles only take into account a single footprint (ie. $|T| = 1$). Apart from carbon constrained energy planning, several derivatives of the basic LP framework have been reported, including land and water-constrained biofuel production[4, 20], segregated targeting for multiple resource networks[22-24], targeting for multiple low-carbon sources[25] and energy demand growth[26]. These extensions are based on replacing the carbon footprint with some other quality index; Table 2.1 lists examples of quality indices but is by no means exhaustive.

**Table 2.1 - Quality Indices for Energy Streams in Case Studies**

| Quality Index | Brief definition and sustainability implications |
|---|---|
| Carbon Footprint | $CO_2$ emissions intensity per unit of energy is essential to address climate change mitigation through effective energy allocation [ De Benedetto and Klemeš, 2009] |
| Agricultural Land Footprint | Agricultural land use intensity is essential for planning of large-scale bioenergy production, in order to minimize conflicts with traditional uses of land (e.g. for food production) [Čuček *et al*., 2012] |
| Water Footprint | Local water resource use intensity is also essential for planning the production of biofuels, which may divert resources from other important uses; in addition, water stress (ie. Local water scarcity) may be induced in some geographic regions as a result of climate change [Allan, 1998] |
| Energy Transformation | Energy transformity provides a quantitative index of the efficiency at which solar energy is converted into various downstream forms of energy; the energy content of any natural resource provides an index of its scarcity or its value by quantifying the cumulative amount of solar energy needed to form the natural resource [Odum, 1996] |
| Inoperability | Inoperability provides a quantitative index of loss of physical output of a resource as a result of natural casualties including drought, earthquakes, and storms [Haimes and Jiang, 2001] |

Tan[27] presents a general source-sink model with inoperability constraints; risk factors are present in energy systems as a result of disruptive natural disasters. Excessive reliance on hydroelectricity can cause a grid to be susceptible to power shortages during drought. Terrorism poses a real and immediate threat to all civilization today.

## GIS Spatial Analysis

As with any GIS model undertaking, data collection and processing remain one of the most important and time-consuming steps. Several procedures and models have been developed by other organizations for estimating carbon emissions for reporting purposes. The first step for this project is to identify the method that would support the purpose of the study, making the best possible use of the available data within the region. A preliminary assessment of the data will be tackled by the GEOG 402/502 project team as an integral task for the 2016 Spring Semester Final Project, Southern Illinois University, Carbondale, IL.

The most straightforward and accurate way to analyze the spatial pattern of carbon dioxide emissions from end-use energy consumption would be to examine the energy consumption data from the utility companies, such as the actual electricity meter readings of each household, commercial building and industry for each community. However, due to utility consumer confidentiality issues, it is predicted that aggregated data, such as total electricity consumption for the entire commercial, industrial, residential or transportation sector, might be the only type of data that can be obtained. The carbon emissions calculations for the $CO_2$ Model proposed in this project has yet to be determined.

There are several methods for estimating and reporting carbon emissions at local levels. The best methods identified were simple, replicable, and maintainable with the least effort. Energy consumption data for the counties of Franklin, Williamson and Jackson will be collected from electric and gas companies, and parcel level data will be collected from the University of Illinois, Springfield, IL GIS department links. Parcel data will be used to calculate energy consumption per parcel based on existing methods; the aggregated electricity and gas data provided by the utility companies will be used to verify the estimated energy consumption at the county level. The model proposed will be developed using the ArcGIS Model Builder platform because of the flexibility it provides to automate and repeat the work flow.

The effects of economic variables on energy consumption will be ignored in this model, at least preliminarily; weather will not be considered to play a significant role because the end-use, bottom-up methodology will not be based on monthly, but rather annual consumption of energy supply, and the study area lies within a single climate zone.[2]

The nonfunctional component of this $CO_2$ Model is that it be simple in nature, replicable, and easily maintained so that it will be widely implemented within the State of Illinois. The functional requirement of the model involves data preprocessing, which includes identifying important attributes as indicators necessary for the modeling, building a file geodatabase to house the data from each source, and automating the workflow through calculation methods employed in the ModelBuilder platform of the Environmental Systems Research Institute's (ESRI) ArcGIS 10.2 software application. Geodatabases will be created for data transfer in ArcCatalog; data will be organized in Microsoft Excel format, then imported as table data, and treated as attributes in ArcMap. In the resulting Attribute table, there will be Latitude and Longitude data which are collected from website and street address information obtained through the data collection process. A coordination system will be defined and "XY" data added using the "Add XY data" in the Tools menu of ArcMap.[28]

# CHAPTER 3

# METHODOLOGY

## Research Design

Decision support systems encompass air quality monitoring, emission inventory, air quality modelling, and air quality mapping together with air quality assessment. Table 3.1 outlines the proposed methodology for developing a regional planning tool for the Southern Illinois Energy Sector.

**Table 3.1 - Methodology [Guinée, 2004]**

| Phase | Steps | Desired Result |
|---|---|---|
| Goal and Scope | Methodology | Functional Units defined, alternatives compared |
| | Goal definition | |
| | Scope definition | |
| | Functions, functional units, alternatives and reference flows. | |
| Inventory analysis | Methodology | inventory, tables, other indication (e.g. missing flows) |
| | Environmental system boundary | |
| | Flow diagram | |
| | Format and data categories | |
| | Data collection | |
| | Data validation | |
| | Data quality | |
| | Cutoff and data estimation | |
| | Multi-functionality and allocation | |
| | Calculation method | |
| Impact assessment | Methodology | Environmental profile |
| | Selection of impact categories | Normalized environmental profile |
| | Classification | |
| | Characterization | Weighting profile |
| | Normalization | |
| | Grouping | |
| | Weighting | |
| Interpretation | Methodology | Well balanced conclusion and recommendations |
| | Consistency Check | |
| | Completeness Check | |
| | Contribution analysis | |
| | Perturbation analysis | |
| | Sensitivity and Uncertainty analysis | |
| | Conclusions and recommendations | |

## Data Sources

There exist numerous websites which specifically address $CO_2$ emission data. The major objective with using website information is to determine the reliability and validity of the data obtained from each of the following $CO_2$ producers in the Southern Illinois Energy Sector.

Supply sources responsible for the majority of $CO_2$ emissions include coal, petroleum, propane, biofuels, natural gas, heating oil, diesel, and gasoline. Renewable and alternative fuels include hydropower, solar, wind, geothermal, biomass and ethanol, while other low carbon generating energy sources include uranium fuel and nuclear generation as well as spent fuel. The most air-polluting industry include the leather, food, textile, paper, machinery, metals, chemical, petrochemical, ceramic, cement, iron-steel, and petroleum refinery.

$CO_2$ generation will be paired with consumption activities in the Residential, Commercial, Manufacturing, Transportation and Municipal sectors. Data will be collected from municipalities, Ameren of Illinois, individual power plants, refineries, and manufacturing facilities specific to the industry listed in paragraph one of this section.

## Acquisition of Data

The Greenhouse Gas Reporting Program (GHGRP) requires annual reporting of greenhouse gas (GHG) data and other relevant information from large direct emissions sources and suppliers of certain fossil fuels and industrial gases in the United States. Data collection began in 2010 for most reporting entities. In 2011, an additional 12 GHG source categories were added and agencies are now reporting on these to the Environmental Protection Agency since 2012. This program requires that certain sources monitor and report GHG information to EPA annually. It does not require control of greenhouse gases. Locating suitable working data can be elusive, however because organizations such as the U.S. Energy Information Administration provides much of their data in the form of excel worksheets and GIS shapefiles from their website, state-based information can be readily accessed from the comfort of one's own computer lab. The challenge of this project was in delineating the local supply and demand from an established state level database. Also problematic were the sheer number of broken links or links that did not deliver the information sought. Furthermore, many links provided the following error message:

**Forbidden** You are not authorized to access the requested resource

The following websites had information relevant and accessible to the research goals.

- ✓ United States Energy Information Administration Independent Statistics & Analysis (2015) https://www.eia.gov/maps/layer_info-m.php
- ✓ United States Environmental Protection Agency (2016) https://www.epa.gov/enviro/geospatial-data-download-service
- ✓ United States Geological Survey – Science for a Changing World (2001-2014) https://nationalmap.gov/small_scale/
- ✓ Illinois Geospatial Data Clearing House (2010) www.clearinghouse.isgs.illinois.edu/
- ✓ Tiger/Line Shapefiles: Transportation (2013-2014) www.census.gov
- ✓ Land Use & Land Cover: Land Cover Institute (2016) https://landcover.usgs.gov/landcoverdata.php
- ✓ Illinois Department of Transportation (2010) http://www.idot.illinois.gov/transportation-system/Network-Overview/highway-system/illinois-travel-statistics

  http://www.gettingaroundillinois.com/gai.htm?mt=aadt

  http://apps.dot.illinois.gov/gist2/

- Illinois is a key transportation hub for crude oil and natural gas moving throughout North America, with more than a dozen interstate natural gas pipelines, two natural gas market centers, several petroleum and petroleum product pipelines, and an oil port.
- Illinois ranked first in the nation in 2014 in both generating capacity and net electricity generation from nuclear power. Generation from nuclear power plants in Illinois accounted for more than 12% of the nation's nuclear power.
- With a production capacity of 1.5 billion gallons per year, Illinois is a top producer of ethanol. Illinois ranked third in the United States in ethanol production in 2013.

## Data Reliability and Validity

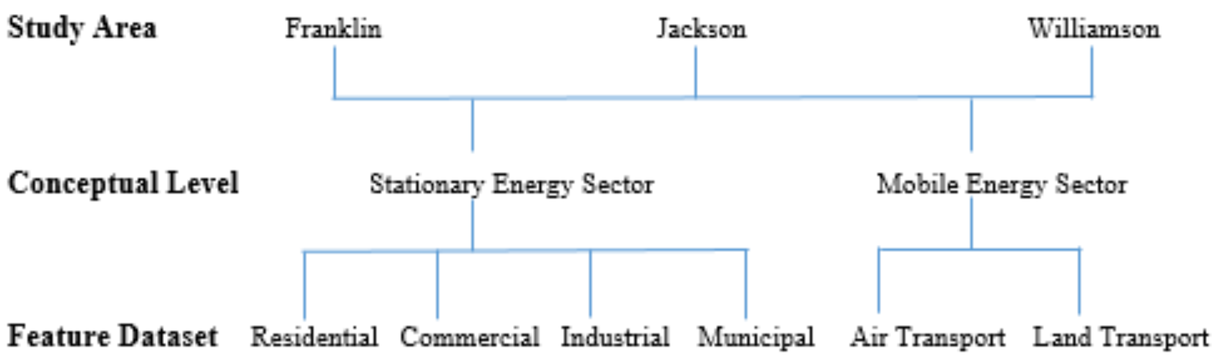
Calculation of GHG emissions per kilowatt-hour (kWh) has been shown to be problematic; recent literature illustrates widely dispersed conclusions due to differing assumptions, comparison baselines, and system boundaries. Key drivers of variability include impact assessment method (e.g., global warming potentials [GWPs] of assessed GHG emissions), technological performance factors such as thermal efficiency and capacity factor, and primary energy resource characteristics such as solar resource and fuel heating value. To minimize the variability, the National Renewable Energy Laboratory employs the technique of harmonizing energy data to develop robust, analytically consistent and updated comparisons of GHG emissions, however data was not accessible to the end user at the local level.

## GIS Database Design

The data required for spatial models to serve $CO_2$ emission modelling can be grouped into several classes. Different scales of the spatial models require variable methods of construction, data management, and spatial data sources. Data is included in the map layers as attributes. Other map layers are added by the methods of spatial interpolation, raster algebra, and case oriented analysis.[29] Successfully applying GIS requires the right data—the data needed to address a specific issue—in a format accessible to tools that can produce meaningful information. The first step in creating the GIS database is to design the geodatabase in such a way that the end user can populate it in an organized and efficient manner. Figure 3.1 represents the design for the GIS database employed in this study.

## GIS System Design

The primary objective of this project will be to develop a carbon emissions model for the Southern Illinois Energy sector designed to quantify and analyze carbon emissions distribution. This model will be designed to combine carbon emissions from both the stationary and mobile energy sectors of Franklin, Williamson and Jackson counties.




**Feature Class**

Stationary Energy Sector –

1. Supply
   a. Coal
   b. Natural Gas
   c. Propane
   d. Petroleum
   e. Nuclear
   f. Wind
   g. Solar
   h. Geothermal
2. Demand
   a. Space Heating
   b. Air conditioning
   c. Water Heating
   d. Appliances, electronics, lighting

Mobile Energy Sector –

3. Supply
   a. Aviation Gasoline
   b. Biodiesel (B100, B20, B10, B5 and B2)
   c. Diesel Fuel (No. 1 and no. 2)
   d. Ethanol/Ethanol Blends (E100, E85 and E10 (Gasohol)
   e. Methanol/Methanol Blends (M100, M85)
   f. Gasoline
   g. Jet fuel (Kerosene)
   h. Natural Gas
   i. Propane
   j. Residual Fuel (No. 5 and No. 6 Fuel Oil)
4. Demand
   a. Aircraft
   b. Railway
   c. Vehicles

**Figure 3.1: Geodatabase Design**

The system design of this $CO_2$ Model will be divided into three general components (Figure 3.2). Existing geospatial data provided by different sources including any City, County, State and/or University GIS Datasets will be stored in a geodatabase. The purpose of building a geodatabase for the $CO_2$-Model application is to organize and manage data files associated with the application; it is not intended to build any structured relationships between features. Not knowing the format and resolution at which the utility company will provide the data makes it challenging to predict the initial work plan; although scheduling may need to be adjusted to accommodate any delays introduced during data collection, the deliverables and major tasks should remain on schedule.

The second component of the system is the $CO_2$ Model itself; this model will be designed to automate the carbon emission calculation using ESRI‘s ModelBuilder extension available with ArcGIS (10.2) software. ArcGIS was chosen as a platform due to its single user capability to support a desktop application for data compilation, query, spatial analysis, image visualization and exploitation, modeling, and data management.

Models have been coupled with GIS to simulate various environmental processes. Recent development of spatial data management in the framework of geographic information systems (GISs) has created a new era of environmental modelling; spatial models and their extensions are being developed in the framework of the ESRI's ArcGIS and ArcView programming tools. The ArcGIS, a descendant of the widely used ArcInfo, can manage spatial data in various levels, such as shapefiles, coverages, and geodatabases.

A desktop application that houses the model together with the supporting data files will be required; with the expected output from the model, an individual should be able to examine the distribution of the carbon emissions from different types of industry. In theory, any computer system consisting of ESRI ArcGIS 10.2 or higher at the ArcInfo license level together with Python 3.5.1 or higher should be able to successfully run the $CO_2$-Model.

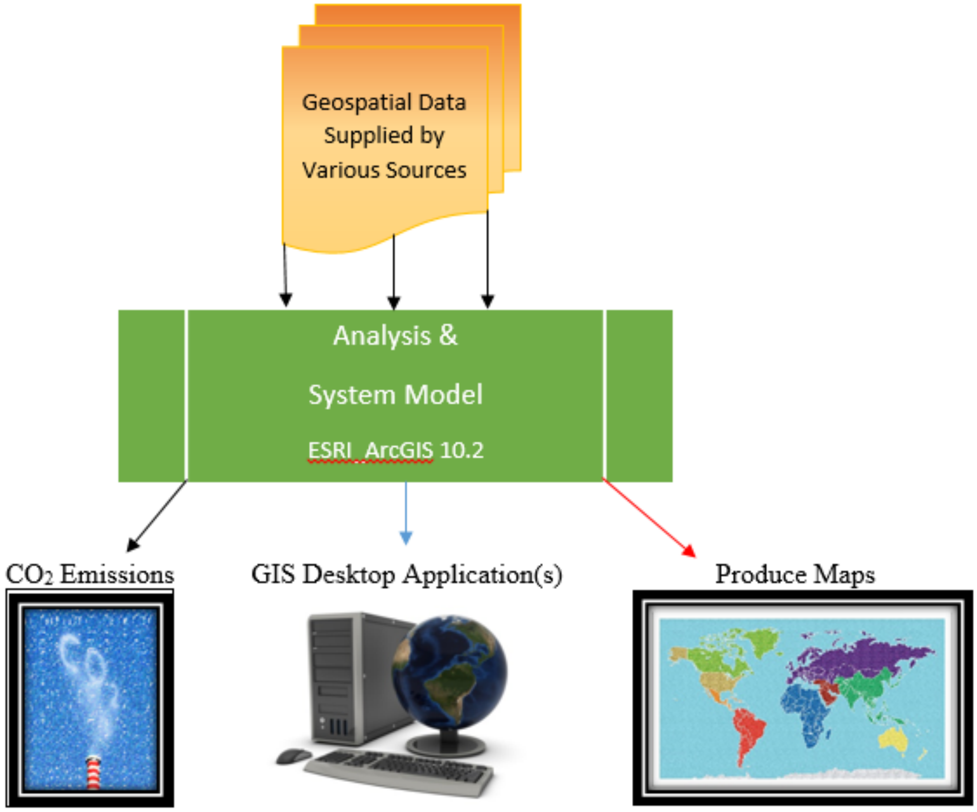



**Figure 3.2: System Design Flow Chart[2]**

## GIS Model Builder

While virtually impossible to enumerate all spatial and non-spatial data required to develop a robust $CO_2$ model, since the more that is known, the better, the accuracy of the model results does not depend exclusively on the data alone. The choice of appropriate modelling tools and their settings represents other key parts of air quality modelling; if the model does not require, or is incapable of evaluating detailed information, there is little benefit in putting that data in any GIS project. The ESRI ArcGIS ModelBuilder environment has been chosen to develop the $CO_2$ model because it allows for consistency, repeatability and GIS can be constructed to have a uniquely simplistic approach to estimating carbon dioxide emissions.

## Carbon Emissions Pinch Analysis

Pinch analysis covers a wide scope of tasks and is comprised of a family of methodologies for combining several parts of energy processes reducing the consumption of resources that lead to harmful emissions into the environment.  It is interesting to note that the ultimate effect to a simultaneous approach of looking at both supply and demand chains is not only an expected reduction in utility consumption, but also a reduction in raw material intake.

Tan and Foo[17] developed the first pinch analysis methodology for carbon constrained energy sector planning, also referred to as *Carbon Emission Pinch Analysis* (CEPA). This approach assumes that within a given dynamic system, there exists a set of energy sources, each with a specific carbon intensity characteristic of the fuel or the technology employed. This system also contains a set of energy demands, and each successive demand has a specific carbon footprint limit. Under the assumption that the enumerated energy sources are fully interchangeable, the original problem sought to minimize the amount of zero-carbon energy sources (i.e., renewable energy or non-combustion-based sources such as nuclear or geothermal power) required to satisfy specified carbon footprint limits.

The original methodology made use of energy planning composite curves similar to those used for water recovery (El-Halwagi et al., 2003; Prakash and Shenoy, 2005) but using energy as the horizontal axis and $CO_2$ emissions as the vertical axis (Figure 2.2). The basic technique has since been applied to energy planning by researchers in Ireland[11] and New Zealand[26].  The work by Atkins et al is interesting in that it considers the growth in energy demand within a sector over time.

A subsequent development in CEPA was the implementation of an equivalent numerical approach to solve similar problems (Foo et al) [20]. The extension is based on the established equivalence between graphical techniques (El-Halwagi et al., 2003; Prakash and Shenoy, 2005) and numerical ones (Manan et al., 2004; Foo et al., 2006a) [36].  In this study, it was recognized that the assumption of zero-carbon technologies had to be eased, because non-combustion-based technologies still had a measurable carbon footprint, especially when a life cycle approach toward the introduction of such technologies is taken into consideration.

A recent publication accounts for low-carbon technologies by allowing CEPA composite curves to be shifted diagonally along a shallow locus, rather than horizontally as in the original method together with the concept of *segregated targeting* in which not all energy sources can be used interchangeably by the demands[22]. And more recently, a new decomposition algorithm was developed to solve the segregated targeting problem[23]. These methodologies have all been developed based on the concept of carbon intensity as the "quality" index for energy streams. Alternative applications have been proposed using different quality indices for biomass-based energy sources, including land area (Foo et al., 2008), water footprint (Tan et al., 2009a), and emergy (Crilly and Zhelev, 2008b; Bandyopadhyay et al., 2009) [36].

Creating a geodatabase with an armament of information from local municipalities, businesses, industries, together with our residential and transportation energy sectors, placing this information in a CEPA composite curve, will assist decision makers in effectively minimizing the nations carbon footprint.

# CHAPTER 4

# RESULTS AND DISCUSSION

## Stationary Energy Sector

The Environmental Protection Agency (EPA) geodatabase(s) provide the background composition and contact information for a number of commercial entities who report to this federal agency. Shapefiles from the agencies geodatabase were loaded into ArcMap 10.3 with the goal of developing a methodology for creating a contact list for both the stationary and mobile energy sectors in the Illinois Counties of Franklin, Jackson and Williamson (Figure 3). The clipping tool was used to delineate the three counties of interest. Through use of the information tool, commercial entities were identified and geospatially located.

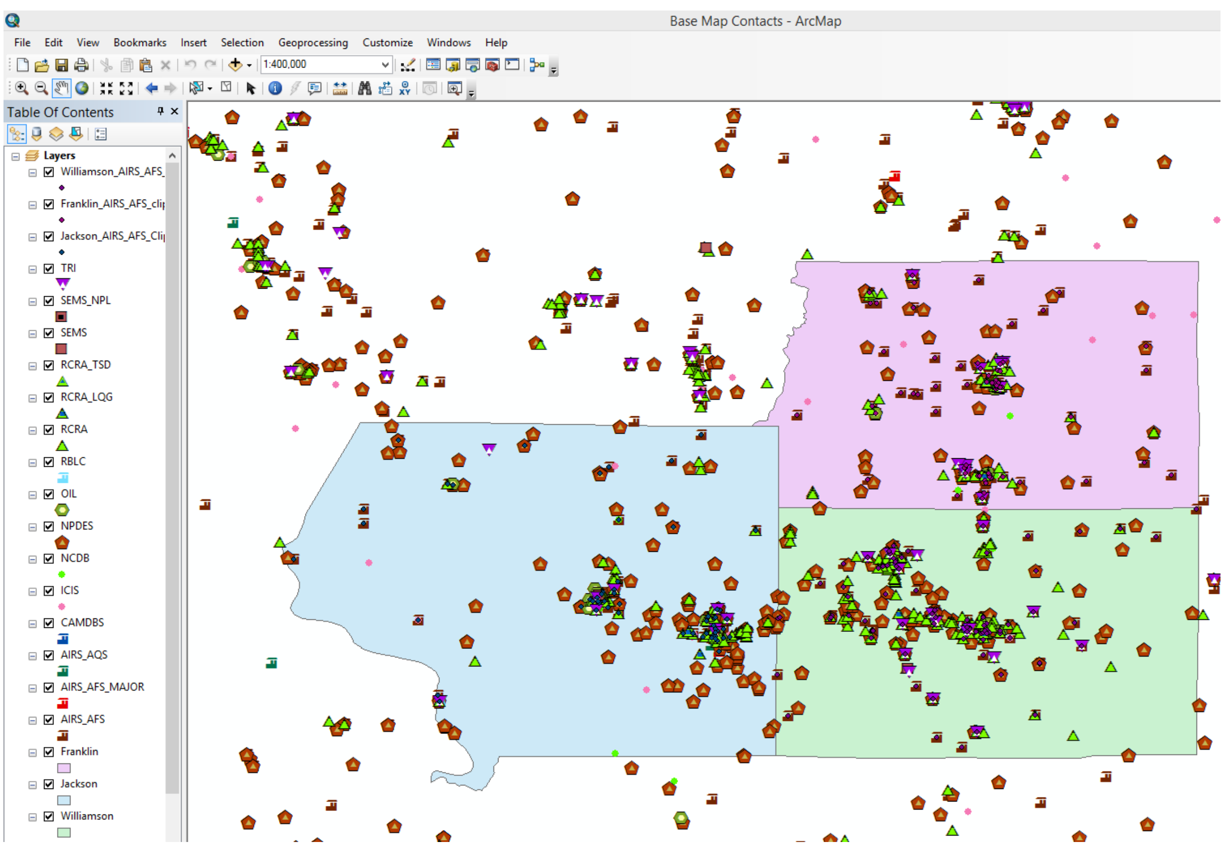



**Figure 4.1: Base Map of EPA Shapefiles**

## Establishing Local Contacts

In determining whether individual shapefile layers/records were relevant to the research, a contact was made locally with a Mr. Scott Arnold from the Illinois Environmental Protection Agency. He provided his list of commercial entities/businesses in Franklin, Jackson and Williamson Counties who report to the EPA, which matched what was able to be obtained from the EPA shapefiles. Mr. Arnold, however, was unaware of any local tracking of carbon dioxide emissions. Appendix A and B summarize the information gathered from the EPA geodatabase together with that provided by the local EPA contact, Mr. Scott.

The following contacts were established:

1. Michael Steinhoff (michael.steinhoff@iclei.org) ICLEI – Local Government for Sustainability
2. Chris Jones (cmjones@berkeley.edu) University of California, Berkeley with Cool Climate
3. Brian Clapp (clapp.brian@epa.gov) at the Environmental Protection Agency
4. Julie A. Dyer (dyar@illinois.edu) with the Illinois Sustainable Technology Center
5. Laura L. Barnes ( l-barnes@illinois.edu) with the Illinois Sustainable Technology Center
6. Kevin O'Brien (kcobrien@illinois.edu) with the Illinois Sustainable Technology Center
7. Sean Henry (shenry@ci.carbondale.il.us) Public Works Director, City of Carbondale
8. Carbondale Chamber of Commerce (info@carbondalechamber.com)
9. Kyle Harfst (researchpark@siu.edu) Dunn-Richmond Center
10. Leonard Hopkins (lhopkins@sipower.org) Southern Illinois Power - Lake of Egypt
11. B. Hollibaugh (bhollibaugh@ameren.com) – Ameren of Illinois

## Data Acquisition at the Local Level

Each contact, while insightful, was unable to provide this research initiative with data needed to build a geodatabase employed in the construction of a carbon emissions pinch analysis (CEPA) model. Individuals at the Illinois Sustainability Institute could not provide any information relevant to energy supply and demand despite the Director, Kevin O'Brien, who was a keynote speaker at the SIU Energy Day conference, espoused energy supply and demand as his contribution to the Institute's breadth and depth. Unable to secure relevant data from the power utility companies such as Ameren of Illinois, EPA or EIA contacts, though the Sustainability Institute did steer this research towards a useful website, Thomas.net which was helpful in finding energy suppliers though the suppliers were not willing to share the data they held. . Armed with information from Thomas.net, consumptive activities of the residential, commercial, industrial, agricultural and transportation energy sectors would have enabled this researcher to calculate an overall efficiency of each energy sector. It was the consumptive activities that then became the focus. After obtaining a Community Master Data Worksheet from the ICLEI – Local Governments for Sustainability, Appendix C, the Public Works Director for the City of Carbondale, Sean Henry, was contacted, a meeting scheduled, yet he acknowledged the City does not track the detail necessary to fill out this worksheet. And while the Cool Climate data, which uses GIS based technologies to estimate local $CO_2$ emissions at the zip code level, the commentary highlighted in the various research articles that accompany the data suggest these emission calculations only be used as a means to evaluate results obtained using a different methodology (Appendix D). Another challenge involved persons simply not responding to requests for a return call and/or email, making it impossible to establish leads or find out if the individual sought has the necessary information.

The most frustrating aspect of this research effort was that an organization such as the Dunn-Richmond business incubator, maintains no database on the commercial, industrial, or manufacturing industry common to the area. It was incomprehensible that a business incubator had no information on commercial business activities within their region. And the local Chamber of Commerce refused release the names of any registered commercial entities in the area because I was not a business owner nor affiliated with the Chamber.

### Mobile Energy Sector

The United States is on the move. Roughly 28% of all energy consumed goes to transporting people and goods from one place to another[5]. And we see only an increase in the energy demand for fossil fuels on the horizon (Figure 4.2). Therefore, the question rests in how a nation such as the United States meets future demand for fossil fuel while at the same time decrease carbon emissions? Widespread electrification of the personal vehicle fleet could reduce the total final energy demand of the transport sector when compared with the business as usual scenarios, and if the modal split from road and air to rail transport occurs, savings increase [34]. Replacement of oil and natural gas-based transport fuels must be technologically and economically viable as well as being environmentally sustainable [3].

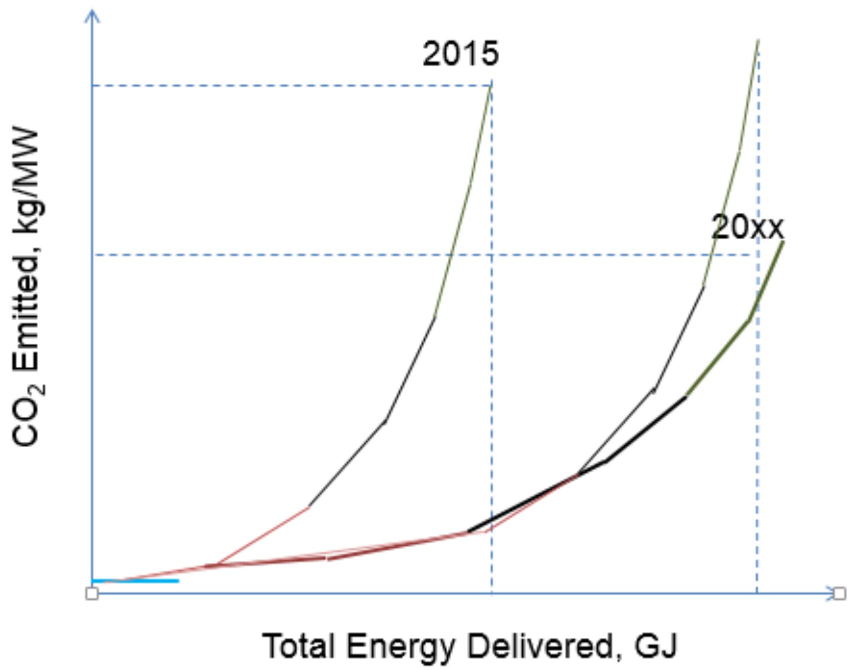



**Figure 4.2: Fate of Fossil Fuel in Carbon Constrained Economy[35]**

Local governments need to quantify and analyze carbon emissions by implementing sound reduction strategies in order to help nations meet global $CO_2$ reduction goals. Most of the models implemented to perform carbon inventories and assessments at the regional and local level are Microsoft Excel-based. To provide a basis for carbon emissions reduction policies, this project proposes to develop an automated $CO_2$ Model by using GIS techniques and, when constructed, makes it possible to estimate and analyze the distribution of carbon emissions from the transportation energy sector.

Though a variety of approaches are available with respects the forecast of annual energy demand for the transportation sector, as has already been argued, emissions must be based on local trajectories to address significant reductions. The GIS model developed in this project will be designed to provide the foundation for calculating indirect carbon emissions at the local level from the mobile energy sectors of Franklin, Jackson, and Williamson counties.

## Mapping

To develop the geographic data base management system for this project, shapefiles specific to each county were downloaded, a geodatabase created, and feature datasets developed. Base maps were created to demarcate the major sources of $CO_2$ emissions in the tri-county area resulting from transportation related activities (local airports, railways, and roads); Figures 4.3 - 4.5 geospatially delineate the study areas which include the counties of Franklin, Jackson, and Williamson, Illinois.

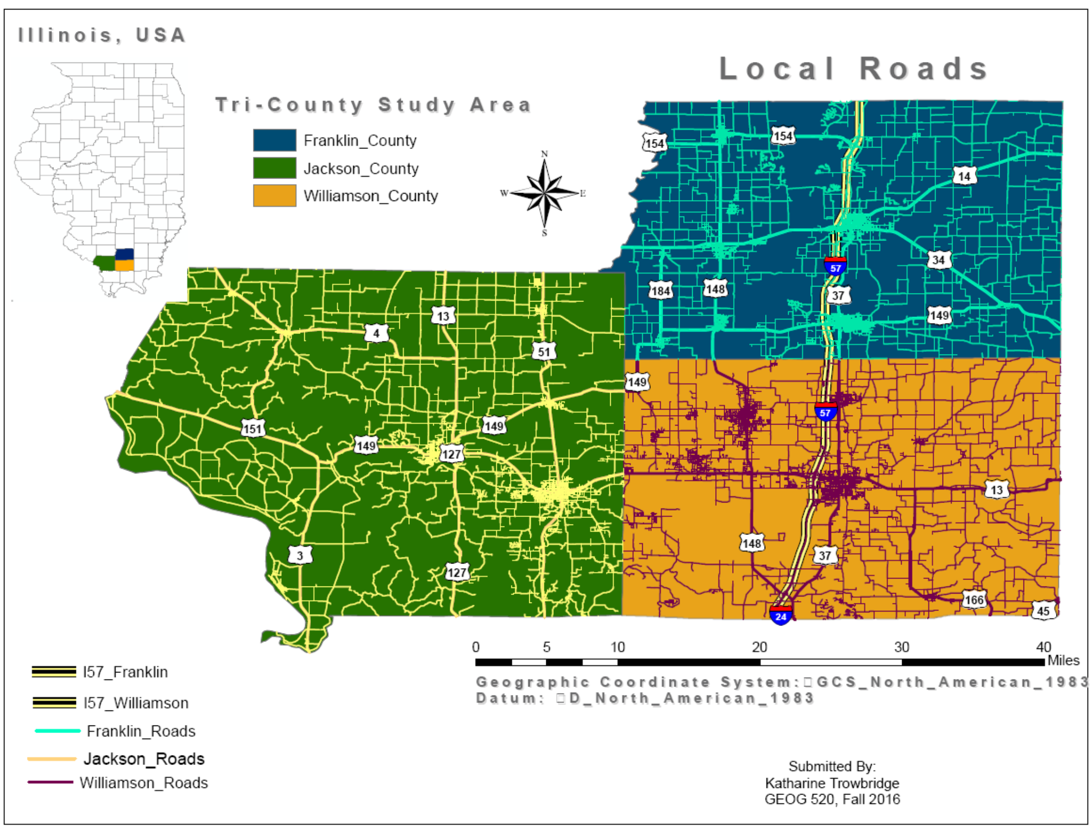



**Figure 4.3: Land Roadway Transport Study Area**

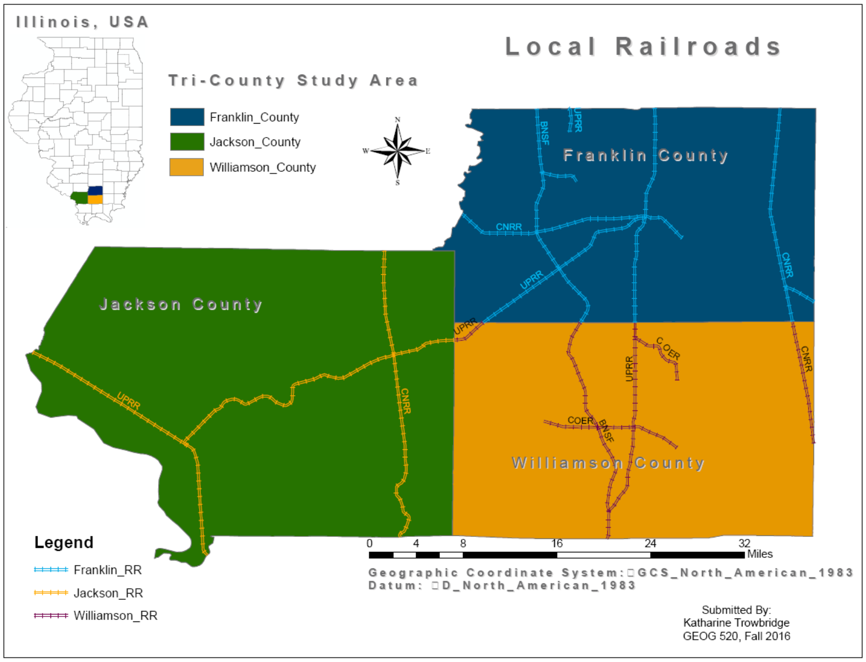



**Figure 4.4: Land Railway Transport Study Area**

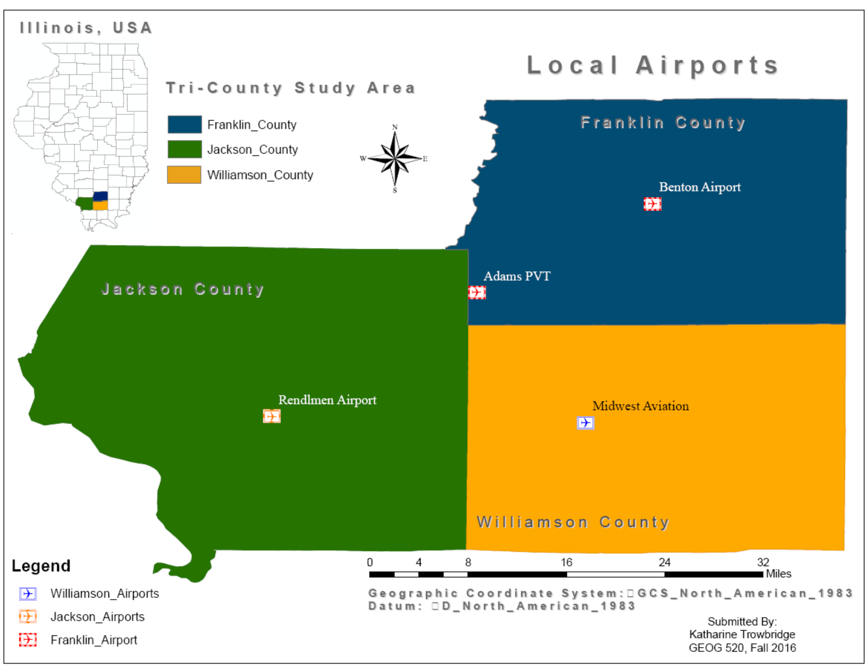



**Figure 4.5: Air Transport Study Area**

Defining the amount of air and railway travel locally would require additional insight from sources outside of information and travel statistics obtained from IDOT exclusively. Those contacts were established, but at a projected cost of $40,000.00 for the data.

As with any GIS model undertaking, data collection and processing remain one of the most important and time-consuming steps. Several procedures and models have been developed by other organizations for estimating carbon emissions for reporting purposes. The first step for this project was to identify the method(s) that could support the purpose of the study, making the best possible use of the available data within each region.

Figure 4.6 represents the flow of activities which accompany data base compilation. Integration of all digital and attribute (tabular) datasets, coupled with geospatial technologies were used to assess locations of $CO_2$ emission concentrations for the mobile energy sector. Transport class emission factors will be taken from the U.S. Energy and Information Administration once vehicle types, efficiency and fuel information are obtained. This data will be added to each attribute table in a separate field, and $CO_2$ emissions calculated.

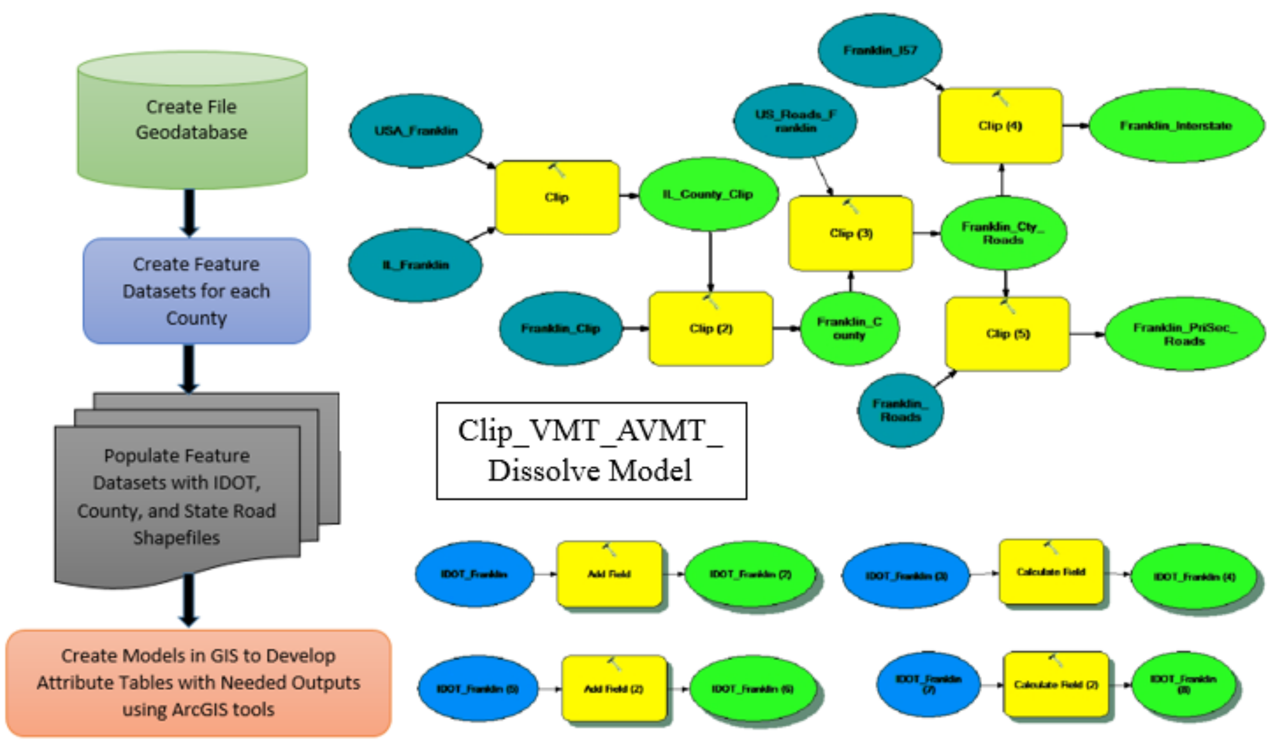



**Figure 4.6: Flow Chart(s) for Constructing AVMT Model in GIS**

## Model Output - Vehicle Miles Traveled

Building the model for each of the three counties of interest – then applying it to data supplied in subsequent feature datasets illustrate a consistency in the results for each county. In each of the model applications, the calculated AVMTs were altogether lower than IDOTs published statistics. In comparing those results from calculations employing the model in Figure 4.6, it was found that % AVMT's (calculated AVMT from IDOT shapefiles/IDOT Statistics per County) are as follows:

- Franklin – 1.04% under the published AVMTs
- Jackson – 6.75% under the published AVMTs
- Williamson – 3.9% under the published AVMTs

**Tables 4.1 - 4.3: Street Functional Class VMTs by County**

Franklin_Dissolve_VMT

| OBJECTID * | Shape * | FCNAME | SUM_VMT | Shape_Length |
|---|---|---|---|---|
| 1 | Polyline ZM | Interstate | 622859.5 | 0.346414 |
| 2 | Polyline ZM | Local Road or Street | 115218.499999 | 14.411475 |
| 3 | Polyline ZM | Major Collector | 196012.25 | 2.829546 |
| 4 | Polyline ZM | Minor Arterial | 365501 | 1.649113 |
| 5 | Polyline ZM | Minor Collector | 1021.25 | 0.050411 |
| 6 | Polyline ZM | Other Principal Arterial | 86065.5 | 0.199593 |

Jackson_Dissolve_VMT

| OBJECTID * | Shape * | FCNAME | SUM_VMT | Shape_Length |
|---|---|---|---|---|
| 1 | Polyline ZM | Local Road or Street | 141985.75 | 13.160546 |
| 2 | Polyline ZM | Major Collector | 243013.5 | 2.77661 |
| 3 | Polyline ZM | Minor Arterial | 325236.75 | 1.273064 |
| 4 | Polyline ZM | Minor Collector | 10827.5 | 0.457836 |
| 5 | Polyline ZM | Other Principal Arterial | 498584 | 1.201675 |

Williamson_Disslove_VMT

| OBJECTID * | Shape * | FCNAME | SUM_VMT | Shape_Length |
|---|---|---|---|---|
| 1 | Polyline ZM | Interstate | 620328.5 | 0.442606 |
| 2 | Polyline ZM | Local Road or Street | 210636.9 | 14.423752 |
| 3 | Polyline ZM | Major Collector | 509178.5 | 3.227935 |
| 4 | Polyline ZM | Minor Arterial | 223952 | 0.636332 |
| 5 | Polyline ZM | Minor Collector | 22989 | 0.385234 |
| 6 | Polyline ZM | Other Principal Arterial | 525064.5 | 0.575663 |

From the Dissolve Tool output, Tables 4.1-4.3, Street Functional Classes were combined and the results from that effort could then be used in conjunction with information available at http://www.gettingaroundillinois.com/gai.htm?mt=aadt to calculate %Truck VMT's from the annual average daily traffic counts (AADTs) for truck traffic. The results of this effort are summarized in Table 4.4. This procedure is still undergoing preliminary analysis to ascertain its reliability and validity in calculating the AVMTs for truck traffic on the interstate and on other principal roadways; shapefiles downloaded from the IDOT website and run through this model resulted in a 93% accuracy to published data.

**Table 4.4: Interstate Truck VMT's by County**

| Traffic Volume | Truck Volume | % Truck Volume | % Traffic Volume | Avg% Truck Volume | Avg% Traffic Volume | VMTs | **Avg Truck VMT** | **Avg Traffic VMT** |
|---|---|---|---|---|---|---|---|---|
| **Franklin County Interstate** | | | | | | | | |
| 30600 | 12000 | 0.392 | 0.608 | | | | | |
| 31300 | 12750 | 0.407 | 0.593 | 0.374 | 0.626 | 622896 | **232806** | **390090** |
| 34500 | 11100 | 0.322 | 0.678 | | | | | |
| **Williamson County Interstate(s)** | | | | | | | | |
| 37500 | 10350 | 0.276 | 0.724 | | | | | |
| 31000 | 9450 | 0.305 | 0.695 | 0.320 | 0.680 | 620329 | **198382** | **421947** |
| 28300 | 8925 | 0.315 | 0.685 | | | | | |
| 29700 | 11375 | 0.383 | 0.617 | | | | | |

The primary objective of this portion of the research was to develop a methodology for quantifying annual vehicle miles traveled (AVMTs) for the Transportation energy sector at the local scale using GIS technology and existing IDOT data obtained at the County level. The model was designed whereby outputs from the model would facilitate the end-user's ability to calculate indirect carbon emissions from the mobile energy sectors of Franklin, Williamson and

Jackson counties, Illinois. This model was developed using the ArcGIS Model Builder platform because of the flexibility it provides to automate and repeat the work flow.

The second component of the system is the $CO_2$ Model itself; this model should be designed to automate the carbon emission calculation using ESRI's ModelBuilder extension available with ArcGIS (10.2) software. In addition to the existing tools available from ArcToolbox, a custom tool was developed for compiling multiple step processes, including the addition of multiple fields to the attribute table in a feature class, calculation of resulting VMTs and AVMTs, and finally, using the dissolve tool and combine road class features necessary for ascertaining $CO_2$ emissions from the transportation sector locally.

A desktop application that houses the model, together with the supporting data files was developed with a comfortable degree of % variation from the published VMT and AVMT statistics through IDOT; with the expected output from the model, an individual should be able to test the distribution of the carbon emissions from different types of transportation modes when vehicle efficiency, type and fuel use becomes available locally.

Armed with this information, it was necessary to uncover efficiency data associated with the different vehicle types responsible for the VMT's calculated using the model. The following contacts were made.

12. John Maples (John.Maples@eia.gov) Sr Transportation Analyst – Energy Information Admin.
13. John Duff (John.Duff@eia.gov) – Sr Ops Research Analyst – Energy Information Admin.
14. Megan Swanson ((DOT.BMPR.RESEARCH) at the Illinois Department of Transportation
15. Thomas C. Brooks (DOT.BMPR.RESEARCH) at the Illinois Department of Transportation
16. Ken Runkle (Ken.Runkle@illinois.gov) Environmental Air & Noise Specialist – IDOT
17. Sue Rankin (Sue.Rankin@illinois.gov) at the Illinois Department of Transportation
18. Ted Prescott (Ted.Prescott@Illinois.gov) at the Illinois Department of Transportation
19. GIS Data Share – DOT.GISTRANSCOALITION@illinois.gov
20. IL Petroleum Marketers Assoc. (bzeck@ipma-iacs.org)
21. Richard Stucky (richard.stucky@ihsmarkit.com) – Source of Critical Information and Insight

Four months establishing the necessary connections resulted in a $40,000 price tag for the desired vehicle type, vehicle efficiency and fuel type information for three (3) IL counties.

# CHAPTER 5

## SUMMARY

Since the time of the Industrial Revolution, cities have often been blamed for causing environmental problems. More recently, cities, and by extension the counties where they are located, have been blamed for generating most of the world's greenhouse gas emissions and contributing disproportionately to global climate change. Few comparative studies have been performed that attempt to draw more precise conclusions about the role played by cities (and by extension their associated counties), in contributing to global greenhouse gas emissions.[10]

Carbon dioxide ($CO_2$) is one of the major greenhouse gases and is studied extensively in research related to greenhouse gas emissions, climate change, and global warming. According to the Energy Information Administration (EIA), 80 percent of the U.S. greenhouse gas emissions are energy-related carbon dioxide emissions (EIA, 2007). Although emission sources are local, research is focused intensively at a global level[13]. There are several methods for estimating and reporting carbon emissions at local levels. The best methods identified were simple and replicable.

The science of global change developed in the late 1990's demonstrates a fairly complete understanding of global trends, averages, means and patterns of change, however, it has become clear that virtually every parameter observed or modeled on a global-scale vary significantly in both a temporal and geographical scale. And while global change is profoundly important, taken alone, it is not able to address the issue of changes that occur at the local level, the very levels at which global change is experienced and where adaptations are most effective. What is missing in a scientific capacity is our ability to move beyond the knowledge and understandings obtained at global scales and extend those insights to discrete places. This re-orientation toward local places (often termed place-based science) is simple in construct but extremely challenging to implement[1].

The methodology developed during this project initiative can serve as the template for obtaining and processing necessary stationary and mobile energy sector data at the local level. In theory, any computer system consisting of ESRI ArcGIS 10.2 or higher at the ArcInfo license level should be able to successfully run the AVMT-Model. For the mobile energy sector, this research initiative developed and implemented a GIS model designed to extract needed information from shapefiles found on the IDOT website with 93% accuracy to the published data. The stationary energy sector research initiative created the geodatabase design needed to house the data obtained in shapefile format published on the EIA and EPA websites. Despite connecting with Cool Climate data which published emissions at the zip code level, this information was not useful in an application of pinch analysis at the local level, with the author suggesting this data be used to measure the accuracy of other methodologies employed for calculating $CO_2$ emissions.

Data necessary to build a geodatabase at the county level is presently so elusive that even the local authorities do not know who acquires and maintains this information; the most concerning aspect of this disconnect is how so much information is available at the State level on websites such as the EIA and EPA, yet there is not one individual locally or at the State level who understands how this information is compiled. Laws currently protect the privacy of owners in possession of disaggregated energy data, and its availability to the public is not presently supported by Federal, State or County policy. And while it was possible to obtain disaggregated data within the mobile transportation energy sector by county, this information is proprietary and only available at a cost that exceeds what most master's students are able to absorb. "Think Globally and Act Locally" will continue to be a worthwhile objective, but one that conventional and affordable data acquisition does not support at present.

# CHAPTER 6

## CONCLUSION

One's carbon footprint is historically defined as "the total set of greenhouse gas (GHG) emissions caused by an organization, event, product or individual." GHGs are generated through transportation activities, land clearance and deforestation, production and consumption of food, fuels, manufactured goods, materials, wood, roads, buildings, and services. The carbon footprint of a region is defined by the total amount of GHGs produced which either directly or indirectly support human activity, usually expressed in equivalent tons of $CO_2$; one's carbon footprint can be measured by undertaking a GHG emissions assessment or other calculative activity enumerated by a process known as carbon accounting. It is only when the size of a carbon footprint is known, that a strategy can be devised to reduce it, e.g. by technological developments, better process and product management, carbon capture, consumption strategies, and carbon offsetting.

This research initiative focused exclusively on methodologies to acquire GHG emissions data at the local level within the mobile and stationary energy sectors in three counties of southern Illinois. In order to develop a statistically relevant and robust planning tool targeting a 30% reduction in a regions carbon footprint, the following data must be obtained:

4) Energy demand data from three adjoining Illinois counties, broken down by both the transportation and stationary energy sectors.
5) Energy supply data from the same three counties, including internal fuel sources.
6) $CO_2$ emissions data by energy sector and fuel source.

The necessary data was unable to be obtained for the residential, commercial, industrial or municipal energy sectors at the local level despite acquiring a Community Master Data Worksheet from the ICLEI which identified the main sources and provides an excel spreadsheet that could be populated to organize and subsequently calculate the required emissions. While the vehicle miles traveled could be calculated from shapefiles available on the IDoT website within 7% accuracy of the published data, the efficiency data and fuel types required to calculate GHG emissions was cost prohibitive and therefore unable to be obtained. There was no data available for land transport associated with train and boat travel, and air transport data was not available at the local level. Therefore, pinch analysis could not be performed at the local level for three Illinois counties to determine GHG emissions and target potential reductions and carbon offsetting.

# CHAPTER 7

## RECOMMENDATIONS

Emission abatement is primarily a local activity that takes place within the context of government and corporate policy, and while many of the observed changes to our environment have led individuals and communities across the nation to undertake recycling, energy conservation measures and other actions to increase our environmental stewardship, governments have been unhurried to establish policies, implement practices and develop technologies to limit the long-term consequences of the observed changes to our environment.

Unlike many air pollutants, greenhouse gas emissions are not measured directly, but are inferred either from the use of materials (internal supply) that yield such gases or from processes that produce them (demand). Such coefficient-based methods result in global and state-scale inventories of greenhouse gas emissions. The importance of obtaining data at the local level lies not in uncovering the differences in descriptions of greenhouse gas emissions by major categories, but in the details that are lost in larger aggregations[10].

Compounding this is the fact that few of the prerequisite incentives, and none of the mandates that might support local action are in place at present. Examples of incentives include tax credits for emission-reducing investments and charges for carbon emissions. Examples of mandates include compulsory emission limitations and more stringent vehicle emission standards. One example of a combinatorial mandate and incentive is an emission cap, defined in terms of permits, which allows for permits to be traded as a means to offset emissions between counties. In this combinatorial approach, a higher emitting county could offset carbon emissions by trading permits with an adjacent county with lower emissions. Also, site specific mitigation opportunities can further reduce emissions; identifying site specific sources and opportunities represent a substantial step toward assessing local capability in the abatement of greenhouse gas contributions[10].

It is relatively transparent from this research initiative that parameters observed or modeled at the state and global-scale vary widely on both temporal and geographical scales; this can be attributed to the fact that the Earth's system's behavior is often sharply discontinuous. As a result, policy makers will continue to be unable to adequately address human-induced climate change effectively devoid of examining and understanding the daily routines that contribute to climate change at the local level. Researchers must be able to access data collected and compiled for individual counties as well as incorporate site-specific data in order to measure and understand local variability. At present, this data is not collected at the local level, nor available in every county within the United States. Until policy clearly and succinctly addresses the disconnect between what scientists need to combat greenhouse gas emissions where they originate, reductions will inevitably become intangible, and the negative effects associated with global warming will continue to accelerate.

# REFERENCES


[1] D. DiBiase, "There's More to Spatial Thinking Than you Think," *Essays in Geography and GIS,* vol. 6, pp. 3-4, 2013.

[2] S. Giri, "Building a Carbon Dioxide Emissions Model for the City of Redlands," 2010.

[3] M. R. Walmsley, Walmsley, T.G., Atkins, M.J., Kamp, J.J., Neale, J.R., "Minimising carbon emissions and energy expended for electricity generation in New Zealand through 2050," *Applied Energy,* vol. 135, pp. 656-665, 2014.

[4] R. R. Tan, Foo, D.C., "Recent Trends in Pinch Analysis for Carbon Emissions and Energy Footrpint Problems," *Chemical Engineering Transactions,* vol. 18, pp. 249-254, 2009.

[5] W. D. Nordhaus, "The economics of climate change: The Stern Review," *Cambridge University Press,* 2006.

[6] A. Ghadreri, Sharifara, A., Shahri, A.A., Vadayekheiri, A., "Assessment of different approaches in reducing CO2 emissions," *Life Science Journal,* vol. 9(4), pp. 1969-1978, 2012.

[7] L. M. Pekala, Tan, R.R., Foo, D.C., Jezowski, J.M., "Optimal energy planning models with carbon footrpint constraints," *Applied Energy,* vol. 87, pp. 1903-1910, 2010.

[8] Wikepedia, 2015.

[9] N. R. E. Laboratory, "Life Cycle Assessments of Energy Technologies," 2015.

[10] T. A. o. A. G. G. R. Team, "Global Change and Local Places, Estimating, Understanding, and Reducing Greenhouse Gases," 2003.

[11] D. Crilly, Zhelev, T., "Emissions targeting and planning: An application of CO2 emissions pinch analysis to the Irish electricity generation sector," *Energy,* vol. 33, pp. 1498-1507, 2008.

[12] S. M. Munir, Manan, Z.A., Wan Alwi, S.R., "Holistic carbon planning for industrial parks: a waste to resources process integration approach," *Journal of Cleaner Production,* vol. 33, pp. 74-85, 2012.

[13] R. W. Kates, Mayfield, M.W., Torrie, R.D., Witcher, B., "Methods for Estimating Greenhouse Gases from Local Places," *Local Environment,* vol. 3, pp. 279-298, 1998.

[14] R. A. Judson, Schmalensee, R., Stoker, T.M., "Economic Development and the Structure of the Demand for Commercial Energy," *Technical Paper,* 1998.

[15] S. Heiple, Sailor, D.J., "Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles," *Energy and Buildings,* vol. 40, pp. 1426-1436, 2008.

[16] E. H. Raymond, Foo, D.C., "Carbon Constrained Energy Planning (CCEP) with Carbon Capture and Storage Incorporating Carbon Credit Exchange," *Computer Aided Chemical Engineering,* vol. 34, pp. 585-590, 2014.

[17] R. R. Tan, Foo, D.C., "Pinch analysis approach to carbon-constrained energy sector planning," *Energy,* vol. 32, pp. 1422-1429, 2007.

[18] V. R. Dohle, Linnhoff, B., "Total site targets for fuel, co-generation, emissions and cooling," *Computer & Chemical Engineering,* vol. 17 (Supplement), pp. 101-109, 1993.

[19] X.P. Jia, Liu, C-H., "Carbon Emission Reduction using Pinch Analysis," *Green Chemical Technology,* vol. GTC 200803, pp. 1-4, 2010.

[20] D. C. Foo, Tan, R.R., Ng, D.K.S., "Carbon and footprint-constrained energy planning using cascade analysis technique," *Energy,* vol. 33, pp. 1480-1488, 2008.

[21] D. Crilly, Zhelev, T., "Further emissions and energy targeting: an application of CO2 emissions pinch analysis to the Irish electricity generation sector," *Clean Technology Environmental Policy,* vol. 12, pp. 177-189, 2010.

[22] S. C. Lee, Sum Ng, D.K., Foo, D.C., Tan, R.R., "Extended pinch targeting techniques for carbon-constrained energy sector planning," *Applied Energy,* vol. 86, pp. 60-67, 2009.

[23] A. Bandyopadhyay, Sahu, G.C., Foo, D.C., Tan, R.R., "Segregated Targeting for Multiple Resource Networks Using Decomposition Algorithm," *AIChE Journal,* vol. 56, pp. 1235-1248, 2010.

[24] G. S. Priya, Bandyopadhyay, S., "Emission constrained power system planning: a pinch analysis based study of indian electricity sector," *Clean Technlogy Environmental Policy,* vol. 15, pp. 771-782, 2013.

[25] A. A. Muis, Hashim, H., Manan, Z.A., Taha, F.M. Varbanov, P.S., "Optimal planning of renewable energy-integrated electricity generation schemes with CO2 reduction target *Renewable energy,* vol. 35, pp. 2562-2570, 2010.

[26] M. J. Atkins, Morrison, A.S., Walmsley, M.R., "Carbon Emissions Pinch Analysis (CEPA) for emissions reduction in the New Zealand electricity sector *Applied Energy,* vol. 87, pp. 982-987, 2010.

[27] R. R. Tan, Foo, D.C., "A general source-sink model with inoperability constraints for robust eergy sector planning," *Applied Energy,* vol. 88, pp. 3759-3764, 2011.

[28] M. U. Gumusay, Unal, A., Aydin, Rukiye, "Use of Geographical Information Systems In Analyzing Vehicle Emissions: Istanbul as a Case Study," *Remote Sensing and Spatial Information Sciences,* vol. 37, pp. 997-1000, 2008.

[29] L. Matejicek, "Spatial modelling of air pollution in urban areas with GIS: a case study on integrated database development," *Advances in Geosciences,* vol. 4, pp. 63-68, 2005.

[30] V. Jeyanny, Balasundram, S.K., Husni, M.H.A., "Geo-Spatial Technologies for Carbon Sequestration Monitoring and Management," *American Journal of Envrionmental Sciences,* vol. 7, pp. 456-462, 2011.

[31] Armstrong, J.M., Khan, A.M., "Modelling urban transportation emissions: role of GIS. "Computers, Environment and Urban Systems, vol. 28, pp. 421-433, 2004.

[32] Thill, J.C., "Geographic information systems for transportation in perspective." Transportation Research, Part C, vol. 8, pp. 3-12, 2000.

[33] Elbir, T., "A GIS based decision support system for estimation, visualization and analysis of air pollution for large Turkish cities." Atmosphere Environment, vol.38, pp. 4509-4517, 2004.

[34] Novosel, T., Perkovic, L., Ban, M., Keko, H., Puksec, T., Krajacic, G., Duic, N. "Agent based modelling and energy planning – utilization of MATsim for transport energy demand modelling." Energy Institute Hrvoje Pozar, Department of Energy Generation and Transformation, Savska 163, 10001 Zagreb, Croatia; Tomislav.novosel@fsb.hr

[35] Mondal, K., "Holistic approach towards sustainable energy under carbon constraints, PPT, Slide 5, 2016.

[36] Tan, R.R., Foo, D.C., "Recent Trends in Pinch Analysis for Carbon Emissions and Energy Footprint Problems". Article DOI: 10.3303/CET0918039, 2009.

# APPENDICES

# APPENDIX A

## Emission Sources by County

# APPENDIX B

## EPA Division of Air Pollution List of Sources

# APPENDIX C

## ICLEI Community Master Data Worksheet

# APPENDIX D

## Cool Climate Emissions Report by Zip Code

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Major Professor: Dr. Kanchan Mondal