AN ENVIRONMENTAL INPUT-OUTPUT ANALYSIS OF BOSTON’S CLIMATE ACTION PLAN

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ABSTRACT

In this thesis, I explore different mitigation policies included in Boston’s Climate Action Plan and build and Environmental Input-Output (EIO) analysis model to calculate the needed investment in different mitigation sectors in order to achieve short-term and long-term mitigation goals. This study concentrates on three main sectors of Boston’s Climate Action Plan, building construction, transportation, and industries, and calculates three benefits of the actions which are reduction in greenhouse gas emission, energy conservation, and job creation. City of Boston is planning to reduce the emissions and energy consumption of the city by 25% based on 1990 levels by 2020 and 80% based on 1990 levels by 2050. By applying EIO, I have found that the City of Boston needs to invest 89.4, 83.6, and 121.6 million dollars on mitigation policies in transportation, industries, and building construction respectively in order to achieve its 2020 goal. Similarly, to reach the 2050 goal, the city needs to invest 274.4, 267.1, and 379.731 million dollars on mitigation policies in transportation, industries, and building construction respectively.
ACKNOWLEDGEMENT

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CHAPTER 1: INTRODUCTION

In this thesis, I explore different components of the Boston’s climate action plan and use Environmental Input-Output (EIO) analysis in order to estimate the cost of implementing climate actions in different sectors. In this chapter, the concept of climate change, climate action plans, and the aim of this study is briefly presented. Then, in chapter two, the climate action plan of Boston is discussed in more details. In chapter three, I explain the Input-Output analysis and EIO. In chapters 4 and 5, I present the data I have used in this thesis and the results, respectively.

The rapid growth in the world’s population, and the growing use of fossil fuels over the last two centuries have created a rapid increase in carbon emissions released in the atmosphere. The carbon in the atmosphere acts like a blanket for our planet, and when the radiation from the sun reaches the earth, it gets trapped under this massive layer of carbon. It creates so many consequences that endanger the future of life on the planet. To reduce the disastrous effects and decelerate the rate of change in our environment, we need to develop and implement climate mitigation plans, to cut down on our emissions and mitigate the consequences.

Meanwhile, Boston is in serious danger from the consequences of global warming. The sea-level rise in the area is higher than the average sea-level rise in the world, and Boston has one of the most rapid rates of sea-level rise among coastal cities (Haer et al. 2013). In response, Boston has developed an extensive and detailed climate action plan to reduce its carbon emissions and increase its preparedness towards global warming and its
consequences. The next chapter includes a broad overview of Boston’s climate action plan and its various sections of mitigation and preparedness for global warming and future consequences.

Implementing this plan is not only crucial for Boston, but it is also vital on a global basis. As the World Health Organization reports, over 54% of the world population now resides in urban areas. The increasing number of people migrating from rural areas to urban areas is predominantly a result of urban area growth, which by itself will lead to more water consumption, more energy demand, more carbon dioxide emissions, and in many cases lack of enough land to accommodate migrating people or new and emerging economies. This can be one of the most considerable reasons for vertical growth in urban areas. In many other cases where land is available as a source and horizontal growth happens, the average transportation demands will increase, clearly resulting in more carbon dioxide emissions. All these sprawling development patterns are significant reasons for policy makers to design instruments to manage urbanization growth and protect the environment. Boston, together with a host of other cities around the world, is taking a lead on these issues. Despite the various climate mitigation efforts occurring throughout the world, Boston alongside many other cities is taking leadership position in climate action planning to not only satisfy its interests towards climate mitigation, but also encourage other cities to take action as well to tackle this global problem (City of Boston Climate Action Plan, 2014).

According to United Nations prediction, the world will soon become predominantly urban with more than 66% of the population living in urban areas by 2050. Rapid urbanization stimulates energy demand, transportation demand, and other urban area
lifestyle needs. All these issues will accelerate climate change. By accurately anticipating its future stages, population growth, and climate change effects, a city can be ready to respond accordingly. In a perfect world where there are no budget limitations, perfect plans can be established to reduce carbon emissions to zero. Under such conditions, cities can also become zero net energy and completely independent from outside sources. They can live the ultimate green style independently. But as we all know, budgets are always a remarkable consideration that defines boundaries for any action. Given all these matters, cities have to start thinking about prioritizing the investments not only to reduce climate change effects, but also to benefit most from the side effects. This decision making process is neither simple nor straightforward.

This study aims to estimate the cost of two main targets of Boston’s climate action plan. The first target is the 2020 goal to reduce the emissions and energy consumption of the city by 25% based on 1990 levels. The 2050 goal aims for 80% reduction in both GHG emissions and energy consumption compared to 1990 levels. The two stated goals of a 25% and 80% reduction in carbon emissions are equivalent to 1.86 MMTCO₂ and 5.76 MMTCO₂, respectively, and 683 MBtu and 2185 MBtu energy conservation. Although climate action plans encompass both mitigation and adaptation plans, in this study, the focus is on mitigation costs and benefits.
CHAPTER 2: BOSTON’S CLIMATE ACTION PLAN

2.1. What is a Climate Action Plan?

A Climate Action Plan consists of a set of policies that a local government will present in order to reduce greenhouse gas emissions and increase the resilience to inevitable climate change. It describes actions to be implemented and the basis of adaptive management.

The mitigation framework guiding the planning is based on greenhouse gas emission reduction as the target. The basis of the measurement is the percentage of the greenhouse gas reduction below a base-year rate for a future-year target.

2.2. Components of a Climate Action Plan

The decision making process in any area starts with a look at the elements that are causing the problem. When a local government decides to work on a climate plan to reduce greenhouse gases (GHGs), the best way it can start a mitigation plan is by looking at the municipality’s emission inventory. For an adaptation plan, the local government needs to base the decisions on the assessment of the community’s risk from climate change components, such as higher temperature and sea-level rise.

Looking at climate action plans adapted by a variety of cities can offer a good general idea of the possible components. The most important indicators in reducing GHG emissions and energy consumption can be water-treatment strategies, public transit
improvement and other transportation-related policies, waste management practice improvement, land-use policies, and renewable energy strategies.

Local governments can promote energy efficiency throughout their jurisdictions by using more energy efficient measures in their public and municipal facilities and commercial and industrial sectors, while encouraging residents to choose a more energy efficient lifestyle. The United States Environmental Protection Agency (EPA) has developed a series of energy efficiency guidelines to help local governments develop and implement strategies for more energy efficient operations in their areas. The American Council for an Energy Efficient Economy (ACEEE) has also developed an online tool to help local governments implement new policies. This free tool provides estimates of energy savings, job creation, cost savings, pollution, and other outcomes of a specific policy through a certain period and helps policymakers to make more informed decisions.

2.3. Why is A Climate Action Plan Crucial for Boston?

Hallegate et al explored the flood exposure in 136 largest coastal cities around the world by using a vulnerability index and in their results Boston is ranked as the eighth most at-risk city to climate change after Guangzhou, Miami, New York, New Orleans, Mumbai, Nagoya, and Tampa in terms of overall cost and economic impact of damage due to flooding and sea level rise (Hallegate et al. 2013).

Sea level rise in Boston, and more generally the East Coast of the United States and eastern Gulf Coast of Florida, is increasing at a faster pace than in other parts of the world (Haer et al. 2013). There are two main local causes of this phenomenon: topography and changes in ocean currents. Global warming not only causes the glaciers
to melt and add extra water to oceans, but also increases the ocean temperature, ultimately changing ocean currents. Based on the oceans’ topography of the region, changes in ocean currents in some places can pull the water away from the shore, while in other places, it can push it back to the shore resulting in a local increase of the sea level.

According to extreme water report published by National Oceanic and Atmospheric Administration (NOAA), in the past decade, Boston has experienced more than a dozen near 100-year floods, on top of breaking the snowfall record. Hurricane Sandy and Hurricane Nemo both conveyed catastrophic flooding and caused damage to buildings and streets. If Hurricane Sandy would have hit Boston at high tide, many Boston neighborhoods and harbor islands would have flooded and this event would be equivalent to a five-foot sea-level rise. A sea-level rise of 7.5 feet would inundate half of Boston’s 12 neighborhoods.

Considering the devastating effects of sea level rise, there is a clear need for Boston to take serious actions to reduce carbon emissions and plan on mitigation strategies to decelerate and weaken the climate change effects.

2.4. Boston’s Climate Action Plan

Boston is working on many ways to reduce carbon emissions. For instance, 12% of homes in Boston receive free energy assessments; this number is rising every year. The city is also conducting a municipal vulnerability assessment and is including climate change preparedness strategies in the new development designs to accelerate climate adaptation efforts.
Energy efficiency policies for buildings are among the city’s most outstanding efforts. According to Massachusetts Energy Efficiency Advisory Council in 2013 more than 14000 homes received weatherization or heating systems installations, and 20000 homes received electricity improvements through the incentivized programs such as MassSave.

New policies in alternative transportation systems, energy consumption, green buildings, renewable energies, and many other areas have resulted in Boston’s designation as the country’s number one city in energy efficiency by the American Council for an Energy Efficient Economy. Boston has also been invited to be a part of the C40 Cities Climate Leadership Group, a global network of successful cities in climate planning that works together to achieve sustainable planning and build a low carbon future. Another goal of the city of Boston is to create green jobs by adapting these new mitigation policies.

2.4.1. Boston’s carbon footprint

CO$_2$e, or carbon dioxide equivalent, is a standard measurement to take into account all the greenhouse gases while calculating the level of greenhouse gas emissions. CO$_2$e is a way to express other greenhouse gases in terms of CO$_2$ based on their relative global warming potential. One can compare the amount of global warming that different greenhouse gases cause by comparing their CO$_2$e measures.

Since 2005, Boston has determined its carbon footprint annually by measuring the carbon dioxide emitted due to the consumption of fossil fuels through any infrastructure
in the city, such as transportation and residential or commercial buildings. The majority of emitted carbon comes from electricity, heating fuels, and transportation (Figure 2-1).

Figure 2-1: Boston’s greenhouse gas emissions by source [City of Boston Climate Action Plan, 2014]

Figure 2-2 shows a diagram of the Boston climate action plan and the categories it is divided into. These categories and the actions they contain are described below.

Figure 2-2: A diagram of Boston’s Climate Actions
2.4.2. Boston Climate Actions for Buildings, Transportation, and Industries

The goal of the actions in this section of the plan is to reduce CO$_2$e of the large buildings and institutions 25\% by 2020 compared to CO$_2$e measurements in 1990.

Buildings:

1- Building and Energy: Expanding energy efficiency programs, piloting high performance buildings, upgrading energy codes, expanding onsite renewable energies, and moving to cleaner fuel and energy sources.


Transportation:

1- Fuel Economy target.

2- Reduce Vehicles Miles Traveled.

3- Development zoning and Land-Use.

Industries:

1- Producer Responsibility, an update to the city’s purchasing policies from outside regions to promote the use of sustainable options and expanding municipal green purchasing.
CHAPTER 3: METHODOLOGY

As discussed in the previous chapters, there is a clear need for Boston to adopt mitigation strategies to reduce the effects of climate change both locally and globally. The main constraint for implementing new mitigation strategies is the budget. Reducing carbon emissions usually needs changes in the infrastructure of the cities or providing incentives which are costly. In this study the objective is to calculate the required budget to reach the two main mitigation goals of the city in 2020 and 2050.

To estimate the cost of implementing policies and strategies to reach the target, one can use the well-established method of Life Cycle Analysis (LCA) of proposed energy efficient measures, strategies, and infrastructure to capture environmental and economic costs and benefits of the mitigation plans and compare it to LCA results of the existing systems. Noori et al used LCA method to account for environmental impacts and economic costs of electric vehicles and used their results for policy analysis purposes (Noori et al, 2015). They also applied life cycle cost analysis (LCCA) in five different road types to find the annuity of roadway rehabilitation for different asphalts (Noori et al, 2014). Iouanno-Ttofa et al used LCA approach to quantify emissions produced during the construction of membrane reactors (Iouanno-Ttofa et al, 2016). Lo-Iacono-Ferreira et al used LCA as an assessment tool for the ecological footprint of different organizations (Lo-Iacono-Ferreira et al, 2016).

In recent years, there has been many efforts on combining LCA with IO analysis. Chang et al developed a disaggregated Input-output life cycle analysis (IOLCA) model for the construction sector in China (Chang et al, 2013). Noori et al combined Environmental Input-Output analysis and LCA and built a hybrid economic analysis model to account
for direct and supply-chain impacts of offshore and onshore wind turbines (Noori et al., 2013).

LCA and hybrid IOLCA methods, however, not only are costly, but also need extensive time and effort. To apply LCA method one needs to break down the studied system into subsystems and analyze environmental impacts and costs of each one. In complicated systems such as a building, one must consider the hundreds of parts that go into a building and study them all in detail, hence, this process is enormously time consuming. Using quality data is another challenge in LCA. Most of the good databases that are fed into LCA software come from private corporations and oftentimes using public data is preferred to dealing with the legalities associated with data from large corporations.

Considering the disadvantages of the LCA method, in this chapter, I am proposing the use of Environmental Input Output (EIO) analysis to capture the cost of mitigating CO\textsubscript{2} and energy conservation as well as creating new jobs. This method is discussed in detail in the next three sections. This method is less resource and time intensive compared to LCA.

3.1. An introduction to Input-Output Analysis

Economic input-output analysis is a well-established technique developed by Wassily Leontief in the 1970s, based on his earlier works in the late 1930s. He received the Nobel Prize in Economic Science in recognition of his work in 1973 (Leontief, 1936, 1941). This framework is used to address the interdependencies of industries in an economic system; today, this method is one of the most applied techniques in economic studies. In its simple and basic form, an input-output model includes a system of linear
equations, and each one introduces the distribution of a single sector’s output throughout the other sectors (Miller & Blair, 2009). Input-output methodology is widely used for economic planning and analysis in the United States and throughout the world (Conway-Schempf, 2006), and it has gained attention in environmental analysis.

The basic Leontief input-output model uses many national and international statistical data sources such as National Accounts statistics, household consumption by expenditure, inter-industry flows, electricity trade and energy balance, and etc. that are all taken into account in the I-O tables presented by the Bureau of Economic Analysis. The basis of I-O analysis is the flow of products among sectors. The rows of the I-O table represent the distribution of a sector’s output to other industries, while the columns represent the amount of input a given industry purchases from other sectors to produce its output. This is represented in the green portion of the table in Figure 3-1, a sample of a basic input output table, which Blair and Miller present as a simplified illustration of I-O tables (Blair & Miller 1985).

<table>
<thead>
<tr>
<th>Producers</th>
<th>Final Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry B</td>
<td></td>
</tr>
<tr>
<td>Industry C</td>
<td></td>
</tr>
<tr>
<td>Industry D</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value Added</th>
<th>Producers as Consumers</th>
<th>Final Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employees Compensation</td>
<td></td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>Business owners and Capital</td>
<td>Profit-type Income and Capital Consumption Allowances</td>
<td></td>
</tr>
<tr>
<td>Government</td>
<td>Indirect Business Taxes</td>
<td></td>
</tr>
</tbody>
</table>
The final demand columns in Figure 3-1 represent each sector’s sales to final markets by their production, such as personal consumption purchases and sales to the federal government. The value added rows account for non-industrial inputs to production, such as imports and indirect business taxes.

Assume our economy has four industries: A, B, C, and D. \( x_i \) represents the total output of sector \( i \), while \( i \in \{1,\ldots,n\} \) and \( f_i \) is the total final demand for output from sector \( i \). The Leontief simple equation shows the relationship between \( i \) and \( f \) as follows:

\[
x_i = Z_{i1} + Z_{i2} + \ldots + Z_{ij} + \ldots + Z_{in} + f_i = Z_{ij} + f_i
\]

Eq. 3-1

where \( Z_{ij} \) represents inter-industry sales from industry \( i \) to industry \( j \). The output of each sector is shown as follows:

\[
x_1 = Z_{11} + Z_{12} + \ldots + Z_{1j} + \ldots + Z_{1n} + f_1 = \sum_{i=1}^{n} Z_{1j} + f_1
\]

Eq. 3-2

\[
x_i = Z_{i1} + Z_{i2} + \ldots + Z_{ij} + \ldots + Z_{in} + f_i = \sum_{i=1}^{n} Z_{ij} + f_i
\]

Eq. 3-3

\[
x_n = Z_{n1} + Z_{n2} + \ldots + Z_{nj} + \ldots + Z_{nn} + f_n = \sum_{i=1}^{n} Z_{nj} + f_n
\]

Eq. 3-4
We can describe the above equations in one equation using the following matrices:

\[
\begin{bmatrix}
  x_1 \\
  \vdots \\
  x_n \\
\end{bmatrix}
= 
\begin{bmatrix}
  Z_{11} & \cdots & Z_{1n} \\
  \vdots & \ddots & \vdots \\
  Z_{n1} & \cdots & Z_{nn} \\
\end{bmatrix}
\begin{bmatrix}
  f_1 \\
  \vdots \\
  f_n \\
\end{bmatrix}
\]

Eq. 3-5

and:

\[
\begin{align*}
x &= 
\begin{bmatrix}
  x_1 \\
  \vdots \\
  x_n \\
\end{bmatrix},

Z &= 
\begin{bmatrix}
  Z_{11} & \cdots & Z_{1n} \\
  \vdots & \ddots & \vdots \\
  Z_{n1} & \cdots & Z_{nn} \\
\end{bmatrix},

f &= 
\begin{bmatrix}
  f_1 \\
  \vdots \\
  f_n \\
\end{bmatrix}
\end{align*}
\]

Eq. 3-6

Hence:

\[
x = Z \cdot i + f
\]

Eq. 3-7

i is a column vector of 1 to create a column vector of Z, which is able to be added to f. Each element of the matrix Z \cdot i is the sum of each row of matrix Z.

To retrieve additional information from the model, one can add a technical coefficient matrix that can be interpreted as the amount of input i used per unit output of product j and we define them as a\textsubscript{ij}:

\[
a_{ij} = \frac{Z_{ij}}{x_j} = \frac{\text{Value of output of sector } i \text{ bought by sector } j}{\text{Value of output of sector } j}
\]

Using the definition of technical coefficient, the Leontief model becomes:

\[
x_j = \frac{Z_{1j}}{a_{1j}} = \frac{Z_{2j}}{a_{2j}} = \cdots = \frac{Z_{nj}}{a_{nj}}
\]

Eq. 3-8

If a specific input i is not used in producing j, then a\textsubscript{ij} would be zero and x\textsubscript{j} will be infinite, so:
Once we have a set of fixed technical coefficients, we can rewrite the Leontief model as follows:

\[ x_1 = a_{11}x_1 + a_{12}x_2 + \cdots + a_{1i}x_i + \cdots + a_{1n}x_n + f_1 \quad \text{Eq. 3-10} \]

\[ \vdots \]

\[ x_i = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{ii}x_i + \cdots + a_{in}x_n + f_i \quad \text{Eq. 3-11} \]

\[ \vdots \]

\[ x_n = a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{ni}x_i + \cdots + a_{nn}x_n + f_n \quad \text{Eq. 3-12} \]

And if we move final demands to the other side and move the \( x_i \) to the right hand side as well, we will have:

\[ x_1 - a_{11}x_1 - a_{12}x_2 - \cdots - a_{1i}x_i - \cdots - a_{1n}x_n = f_1 \quad \text{Eq. 3-13} \]

\[ \vdots \]

\[ x_i - a_{i1}x_1 - a_{i2}x_2 - \cdots - a_{ii}x_i - \cdots - a_{in}x_n = f_i \quad \text{Eq. 3-14} \]

\[ \vdots \]

\[ x_n - a_{n1}x_1 - a_{n2}x_2 - \cdots - a_{ni}x_i - \cdots - a_{nn}x_n = f_n \quad \text{Eq. 3-15} \]
And with a simple grouping, we will have:

\[
(1 - a_{11})x_1 - a_{12}x_2 - \cdots - a_{1i}x_i - \cdots - a_{1n}x_n = f_1 \quad \text{Eq. 3-16}
\]

\[
\vdots \quad \vdots \quad \vdots
\]

\[
-a_{i1}x_1 - a_{i2}x_2 - \cdots + (1 - a_{ii})x_i - \cdots - a_{in}x_n = f_i \quad \text{Eq. 3-17}
\]

\[
\vdots \quad \vdots \quad \vdots
\]

\[
-a_{n1}x_1 - a_{n2}x_2 - \cdots - a_{ni}x_i - \cdots + (1 - a_{nn})x_n = f_n \quad \text{Eq. 3-18}
\]

We can show the above set of equations in a simple matrices equation. From now on, \( x \) denotes a diagonal matrix with the elements of the main matrix on the main diagonal, 

\[
\begin{bmatrix}
x_1 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & x_n
\end{bmatrix}
\]

hence \( xx^{-1} = I \). Therefore, the technical coefficient matrix of \( A \) can be represented as:

\[
A = Zx^{-1} \quad \text{Eq. 3-19}
\]

Hence:

\[
x = Ax + f \quad \text{Eq. 3-20}
\]

And,

\[
(1 - A)x = f \quad \text{Eq. 3-21}
\]
Then,

\[ x = (I - A)^{-1} f = Lf \]  \hspace{2cm} \text{Eq. 3-22}

where \((I - A)^{-1}\) is \(L\), known as the Leontief inverse, the total requirements matrix.

3.2. Environmental Input-Output (EIO) Analysis

The implication of IO analysis in environmental studies goes a long way back to when Walter Isard, also known as father of Regional Science, began making his contributions to Environmental and Ecological Economics (Pan & Kreines, 2001). He started the basics of economic-environmental interaction studies. It was mainly based on a generalized input-output analysis for ecologic-economic systems. He implemented this for the very first time for a marine ecosystem (Miller & Blair, 1985). Hannon later extended his model into a general IO model for an ecological ecosystem where the net output (the GDP of the ecosystem) was its net exports, inventory change, respiration, and its new bio-capital formation (Hannon, 2010). Jin et al. illustrated a complete economy-ecology interactions system based on Isard’s model. They merged an IO model of a coastal economy with a model of marine food web and they illustrated the effects of incorporating the impacts of habitat destruction and ecosystem structure on resource multipliers (Jin et al., 2003). Noori et al used an EIO model to quantify the direct and indirect environmental impacts of onshore and offshore wind energy technologies in United States (Noori et al, 2015).
One particular expansion of the Leontief Model relevant here is that of Pollutant Abatement. In this model, the economy consists of conventional production sectors and pollutant abatement sectors. The operations of production sectors emit pollutants, while the operation of the abatement process deals with these pollutants. The beauty of the Leontief pollution abatement model is hidden in the reflection of the tolerance or acceptance of pollution generation by the final demand sectors (Lenzen et al, 2003). If society accepts all the emissions generated by the production sectors, then the operation of the abatement sectors would be zero.

A new situation will rise if the society is not ready to accept all the pollutants generated by industries. That is where the pollutant abatement sector starts to operate. For more pollutant reduction, the sectors need more labor, thus, the output of sectors will increase. These growths are the remarkable results of the increase in direct and indirect demand by their products, which is invoked by the operation of the abatement sector (Mattila et al, 2011).

Consider a situation in which the city of Boston is investing in pollution abatement activities in different industries. These activities are categorized into different strategy categories, such as upgrading the transportation systems and creating new recycling technologies. The final demands for each of the named industries are certain prior to the investment. Once the city spends money on abatement activities in different sectors, the money is being added to the final demand. Investments by the local governments to build new or improve existing goods, services, and infrastructures are added to the final demand (Miller & Blair 1985). To illustrate, consider upgrading the transportation system as an activity. One of the subcategories can be purchasing new, more efficient trains for
the city’s transportation system. While the train can be purchased from an outside region, the money used to buy the train will flow to other regions and will not have economic and multiplier effects in Boston. This may be true about many other activities. Even if the company that produces the train is actually located in the Boston area, there is a great chance it buys needed materials for production from an outsider. Using RIMS II for regional input output analysis would account for all the leakages from one region to another among all industries. Leakage is the amount of money that leaves the flow of regional economy. It can be in form of savings, imports, or taxes. Although, it may come back to the economy in the form of exports, spending of savings, or government injections (funds received by firms that does not come directly from households).

A straightforward approach to calculate pollution generation is by using generalized input-output analysis. Assume a matrix of pollution output or direct impact coefficients, which here is called $D^p$, and $D^p=[d_{kj}^p]$. The elements of this matrix are the amount of pollutant abatement per dollars’ worth of industry. Meanwhile, we have a vector of total outputs, which we call $X^p*$. The level of pollution associated with the total output can be seen as:

$$X^p*=D^pX$$ \hspace{1cm} \text{Eq. 3-23}$$

$$X=Lf$$ \hspace{1cm} \text{Eq. 3-24}$$

while $f$ is the final demand and $L=(I-A)^{-1}$, thus:

$$X^p*=[D^pL]f$$ \hspace{1cm} \text{Eq. 3-25}$$

where $X^p*$ is the vector of final pollution level and $[D^pL]$ is the matrix of total
environmental impacts.

As previously stated, $D^p$ is the matrix of the direct impact coefficient, but we could easily replace this with a corresponding matrix for any factor associated with inter-industry activity, while we assume it varies linearly with the output, such as energy consumption or employment.

The relationship between all factors can be shown as the following equation:

$$[\text{Total impacts}] = [\text{coefficients}] \times [L] \times [\text{Final demand}]$$

The matrix $[D^pL]$ is the total environmental impact of coefficients and elements of this matrix, which represent the pollution generated per dollar’s worth of final demand presented to the economy.

If we replace the final demand vector with the vector of changes in final demand (vector of investments), then we will have the total impacts due to the particular investments as the output:

$$[\text{Impacts from the investments}] = [\text{Coefficients}] \times [L] \times [\text{Investments}]$$

3.3. Advantages and disadvantages of environmental input-output analysis

The input-output model is a useful tool to analyze regional economic interdependencies. It is very suitable to display the interdependencies of regional sectors and their connection to final consumers and consequently the rest of the world. The construction of a regional input-output table poses one of the biggest challenges. Subsequent economic changes can be calculated from direct to indirect effects.
Understanding the impacts of economic changes in a region is especially important for policy makers. The results from input-output models can indicate the impact of different measures on production, income, and employment in the studied region. A very serious problem is the constant production multipliers that limit any kind of adjustment processes like substitutions. There are further disadvantages to the input-output framework, which makes it inferior in comparison to other growth models, especially in long-run analysis. This model is suitable if one plans to show a static picture of the economy that does not take substitution effects, technological progress, and economies of scale into account. Nevertheless, the input-output model can deliver insight into the impact chain in an economy, and the results are quite simple to understand and communicate to the public. Therefore, an input-output model is a useful additional tool to model an economic system with a closed framework.
CHAPTER 4: DATA COLLECTION

4.1. Introduction

In this chapter, the process of data collection for the quantifying the cost of implementing mitigation policies in city of Boston to reach the 2020 and 2050 CO$_2$ reduction target will be explained. Collecting data is one of the most crucial steps in any study and analysis, as the accuracy of results is dependent on the precision of collected data. In this chapter, the scope of study and the functional unit used for the analysis are explained.

4.2. Scope of the Study and Functional Unit

In this study, analysis of the environmental impacts of three different main sectors in Boston’s Climate action plan: mitigation plans in Transportation, Industries, and Buildings is performed by using the Environmental Input Output modeling discussed in Section 3.2. The three main environmental and economic impacts of these actions are energy conservation, GHG abatement, and job creation.

I aim to calculate the relationship between the mitigation actions and their benefits. There are many co-benefits associated with each action, such as improvements in public health outcomes. However, I am limiting this research to three benefits of GHG abatement, energy conservation, and job creation.
In the 1970s, the Bureau of Economic Analysis (BEA) developed a method for estimating regional I-O multipliers known as RIMS (Regional Industrial Multiplier System), which was based on the work of Garnick and Drake in 1976. In the 1980s, BEA completed an enhancement of RIMS, known as RIMS II (Regional Input-Output Modeling System) and continues to update it since. The IO table in RIMS II is derived mainly from two data sources: BEA’s national I-O table, which shows the input and output structure of nearly 500 U.S. industries, and BEA’s regional economic accounts, which are used to adjust the national IO table in order to reflect a region’s industrial structure and trading patterns. The RIMS II model and its multipliers are prepared in three major steps. First, an adjusted national industry-by-industry direct requirements table is prepared. Second, the adjusted national table is used to prepare a regional industry-by-industry direct requirements table. Third, a regional industry-by-industry total requirements table is prepared, and the multipliers are derived from this table. The RIMS II industry-by-industry direct requirements table is derived from the make and use tables (This table indicates the amount of output required from each industry to produce a dollar’s worth of output) in BEA’s 1987 benchmark IO accounts for the U.S. economy by adjusting national IO relationships with regional data and Earnings-by-industry. Also, in RIMS II personal consumption expenditure data are used to expand the model to include households as both suppliers of labor and purchasers of final goods and services. The use table is adjusted so that it includes only the use of domestically produced commodities. RIMS II provides both Type I and Type II multipliers. Type I multipliers account for the direct and indirect impacts based on how goods and services are supplied within a region. Type II multipliers not only account for these direct and indirect impacts, but they also
account for induced impacts based on the purchases made by employees (Bess and Ambargis, 2011).

In this study, the input-output framework for the Suffolk county region (RIMS II for 2012) is used, which also accounts for leakages from other regions, and our system of study does not need to be a closed economic system. The advantage of using RIMS II makes input-output modeling a powerful tool to calculate the environmental outputs of investments in an urban area as an economic system.

To start with EIO, first we need the elements of the coefficient matrix, which are the amount of benefits per dollars’ output of industry. The benefits are pollutant reduction in metric tons of CO₂ equivalents, energy conservation in Btus, and number of new jobs created by implementing mitigation policies. The energy conservation is reduced energy purchased by the grid, and is the sum of energy by the grid conservation and renewable energy consumed. This data is obtained from the 2012 report of the Massachusetts Energy Efficiency Advisory Council (EEAC). The amount of GHG abatements are obtained from the Massachusetts Greenhouse Gas Inventory, published by the Department of Environmental Protection of the Commonwealth of Massachusetts in 2012. And finally, RIMS II tables published by the Bureau of Economic Analysis in 2012 includes a job creation coefficient that allows for estimating the number of new employment opportunities by changes in the final demand, and in this case by investing in the abatement activities. The following table (Table 4-1) shows the amount of energy conservation in trillion Btus, CO₂ abatement in million metric tons of CO₂ Equivalent, and number of new jobs created by each sector. The fourth column represents the total
output of each sector in million dollars which are represented in the input-output tables by the Bureau of Economic Analysis for Massachusetts.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Energy conservation (Trillion Btu)</th>
<th>GHG abatement (MMTCO₂)</th>
<th>Job creation</th>
<th>Total Output (MDollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation</td>
<td>450.3</td>
<td>30.37</td>
<td>86741</td>
<td>17163.67</td>
</tr>
<tr>
<td>Industry</td>
<td>256.8</td>
<td>3.35</td>
<td>348883</td>
<td>60161.649</td>
</tr>
<tr>
<td>Buildings</td>
<td>678.9</td>
<td>17.08</td>
<td>140766</td>
<td>20482.738</td>
</tr>
</tbody>
</table>

Table 4-1: Amount of Energy Conservation, GHG Abatement, and job creation in each sector.

Based on Table 4-1, one can build the technical coefficient matrix, which in this case is a 3x3 matrix representing benefits (GHG abatement, energy conservation, job creation) per dollar’s output of each industry. For example, the energy conservation technical coefficient of this matrix for transportation would be the amount of energy conservation in transportation divided by total output of transportation. Benefits divided by the total output will form the technical coefficient matrix. Moreover, by using input-output tables one can calculate the technical coefficient matrix, A, and ultimately the Leontief’s inverse matrix as shown in equation 4-1. The A matrix for transportation, industries, and building construction is a 3x3 matrix; it is taken from the input-output tables of RIMS II, as shown below:
The sectoral input-output matrix shows the output of industry \( j \) if we inject $1 to industry \( i \). For more clarity and as an example, each dollar added to the final demand in transportation produces $1.0879 in transportation, 9.21 cents in industries, and 1.95 cents in building construction.

Thus the Leontief's inverse matrix is:

\[
L = (I - A)^{-1}
\]

\[
L = \begin{bmatrix}
1.0879 & 0.0921 & 0.0195 \\
0.0276 & 1.209 & 0.0075 \\
0.0291 & 0.1948 & 1.0067
\end{bmatrix}
\]

Now that we have the technical coefficient matrix and Leontief’s inverse matrix, we only need the final demand change in each sector, which are the investments on the actions to calculate outputs based on the methodology expressed in chapter 3. The formula to calculate the outputs is:

\[
X^*=DLf
\]

In other words, \([\text{Total impacts}] = [\text{coefficients}] \times [L] \times [\text{Final demand}], \) and furthermore, \([\text{Impacts from investments}] = [\text{coefficients}] \times [L] \times [\text{Change in final demand}], \) As mentioned before, changes in final demand are the investment amounts.

Boston’s climate action plan has two main goals for the city’s carbon mitigation strategy are to reduce emissions 25% by 2020 and 80% by 2050. This will aim for 1.86
MMTCO$_2$ and 5.7 MMTCO$_2$ reduction, respectively. The next chapter details the analysis used to determine the amount of investment required for both goals to be reached by three sectors combined. The outputs of the EIO method are combined GHG abatement of three sectors, total energy conservation of three sectors, and also number of created jobs by all three sectors.

All linear algebra and matrices calculations presented in the next chapter have been done through R software, an open-source software for statistical and mathematical coding.
CHAPTER 5: ANALYSIS OF THE RESULTS

5.1. Introduction

In this section the results of EIO analysis are presented in terms of investment needed for reaching the 2020 and 2050 target of three benefits as outputs of mitigation strategies in three different sectors of economy in Boston. The three benefits are GHG abatement, energy conservation, and job creation, and three sectors of economy in this analysis framework are transportation, industry, and building construction. The proposed method of using EIO has been described in detail in chapters 3 and 4. In section 5.2 the network of climate actions and its benefits is illustrated and the amount of required investments in different sectors in order to achieve 2020 and 2050 goals have been calculated. In section 5.3 I have explored how Boston can best spend its actual investments to get closest to achieving its goals.

5.2. Environmental Input-Output Results

Figure 5-1 illustrates the relationship between actions and their consequences based on Input-Output modeling. The units of the quantities on the arrows are metric tons of CO₂ per $1 million investment for GHG abatement, million Btu per $1 million investment for energy conservation, and number of jobs created per $1 million investment in abatement activities. The weights on each arrow are the elements of the
D x L matrix that illustrates the relationship between the benefits and actions. As a reminder, D is the coefficients matrix and each element in this matrix represents either energy conservation, GHG abatement, and job creation per dollar output of three different sectors, transportation, industries, and buildings (refer to table 4-1). L is the Leontief’s inverse matrix which is derived from the IO tables presented by the Bureau of Economic Analysis and was previously discussed in detail in chapter 4. The multiplication of these two matrices shows the relationship between the economic sectors and the benefits.

\[
D = \begin{bmatrix}
0.02623 & 0.00427 & 0.03314 \\
0.00177 & 0.00006 & 0.00083 \\
5.05375 & 5.79900 & 6.87242
\end{bmatrix}
\]

\[
D \times L = \begin{bmatrix}
21.5496 & 24.6600 & 27.1683 \\
10.0433 & 7.4003 & 12.4496 \\
30.9672 & 51.83891 & 56.78414
\end{bmatrix}
\]
Based on this network, if Boston spends $X$ million dollars in transportation, $Y$ million dollars in industries, and $Z$ million dollars in building construction, the amount of benefits would be:

$$\text{CO}_2(\text{MMTCO}_2) = 10.0433X + 7.4003Y + 12.4496Z$$  \hspace{1cm} \text{Eq. 5-1}

$$\text{Energy(MBtu)} = 21.5496X + 24.66Y + 27.1683Z$$  \hspace{1cm} \text{Eq. 5-2}

$$\text{Number of jobs} = 30.9672X + 51.8389Y + 56.741Z$$  \hspace{1cm} \text{Eq. 5-3}

The optimized solution for allocating a certain financial amount between the three sectors differs and depends on the goals to be achieved.

This study’s main finding is seen in the figure and equations above (figure 5-1 and
equations 5-1 through 5-3). As one can see, $1 million investment in Boston’s transportation sector can result in 10.04 metric tons of CO$_2$ reduction, 21.54 million Btu energy conservation, and 309 new jobs. The same goes for $1 million investment in building constructions that would result in 7.4 metric tons of CO$_2$, 24.66 million Btu in CO$_2$ and energy consumption reduction respectively and create 518 new job opportunities. Investing $1 million for enhancing industries’ performances would result in 12.44 metric tons of CO$_2$ reduction, 27.16 million Btu energy conservation, and 567 new jobs.

5.2.1. 2020 and 2050 Goals

To achieve the 2020 goal of Boston’s Climate Action Plan and to reduce emissions 25% by 2020, we should aim for 1.86 MMTCO$_2$ reduction. The city’s goal is also to reduce energy consumption by 683 MBtu and create 2,000 new jobs. To achieve these goals, the matrix of final demand change or investments consists of three unknown elements: investment in transportation, investment in industries, and investment in building construction. Solving the set of linear equations will show us how much money should be invested in each sector.

Meanwhile, Boston’s second goal is to reduce GHG emissions 80% by 2050, which is an effort of 5.76 MT CO$_2$ reduction, 2185 MBtu energy conservation. It also creates 8,000 new jobs. Figure 5-2 shows the amount of investment needed in each sector to reach these goals.
5.2.2. Results of current investment

The city of Boston has allocated $4 billion toward mitigation plans each year since 2014. If we assume the city continues investing the same amount each year, by 2020 the total investments on mitigation plans will be $24 billion. However, since this calculation is based on the EIO model using RIMS II tables for 2012, we are not accounting for technological and behavioral changes that can happen in this time frame.

In Section 5.2.1 I showed that in order to meet the 2020 goal, Boston needs to invest $29.46 billion in the three sectors. Let us illustrate what the city can achieve with this investment. The following table (Table 5-1) shows the amount of investment in the three sectors in different scenarios. In each scenario, the total investments add up to $24
billion. The scenarios are based on allocating different investment amounts that are multipliers of four billion dollars on three sectors. In the right three columns of the table the three consecutive benefits of each scenario are presented as well.

Based on the scenario analysis below (table5-1), and by looking at the amount of benefits Boston can gain in different scenarios, the closest the city can get to its 2020 goal is by concentrating all of its investments on building technologies. However, it is never a reasonable idea to concentrate all the investment on one sector, it is politically impossible and also against climate preparedness acts. Scenarios 5, 8, 12, and 17 are among the scenarios that can help the city approach its goals, and choosing the best scenario can be different in various political, social and technological environments. However, having knowledge on the benefits of each scenario can advise the decision makers profoundly. As a reminder, the 2020 goal of the city is to mitigate carbon emissions by 1.86 MMTCO₂ and reduce energy consumption by 683 MBTus, as well as creating 2000 new jobs. This conclusion also reflects the reality since according to US department of energy data book published in 2010 the primary source of energy consumption in United States is buildings (including three phases of construction, operation and maintenance, and demolition and end of life) and according to inventory of US greenhouse gas emissions and sinks: 1990-2014 the primary source of CO₂ emission is electricity consumption and oil consumption in commercial and residential buildings.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Transportation (Billion Dollars)</th>
<th>Industry (Billion Dollars)</th>
<th>Buildings (Billion Dollars)</th>
<th>Energy Conservation (MBtus)</th>
<th>CO₂ Mitigation (MMTCO₂)</th>
<th>New jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>587.0208</td>
<td>1.49415</td>
<td>1115.2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>604.4784</td>
<td>1.491075</td>
<td>1208.6</td>
</tr>
</tbody>
</table>
Table 5-1: Comparing benefits of different scenarios of allocating $24 billion.

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>10</td>
<td>4</td>
<td>10</td>
<td>585.816</td>
<td>1.5901875</td>
<td>1083.2</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>570.768</td>
<td>1.4011875</td>
<td>1053.8</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>12</td>
<td>8</td>
<td>599.4624</td>
<td>1.428075</td>
<td>1198.8</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>609.4944</td>
<td>1.554075</td>
<td>1218.4</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>4</td>
<td>8</td>
<td>574.5792</td>
<td>1.560225</td>
<td>1031.6</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>4</td>
<td>12</td>
<td>597.0528</td>
<td>1.62015</td>
<td>1134.8</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>12</td>
<td>4</td>
<td>576.9888</td>
<td>1.36815</td>
<td>1095.6</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>8</td>
<td>4</td>
<td>564.5472</td>
<td>1.434225</td>
<td>1012</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>12</td>
<td>12</td>
<td>621.936</td>
<td>1.488</td>
<td>1302</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>0</td>
<td>12</td>
<td>584.6112</td>
<td>1.686225</td>
<td>1051.2</td>
</tr>
<tr>
<td>13</td>
<td>12</td>
<td>12</td>
<td>0</td>
<td>554.5152</td>
<td>1.308225</td>
<td>992.4</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>16</td>
<td>8</td>
<td>611.904</td>
<td>1.362</td>
<td>1282.4</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>8</td>
<td>16</td>
<td>631.968</td>
<td>1.614</td>
<td>1321.6</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>0</td>
<td>8</td>
<td>562.1376</td>
<td>1.6263</td>
<td>948</td>
</tr>
<tr>
<td>17</td>
<td>8</td>
<td>0</td>
<td>16</td>
<td>607.0848</td>
<td>1.74615</td>
<td>1154.4</td>
</tr>
<tr>
<td>18</td>
<td>8</td>
<td>16</td>
<td>0</td>
<td>566.9568</td>
<td>1.24215</td>
<td>1076</td>
</tr>
<tr>
<td>19</td>
<td>16</td>
<td>8</td>
<td>0</td>
<td>542.0736</td>
<td>1.3743</td>
<td>908.8</td>
</tr>
<tr>
<td>20</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td>517.1904</td>
<td>1.50645</td>
<td>741.6</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
<td>24</td>
<td>0</td>
<td>591.84</td>
<td>1.11</td>
<td>1243.2</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>652.032</td>
<td>1.866</td>
<td>1360.8</td>
</tr>
</tbody>
</table>

5.3. What should Boston do?

The main target of Boston’s climate mitigation plan is to reduce GHG emissions in the coming years and play an important role in maintaining the planet for future generations. Based on the results presented in the previous two sections, the most important step that the city can take is to improve energy efficiency of existing and new buildings. But this result is based on using the RIMS II multipliers for 2012 and might not reflect the best strategy for the future years. The multipliers change with the technological changes. Innovations, technical breakthroughs, and updated energy efficiency measures in three sectors will result in the changes in benefits per dollar of
investment in different sectors. As an example, if in the next few years, an electric vehicle with primary source of solar energy is common to use, the output of energy savings and CO₂ reduction per dollar of investment in transportation might be more than the benefits gained from a dollar of investment in building sector.

Although the results of this analysis advise the city of Boston to concentrate on improved building technologies, but it is necessary for the city to continue updating the multipliers in the analysis to account for technical and social changes and update the mitigation strategies appropriately.

CHAPTER 6: CONCLUSIONS

In this study, an Environmental Input-Output model has been used to illustrate the relationship between a climate action plans in the Boston area and the consequences that could benefit the city. RIMS II allows us to account for the leakages from all other regions in our selected economic system, which makes input-output modeling a suitable tool for our assessments. The environmental input-output model was created by using the inter-industry Input-Output tables presented by the Bureau of Economic Analysis, and public data on greenhouse gas emissions from different Massachusetts economic sectors, data on Massachusetts’ energy consumption, and employment statistics. The result of this
analysis elaborates the connections between different sectors and their benefits, directly and indirectly through other sectors.

Although, adaptation activities for Boston is crucial for many reasons and the city needs to be prepared in facing regional changes in climate and sea-level, mitigation strategies are very crucial as well to. Boston cannot stop climate change or eliminate the risks by adopting mitigation policies but the city is able to take meaningful actions to play a key role in reducing the speed of climate change and sea-level rise.

With regards to how fast the climate of our planet is changing, sea-level rise rate, and more frequent hazardous events, having a plan to mitigate GHG emissions in a city to reduce climate change rate is among the most vital steps for any city. How much does a plan cost to achieve certain mitigation goals? This question was answered in a small scale of a three-sector economy in Boston: transportation, industries, and building construction. The Environmental Input-Output modeling is a tool that calculates the output of the industries in physical terms, or estimates the cost of achieving a certain amount of benefits.

The table below (Table 6-1) shows the goals and investments needed for each sector that would ensure Boston’s achievement of its 2020 and 2050 mitigation goals.

<table>
<thead>
<tr>
<th>Target Year</th>
<th>Sectors</th>
<th>GHG Abatement (MMTCO₂)</th>
<th>Energy Conservation (MBtu)</th>
<th>Job Creation</th>
<th>Cost (Million Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>Transportation</td>
<td>1.86</td>
<td>683</td>
<td>2000</td>
<td>89.4</td>
</tr>
<tr>
<td></td>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
<td>83.6</td>
</tr>
</tbody>
</table>
This model can be expanded to include more economic sectors and to represent more benefits, such as improved health, improved quality of life, water conservation, natural resource preservation, etc. I hope to continue working on this network in the future and turn it into a tool that will analyze the costs and benefits of certain policies in climate change to make more cost-effective citywide decisions. The decision making process in the policy world is often a multi-criterion atmosphere that stands to be optimized. Looking at a problem with a true vision of the cost-benefit relation is the best way to tackle it.

REFERENCES


Noori, M, O Tatari, B Nam, B Golestani, and J Greene. (2014). "A stochastic optimization approach for the selection of reflective cracking mitigation techniques."


