ANALYSES OF SUSTAINABILITY GOALS: APPLYING STATISTICAL MODELS TO SOCIO-ECONOMIC AND ENVIRONMENTAL DATA

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ANALYSES OF SUSTAINABILITY GOALS:

APPLYING STATISTICAL MODELS TO SOCIO-ECONOMIC AND ENVIRONMENTAL DATA

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For All Of Those Who Came Before Me.

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TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS i

LIST OF TABLES v

LIST OF FIGURES vi

SUMMARY ix

CHAPTER

1 Introduction 1

- Motivation 1
- Corporate Environmental Performance 4
- Residential Electricity Demand in South Africa 7
- Lifecycle Cost-Benefit Analysis of Transit 10
- Structure of Dissertation 11

2 Statistical analysis of environmental performance of manufacturing facilities: A case study of beverage manufacturing 12

- Introduction 12
- Data 14
- Environmental Metrics 16
- Statistical Methodology for Composition Analysis 19
- Results 22
- Cross Validation 28
- Discussion 28
- Conclusions 30

3 Risk Stratification and Assessment in the Environmental Management of Multinational Firms: a case study of beverage manufacturing 32

Introduction 32

Methodology 39

Data 44

Environmental Performance Indicators 46

Vulnerability Assessment 48

Risks and Exposure Assessment 55

Discussion 59

Conclusions 65

4 Agent-Based Modeling of Energy Choices and Demand in the Residential Sector of Developing Economies: a case study of South Africa 67

Introduction 67

Electricity Demand – A Case Study of South Africa 68

Agent-based Model Framework 76

Results 87

Discussion 93

Conclusion 98

5 The Role of Transit Mobility Developments in Greenhouse Gas Emissions Reduction Schemes: A Case Study of the Atlanta BeltLine 100

Introduction 100

Literature Review 102

General Methodology and Framework 103

Case Study – Atlanta BeltLine 106

Energy and greenhouse gas implications of public transit in Atlanta 107

Direct Energy and Greenhouse Gas Implications 109

Energy and Greenhouse Gas Savings from Residential Development 115
Lifecycle Cost Benefit Analysis 122
Discussion 132
Conclusion 140
6 Conclusions 141

APPENDIX A: Environmental Performance Statistics - Chapters 2 and 3 145
APPENDIX B: Agent-based Model Results - Chapter 4 147
REFERENCES 148
VITA 171

LIST OF TABLES

Page

Table 1: Production Facilities Global Distribution 15

Table 2: Global Environmental Performance Regression on the Production Mix (Logarithmic) 22

Table 3: U.S. Environmental Performance Regressions on the Production Mix (Logarithmic) 24

Table 4: Global Environmental Performance Regressions on the Production Mix and Region (Logarithmic) 26

Table 5: Global Average Incremental Change in Water and Energy Use and CO_2 Emissions 28

Table 6: U.S. Average Incremental Change in Water and Energy Use and CO_2 Emissions 30

Table 7: Production Facilities Global Distribution 45

Table 8: Environmental Performance Estimates considering demand changes within specific regional groups and within the MNBM production system. 58

Table 9: Monthly Income by Locale and Living Standard (in SA Rand) 82

Table 10: Selection of Initial Model Parameters 87

Table 11: Light rail system statistics for several US cities 111

Table 12: Cost and Benefit Estimates for Belt Line (in 2012 USD) 129

Table 13: Monte Carlo Variable Distribution Characteristics 129

LIST OF FIGURES

Page

Figure 1: 3-E Model of Sustainability 2

Figure 2: Transformation of 3E Model to 3P Model 4

Figure 3: Water Risk Map of Case Study Facilities 6

Figure 4: Transformation of 3E to 3E' model 7

Figure 5: Residential Energy Use in South Africa 9

Figure 6: Distributions Water Use, Energy Use, and CO_2 Emissions per Liter of Product 18

Figure 7: Historical Water Ratio Distributions 19

Figure 8: Overview of Problem Supply Chain Boundaries and Metrics 34

Figure 9: Climate Change Risk Framework for a Multinational Manufacturer developed from (Crichton, 2001) 38

Figure 10: Framework Diagram detailing procedural steps in environmental performance indicator (EPIs) statistical analysis 41

Figure 11: Production Facilities across the entire MNBM 49

Figure 12: HDI values compared to Facility Water Ratio Values 50

Figure 13: HDI compared to Facility Water Ratios without "Very High Performing" Countries on the HDI Index (Values 0.8 – 1.0) 51

Figure 14: Water Ratio and Overall Water Risk 52

Figure 15: Facility Average Emissions Ratio (Aggregated by Country) and Estimated Country Carbon Dioxide Emissions 54

Figure 16: Total Aggregate and Electrified Households in South Africa (data from S.A. Department of Energy, 2012) 71

Figure 17: Electricity Consumption and GDP per capita in 2013 $USD 73

Figure 18: Historical Electricity Prices in South Africa from (ESKOM, 2012) 74

Figure 19: Projections on per capita energy demand in South Africa 75

Figure 20: Electricity Demand Projections Per Household in South Africa 76

Figure 21: Energy End-Use Agent-based Model Organization 78

Figure 22: Energy States of Consumers 79

Figure 23: Consumer Agent Decision Process 81

Figure 24: GDP Distribution for South Africa over last 40 years 83

Figure 25: Simulated Spatial Network of an Observed Agent 84

Figure 26: Projected electricity demand for all scenarios 88

Figure 27: Scenario Riot Count 89

Figure 28: Income Expenditure on Electricity by Scenario 91

Figure 29: Distribution of HH Energy-consuming Types 92

Figure 30: Aggregate Residential Carbon Dioxide Emissions Model Results over 30 years 96

Figure 31: Model framework 105

Figure 32: Average system energy use per passenger mile for Atlanta's MARTA heavy rail 108

Figure 33: Greenhouse gas emissions per passenger mile from Atlanta MARTA heavy rail and buses, and a 20-mile per gallon passenger vehicle. 109

Figure 34: The Atlanta Beltline Study Area 110

Figure 35: Projected average fuel efficiency of in-use cars and light duty trucks 112

Figure 36: Future GHG emissions per kilowatt-hour estimates for Georgia based on Choi and Thomas (2012) 113

Figure 37: Estimate of greenhouse gas emissions from the BeltLine in 2030 114

Figure 38a and 38b: Population density distribution in the Atlanta Beltline corridor, 2008 (a) and projection for 2030 (b) 116

Figure 39: Annual VMT per household and population density 120

Figure 40: CO_2 emissions per resident-year considering residential densities of 4,500 and 8,300 persons per square mile 121

Figure 41: Estimated social carbon dioxide costs over the next 40 years (White House et al., 2013) 125

Figure 42: Results of Monte Carlo simulation used to find the distribution of NPVs of the Atlanta BeltLine 131

Figure 43: The 2035 Projected Per Capita Emissions of BeltLine Residents where the Baseline is the current emissions per capita and the rest of the values are 2035 projections 134

Figure 44: Accumulated Descending Graph for the Benefits-Costs Ratio (BCR) in the scenarios using a 3%, 5%, and 7% discount factor 135

Figure 45: Disaggregated system costs for the BeltLine over a 30-year period 136

SUMMARY

In this research, the environment and development issues of three stakeholders are investigated at multiple scales—global, national, regional, and local. Through the analysis of financial, social, and environmental metrics, the potential benefits and risks of each case study are estimated, and their implications are considered.

In the first case study, the relationship of manufacturing and environmental performance is investigated. Over 700 facilities of a global manufacturer that produce 11 products on six continents were investigated to understand global variations and determinants of environmental performance. Water, energy, carbon dioxide emissions, and production data from these facilities were analyzed to assess environmental performance. The relationship of production composition at the individual firm and environmental performance were investigated. Location-independent environmental performance metrics were combined to provide both global and local measures of environmental performance. These models were extended to estimate future water use, energy use, and greenhouse gas emissions considering potential demand shifts. Natural resource depletion risks were investigated, and mitigation strategies related to vulnerabilities and exposure were discussed. The case study demonstrated how data from multiple facilities can be used to characterize the variability amongst facilities and to preview how changes in production may affect overall corporate environmental metrics. The developed framework adds a new approach to account for environmental performance and degradation as well as to assess potential risk in locations where climate change may affect the availability of production resources (i.e., water and energy) and thus, is a tool for understanding risk and maintaining competitive advantage.

The second case study was designed to address the issue of delivering affordable and sustainable energy. Energy pricing was evaluated by modeling individual energy consumption behaviors. This analysis simulated a heterogeneous set of residential households in both the urban and rural environments in order to understand demand shifts in the residential energy end-use sector due to the effects of electricity pricing. An agent-based model (ABM) was created to investigate the interactions of energy policy and

individual household behaviors; empirical data was used to develop agents' beliefs and perceptions of energy. The environmental beliefs, energy pricing grievances, and social networking dynamics were integrated into the ABM model structure. This model projected the aggregate residential sector electricity demand throughout the 30-year time period as well as distinguished the respective number of households who only use electricity, that use solely rely on indigenous fuels, and that incorporate both indigenous fuels and electricity. The model is one of the first characterizations of household electricity demand response and fuel transitions related to energy pricing at the individual household level, and is one of the first approaches to evaluating consumer grievance and rioting response to energy service delivery. The model framework is suggested as an innovative tool for energy policy analysis and can easily be revised to assist policy makers in other developing countries.

In the final case study, a framework was developed for a broad cost-benefit and greenhouse gas evaluation of transit systems and their associated developments. A case study was developed of the Atlanta BeltLine. The net greenhouse gas emissions from the BeltLine light rail system will depend on the energy efficiency of the streetcars themselves, the greenhouse gas emissions from the electricity used to power the streetcars, the extent to which people use the BeltLine instead of driving personal vehicles, and the efficiency of their vehicles. The effects of ridership, residential densities, and housing mix on environmental performance were investigated and were used to estimate the overall system efficacy. The range of the net present value of this system was estimated considering health, congestion, per capita greenhouse gas emissions, and societal costs and benefits on a time-varying scale as well as considering the construction and operational costs. The 95% confidence interval was found with a range bounded by a potential loss of $860 million and a benefit of $2.3 billion; the mean net present value was $610 million. It is estimated that the system will generate a savings of \$220 per ton of emitted CO_2 with a 95% confidence interval bounded by a potential social cost of \$86 cost per ton CO_2 and a savings of \$595 per ton CO_2.

CHAPTER 1

INTRODUCTION

Motivation

Since its inception from the 1987 Brundtland Commission, the concept of sustainability has focused on “meeting the need of the present” while ensuring the prosperity of “future generations.” Sustainability research has encompassed the dynamics of balanced ecological-economic-equity goals for development of all types and has required the literature to move past the conventional paradigm of considering “sustainable economic development” and “ sustainable human development” separately and balances the two notions (Neumayer, 2012; Steurer, Langer, Konrad, & Martinuzzi, 2005).The concept of sustainability has created a balance of socio-economic, socio-ecological, and enviro-economic goals and has evolved into the 3-E – economic, environment, and equity – model shown in Figure 1 (S. Campbell, 1996). However, deeper problems exist currently within this realm that involve the interconnections of the institutional, civil, and techno-economic domains of sustainability (Pezzoli, 1997).

All levels of development are—or at least are at risk to— becoming impeded by the increased environmental degradation, increased demand for natural resources, amplified income inequality and the pressing societal needs surrounding health, education, nutrition, and poverty. Governments, corporations, and households facing these issues are considering how to develop strategies and adaptive capacity for a sustainable future.

The developing world struggles with providing adequate and affordable energy, promoting economic growth, and developing a sustainable delivery infrastructure. Developing countries are not alone; corporations and municipalities are also concerned with global population growth, per capita income growth, and their effects on the consumption of finite water and energy resources. Corporate firms will continue to make products to fill the demands of consumers, and governments will continue to balance policies that prioritize economic growth, the efficiency of financial resources, and the growing threat of environmental degradation. The growing global population creates a new supplement of consumers, especially in the developing world, that will place additional strains on natural resources and ecosystems. Economic growth in developing countries will enable more people to have modern lifestyles and to seek levels of consumption on par with the already developed world. This, in turn, will encourage even higher emissions rates of greenhouse gases. This growth trend has already started, as developing countries had significant growth in greenhouse gas emissions during the recent global financial crisis. Their CO_2 emission growth rates were by 4.4 and 3.9 percent in 2008 and 2009 even though global emissions decreased by 40 percent during this period, and was driven by economic production and trading activities (Peters et al., 2012).

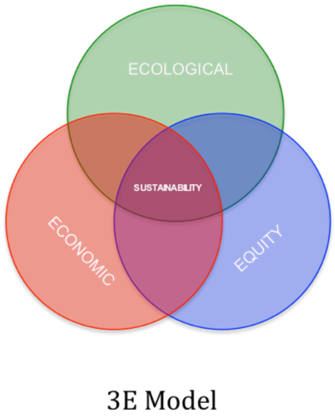


Figure 1– 3-E Model of Sustainability

All of these actors will increase their contributions to the growth of anthropogenic greenhouse gas emissions. The resource burden is a threat to human needs and adds to the portfolio of environmental issues. As drivers of global climate change, many of them are concerned with the future viability of ecosystems and livability of different regions.

Ecological, sociological, and economic ideas and constraints influence these actors' impact on the environment. Research into these problems and their potential outcomes is required to discover robust pathways for sustainable growth and mitigate the collapse of environmental systems. It also enhances the understanding of the synergies between development and the environment and addresses regional and global sustainability challenges (Mason, Dixon, & Redwood, 1994).

Systems analyses are an appropriate approach to tackle the sizeable breadth of these problems. System analyses incorporating quantitative models paired with qualitative analysis of the social and economic environment provide a robust framework for investigating these problems. These analyses can be used in investigations into environmental risks, exposure, and vulnerabilities, which are important to developing solutions to mitigate future issues and improve the resilience of systems. Here, data analytics make it possible to develop systematic procedures of risk assessments and support suggestions of policies that reduce this risk.

This dissertation describes three approaches that address some of the complex socio-economic and socio-ecological issues of sustainability of different actors of different scales. These studies explore many of the original themes of sustainability such as expanding the scope of environmental assessment, reinforcing social dimensions, mainstreaming global concerns, and leveraging private initiative (Mason et al., 1994). Multi-level frameworks, in each case, are presented that address the problem and explore potential solutions. The first case study evaluates the facilities of a global manufacturer of similar products to find correlations related to water usage, energy consumption, and the production of emissions. The second case study investigates the behaviors and perceptions of residential energy consumers under different scenarios of sustainable energy development. The final case study evaluates the social, health, and environmental costs and benefits of developing a transit-oriented development with newly constructed light rail infrastructure.

Corporate Environmental Performance

Corporate environmental sustainability can be defined “as meeting the needs of a firm’s direct and indirect stakeholders such as shareholders, employees, clients, external groups, and communities without compromising its ability to meet the needs of future stakeholders as well”(Dyllick & Hockerts, 2002). The 3E model is transformed into the 3P model of business sustainability, which incorporates people, profit, and planet (Figure 2) (Global Environmental Management Initiative, 1998).

Resource-based theory (RBT) of firms is one approach to understanding sustainability motivations in firms (Barney, Ketchen Jr, & Wright, 2011). RBT establishes the importance of resources and capabilities in a firm as sustainable sources of sustained competitive advantage. Hart (1995) developed the natural resource based theory of firm, which accepts that the most vital resource of firms – production, people, and profit – cannot ignore the constraints of nature or degradation of the ecosystem.

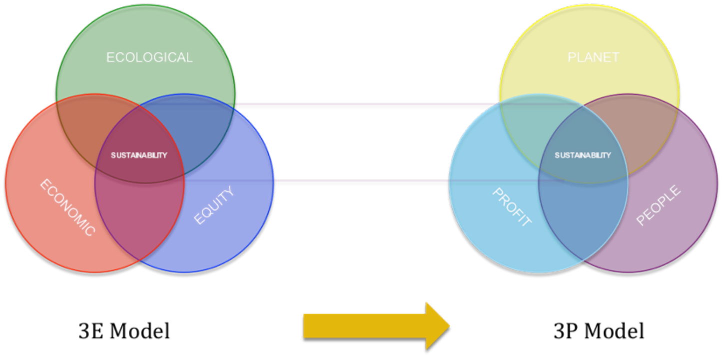


Figure 2 - Transformation of 3E Model to 3P Model

Environmental management has been proven to make companies more efficient and create a competitive advantage (Berry & Rondinelli, 1998). The most important aspect of environmental management is “the need to protect the environment and conserve natural resources”. To do so, performance requirements must be integrated into a company’s environmental business strategy. The development of performance requirements necessitates the objective assessment of facility efficiency, the quantification of environmental liabilities, and the development of mitigation plans.

Environmental performance indicators are the most important to this cause as their monitoring and continual assessment deliver value and bring new efficiencies to the firm.

Competitive advantages can be gained by firms that use these data and develop strategies in the areas of waste minimization, sustainable product design [i.e., Design for the Environment (DFE)], and technology cooperation (Hart, 1995). Environmental models will be at the forefront of evaluating performance, especially in manufacturing. However, it will not be enough to develop models that only serve to estimate performance. These models must be leveraged to evaluate risk from natural resource depletion if firms want to develop their supply chain resiliency and adaptive capacity.

The evaluation of these supply chain risks may be increasingly important as regions around the world are predicted to experience water resource depletion, increased energy shortages, and augmented air pollution. Risk assessments must include geospatial and region specific data in order to support firm-level environmental and economic strategies. Climate change model data are useful to these analyses as they provide external metrics and indicators for firm and intra-firm analyses.

Global firms acquire large amounts of data on their production facilities. These data are commonly used for simple average trend analyses on energy use, greenhouse gas emissions, and water consumption. These data also can be investigated to uncover the main factors in performance variability. However, many firms lack the data analytics capabilities for these investigations, especially within areas of sustainability.

This research creates a framework for these investigations and develops multivariate regressions to assess environmental performance. The general framework uses environmental performance indicators to do a bottom-up analysis of environmental efficiency and gauge environmental risks.

A case study of The Coca Cola Company, Inc. investigates their global production facilities. Data from over 700 facilities of a global manufacturer provide a prism for understanding global variations and determinants of environmental performance. Water, energy, carbon dioxide emissions, and production data for 11 product categories on six continents are analyzed.

Compositional data of the production of different product lines are evaluated and a procedure is developed for their transformation into independent variables for multivariate regressions. Location-independent environmental performance metrics (water use, energy use, and greenhouse gas emissions per unit of production) with location specific metrics (water stress and greenhouse gas emissions from grid electricity) are combined to provide both global and local measures of environmental performance (Figure 3). Lagging indicators—statistics on past environmental performance—are used to project future environmental performance as production composition changes in order to identify potential risk mitigation strategies and how high-risk facilities are distributed with regard to geography, facility size, and facility management features.

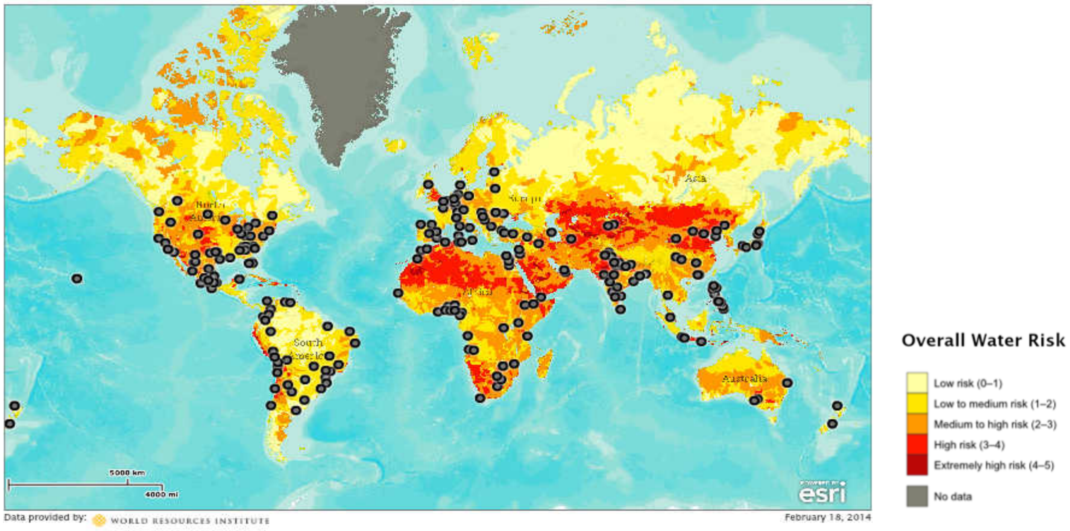


Figure 3 - Water Risk Map of Case Study Facilities

Previous authors have investigated environmental risks in the manufacturing sector, in the areas of wastewater treatment, environmental performance competitiveness, financial investment, and occupational risks. This study closes a gap in the literature, by quantitatively investigating intra-firm environmental performance variability, developing performance models, and assessing future natural resource risks due to climate change.

This study also contributes to the literature by investigating the differences in production between firm facilities as a factor in variability in environmental performance.

Residential Energy Demand in Developing Coutnries

A systems analysis approach is especially appropriate to evaluate problems in developing countries, where there are considerable underlying issues surrounding sustainable development. Growing environmental problems, increased demand for natural resources, income inequality, and pressing societal needs surrounding water, health, education, nutrition, and poverty are some of the major issues faced by these countries; their careful evaluation will encourage the development of impactful sustainability initiatives. In particular, these countries struggle with the balance of providing adequate energy benefits, expanding electric power generation capacity, and developing environmentally sustainable strategies, which can increase the upfront system development and integration costs. These costs can be contrary to the promotion of economic growth and providing access to low cost energy to consumers (Figure 4).

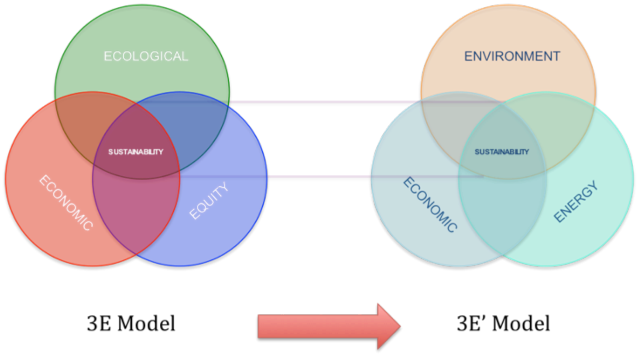


Figure 4 - Transformation of 3E to 3E' model

Many rapidly developing countries expect household income growth, enabling more demand for electricity. However, future trends are not wholly dependent on pricing or income as many households have different beliefs and perceptions related to electricity prices and their demand for it. Also, many households in the developing world continue to use indigenous fuels for their household energy needs so it is important to understand the factors that affect their transition to electricity and their subsequent demand across different household types.

South Africa provides an interesting case study for studying energy development. While the country has a more developed electricity generation infrastructure than most developing countries, access to electricity was limited to less than 40 percent of the country during Apartheid. In the post-Apartheid era, the country has policies that aim to provide universal access to electricity to its socioeconomically disadvantaged populations and fully connect every household to the national grid. This research investigates the heterogeneity of these residential households in both the urban and rural environments and evaluates their access to and demand for electricity in relation to changes in pricing.

In the residential sector, cooking, lighting and heating (water and space) are the primary energy-consuming activities. The energy consumption distribution by activity in South African households is shown in Figure 5. Many of these activities do not solely require the use of electricity as they can be completed with other indigenous fuels. In South Africa as well as other developing countries, electricity is not the primary fuel for households due to its prohibitive costs. Paraffin (kerosene), liquid petroleum gas, coal, wood, and animal dung are used, sometimes in combination, to meet the household heating, lighting, and cooking needs.

The continued use of these fuels in some households presents a challenge in the prediction of electricity demand, but it is not the only issue. For some households, a connection to the electricity grid does not constitute use of electricity, as there are portions of the population who cannot afford the expense or presume there is greater expenditure with using electricity.

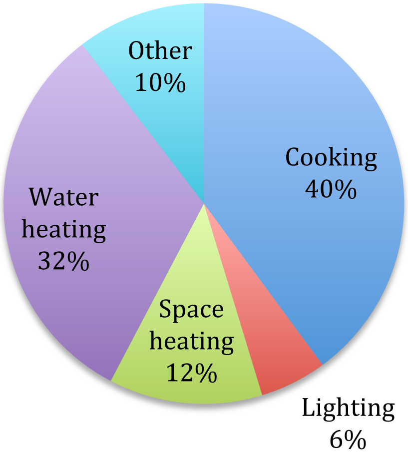


Figure 5 - Residential Energy Use in South Africa

This study analyzes household-level energy consumption in relation to pricing and aggregates them to project the entire residential energy demand in South Africa over time. A spatially explicit agent-based model (ABM) is created to investigate the interactions of electricity pricing policies at micro-scale (household level) and project electricity demand in the future at the household level. This model captures the complexities of the residential sector and provides insight into effective policy.

The model incorporates household beliefs on energy, perceptions about electricity pricing, and propensity to riot about electricity service delivery. Exogenous factors such as socio-economic mobility within the population and urbanization are captured within the model. The results at the household level are aggregated and scaled to estimate the future electricity demand in the residential sector of South Africa.

Additionally, this model captures the number of electricity-only users as well as the number of multi-energy users who may or may not use electricity in their energy mix at each period. The relationship of electricity demand and pricing is addressed, as well as the dynamics in residential energy end-use behavior. Utilizing research on service delivery grievance and social networks, the analysis provides insight into the frequency of riots in relation to electricity expenditure.

This analysis provides a foundation for further research on civil disobedience, greenhouse gas reduction impacts on electricity demand, the health impacts of fuel transitions, and energy systems of developing countries. This model application is not limited to South Africa as it can be applied to other developing countries facing similar energy issues.

Lifecycle Cost-Benefit Analysis

Many cities are developing policies and programs to reduce greenhouse gas emissions, some of which include the development of transit systems and transit-focused development. Various government stakeholders separately develop and assess the costs of these projects; the external benefits such as health and wellness and added value to property; and, the lifecycle greenhouse gas emissions. This case study presents a newly developed framework for a broad cost-benefit evaluation incorporating the social cost of the greenhouse gas emissions and the social benefits of transit and associated developments.

A case study is developed of the Atlanta BeltLine, a planned 22-mile loop around Atlanta that will include light rail transit, residential and non-residential development, trails, parks, and other recreational features. The net greenhouse gas emissions from the Atlanta BeltLine light rail system depends on the energy efficiency of the streetcars themselves, the greenhouse gas emissions from the electricity used to power the light rail cars, the extent to which people use the BeltLine instead of driving personal vehicles, and the efficiency of their vehicles. The overall efficacy of the proposed system is found to be dependent on creating the appropriate ridership, residential densities, and housing mix. These factors are found to have considerable impact on the per capita emissions of the residents of the corridor and are considered in this analysis.

A methodological framework is developed to evaluate the costs and environmental benefits of transit-oriented developments and their benefits to the overall municipal environmental goals. The analysis uses two models – a transportation model and a residential lifecycle model and integrates them into a cost-benefit analysis model that incorporates the temporal variance of model parameters.

The range of net present value of this system considering health, congestion, and societal costs and benefits on a time varying scale as well as construction and operational costs is found using a Monte Carlo analysis. Different discount factors are used in the estimation of the mean net present value of the system and the 95% confidence interval. Uniquely, the potential savings (costs) per ton of emitted greenhouse gases considering all cost and benefits of the system are estimated.

Structure of Dissertation

This dissertation is structured as a compilation of the aforementioned three research projects. All of the case studies have their own respective chapters containing a detailed problem statement, literature review, methodology, model parameters and results. Thusly, Chapter 2 and 3 presents the results of corporate environmental performance analysis. Chapter 2 details the methodological framework for developing environmental performance models and the insight provided from the models. Chapter 3 presents a firm-level climate change risk exposure and vulnerabilities analysis. Chapter 4 presents the development of the agent-based model of South African residential energy demand. Chapter 5 contains the framework development and results from the cost-benefit analysis of the BeltLine. Chapter 6 offers the concluding remarks on these research projects.

CHAPTER 2

STATISTICAL ANALYSIS OF ENVIRONMENTAL PERFORMANCE OF MANUFACTURING FACILITIES: A CASE STUDY OF BEVERAGE MANUFACTURING

Introduction

Corporate social responsibility (CSR) has grown to have major importance in firms. Led by calls for environmental responsibility by investors, activists, and the public, corporations developed strategies to understand their environmental impacts, limit their legal liabilities, and identify opportunities for improvement.

Through development of sustainability goals, targets, and metrics, firms can acquire large amounts of sustainability related data on their facilities. The direct application of these data is for analysis of which facilities are on track to meet goals and how far each facility is from meeting the goals. However, in addition, these data may provide insights into how differences between facilities, in terms of their products and processes or other features, relate to environmental performance.

We explore the potential for drawing insights from environmental data, by combining production data with data on water and energy use and greenhouse gas emissions from a large multi-national manufacturer. This study is the first, to our knowledge, to analyze environmental statistics from hundreds of facilities manufacturing similar products in different regions, and the first to use this type of data to analyze the factors influencing environmental performance. Specifically, we show how manufacturers can potentially project changes in environmental emissions as their portfolio of products changes. The distribution and variation of emissions can also be quantified, supporting the development of robust product lifecycle analyses.

Previous studies on the variability and determinants of industrial water and energy use and greenhouse gas emissions have been able to use national, average, or inter-firm data. With respect to water, Lévová and Hauschild (2011) have studied industrial water use impacts in the contexts of limitations to water withdrawal in different global regions. Blackhurst, Hendrickson, and Vidal (2010) have discussed both direct and indirect water withdrawals from different U.S. industrial sectors. Jeswani and Azapagic (2011) address methodological issues of water impact assessment and highlight regional differences in water stress and impacts.

With respect to energy, Mandal and Madheswaran (2011) analyze one sub-sector of the industrial sector (cement production) to investigate inter-firm variations in energy use and energy efficiency. Using a data envelopment analysis, they show that different firms overall can significantly reduce their energy consumption by using costs- and emissions-minimization framework. Soytas and Sari (2007) show that manufacturing and energy inputs are positively correlated using co-integration methods on national data. Globally the food & beverage industry, the focus of this case study, use 5 percent of the primary energy of all industrial sub-sectors (Abdelaziz, Saidur, & Mekhilef, 2011); this value includes just the direct industrial energy use. Consideration of lifecycle and indirect energy use, as for the water use studied by Blackhurst et al. (2010), can potentially address the full impacts of the supply chain.

With respect to greenhouse gas emissions, especially carbon dioxide, the emission-intensity studies of Worrell, Price, and Martin (2001) and Al-Ghandoor, Al-Hinti, Jaber, and Sawalha (2008) have shown a parallel synergy with energy consumption, with variation in the emissions per unit of energy depending on the power or primary energy source. A number of studies have found that per unit emissions intensity has decreased significantly over the past decade (Lim, Yoo, & Kwak, 2009) and are primarily linked to a reduction in energy intensity (Hammond & Norman, 2012; Plambeck, 2012). Studies have also shown that significant progress can be made in decreasing greenhouse gas emissions without compromising economic growth (Liaskas, Mavrotas, Mandaraka, & Diakoulaki, 2000).

Previously, the product mix (or production mix) has been investigated primarily from a decision science and planning aspect. Researchers have used linear programming techniques to develop the optimal product mix of facilities by looking at capacity allocations (Chou & Hong, 2000). Other investigations have used activity-based costing (ABC): Kee and Schmidt (2000) use ABC to investigate the causal relationship between products and the production resources.

There is a breadth of work and algorithms on locating facilities of a firm, with environmental considerations included (Dou & Sarkis, 2010; Lahdelma, Salminen, & Hokkanen, 2002; Roberts, 2004). However, there is limited work on firm performance in relation to the global locations of its facilities. Molina-Morales (2002) finds that corporate performance is linked to the globe scope of the firm. Luger and Evans (1988) studied production facilities within the same industry on the east and west coast of the US and found differences in production characteristics stemming from production technology, labor, and other practices.

This study analyzes and assesses environmental performance indicators of a firm's product lines and facility locations, using regressions and statistical analyses of environmental performance indicators. We consider the role of product mix and geographic location in environmental performance.

Data

This case study utilizes data from a large beverage manufacturer that has facilities in over 100 countries. These facilities are aggregated into 21 regional groups based on their geospatial distribution. These groups consist of firm-owned and non-firm-owned manufacturing facilities. These regional business groups and the facilities under their direction all work under the same guidelines and work towards the sustainability goals set forth by the firm. Table 1 shows the number of facilities and a summary of the production mix in each region.

Table 1 - Production Facilities Global Distribution

Region	Number of Facilities	Percent of Production Volume			
		Carbonated Beverages	**Finished Water**	**Juices Product**	**Coffee/Tea Products**
Asean	49	0.84	0.08	0.02	0.04
Brazil	42	0.85	0.08	0.05	0.02
Canada	7	0.86	0.00	0.02	0.00
Central & Southern Europe	47	0.80	0.11	0.09	0.00
Central East & West Africa	87	0.90	0.04	0.06	0.00
China/Korea	53	0.75	0.02	0.21	0.01
Germany	25	1.00	0.00	0.00	0.00
Iberia	15	0.80	0.20	0.00	0.00
India & Southwest Asia	58	0.94	0.06	0.01	0.00
Japan	28	0.29	0.08	0.03	0.49
Central Latin	40	0.93	0.05	0.01	0.00
Mexico	57	0.82	0.14	0.02	0.01
Middle East & North Africa	61	0.97	0.03	0.00	0.00
Northwest Europe & Nordics	22	0.91	0.05	0.01	0.00
Russia, Ukraine & Belarus	19	0.74	0.11	0.04	0.00
South Africa	16	1.00	0.00	0.00	0.00
South Latin	37	0.89	0.06	0.05	0.00
South Pacific	23	0.63	0.37	0.00	0.00
Turkey & CCA	17	0.84	0.13	0.02	0.00
United States	75	0.81	0.05	0.06	0.01
Total	778				

We removed non-manufacturing facilities from the database as well as any facilities missing production data by product type or missing water, energy or CO_2 emissions data. The final number of facilities used in the analysis is 778. Eleven different product types are made across all facilities; various production compositions of these product types can be found at each respective facility. For this particular firm, nearly two-thirds of the facilities are producing one product type only (i.e., 100 percent of production).

Environmental Metrics

The normalized (per output volume) environmental performance indicators for this case study are:

- Water Use (L / L) = $\frac{Total\ Freshwater\ Intake}{Total\ Volume\ of\ Facility{-}made\ Products}$
- Energy Use (MJ / L) = $\frac{Total\ Energy\ Expenditure}{Total\ Volume\ of\ Facility{-}made\ Products}$
- Carbon Dioxide Emissions (g / L) = $\frac{Scope\ 1\ Emissions + Scope\ 2\ Emissions}{Total\ Volume\ of\ Facility{-}made\ Products}$

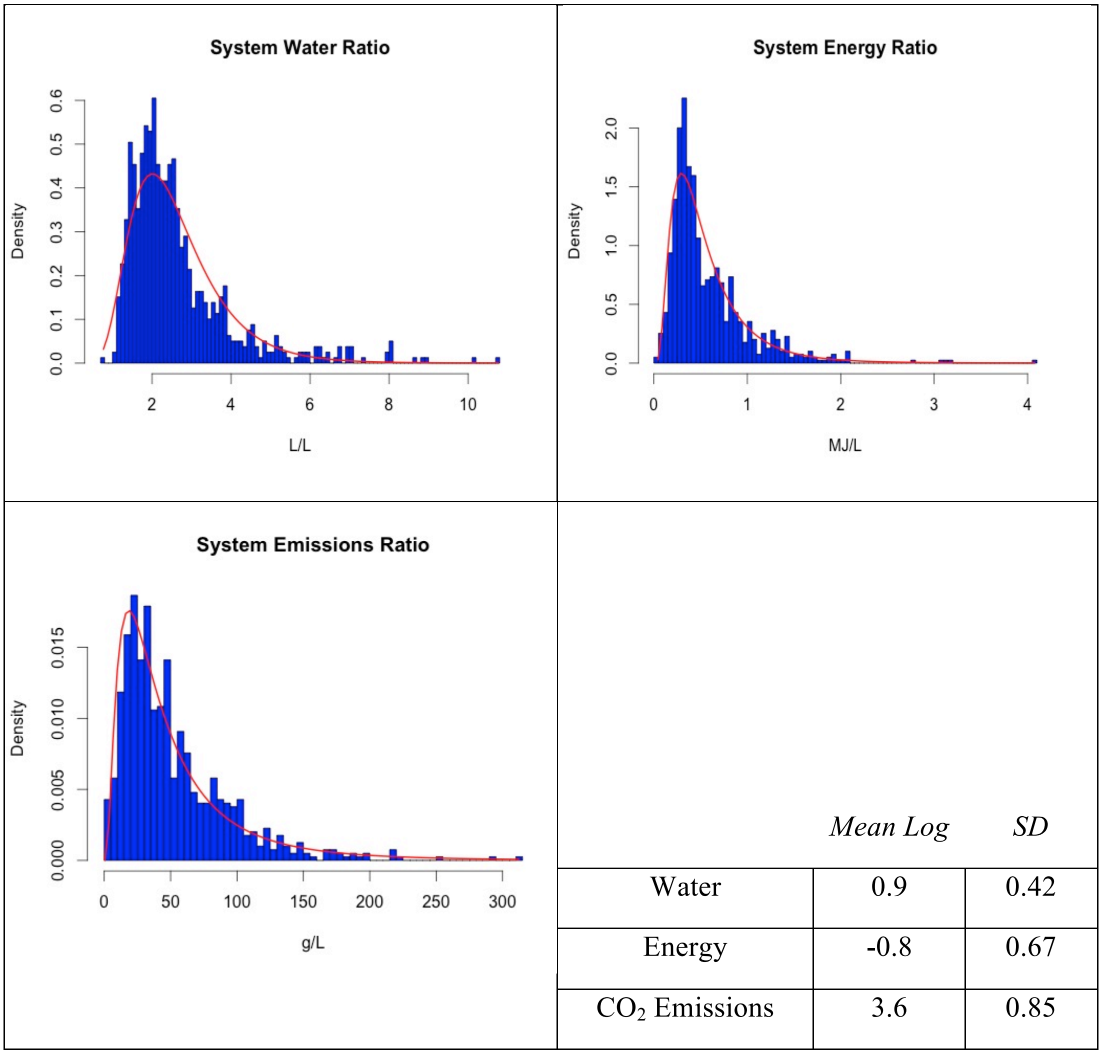
The water ratio is the amount of water per liter of product. Although the firm has set a goal for water efficiency in terms of liters of water use per liters of product, here we consider simply that the lower limit for complete products is 1 liter of water per liter of product. Beverage industry studies indicate that as of 2011, production of bottled water uses 1.47 liters per liter globally, with North American facilities achieving 1.39 liters per liter (Antea Group 2013). Globally, production of carbonated soft drinks uses an average of 2.02 liters per liter as of 2011, with a range of 1.48 to 3.95 liters per liter (Antea Group & BIER, 2012).

Energy use is the amount of energy used in the facility per liter of product. Although the product manufacturing specifications could indicate a minimum energy requirement for production of a liter of product, this minimum energy requirement has not been determined and we use this metric without a natural scale.

Carbon dioxide (CO_2) emissions is the amount of CO_2 emissions from the facility (“scope 1) and from the electricity used by the facility (“scope 2”), per liter of product. We consider the minimum achievable value to be zero, which would correspond to a facility using non-carbon-based energy.

The distributions of the three metrics are shown in Figure 1, using data for 2011; each data point represents the annual average for a single facility. Kolmogorov-Smirnov (K-S) statistics were used to test the goodness-of-fit of the data to log-normal distributions; something like a log-normal is an expected distribution since each of the metrics is bounded below. The energy and emissions variables are log-normally distributed with a 95% of higher confidence. There is lower confidence in the fit of the log-normal distribution ($p<0.01$) of the water variable. Data on the facilities producing only one product type are also log-normally distributed. A simple log-transform of the variable can be used to gain normality (Tabachnick, Fidell, & Osterlind, 2001).

Note that the standard deviation of the energy use is about 50% greater than the standard deviation of the water use, and the standard deviation of the greenhouse gas emissions is about 25% greater than the standard deviation of the energy use.



	Mean Log	*SD*
Water	0.9	0.42
Energy	-0.8	0.67
CO_2 Emissions	3.6	0.85

Figure 6 - Distributions Water Use, Energy Use, and CO_2 Emissions per Liter of Product

The distributions show a narrowing over time, although maintaining log-normality (shown in figure 2 for water) as sustainability programs were implemented.

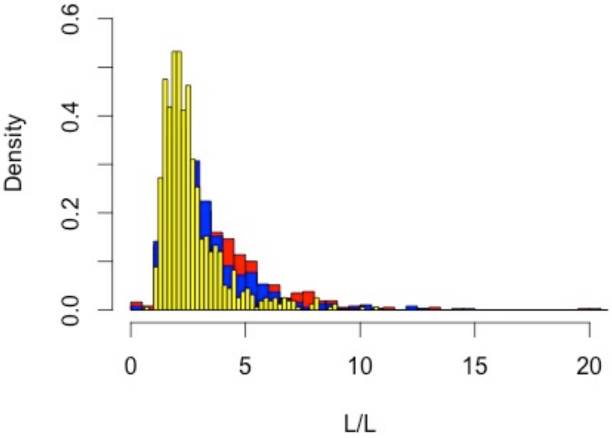


Figure 7 - Historical Water Ratio Distributions

*** The years 2004, 2007, and 2011 are in the colors red, blue, and yellow, respectively.*

Statistical Methodology for Compositional Analysis

The data on the product mix are composed of the fractional volumes of the 11 different manufactured products. Since these fractions must sum to 1, the fractions are not independent of each other. Regression analysis assumes that the independent variables (i.e., fractional volumes) are uncorrelated. So, in order to develop a regression analysis using the production fractions, a technique to create independent representations of the production fractions is needed.

Aitchison (1981) takes on this challenge by determining an appropriate procedure to transform the variables so that they can be used in analysis that assumes their independence. His analysis considers that there is a vector *y* of *n* positive fractional values that sum to unity.

$$y = (y_1, \dots, y_n) \qquad \text{Eq. 1}$$

$$\sum_{j=1}^{k} \boldsymbol{y_j} = \mathbf{1} \qquad \text{Eq. 2}$$

The Aitchison transformation takes the vector *y* and creates a vector of (*n-1*) values using a ratio transformation. The ratio transformation is using one arbitrary vector value from vector *y* (denoted by the index *m* below), where *log* refers to the natural log.

$$v_j = \log(y_j / y_m) = \log(y_j) - \log(y_m) \qquad \text{Eq. 3}$$

This transformation is appropriate and valuable for regression because the vector *v* can be transformed back to *y* using the generalized logistic transformation. It is a natural link between the composition and its equivalent bases (Aitchison, 1981). This transformation procedure mitigates the difficulty that arises with having data in simplexS^n and moves it into the corresponding space within the real space with dimension n-1, $\Re^{n-1}$.

$$\boldsymbol{y_i = e^{v_i} / \left\{1 + \sum_{j=1}^{d=n-1} e^{v_j}\right\} \quad (i = 1, \ldots., d)} \qquad \text{Eq. 4}$$

In our data set, the facilities do not all produce all of the 11 different product groups, which causes zeros in the compositional data. This is quite different than other applications of this method such as Abayomi, Luo, and Thomas (2010) and Pawlowsky-Glahn and Egozcue (2006) that look at composition of macro-level crop production and geochemical data, respectively, with positive values of all vector values. Zeros cannot be used in the Aitchison process because the log ratio transformation of such a value (in the numerator or denominator) would be positive or negative infinity. Hence, there is a restriction on the vector values.

$$log(0) \rightarrow \infty \qquad \text{Eq. 5}$$

$$S^d = \{\ y: y_i > 0 \quad (i = 1, \ldots, d) \sum_{i=1}^{d} y_i < 1\ \} \qquad \text{Eq. 6}$$

Therefore, another transformation will be needed to make the data available for analysis. A zero-replacement technique was selected from Fry, Fry, and McLaren (2000), which provides an enhanced procedure for the zero-replacement approach detailed in Aitchison (1986); the enhanced procedure perturbs the each component of the vector so that all ratios of weights are held constant.

The perturbation for *M* zero components adds a positive quantity τ_A to the zero value while subtracting τ_s from the *N-M* components of the vector. The δ value is the maximum rounding error, which is typically assigned as 0.01.

$$\tau_A = \frac{\delta(M+1)(N-M)}{N^2} \qquad \text{Eq. 7}$$

$$\tau_s = \frac{\boldsymbol{\delta(M+1)(M)}}{\boldsymbol{N^2}} \qquad \text{Eq. 8}$$

Regressions were run on the transformed compositional data. The regressions take the form of Φ_s where $\hat{\Gamma}$ is a vector of other variables such geographic location, facility characteristics, etc.

$$\log(\Phi_s) = \alpha + \sum_{i=1}^{n-1} \beta_i \cdot \log(y_i) + \hat{\Gamma} \qquad \text{Eq. 9}$$

All regression analyses were performed with the R statistical package.

Results

Role of product mix

Using the above referenced transformation, the compositional data vector has been reduced from 11 variables to 10 variables. Correlation analyses were run on all ten of the transformed variables to see if there were any significant trends between production groups.

Table 2 – Global Environmental Performance Regressions on the Production Mix (Logarithmic)

Production Fraction (log)	Water	Energy	CO_2 Emissions
(Intercept)	0.737***	-0.871***	3.494***
Carbonated Beverages	0.049**	0.037	0.049
Water	-0.057***	-0.165***	-0.13***
Juice	0.022	0.132***	0.169***
Coffee and Tea	0.177***	0.237***	0.246***
Isotonic Beverages	0.113***	0.086	0.004
Other Beverages	0.081	0.076	0.096
Concentrated Beverages	-0.011	-0.227	-0.405*
Concentrated Juice	0.057	0.283**	0.273
Syrup	-0.107**	-0.157**	-0.136
R-Squared	0.151	0.171	0.093

****, ** and * indicate significant at the 1%, 5% and 10% level, respectively.*

Table 2 indicates that water use is significantly correlated at the 1% confidence level, with the production fraction of water, coffee and tea, isotonic beverages, and syrup, and that energy and CO_2 emissions are correlated at the 1% level with the production fractions of water, juice, and coffee and tea. These regression coefficients suggest a relationship among the products, potentially using these correlations to project how the environmental metrics might change with a changing mix of products. Specifically, the coefficients suggest that an increase in production of coffee and tea could result in an increase in water, energy, and CO_2 emissions, whereas an increase in production of water could result in a decrease in water, energy, and CO_2 emissions. However, the underlying cause of the correlations of different products with environmental variables may include other factors that product mix. Below we consider facility size and facility location.

Role of Facility Size

Analysis of the role of facility size, in terms of annual production volume or other variables, provides another exploratory view of the data. Cluster analysis is a group of multivariate techniques that assemble variables by their characteristics (Shrestha & Kazama, 2007). Cluster analyses are used in biology (taxonomy); psychology and medicine (types of illness subcategories); and even in business (customer segmentation). The two main types of clustering are hierarchical and partitioning cluster. Hierarchical analyses create a nested cluster that has its roots in a tree (McKenna Jr, 2003). Partitioning creates clusters that are non-overlapping subsets – each data object or variable belongs to one and only one subset.

Partitioning is used here to delineate subsets of the firm facilities. We use production volume quartile as a metric of facility size, and include this variable in the following analyses.

Regional Analysis: US Facilities

Regression results may differ by region. There are 75 facilities in the US with different production mixes across all of the 11 different product types. The form of the multivariate regressions are shown below where $\hat{\theta}_{i_{capacity}}$ is an interval variable that references the capacity cluster of the facility.

$$\log(\Phi_s) = \alpha + \sum_{i=1}^{n-1} \beta_i \cdot \log(y_i) + \hat{\theta}_{i_{capacity}} \qquad \text{Eq. 10}$$

The US data appear to have a log-normal distribution for the water ratio, although the fit is inconclusive, which lessens the predictive power of the regression model. The energy and CO_2 emissions fit a log-normal distribution well. The model, as shown in Table 3, has an adjusted R^2 of 0.371 for water, 0.72 for energy, and 0.755 for CO_2 emissions, which is considerably better than the global analysis shown in Table 2. Note that in comparing this analysis with the global analysis, the production fraction of water and of coffee and tea, which were significant in the global analysis, do not show up as significant in the US analysis, while the production fraction of juice remains significant and with the same sign, but with a substantially different correlation coefficient. The facility size indicator *Production Volume Quartile* was only significant for water.

Table 3 – U.S. Environmental Performance Regressions on the Production Mix (Logarithmic)

Production Fraction (log)	**Water**	**Energy**	**CO_2 Emissions**
(Intercept)	0.976***	-0.8***	3.859***
Carbonated Beverages	-0.022	-0.039	-0.107
Water	-0.021	-0.002	0.016
Juice	0.113	0.356***	0.241***
Coffee and Tea	-0.025	0.048	-0.093
Isotonic Beverages	-0.018	0.052	0.058
Concentrated Juice	0.098	0.243**	0.334***
Syrup	-0.123	-0.007	0.022
Production Volume Quartile	-0.108***	-0.065	-0.046
R-Squared	0.371	0.72	0.755

****, ** and * indicate significance at the 1%, 5% and 10% level, respectively.*

Model Improvements by Geographic Units: A Global Case Study

Since we are dealing with a global firm, it is important to understand any associated regional effects. The regional location data were coded within the analysis using a dichotomous variable scheme. The dependent variable data were log transformed in order to reduce skewness and outliers in the data set. This helps to improve the normality, linearity, and homoscedasticity of the residuals (Tabachnick et al., 2001).

Thus, our general equation has the form, where $\hat{\Gamma}_{globalregion}$ is a vector of dichotomous geocoded variables:

$$\log(\Phi_s) = \alpha + \sum_{i=1}^{n-1} \beta_i \cdot \log(y_i) + \hat{\theta}_{i_{capacity}} + \hat{\Gamma}_{globalregion} \qquad \text{Eq. 11}$$

The results, in Table 4, show that there is some correlation, both positive and negative, of the environmental metrics with specific regions, but also that there is no region that has significant correlation for all three environmental metrics.

Table 4 – Global Environmental Performance Regressions on the Production Mix and Region (Logarithmic)

Variable	Water	Energy	GHG Emissions
(Intercept)	0.241***	-1.47***	3.208***
Carbonated Beverages	0.036***	0.076***	0.065*
Water	-0.011	-0.061**	-0.059*
Juice	0.006	0.129***	0.111**
Coffee and Tea	0.036**	0.133***	0.131**
Isotonic Beverages	0.021	0.084	0.057
Other Beverages	-0.005	-0.042	-0.004
Concentrated Beverages	0.016	-0.162	-0.15
Concentrated Juice	0.043	0.321***	0.413***
Syrup	-0.018	-0.052	-0.104
ASEAN	-0.075**	-0.068	0.143
Brazil	0.002	-0.19**	-1.185***
Canada	0.028	-0.101	-0.8***
Central...Southern.Europe	0.008	0.038	-0.036
Central.East...West.Africa	0.081**	-0.126	-0.319***
China.Korea	-0.035	0.003	0.511***
Germany	-0.065	-0.154	-0.209
Iberia	-0.031	-0.046	-0.265
India...Southwest.Asia	-0.015	0.378***	0.657***
Japan	0.384***	0.143	0.088
Latin.Center	0.037	-0.164*	-0.445***
Mexico	-0.007	-0.431***	-0.398***
Middle.East...North.Africa	0.045	0.159*	0.344***
Northwest.Europe...Nordics	-0.057	0.022	-0.744***
Russia..Ukraine...Belarus	0.018	0.485***	0.292*
South.Africa	-0.06	-0.378***	0.394**
South.Latin	-0.046	-0.416***	-0.674***
South.Pacific	-0.029	-0.172	-0.032
Turkey...CCA	-0.049	0.094	0.062
Production Volume Quartile	0.244***	0.256***	0.19***
Energy Quartile	-0.099***	-0.04	-0.054
R-squared	*0.834*	*0.554*	*0.493*

***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.

For water, an R^2 of 0.83 was found, which is considerably better than the R^2 of 0.151 for the model without the regional variables (Table 2). Moreover, while water use is positively correlated with carbonated beverage production and coffee and tea production in both Table 2 and Table 4, in Table 4 the correlation coefficients for carbonated beverages and for coffee and tea are identical, indicating that no additional water use would be expected from a shift from carbonated beverage production to coffee and tea production. Moreover, the correlations of water use with production of water, isotonic beverages, and even syrup production no longer show up as significant in the model of Table 4.

For energy, the model has an R^2 of 0.56. As for the simpler global model of Table 2, this model finds that energy use is positively correlated with production of juice, coffee and tea, and concentrated juice, and negatively correlated with water production. Moreover, the correlation coefficients relating juice and concentrated juice production to energy use are similar in Tables 2 and 4. However, the model in Table 4 has a smaller correlation coefficient relating production of water to energy use and relating coffee and tea production to energy use; that is, this more detailed model of Table 4 shows a smaller energy penalty for coffee and tea production than indicated by the simpler model of Table 2.

For CO_2 emissions, the model has an R^2 of 0.5. The correlations with product type are similar to correlations of energy use with product type, because CO_2 emissions result almost entirely from energy use.

Cross Validation

Cross validation techniques were used to understand the error of the three models. It is a technique that is recommended for statistical regression and ensures that there is no overinflating of predictive estimators (Heyman & Slep, 2001; Tabachnick et al., 2001). *k*-fold cross-validations (k = 50, in this case) were performed on the generalized linear models considering the original data points. The cross validation estimate of prediction error was small for the water model ($\delta = 0.03$). The energy and CO_2 emissions models had percentage error estimates significantly higher ($\delta = 0.22$ and 0.41) than water. This was expected as the r-squared for these models were significantly lower and suggested that some variables needed for prediction were missing from the model.

Discussion

The correlation coefficients can, with care, indicate the amount that water and energy use, and CO_2 emissions may change with a change in the product mix. Table 5 shows the incremental change in water and energy use and greenhouse gas emissions indicated by the significant correlation coefficients shown in Table 5. These may be interpreted, that on an average across all facilities worldwide, a shift from carbonated beverages toward production of water may result in a 3.7% decrease in water use per liter of product, a (7.9+5.9~) 14% reduction in energy use and a (6.7+5.7~) 12% reduction in CO_2 emissions, per liter of product. Similarly, a shift from carbonated beverages toward juice could be expected to result in a (13.8-7.9~) 6% increase in energy use and a (11.7-6.7~) 5% increase in CO_2 emissions per liter of product.

Table 5 – Global Average Incremental Change in Water and Energy Use and CO_2 Emissions

Variable	Water	Energy	CO_2 Emissions
Carbonated Beverages	3.7%***	7.9%***	6.7%*
Water		-5.9**	-5.7*
Juice		13.8%***	11.7%**
Coffee and Tea	3.7%**	14.2%***	14.0%**
Concentrated Juice		37.9%***	51.1%***

A more refined analysis would use region-specific correlations. The production characteristics of the facilities in the region, or management practices of the regional business unit could play a role in regional variations. Facility technology could affect how well some facilities perform to the baseline goals. Table 6 shows the US values corresponding to the global values shown in Figure 5. In particular, the analysis of US facilities shows that there is no significant correlation of either carbonated beverage production or water production and higher or lower water use, energy use or CO_2 emissions. This means that a shift in production from carbonated beverages toward more water production would not be expected to change water use, energy use or CO_2 emissions. However, a shift from carbonated beverage production toward juice could result in a 43% increase in energy use and a 27% increase in CO_2 emissions per liter of product.

Table 6 – U.S. Average Incremental Change in Water and Energy Use and CO_2 Emissions

Variable	Water	Energy	CO_2 Emissions
Carbonated Beverages	--	--	--
Water		--	--
Juice		43%***	27%**
Coffee and Tea	--	--	--
Concentrated Juice		27%***	40%***

These statistical results reflect production characteristics at a specific time. Far from indicating a fixed relationship between production and water and energy use and CO_2 emissions, or fixed differences between regions, they suggest that there is potential for improvement in production processes.

Conclusions

The development of large multi-facility databases on production, material and energy use, and environmental emissions from manufacturing facilities provides an opportunity to incorporate data analytics into sustainability analysis. This approach can be contrasted with, and is complementary to, process based environmental lifecycle assessment. Environmental lifecycle assessment can provide details of production processes, can determine why and how one process may use less water and energy and emit less CO_2 than another process. In contrast, this “big data” statistical approach can provide fast insight across hundreds of facilities, and can highlight areas for further detailed inquiry and potential process improvement.

The question addressed here is how changes in product mix may change environmental profiles. This approach could be applied to other types of manufacturing, including electronics, clothing, automotive, etc. As new types of products are added into a manufacturer’s portfolio, there will be changes in environmental metrics. The type of statistical analysis developed here can provide foresight for manufacturers, and can also highlight facilities that are achieving efficiencies that other facilities may be able to adopt.

Environmental lifecycle assessment is a key approach to evaluating and understanding the environmental impacts of facilities, services, and firms. The statistical approach developed here does not provide the kind of detailed understanding that process based lifecycle assessment can provide. But as a fast comprehensive view of environmental metrics, it may provide a useful approach for global manufacturers to find ongoing dynamic insight into environmental performance.

CHAPTER 3

RISK STRATIFICATION AND ASSESSMENT IN THE ENVIRONMENTAL MANAGEMENT OF MULTINATIONAL FIRMS: A CASE STUDY OF BEVERAGE MANUFACTURING

Introduction

Through development of sustainability goals, targets, and metrics, firms acquire large amounts of sustainability related data. The data analyses can show the inefficiencies of some facilities. In addition, these data may provide insights into how differences between facilities, products and processes correlate with environmental performance. These findings can be used in production risk assessments that consider the changes in natural resources due climate variability. In this study, risk is conceptualized as the threat of natural resource depletion by inefficiencies in industrial production, geospatial considerations, and consumer demand. A framework is developed around this idea. Production composition and resource flow data from a large multi-national manufacturer (MNBM) are used as a case study to assess the environmental vulnerabilities and risk exposure and draw insights from environmental data.

Environmental Performance and Corporate Social Responsibility

Environmental performance is tied to firms integrating performance requirements into their business strategy, including objective assessment of environmental impacts (sustainability programs), quantification of environmental liabilities and development of mitigation plans (Berry & Rondinelli, 1998). The three elements of successful performance are good management, environmental strategy, and, most importantly in our case, goals, targets, and metrics. Their monitoring and assessment is key to harnessing their value and effectiveness.

Performance metrics design is a powerful tool and methodology that can integrate firm desires and societal considerations (Sikdar, 2004). In some industrial cases, data for creating metrics has been limited. If available, it has been “black-box” in nature meaning that the final metrics are known at the facility level, but not comprehensively understood. In this case study, data is limited to the boundary of the facility; a complete life-cycle analysis is unattainable as there is no upstream and downstream data and little at the MNBM-level of all of the internal processes. Energy, water, and material flows are only known at facility level. These metrics create an opportunity for improvement, when analyzed in conjunction with compositional production data.

These opportunities are especially important in the food and beverage industry (FBI), which is the focus of this case study. Most manufacturing facilities either wholly or through a supply chain go through a variety of processes to manufacture food and beverage product at one facility. Key steps in the creation such as preparing raw materials, utilizing heat/cold, dewatering, modulating product composition, and concentrating create environmental performance differences at the facility level (Maxime, Marcotte, & Arcand, 2006).

Figure 8 provides an overview of the main resource flows into production facilities, including:

- Inbound Flows: fuels, electricity, raw materials, and production goods
- Internal Flows: processing, production movement, and vehicle preparation
- Outbound Flows: final productions, wastewater, and emissions

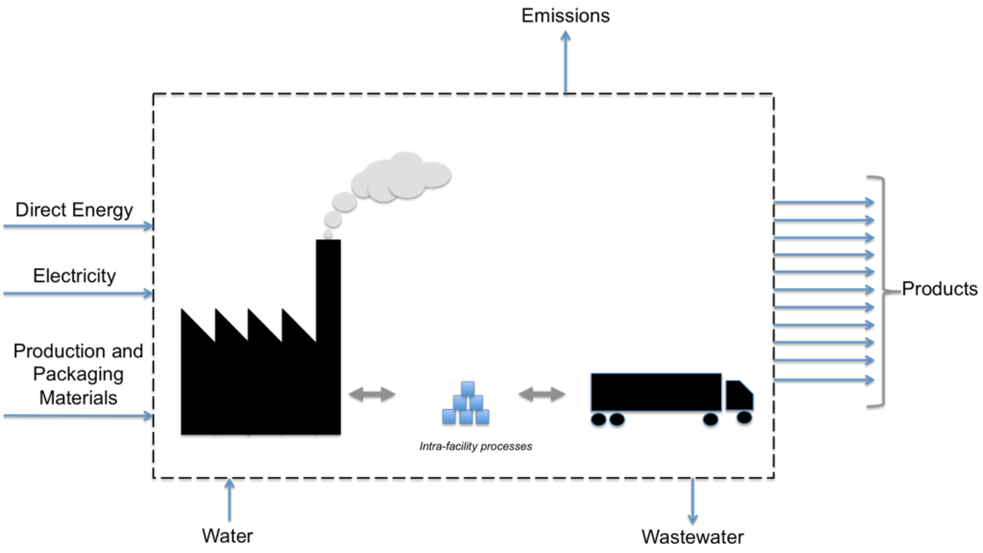


Figure 8 - Overview of Problem Supply Chain Boundaries and Metrics

Firms recognizing potential resource constraints can maximize this opportunity by designing effective environmental risk mitigation strategies (P. M. Clarkson, Li, Richardson, & Vasvari, 2011). This research investigates the environmental performance indicators of multi-national beverage manufacturer (MNBM). Relationships between production composition and firm-scale environmental performance are investigated as well as the production volumes, water usage, energy use, and CO_2 emissions.

Water Use in Manufacturing

Freshwater is vital to the industrial sector as it is a major direct and indirect input. Water is the main component in beverages and its production involves liters of water throughout the supply chain to create a liter of consumable product (Ercin, Aldaya, & Hoekstra, 2011). Globally, production of carbonated soft drinks uses an average of 2.02 liters per liter as of 2011. Even bottled water production uses more water than what is in the final product – an average of 1.47 liters of water per liter according to the Antea Group and BIER (2012).

Information is necessary in order to assess sustainable water use and ensure ecosystem health according to Blackhurst et al. (2010). Their study of direct and indirect water withdrawals in the U.S. industrial sector showed that only 5 percent of the all water withdrawals are attributed to self-supplied water to the industrial sector. It was pinpointed that the overall withdrawals worldwide are associated with the agricultural, food processing, and power generation sectors. Their study was limited in that it is EIO-LCA study on the national scale, and thus should combine process data of regions and plants with national averages.

There is a continued evolution in developing methodologies and indicators for water withdrawal impacts in the literature. Many of these methodologies quantified the volume of water instead of the system impacts (Jeswani & Azapagic, 2011). They also concluded that water stress indicators could mask large variations in geographically diverse countries and regions. Hence, Jeswani and Azapagic (2011) emphasized the need to include a spatial indicator in water impact models. These indicators become important because water availability can change over short distance as a consequence of both local and climate change (Lévová & Hauschild, 2011). Thus, there is a need for higher resolution indicators in water impact assessments; and, we include these recommendations into this study.

Energy in Manufacturing

Energy use in the industrial and manufacturing sector is important to investigate as this sector continuously grows. Studies predict that industrial energy growth will be on the order of four percent per year over the next three decades (Abdelaziz et al., 2011). This level of growth will lead to the industrial sectors energy consumption to be nearly equal the total energy consumed by all other sectors. EIA (2013) reported that industrial energy would reach nearly 324 EJ in 2040. With this level of consumption that will rely heavily on fossil fuel combustion, all industrial processes should strive for energy efficiency. Abdelaziz et al. (2011) found that 5 percent of the primary energy of all industrial sub-sectors is attributed to food and beverage industry. As the global population grows and developing countries advance their consumer power, consumption will grow in this sector.

The effects of the production mix on energy intensity have not been explicitly investigated in the literature. Studies such as Soytas and Sari (2007) showed that manufacturing and energy inputs are positively correlated using co-integration methods on national data. Mandal and Madheswaran (2011) analyzed a sub-sector of the industrial sector (cement production) to investigate inter-firm variations in energy use and energy efficiency using a data envelopment analysis. They show that different firms overall can significantly reduce their energy consumption by using costs- and emissions-minimization framework. However, this study did not conclude that intra-firm variation or differences in production composition in their analyses was a cause of environmental performance differences.

Emissions in Manufacturing

Greenhouse gas emissions have been heavily investigated in the industrial sectors. Emissions-intensity studies (Al-Ghandoor et al., 2008; Worrell et al., 2001) established that variation in the emissions per unit of energy was dependent on the power or primary energy source. The emissions intensities from the industrial sector have decreased significantly (Lim et al., 2009) and have been primarily linked to a reduction in energy intensities (Hammond & Norman, 2012; Plambeck, 2012). Yet, there is still a lack of research that reviews the problem of production composition and emission intensity.

Risks in Global Manufacturing

Manufacturing environmental risks have been investigated by previous authors and have tackled many issues from wastewater treatment, environmental performance competitiveness, financial investment, and occupational risks. However, there is a gap in the literature as many studies concentrated solely on water or energy efficiency improvement within industrial sectors. Investigations on the impacts of the production composition on the manufacturing facility are lacking as there has been no research that assess environmental performance and risks considering varying consumer demand.

This study evaluated risks in global manufacturing as the likelihood of loss or lack in supply of natural resources vital to firm production. This risk, as posited by Crichton (2001), was considered a function of hazard, exposure, and vulnerability, where the decrease in one of these factors limits the overall risk. These assessments are important in the mitigation potential financial losses caused from production disruptions, bad publicity in response to perceived environmental degradation, and demand change. This idea extends the insurance industry perspective into a framework more reflective of a manufacturing firm that need to understand the suitability of facilities and its supplies of water and energy resources, and potential emissions costs. Within this sector, the mitigation of supply chain risks is important, as there is high probability of natural resource supply constraints with expected atmospheric warming and weather pattern change due to climate change.

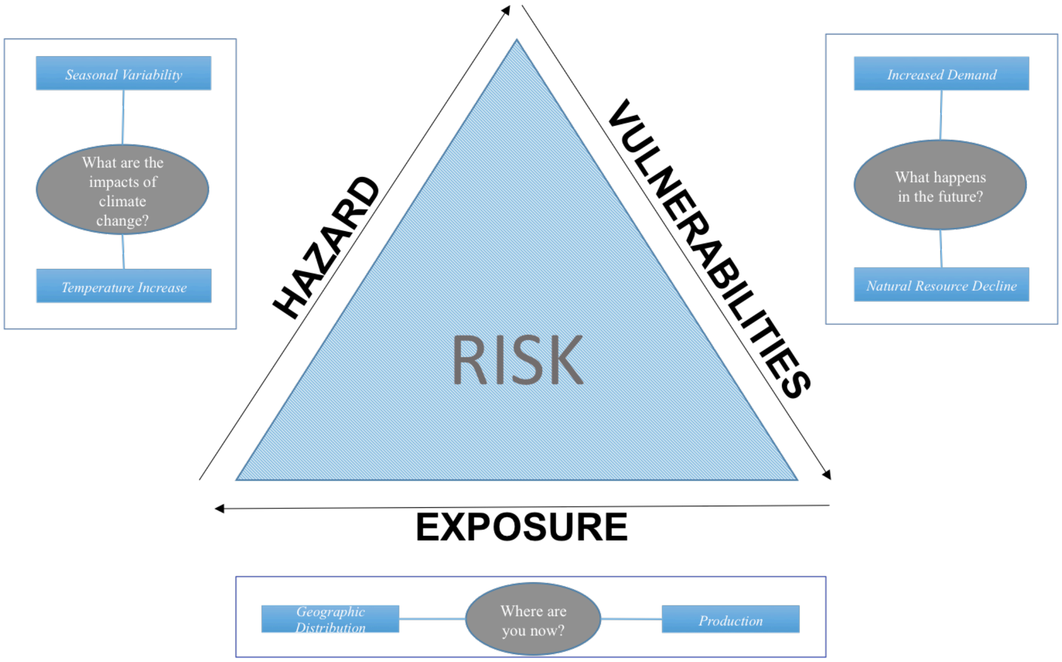


Figure 9. Climate Change Risk Framework for a Multinational Manufacturer developed from (Crichton, 2001)

Aim of Study

The aim of this paper was to introduce a methodological framework that firms, in general, use to evaluate overall risks to their facilities and natural resources vital to their supply chain. This research is important to firms with globally distributed production facing increased possibility of subsidence, floods, terrorism, disease outbreak, and extreme weather patterns. Further, this paper established a method to understand firm exposure and vulnerabilities in order to decrease their environmental risk related to water, energy, and greenhouse gas emissions.

This structure of this paper is as follows: Section 2 presents the methodological framework into developing environmental performance model. Section 3 and 4 provide a profile of the MNBM and its environmental performance indicators. Section 5 shows the results from the vulnerability analysis. The exposure assessment is discussed in Section 6. Section 7 and 8 summarizes the findings of this study and presents the conclusion, respectively.

Methodology

There are different options to assess the overall environmental performance of a firm. A common approach is lifecycle assessment (LCA). Lifecycle assessments are static analyses of the inputs and outputs of products, activities, or processes (Curran, 1993). For this analysis, an LCA is not applicable due to data constraints related to the lack of upstream and downstream information. LCA is out of this scope of work as this study works to create models that can be used in predictive analyses. While the firm maybe concerned about the overall supply chain, the firm metrics are constrained to boundary of the production facilities alone. Also, while studies such as (Hermann, Kroeze, & Jawjit, 2007) integrated regional assessment into their analysis, this study does not comprehensively assess ecological impacts due to limited watershed and environmental data. Multi-criteria assessment (MCA) is another form of environmental performance assessment that ranks different options of a firm. This practice works well for investigating the efficiency of policies at country level, impacts of energy policy, and assessing complex production processes (Zopounidis & Doumpos, 2002). This method is again out of scope since we are not assessing different policies or technologies at the plant level.

Environmental Performance Indicators (EPIs) are a powerful tool for gaining understanding of resource efficiency and have been discussed in the previous section. EPIs are important to the Environmental Performance Evaluation (EPE) tool. This tool provides firms the ability to reliable assess overtime its performance and compare them to firm goals (Jasch, 2000). These performance indicators allow overall generalizations of the firm performance through statistical analysis. This study analyzes environmental performance indicators of the firm product lines and facility locations via regression analysis.

We considered the role of product mix and geographic location in environmental performance, and we develop approaches for interpreting, evaluating and prioritizing environmental performance across hundreds of facilities worldwide. Previously, the product mix (or production mix) has been investigated primarily from a decision science and planning aspect. Researchers have used linear programming techniques to develop the optimal product mix of facilities by looking at capacity allocations (Chou & Hong, 2000). Other investigations have used activity-based costing (ABC): Kee and Schmidt (2000) used ABC to investigate the causal relationship between products and the production resources. However, there is little if any posterior environmental analyses on the role of product mix in environmental performance.

Yet, there is limited understanding on relationships between environmental performance variation and facility location. This analysis explored geographic differences and their association to environmental performance. Few studies are found that analyze the relationship between firm performance and geospatial composition. Molina-Morales (2002) found that corporate performance is linked to the globe scope of the firm. Luger and Evans (1988) determined that facilities within the same industry have performance differences related to geographic differences. Their study identified that production technology, labor, and practices are the cause of these differences.

Our research was conceptualized around a framework that establishes models that can estimate environmental performance of facilities respective of its production demand. This framework, shown in Figure 10, was built on knowing environmental targets of the firm and builds the appropriate environmental metrics for a specific firm. Subsequently, the statistical distributions of these metrics were evaluated in order to build models that estimate environmental risk and performance within a changing resource and demand landscape.

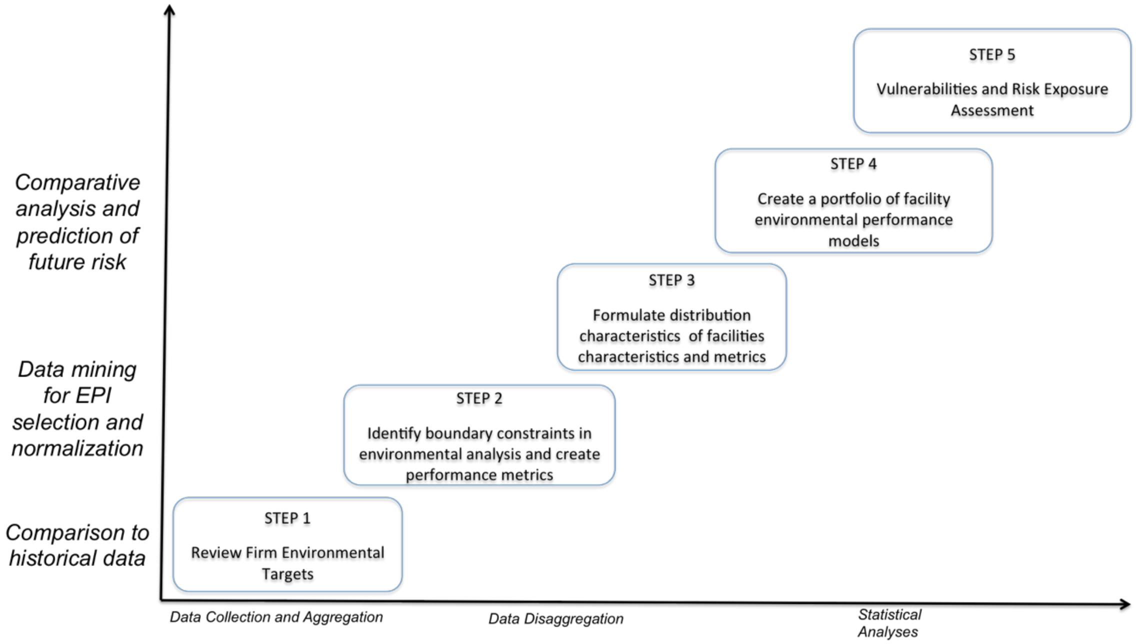


Figure 10 - Framework Diagram detailing procedural steps in environmental performance indicator (EPIs) statistical analysis

A methodological framework was established for evaluating the production composition and its subsequent effects on EPIs at the facility level. A five-step model was developed as a roadmap to these types of explorations, and applied to a case study here.

First step, after data attainment, was to understand the historical growth patterns of the firm, in both cases of sales and resource utilization. In this case study, we evaluated the historical volumetric growth of all product types. It was also important to develop trend lines for the aggregate water, energy and emissions of the firm. This step was in accordance with most analyses performed of CSR reporting.

The second step defined the life-cycle boundaries for the problem. In this case, the processes within the facilities served as the lifecycle analysis boundary. This became important as we considered the purpose of your models, which was to evaluate the production composition. In the creation of environmental metrics, data points were created that are normalized per unit output (i.e., water per liter of overall output product).

After the creation of such metrics, data was investigated for feasibility and any outliers were removed. These data required a transformation in which the compositional data needed to be transformed from dependent into independent variables (see Section 4). The data was evaluated to find additional indicators that incorporate known geospatial characteristics and performance clusters that could be a source of variation between facilities. Country-level development data was considered useful as it provided insight on facility performance and its relationship to management culture, workforce, and policy environment.

The third step was the characterization of the various variables found within the data. Sikdar (2004) distinguished environmental variable (which he calls a metric) classes – performance metrics versus content metrics. While content metrics are those that indicate the state of the system, performance metrics, which were the metrics used for this study, measure the behavior of the system. These metrics integrate the three aspects of the triple bottom-line theory of sustainable systems – economic, environmental, and social impacts. The combination of these factors is considered one-, two-, or three-dimensional if one, two or three factors are considered, respectively. For this study, the collected data are two-dimensional.

The data had economic and environmental aspects due the incorporation of sales volume and environmental resources (or waste). This was important because it created a functional unit for analysis that can be compared across all facilities and sub-firm level units. The normalized (per output volume) EPIs established for this case study were:

- Water Use (L / L): $\frac{Total\ Freshwater\ Intake}{Total\ Volume\ of\ Facility-made\ Products}$
- Energy Use (MJ / L): $\frac{Total\ Energy\ Expenditure}{Total\ Volume\ of\ Facility-made\ Products}$
- Emissions (g / L): $\frac{Scope\ 1\ Emissions+Scope\ 2\ Emissions}{Total\ Volume\ of\ Facility-made\ Products}$

Correlation plots were necessary in visual determining correlations between independent variables. It was hypothesized that within the facility boundary that there was similar water-energy nexus issues as there are with power production facilities. However, this was not the case, but provided an interesting exercise.

Regression analyses were performed considering the product mix. Compositional production data were used in this case study, which was treated appropriately as these data were not explicitly independent. Once these variables were transformed to an independent space, regressions were found using the EPIs are the dependent variables. The regressions took the general form found in Eq. **12**, where Φ_{EPI} was one of the environmental performance indicators and the dependent variable of the regression. $y_j$was a transformed variable related to the percent volume of a particular product category and $\mathrm{G}\widehat{(\otimes)}_{k}$ was a vector of dichotomous variables related to geographic locations and Z_k was a vector of facility characteristics variables containing interval data related to facility performance within the entire firm production system (i.e., in once case, the quartile in which a facility in located is dependent on how much production volume is produced at the facility). α_{EPI} , β_i, γ_j, and δ_k were the respective coefficients for the individual variables in the regression. The complete methodology and regression data are found in the previous chapter.

$$\mathbf{log}\,(\boldsymbol{\Phi}_{\mathbf{EPI}}) = \boldsymbol{\alpha}_{\mathbf{EPI}} + \sum_{\mathbf{i=1}}^{\mathbf{n-1}} \boldsymbol{\beta}_{\mathbf{i}} \cdot \mathbf{log}(\mathbf{y}_{\mathbf{i}}) + \sum_{\mathbf{j}} \boldsymbol{\gamma}_{\mathbf{j}} \cdot \mathbf{G}(\otimes)_{\mathbf{k}} \widehat{+ \sum_{\mathbf{k}}} \boldsymbol{\delta}_{\mathbf{k}} \cdot \mathbf{Z}_{\mathbf{k}} \qquad \text{Eq. 12}$$

The concluding step was to use the environmental performance models to assess vulnerability and exposure to environmental risk. External socio-ecological and socio-economic data were beneficial to this analysis as the potential effects of demographic and development patterns on firm performance were evaluated. The regression models were then used to investigate risk in manufacturing. Their results were then compared to the socio-ecological and socio-economic data to investigate firm exposure and vulnerabilities. Vulnerabilities were investigated throughout the production supply chain to provide qualitative and quantitative insights. The methodology was extended to explore the potential outcomes within highly vulnerable facilities of the production supply chain using the developed quantitative models.

Data

Facility Profile

This study utilized data from a MNBM based in the US. Its core markets are North America and Europe, but there is fast-growth within the markets in Asia, Africa, and South America. In order to fulfill demand in all of these regions, the MNBM has production facilities in over 100 countries that final primarily produce ready-to-serve beverage products.

Considering the potential growth of the core and developing markets, the MNBM plans to double its business over the next decade. It has not considered these plans without understanding its ecological footprint. It partnered with environmental organizations to create a sustainability plan including a net zero water use goal, reduction in packaging materials, and net zero growth of their carbon footprint.

This MNBM, however, faces headwinds in the global markets, as decreasing carbonated beverage sales will continue in some markets reducing revenues. However, these market declines do not outpace by the increasing growth. Much of this growth comes from developing economies that make it possible for more beverage consumption and urbanization, which will increase the demand of on-the-go, ready-to-drink beverage consumption. The company also has bottled water, juices, coffee, and teas within its product mix, which can potential stabilize revenues as consumers in some health conscious markets may possible shift from carbonated beverages to these products.

This firm for many years has developed sustainability reports that outline their water, energy and emissions for the entire firm. Notably, the MNBM wants to improve its water efficiency in product manufacturing and reduce the carbon footprint over the entire supply chain of its product.

The MNBM has facilities that are aggregated into 21 regional groups based on their geospatial distribution. Facilities within these groups are directly owned by the firm or owned by independent operators. These groups consist of firm-owned and non-firm-owned manufacturing facilities. However, these regional business groups and the facilities under their direction all work under the same guidelines and work towards the sustainability goals set forth by the firm. Data cleaning led to 778 facilities being analyzed across the 21 different regions all with different production compositions.

Table 7 - Production Facilities Global Distribution

Region	Number of Facilities
Asean	49
Brazil	42
Canada	7
Central & Southern Europe	47
Central East & West Africa	87
China &Korea	53
Germany	25
Iberia	15
Indian subcontinent	58
Japan	28
Central Latin America	40
Mexico	57
Middle East & North Africa	61
Northwest Europe & Nordics	22
Russia, Ukraine & Belarus	19
South Africa	16
South Latin America	37
South Pacific	23
Turkey	17
United States	75
Total	778

Environmental Metrics

All products are expected to have greater than one liter of water per liter of product, considering the loss of water due to evaporation, use for cleaning, etc., we used this value as a metric for statistical analysis. Although the product specifications would indicate a minimum energy requirement for production of a liter of product, this minimum energy requirement has not been determined and so we use this metric without a natural scale.

This emissions metric considers the amount of CO_2 emissions from the facility and from the electricity used by the facility per liter of product. We consider the minimum achievable value to be zero, which would correspond to a facility using non-carbon-based energy. This emissions ratio were a composite of the Scope 1 and 2 emissions.

The distributions found all three environmental performance indicators have lognormal distributions. Even though these distributions are deviate from normality, they can be used in regression analyses. Normality of the variables is not required for multivariate analysis; however, the lack of normality may degrade the solution. Positively, degradation is hindered when all variables exhibit the same type of skewness (Tabachnick et al., 2001). Therefore, a simple log-transform of the variable can be used to gain normality.

Environmental Performance Indicators

The product mix variables were not all statistically significant in the regression models. The production of carbonated beverage is significant ($p < 0.01$) in the water and energy models only. The coefficients are positive meaning that additional production of carbonated beverages increase water and energy consumption.

The most notable variable within the regression was the variable corresponding to the production of coffee and tea productions. This variable was highly significant ($p <$

0.01) in all three regressions. Their coefficients showed that the additional coffee and tea production contributes heavily to the resource consumption [ratio] in comparison to any of the other coefficients of statistically significant variables. This result was not completely surprising. In the preliminary analysis and discussions with management, it was hypothesized that the coffee and tea production may negatively impact (increase) resource consumption, especially water and energy. It was believed that increased water use stemmed from possible losses during brewing from hot water boiling, and water absorption into grinds and leaves. The increase energy in coffee and tea production was due to the high heat input needed for water boiling. This synergy is extended further into the model as the geospatial indicator for facilities in Japan is found to be statistically significant in the water model. In a further quantitative analysis, it was found that there were high levels of production of coffee and tea products in this region/business unit.

The geospatial variables were statistically significant in the regressions as well. In all cases except for facilities in the Japan and Russia, the coefficients for statistically significant variables were negative, meaning that the presence of the facility in a particular region leads to a reduction in its resource consumption impact. While it is not exactly clear as to why these coefficients are negative, it was believed that it is due to the production characteristics of the facilities in the region; consumer demand for products; or, management practices of the regional business unit. Facility technology may play a role in how well some facilities perform to the baseline goals. If technology within the plant was old or inefficient, it may affect the facility's emissions and energy performance.

Vulnerability Assessment

The level of vulnerability of a subject was a function of its susceptibility to harm from exposure to stresses associated with environmental and social change from the absence of adaptive capacity (Adger, 2006). In relation to manufacturing, vulnerability of manufacturing was examined in previous literature by (Clark, Kaserman, & Mayo, 1990; Haywood & Peck, 2003; Sapountzaki, 2005; Wagner & Neshat, 2010). Much of this literature focused on manufacturing resilience related to disruptions caused by natural disasters, civil conflict, supply chain breakdowns, etc. There has been no literature found that focuses on climate change as a hazard to a firm related to changes in environmental performance and evaluates the vulnerabilities that lie both in the present and future. We investigated the accumulation or loss of socio-ecological elements that influence vulnerability.

External socio-ecological indicators were used in the investigation of the effects of development and environmental awareness on facility environmental performance at the country level. The facility geo-coordinates were mapped into the independently-developed water risk assessment model Aqueduct (Reig, Shiao, & Gassert, 2013). From this model, data was provided on the physical and regulatory risk of water resources. The high-resolution data provided a pathway to understanding the current water constraints of facilities and provides an indicator of future water risk.

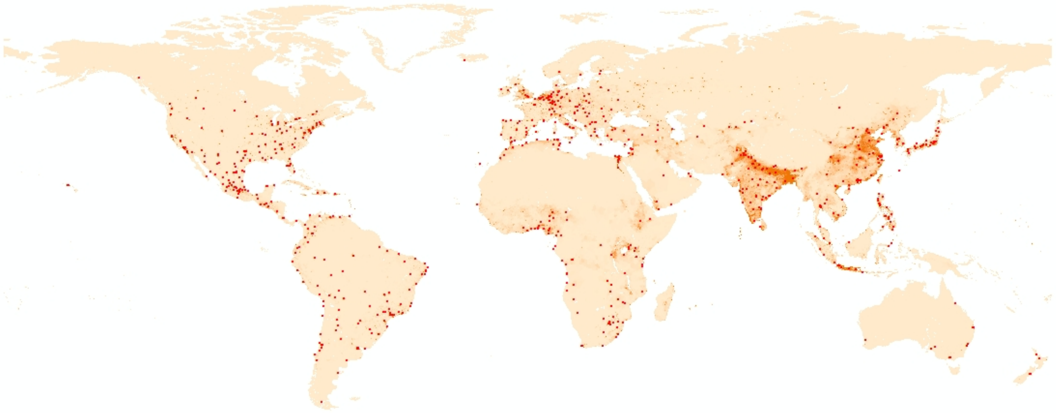


Figure 11 - Production Facilities across the entire MNBM. A map was generated showing the facilities and population density (orange color). The polygons of urban (metropolitan) areaswere overlaid in the mapping and show as purple polygons, but are not visible due to the scale of the map. The GIS data are from NASA, CIESIN, and CIAT (2005) and Natural Earth (2009).

Country-scale characterizations (e.g., policy and performance indexes) quantitatively reflect the current environmental direction of policy and practice within a country; their use in environmental performance analyses may reveal apparent or unrevealed trends. The UN Human Development Index (HDI) data were used to establish a connection to facility management and facility inefficiencies. Other studies such as Neumayer (2012) linked the HDI to sustainability. The Yale Environmental Performance Index (EnvPI) were to match facilities to match facilities to the overall environmental ideology and actions of their country; this index in particular of investigating not only on the current environmental state of countries, but incorporates the environmental trends over the last five years into the indices (J.W. Emerson, 2012). Using these two indicators, we furthered this methodology to understand the character of individual manufacturing facilities to observed outcomes such as the management practices and beliefs in matters of CSR (Aguinis and Glavas (2012); Basu and Palazzo (2008)).

It was understood that the data points of HDI and EnvPIs do not have high geospatial resolution to give specifics to each facility. Yet, it was recognized that analyses these lower level entities (facilities) are nested within higher level collectives and thus have some correlation. This type of multilevel corporate sustainability research is discussed in Aguinis and Glavas (2012). It was not expected to have complete one-to-one relationship between these variables as we expect some co-variation between them. Higher resolution geospatial indicators were used in the investigation to find correlations between the environments surrounding the facilities. GIS shapefiles were used to match respective population density estimates to the production facilities as well as to a dichotomous variable relating the facilities presence within an urban area. The GIS data was obtained from NASA et al. (2005) and Natural Earth (2009) with a 2.5' min raster resolution; the data is shown in Figure 11.

Trends in Water

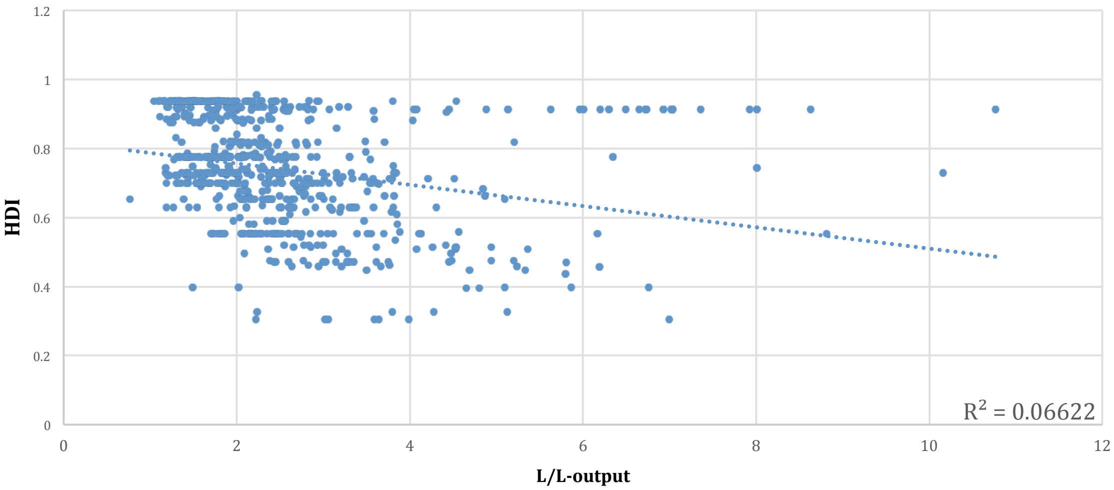


Figure 12 - 2012 HDI valuescompared to facility water ratio values

This macro-level analysis revealed no correlations between the HDIs and facility water usage. It was initially posited in this analysis that facilities in countries with strong educational systems, healthcare, and finances will perform significantly better in terms of environmental performance than facilities that are not based on considering the analyses of Dasgupta, Hettige, and Wheeler (2000). The analysis showed significant scatter in bivariate plots and no linear trend. It was assumed that the national environmental performance would correlate to the performance at the facility level; however, this was not the case ($R^2 = 0.06$). Further analysis indicated that countries higher on the index could be skewing a possible linear relationship between the HDI and the water usage in facilities located in countries with lower HDI ranking (HDI < 0.8). The facilities located in "very high performing" countries - countries that have scores between 0.8 and 1.0 as defined by the UN Development Programme – were removed from a secondary regression analysis and were plotted in Figure 13; a correlation was found ($R^2=0.28$).

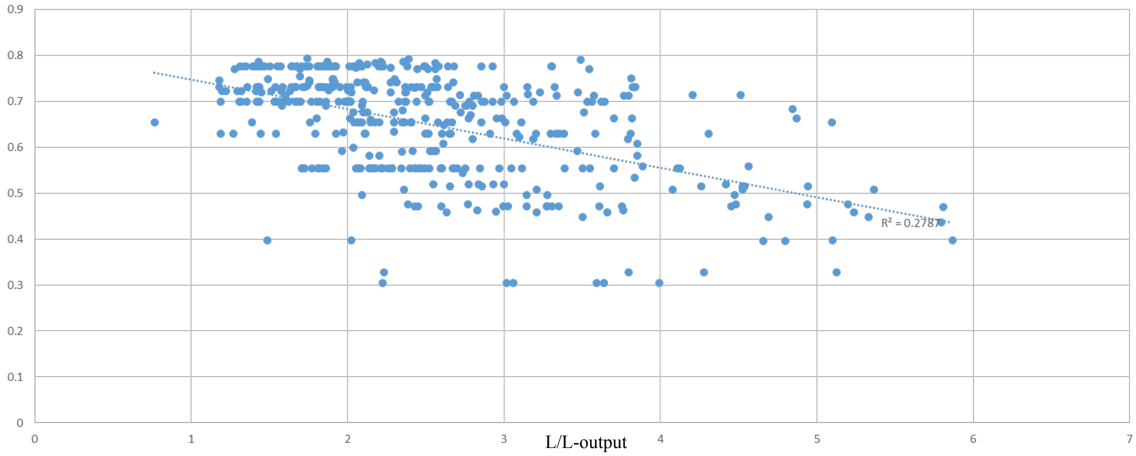


Figure 13 – HDI compared to Facility Water Ratios without "Very High Performing" Countries on the HDI Index (Values 0.8 – 1.0)

Figure 14 shows the overall water risk index in comparison to facility water use. This graph revealed that the distribution of water use exhibited less variance as the water scarcity increases. Outside of the four facilities that have a water risk index of 1 (these facilities are located in South America near the rainforest), the distributions as the water risk index increased decrease in terms of the average water ratio. Hence, facilities operating in water scarce locations have greater water efficiency in their production in comparison to their counterparts. These facilities most likely have better operating performance as they have considerably less dispersion within their distribution. There were some major outliers (*N=21*) that have water use intensities over 6 L per L of output volume (shown in Figure 13). But, overall, it was assumed that most of the water-intensive facilities are operating in water-abundant locations.

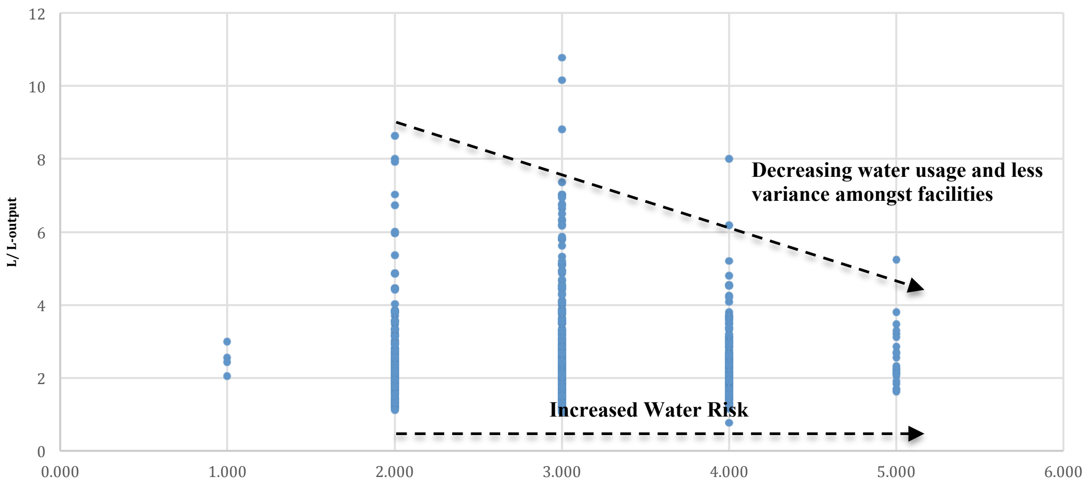


Figure 14 - Water Ratio and Overall Water Risk

Correlations between water efficiency and the urban geospatial indicators and population densities were investigated. Water use in urban areas was slightly higher than in non-urban/rural areas by 7 percent. This was unexpected as water use in urban areas was expected to be lower in areas where there would likely be more competition for water. Further analyses found that water use in urban areas in water scarce or high risk (risk level 4 and 5) areas was approximately 10 percent less than the average of all urban facilities. This may highlight a potential casual relationship similar to the results found in Figure 14 that shows water efficiency improved as water became scarcer or has increased competition for it. However, rural facilities with water high risk are approximately 10 percent less efficient compared to its urban counterpart. In relation to the product mix, these facilities in non-urban/rural areas manufactured other beverage products that were less water dependent in regression analyses. This relationship potentially reveals that management or facility technology in rural areas may be impeding environmental performance.

Ownership appears to be an indicator in water efficiency improvement. Overall, firm ownership in comparison to independent bottling operators (the smaller “Mom and Pop” operations) showed a 20 percent improvement in water efficiency with production mix being nearly constant. This relationship held true for facilities under firm ownership in urban and water scarce areas locations. It was expected that water efficiency would have an inverse relationship with the population density data. However, population density showed no correlation with water efficiency in the regressions.

Trends in Energy

The same external indicators were used to investigate energy. Again, the analysis did not reveal any significant relationships with the HDI and EnvPI indices. The regressions did not suggest any influence or significance of the variable ($R^2=0.057$). In the case of energy, the analysis showed a large distribution within the water intensity ratio data points of facilities located in very high performing countries. These data were removed in a subsequent analysis as well; however, no correlations or detection of possible influence were revealed.

Surprisingly, the energy ratio data were not correlated with the EnvPIs of their respective country. The results are found in the Appendix (Figure 47 and Figure 48). The data had a large amount of scatter and exhibited a slight negative linear trend. However, this finding was not understood to mean that the energy performance of the facilities improved with environmental progress and action in its respective country.

Trends in CO_2 Emissions

Carbon dioxide emissions were investigated at the country-level in order to understand if carbon emissions improvements (or increases) may possibly be attributed to changes within in the electricity grid and not due to facility improvements. While the emissions ratio at the facility-level consist of natural gas, electricity, renewables, and other fuel sources, these facilities primarily used electricity from national grids.

Country-level emissions per liter output ratio averages were aggregated considering all facilities in each country for the years 2004 and 2011. The percent difference between production years 2004 and 2011 were found and compared to the percent change in electricity emissions per kWh at the country level. The country-level data were found in (IEA, 2012). It was posited initially that the changes at the facility-level would match that at the country level, and would thus create a linear pattern of improvement. However, no patterns (or subsequent significant regression) were found in the data. There is significant dispersion in the data, which is shown in Figure 15. In some cases, significant improvements at the facility-level were found, but there were still significant increases in the emissions per kWh. Therefore, it was assumed in these cases that the facilities are improving (or worsening) due to their own internal management and operational practices.

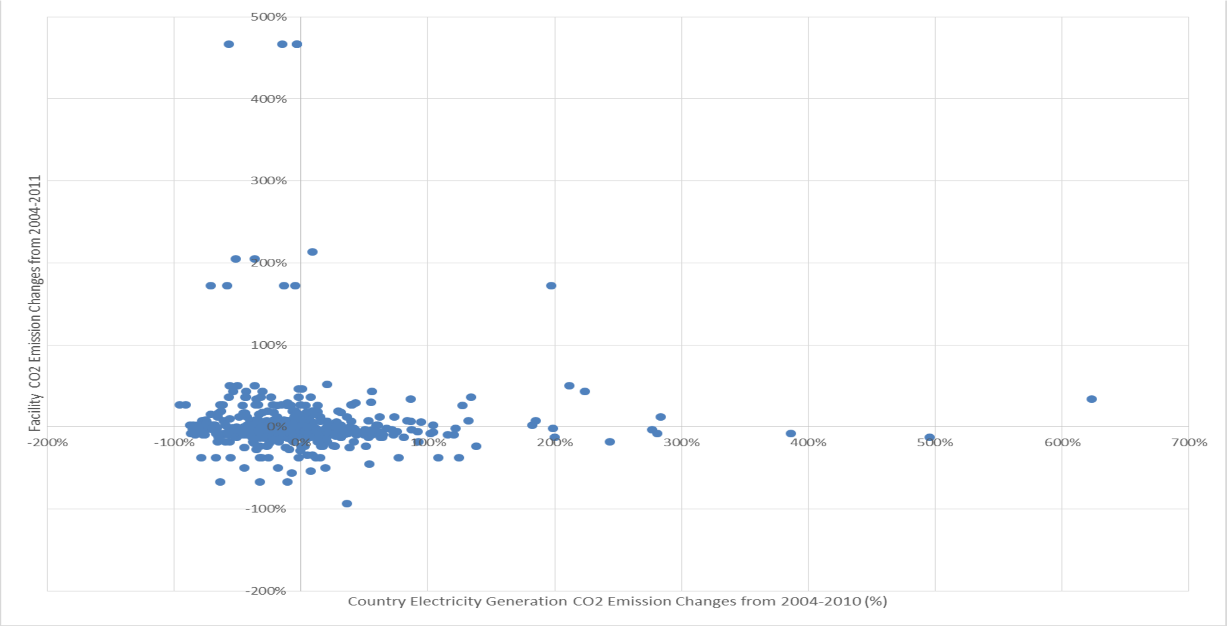


Figure 15 – Facility Average Emissions Ratio (Aggregated by Country) and Estimated Country Carbon Dioxide Emissions

Risks and Exposure Assessment

Geospatial Distribution of Risk

There were variety of risks that plague the beverage and overall agricultural industry. Many of these risks have been related to overall natural resource risk, in particular water. Water is important as the main ingredient in beverage products and a vital component in the production of beverage additives like the sugar and flavorings. The water supply for production is not just at risk from climate change as there is competition to firms from human needs. Firms have a strenuous challenge of trying to mitigate this risk while being able to access depleting (or strained) water resources important to their product supply chains. However, on the positive side, Mirasgedis, Georgopoulou, Sarafidis, Papagiannaki, and Lalas (2013) found that climate change can have a positive effects on the sales on carbonated and non-alcoholic beverages. This poses a challenge to beverage firms because of water's rising resource scarcity and competition.

Competition within watersheds will come from other industrial organization, water supply and sanitation systems, tourism, energy, agriculture, and settlements (Kundzewicz et al., 2008). Urban areas are faced with a challenge, as many of its citizens will be competing for massive amounts of water resources. Cities typically desire economic growth brought on by industrial development and consumer expenditure increases, all of which put stress of urban water infrastructure (Bettencourt, Lobo, Helbing, Kühnert, & West, 2007). However, this type of growth should be approached with caution as firms may face the challenge of satisfying their demand. This risk is compounded by social and economic factors such as increased water rates, water abuse public relations, and potential geo-physical factors that limit (in particular) urban systems from access water sources many kilometers away.

Environmental risks associated with this beverage firm were investigated through exploring urban location, firm ownership, and water scarcity. Facilities in urban locations did not necessarily show a difference in water and energy efficiency from their non-urban/rural counterparts. The urban facilities showed opportunities for improvement in their emissions efficiency, as they are nearly 20 percent higher than those facilities in non-urban/rural areas. The differences here were harder to attribute to any one source.

Firm ownership was a significant indicator in water performance. The results showed that water efficiency was nearly 20 percent lower in facilities that are wholly owned by the MNBM than those facilities owned by independent bottling operators. In a more detailed inspection of production, the MNBM-owned facilities had a nearly comparable production composition than the independent operators. Considering this result, there were opportunities for limiting vulnerabilities within the supply chain in the future. Energy and emissions performance between MNBM-owned and independent operators had no significant differences.

Urban and non-urban areas showed differences in emissions intensity of production facilities with urban-located facilities performing approximately 10 percent worse than those facilities located in non-urban and rural areas. Their average production composition varies with the urban-located facilities producing more carbonated beverage products and less juice, coffee, tea, and consumer water products. Thus, it is expected considering the regression analysis that the emissions would be greater in urban-facilities.

Water scarcity was evaluated using overlay Aqueduct and GIS data. Nearly 25 percent of the facilities are located in high-risk areas for water scarcity. The index was on a scale from 1 to 5. This study considered low-risk areas as having a risk index from 1 to 3 and high-risk with an index of 4 and 5. Facilities located in these high-risk areas performed approximately 10 percent better than those in low-risk areas. Figure 9 provides more insight on this result as it charts the facility water performance with its respective water indices. However, much of this improved performance was attributed to the production mix favoring higher water-intensive product.

Demand Changes

Other risks stem from demand changes in the consumer palette. There has been growing concern amongst beverage consumers about the risks associated with high fructose corn syrup and caffeine. Considering these health and obesity awareness factors into the daily nutritional lives of consumers, there has been a shift in demand across the entire production mix within the beverage industry. According to (Weissmann, 2012), soda sales in the US have dropped by 16 percent. In response to these changes in demand, companies like PepsiCo, Dr. Pepper Snapple, and Coca-Cola have increasingly relied on other non-carbonated products like bottled water, tea, and sports drinks. Yet, the change in demand does not spell the demise of this product category as carbonated beverage sales are continuing to have strong growth in other regions of the world (Esterl, 2013).

From the above investigation, the Middle East & North Africa and the Indian Subcontinent were found to be the regions most at-risk from water stress and resource depletion due to climate change. These regions are investigated along as well as the United States. The entire firm was investigated within this exercise to understand overall environmental impacts to demand change.

Using the environmental performance regressions discussed in Section 2, future demand change was investigated. The compositional data of production volumes attributed to various product lines were analyzed by region and the average production compositions are found. These data were used to represent the current base line for the average production facility in the regression models. These compositions were altered to reflect the changing demand within product lines over a 5-year and 10-year period. Publicly available market growth data from the MNBM was used to estimate these compositional demand changes within the entire system. As discussed previously, the product demand projections showed a consumer palette movement from carbonated beverage products and a movement to juice, tea, coffee, and consumer water products. These data were omitted to maintain confidentiality.

The compositions reflective of projected demand change were applied to the regressions and the environmental performance estimates for water, energy, and emissions were found. A Monte Carlo simulation was used to estimate the EPI range assuming a standard deviation in 1% volumetric growth. The EPI regression estimates using the current demand were compared to those generated with the new demand scenarios. The difference in EPI across the two demand compositions was calculated. Since this difference accounts for the difference in usage per liter of final beverage, the projected yearly sales projections were applied to these estimates in order to calculate the overall environmental impact within five and ten years. These estimates are presented in Table 8.

Table 8 – Environmental Performance Estimates considering demand changes within specific regional groups and within the MNBM production system.

	Demand Response	**5-year Growth** *(in Million Liters)*	**10-year Growth**

WATER	Δ L/L	*Low*	*High*	*Low*	*High*
Indian Subcontinent	0.14	764	882	1,072	1,237
Middle East & North Africa	0.115	906	988	1,270	1,386
US	0.005	0	202	0	212
Firm Level	0.03	3,537	7,073	4,303	8,606
ENERGY	Δ MJ/L	*(in Million GJ)*			
Indian Subcontinent	0.21	1.12	1.35	1.57	1.90
Middle East & North Africa	0.215	1.65	1.89	2.31	2.66
US	0.01	0.00	0.40	0.00	0.42
Firm Level	0.0144	1.66	3.43	2.02	4.17
EMISSIONS	Δ g/L	*(in kilo metric tons)*			
Indian Subcontinent	19.9	52.6	64.4	73.8	90.3
Middle East & North Africa	31.05	121	135	169	189
US	9.585	3.0	190	3.2	200
Firm Level	(14.25)	(1,370)	(1,149)	(1,667)	(1,398)

The results from this analysis showed that the demand shift produces negative environmental penalties for the firm by using more water and energy as well increasing the amount of emitted CO_2. However, in the case of the firm, the CO_2 emissions decreased as a whole. These findings were troubling as it is points to the increased water stress and more rapid water resource depletion due to firm production in the areas. The increased use of energy does not have immediate impacts on the surroundings, but the future energy costs could impact the profit of the MNBM.

Discussion

The vulnerability analysis highlights the current environmental performance at the facility-scale considering socio-ecological and socio-economic variables. The results showed that the water risk index has association with increased water efficiency in facilities. This may show that firm management may inherently understand water risk that they either move production of water-intensive product to areas where there is less water risks. It could also mean that water resource constraints have forced these facilities to adopt better conservation procedure. This hypothesis seems plausible from the results in Figure 14, which shows decreased water usage mean and variance conditioned upon increased water risk.

The socio-ecological and socio-economic data (UN HDI and EnvPI) provided interesting insight into the association environmental performance between country-level economic, social, and environmental development. The analysis of the HDI had mixed results. An analysis including all levels of development did not show a direct relationship with environmental performance. Yet, further investigation showed that the indexed highly developed countries skew any potential association due the large amount variance in water usage and energy efficiency of the plants. The large variance within the water ratio distribution of "very high performing" countries is not surprising. When we consider the literature on these environment attitude and economic development (i.e., Environmental Kuznets's Curve), these facilities located in these countries would be expected to have worsening water ratio values as environmentalism is tabled in lieu of higher consumption. There was some association to economic, education, and health development when developing and those aspiring to be highly developed countries were only considered.

The EnvPI was used to find associations with facility performance and country-level environmental policy, performance, and practice. However, this index did not provide any explanatory insight as to why some facilities have better environmental performance. This was surprising as this index provides a direct quantitative reference point to country-level environmental attitudes. After much though, it was assumed that the index may aggregate country-level factors that out of the scope of this analysis and may not be the best gauge for facility-level investigations.

Emissions performance and vulnerability were explored by investigating their association to country-level electricity emissions changes. Temporal data was used in the only exercise due to its availability, which proved to be fruitful in that it showed that most of the facilities environmental performance improvements were not associated with environmental performance improvements of electricity generation in the country. This was understood by having no positive linear trend in the data, which would suggest that there was a unique relationship between plant emissions and emissions from electricity generation.

This analysis pointed to considerable vulnerabilities in emissions performance of the facilities. The results showed that some of the facilities are making progress in reducing their environmental liabilities (risk) related to CO_2 emissions. But, nearly half of all of the facilities had worsening emissions performance and nearly half of those facilities had worsening emissions performance in countries that have improved electricity generation. While there is considerable vulnerability and exposure due to potential economic and social risks it showed that there are opportunities to improve performance at the firm level and at individual facilities. Generally, this result showed that facilities do not receive the complete environmental benefit from electricity generation emission reductions at the country scale.

Urban-located facilities composed nearly 65 percent of all of the firm facilities. Environmental risks from water and energy use were not exacerbated by facilities being located in urban areas in comparison to the rest of the MNBM production system. Conversely, there was a near 20 percent difference in emissions performance exists between urban and non-urban facilities with no production composition differences; urban facilities performed worse than those in non-urban locations.

The initial hypothesis was that facilities in urban locations would have increased environmental risks due to increased competition with growing populations and increased water scarcity. Urban populations have been found to be more worried about pollution issues than rural populations (Berenguer, Corraliza, & Martín, 2005). Thus, firms have risks from urban populations being worried about water withdrawal, water quality, local emissions, and potentially energy disruptions being caused by these facilities. These results did not show a direct contribution to natural resource risks. Yet, they showed potential distribution and facility location risks as these facilities may face additional scrutiny from local constituents.

The impact of future demand growth showed that emissions were not a significant risk. Typically, city dwellers would directly contribute local air pollution to having these production facilities via close proximity. However, the “smoke stack” issue is not a contributing factor to risks in this case because urban dwellers would not have visuals of pollution being emitted into the atmosphere from the MNBM facilities (Berenguer et al., 2005). The majority of greenhouse gases, in most cases, are attributed to their electricity usage, which is produced off-site. However, these issues may exists as risks when these facilities are burning natural gas or oil at their facilities.

Future demand growth and change in composition increased the water withdrawals and overall energy use. Yet, there was concern because water withdrawals will increase as demand requires more water use overall; thus, these facilities will have to face social and environmental implications related to accusations of water grabbing and contributing to water scarcity, especially if they are located in urban and dry regions (Rulli, Saviori, & D’Odorico, 2013). These firms may want to investigate the watershed surrounding their facilities are located and develop goals that include the community, firm, and the region so that social and physical environmental risks are mitigated (Winston, 2014). The association between population density and facility environmental performance was investigated as well, but no association was found. Therefore, it can be assumed that urban location and population density are not significant factors in the prediction of environmental performance.

Firm ownership was not a significant indicator of changing energy and emissions performance. However, MNBM-owned facilities had a 20 percent lower water usage in comparison to independently owned producers. There were no differences between their mean production compositions. This insight is helpful in risk mitigation strategy and closing the efficiency gaps between facilities. The MNBM has been acquiring independent operations for strategic supply chain and profitability objectives. However, research from Berchicci, Dowell, and King (2012) found that these types of acquisitions will create new efficiencies in formerly independent facilities with the transfer of environmental capabilities. Thus, there is a possibility to improve water use efficiency by 20 percent at these facilities that constitute nearly 25 percent of all of the production facilities in the MNBM. Other improvements may potentially come from increasing efficiencies in non-MNBM facilities, which are most likely small- and medium-sized enterprises (SMEs). The literature suggests that these firms have a significant barriers to implementing conservation efforts as they face issues related to risk of production disruptions, lack of financing, data limitations from the lack of sub-metering, and other facility priorities. Firms overall may weigh these considerations as the develop environmental performance plans across their production systems (Cagno & Trianni, 2013).

The investigations into vulnerabilities allowed this study to further investigate risk exposure in the firm. It was investigated from the standpoint of wanting to understand how future demand changes would impact environmental performance as a whole. In particular, this study explored changes within water withdrawals, energy use, and emissions of greenhouse gases. The MNBM exposure is investigated along with the US and its two most water vulnerable regions - Middle East & North Africa and Indian subcontinent.

Even if firms push to pivot and push innovation and management in facilities, considerable risk can come from changing demand; hence, it was explored in this study. Consumer demand has been changing recently as consumers are choosing juice, tea, coffee, and bottled water beverages over carbonated beverages. Using public data on the expected demand trends, the results showed that at the firm level consumer trends that favor other beverage products over carbonated beverages may lead to increased water and energy usage per liter. The emissions surprisingly decrease at the firm level.

In the case of the US, Middle East & North Africa, and Indian subcontinent, the environmental performance worsened. This exercise in the case of the two most vulnerable regions showed that the firm may need to investigate options that would limit potential supply chain disruptions. Investments in desalination at coastal locations or marketing to encourage demand of more water efficient products have potential to lower their water risks, but could encourage an increase in their energy usage or emissions per liter as already shown in the above exercise. Supply chain schemes where final beverage products are imported from water rich areas may potentially mitigate risks. This type of production shifts across industries, which has occurred with greenhouse gas emissions ("carbon leakage"), as there are increased prices and resource constraints of water and energy (Backlund, Thollander, Palm, & Ottosson, 2012). There are considerable risks to extremely water-dependent firms considering this option as it adds to the complexity of virtual water distribution (Biro, 2012).

Firms that are explicitly dependent on water as the main component of their products will be in an intense competition with agriculture, electric power generation, and human society due to climate change. However, it has been claimed that climate change may improve profitability for the beverage industry as temperatures rise in the long-term. Blom (2009) investigated the weather risk derivatives of the beverage market. His revenue hedging research finds that as temperatures increase beverage sales increase such that for every 1°C increase has historically caused a 3.4% growth in beverage demand in his study of a Norwegian brewer. Considering this finding, in the case of a 2°C increase in global climate change, which has been predicted from most climate models, the MNBM may use an additional 600 million liters of water each year on top of the predicted water use considering demand and growth projections (National Resarch Council of the National Academies, 2011).

Some regions such as the Middle East and Northern Africa are expecting even high temperatures than the baseline estimates (World Bank, 2013a). This poses considerable for this firm as others as this region has the least amount of renewable resources and arable land (Sowers & Weinthal, 2010). Many production firms, particularly those in the food and beverage industry, should be concerned with the potential supply chain disruption due to increased water withdrawal, water scarcity, and increased consumer demand for beverage products due to rising temperatures. Further investigations should investigate the impact of these interactions as well as address the adaptive capacity of individual firms and industries.

None of the delineators in this assessment highlighted differences in energy consumption. However, this case study at least brought attention to the growing energy use of the firm due to increased demand and product mix changes. Backlund et al. (2012) claimed that the present technical efficiency gap create opportunities for nearly 25 percent reductions in energy use in firms. With the addition of component of a knowledge workforce guided by energy management practices will add to that reduction (Thollander & Ottosson, 2010).

Conclusions

A methodological framework was established to study firm-scale environmental performance that can predict the environmental efficiency of production facilities based on its production composition. A regression analysis using compositional production data was adopted to provide insight into associations between facility-level environmental performance and risk. From our best knowledge, this is one of the first approaches to understanding production composition in facilities and the potential risks related to climate change.

This analysis adds to firms' ability to account for environmental performance and degradation as well as assess potential risk in locations where climate change may affect the availability of production resources (i.e., water and energy). Thus, it is a tool for understanding risk and maintaining competitive advantage.

There were limitations to this research, as it did not explore the entire lifecycle of the supply chain. It is an investigation of production facilities within a firm. An opportunity was missed with not being able to do an upstream and downstream analysis on the supply chain. In beverage production, the upstream production of agricultural products and basic ingredients has significant resources inputs. These inputs can lead to higher resource efficiency ratios related to water, energy, and emissions. The lack of knowledge of the different technologies used at the various facilities was also a limitation. There was no data on equipment differences to include in the environmental performance models. It was assumed that the technology across plants was similar due to the desire to have consistent product quality across the MNBM system. However, as investigated here, it was shown that there were significant differences between MNBM-owned and independent operations and, outside of management structure and culture, technology differences may prove a significant indicator of environmental performance. Future studies should investigate these possibilities.

CHAPTER 4

AGENT-BASED MODELING OF ENERGY CHOICES AND DEMAND IN THE RESIDENTIAL SECTOR OF DEVELOPING ECONOMIES: A CASE STUDY OF SOUTH AFRICA

Introduction

Developing countries struggle with the balance of providing low-cost energy benefits and developing in an environmentally sustainable way. In doing so, these countries also struggle with the need to promote economic growth and provide low-cost energy to their citizens and businesses. Providing electric power at the household level presents the challenge not only of balancing cost, sustainability and supply, but also micro-level considerations of household demand, choices, and responses to prices.

Many households in developing countries use different fuel sources outside of electricity to meet their energy needs. While access to electricity services may be a challenge, an individual's personal cost of using electricity (i.e., the cost of grid connection, appliances, and everyday electricity usage) may prevent them from using electricity services (Louw, Conradie, Howells, & Dekenah, 2008). (Davis, 1998b; Thom, 2000) point out the important role of paraffin, especially in low-income, rural, electrified households, as a fuel for cooking and water heating. They find that many households consider paraffin to be cheaper than electricity, and therefore continue to use paraffin even though there may not be a cost differential between the two fuels. Transitioning from indigenous fuels to more conventional fuels is a challenge that is primarily influenced by income. These socio-economic issues challenge the universality of the electric power system, create uncertainty in demand planning, and create a barrier for determining specific and effective policy.

The household transition to electricity in developing countries tends be associated with a shift away from wood and kerosene toward electricity in rural areas (Davis, 1998b). These transitions can occur in both rural and urban households. Other studies have investigated the electricity demand in developing countries using aggregate country-level data (Amusa, Amusa, & Mabugu, 2009; Inglesi, 2010; Ziramba, 2008). Here we provide a new contribution by examining household energy demand issues at the micro-scale and considering the heterogeneity of ideas and behaviors within households across different socio-economic levels and location.

The price of electricity affects the amount of electricity that is consumed by households and their elasticities are negative (Cassim, Ewinyu, & Sithebe, 2012; Inglesi, 2010). These households may tire of the large expenditures on electricity service, which also may have inconsistent delivery, and may switch to lower cost fuels in order to decrease their household expenses. Households may have to search out other fuel sources (such as firewood) or expose themselves to toxic vapors. This environment creates situations where protests may occur. Protests are frequent and may be violent in some developing countries (Dolley, 2014; Krasimirov, 2013; Z News, 2014; Zhong, 2014).

Considering these issues, we develop an agent-based model (ABM) to investigate the interactions of energy pricing and consumption of individual households and its implications for aggregate country-level demand in the future. We examine the effect of (*i*) electricity prices, (*ii*) response to energy policy, (*iii*) agent grievances, and (*iv*) social interactions on agent behavior related to electricity usage in a case study of South Africa. These results are used to calculate aggregate energy demand from the residential sector from both electricity and traditional fuels sources as well as the aggregate greenhouse emissions.

This paper is organized as follows. Section 2 contains an overview of energy use in South Africa and a review of research on household energy choices. Section 3 discusses the agent-based model framework. Section 4 presents results of the model. The applications of results are discussed in Section 5 followed by the conclusion in Section 6.

Electricity Consumption – A case study of South Africa

For South Africa and other developing countries, household energy choices are not only tied to social and economic growth, but also to national energy security. South Africa relies heavily on its own coal resources to produce electricity and for the creation of its liquid fuels. Currently, the only energy diversification comes from importing natural gas from Mozambique and imported petroleum from the Middle East. Considering potentially rising fossil fuel prices and enviro-economic penalties in the future, South Africa's energy portfolio poses some risks, as it has one of the highest energy and greenhouse gas intensities in the world (Energy Research Centre, 2009).

In its National Strategy for Sustainable Development and Action Plan, South Africa outlines its approach to stabilization of greenhouse gases (GHG) in the atmosphere by contributing its "fair" share (SA Department of Environmental Affairs, 2011). It is acknowledged that are eminent developmental challenges of providing energy and basic services to its population; all of which contribute to growing GHG emissions. In spite of this, South Africa has outlined a goal of reducing GHG emissions by 34 percent by 2020 and by 42 percent by 2025. However, developing renewable energy systems is characterized as not an affordable and is not always believed to be a necessity for economic development. The pricing of electricity and other basic services has been a contentious issue in South Africa and the cause of an increasing number of protests (Berazneva & Lee, 2013; Dolley, 2014; Ngwane, 2014).

South Africa is a developing country still struggling with many of the economic and social effects stemming from its Apartheid era. The country is still considered to be divided into "first-world" strata with well-developed infrastructure and a "third-world" strata which resembles a poorly developed country (Praetorius & Bleyl, 2006). Within the lower economic strata, a significant portion of the population, in both the rural and urban areas, is not connected to the electrical grid.

Sustainable Development in South Africa

South African policy aims to fully connect all households to the grid; during Apartheid, less than 40 percent of the population was connected. The government has pursued a stringent policy towards "universal access" to electricity to alleviate energy poverty among historically disenfranchised people and to begin the modernization process of their homes and fuel sources. Mehlwana (1997) used a South African transitional energy model to explore the social ramifications of this transition. He found that transitional models have limitations when they rely on the assumption that "urbanization equals modernization." Many of the newly- and potentially-connected electricity-consuming households still continue to use a mix of cheaper, more readily available fuels, possibly along with electricity, to meet their energy usage needs (Madubansi & Shackleton, 2006). Thus, we do not assume that a class or location transition of households automatically equals the use of only conventional fuels. The model developed here considers agents to have heterogeneous views on electricity pricing, electricity usage, and fuel affordability.

Energy Distribution

The residential sector accounts for approximately 18 percent of the total primary energy used in South Africa (SA Department of Minerals and Energy, 2009). Cooking, lighting, and heating are the primary energy-consuming household activities. Energy end use in the residential sector is dominated by cooking activities in households, performed with one or a combination of cooking apparatuses such as a liquid petroleum gas (LPG) stove, primus stove, conventional stove, or an open fire pit.

As is often the case in developing countries, electricity is not the dominant fuel source in the some households due to its prohibitive costs. Fuels such as paraffin (kerosene), LPG, coal, wood, candles, and animal dung chips are used. Households make energy transitions as income grows and as the more expensive fuels become affordable (B. Campbell, Vermeulen, Mangono, & Mabugu, 2003; Davis, 1998a; Kituyi et al., 2001; Madubansi & Shackleton, 2006).

Figure 16 shows that there is an upward trend in the number of households with access to electricity (South African Department of Energy, 2012). The trend indicates that South Africa will continue to have a considerable gap between the number of total households and those that are electrified past the year 2050.

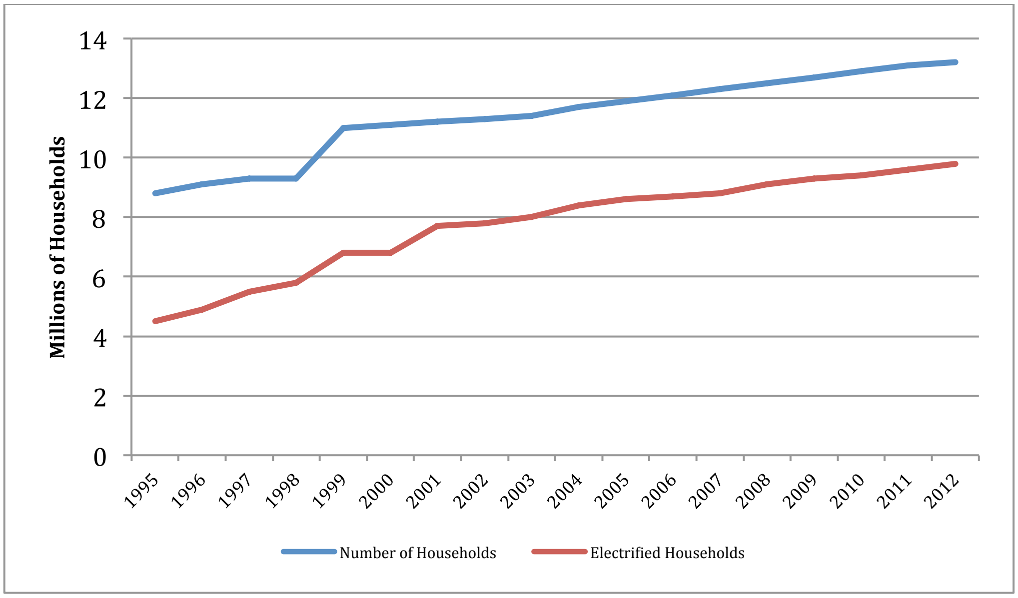


Figure 16 - Total Aggregate and Electrified Households in South Africa (data from S.A. Department of Energy, 2012)

Population Demographics and Future Development

Urbanization

Madlener and Sunak (2011) posited that energy consumption is likely to grow as cities in Africa further urbanize this century. Sadorsky (2013) found that a 1-percent increase in urbanization leads to over a 2-percent increase in energy intensity (elasticity, $\varepsilon = 2.11$). In South Africa, an estimated 8 million persons will move into the urban centers by 2030 (SAinfo, 2012). Urban areas such as Durban, Johannesburg, and Cape Town are expected to increase in population by nearly 20 percent from 2010 to 2025 (Turok, 2012; UN-Habitat, 2010).

Some of the most vulnerable populations are living in the fastest urbanizing areas: the townships. The lack of adequate income and household stability forces energy trade-offs between sustainable or "clean" fuels and cheap, available fuels. This also exacerbates problems within the households; these problems include inadequate insulation from the exterior environment, fire, interior air pollution risks, and personal safety issues (Huchzermeyer & Karam, 2006). Older and some newer post-Apartheid housing still suffer many of the ills of bad insulation, sanitation, and lack of full services of the pre-Apartheid era (IESS, 2008); there is inability to adequately provide better basic housing and other services (Cohen, 2006; Martínez-Zarzoso & Maruotti, 2011). The continued lack of services perpetuates the use of more traditional fuels rather than electricity.

Rise of the Middle Class

Since the post-Apartheid transition, the South African middle class has grown from 3.2 million individuals in 1993 to 7.2 million in 2012 (ReSEP, 2013). This growth of the middle class has made a significant economic impact, especially in the market for durable goods and residential property (ReSEP, 2013). This, in turn, has led to the flourishing of the retail, banking, and telecommunications industries and the increased flow of private investments, which keeps the South African economy growing (Leke, Lund, Roxburgh, & van Wamelen, 2010).

A high level of inequality remains. South African unemployment hovers at nearly 25 percent, which is among the highest in the world (Chetty, 2013). The South African government is initiating programs that address intergenerational poverty and that broaden access to employment, strengthen the social wage, and improve public transport (SAinfo, 2012). Higher incomes will increase transportation and energy demands, especially in the electricity sector. With a growing middle class, there is a growing salaried employment, greater use of technology, the creation of larger and more modern homes, and more recreational time (Deloitte, 2013). This, in turn, drives the increase in use of energy services.

Even though there is a growing middle class in South Africa, there is still a significant population within the country that is trapped within the low income brackets. The consideration of this dynamic within the model is important because economic mobility has a significant impact on households moving from primitive to more conventional fuel sources and on increased demand for electricity services. The dynamics of the poor are not trivial as movement to higher classes can be difficult. Özler (2007) found that poor South African households were not able to dynamically escape poverty in the period from 1993 to 1998. Even 15 years after this study, this is still the case, as indicated by South Africa's high unemployment rate (Chetty, 2013). Social mobility has been addressed in other probability models by researchers such as (McFarland, 1970; McGinnis, 1968).

Electricity Demand Projections

Demand Modeling

Using data from the World Bank (2013b), Figure 17 shows electricity consumption and GDP growth in South Africa; the data indicate a period in which GDP and per-capita electricity consumption grew in tandem, followed by a period in which electricity consumption grew more slowly than GDP (Khanna & Rao, 2009; Suri & Chapman, 1998; Wolde-Rufael, 2006).

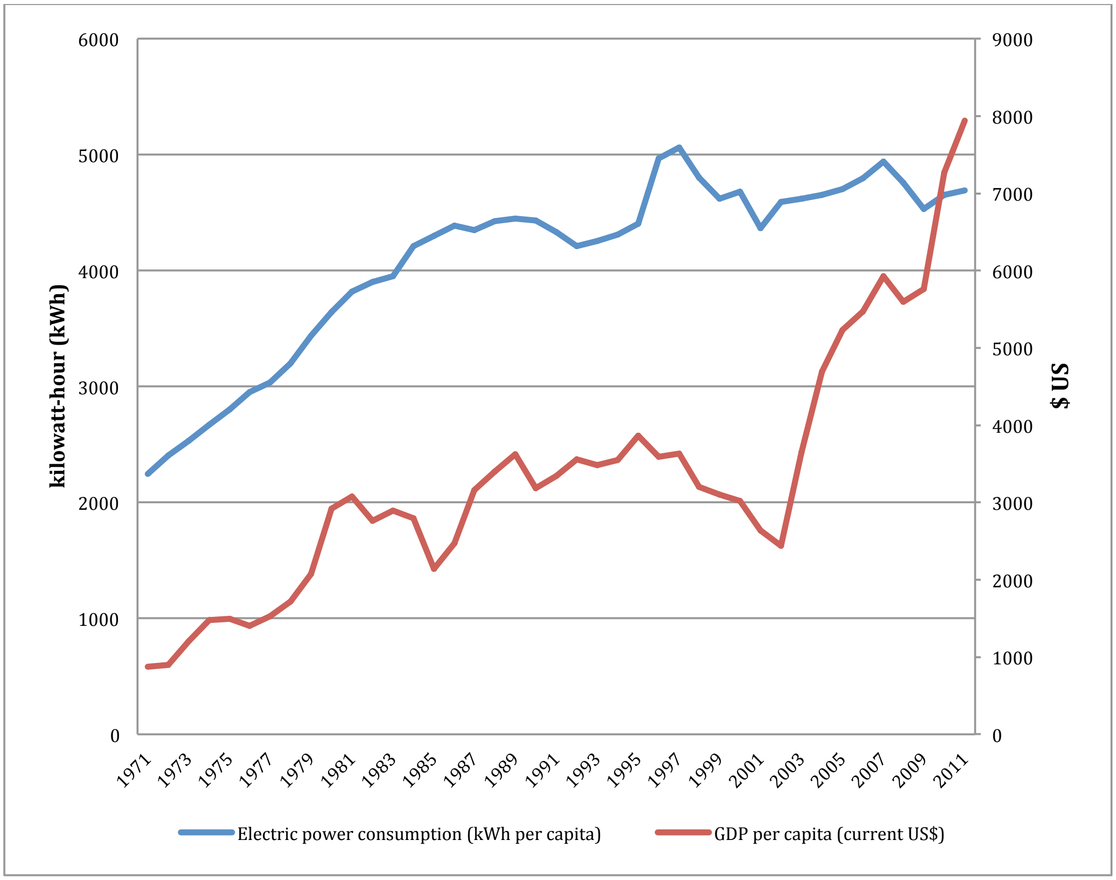


Figure 17 - Electricity Consumption and GDP per capita in 2013 $USD

In some cases, the growth of electricity consumption can be linked to a decrease in prices. In the case of South Africa, the real price of electricity has varied little over that last five decades. The historical electricity prices from Eskom, the South African electricity monopoly, have ranged from 20 to 30R c/kWh (in 2008 Rand) over this time period (shown in Figure 18). This further supports the choice of a simplified electricity consumption growth rate based on predicted GDP.

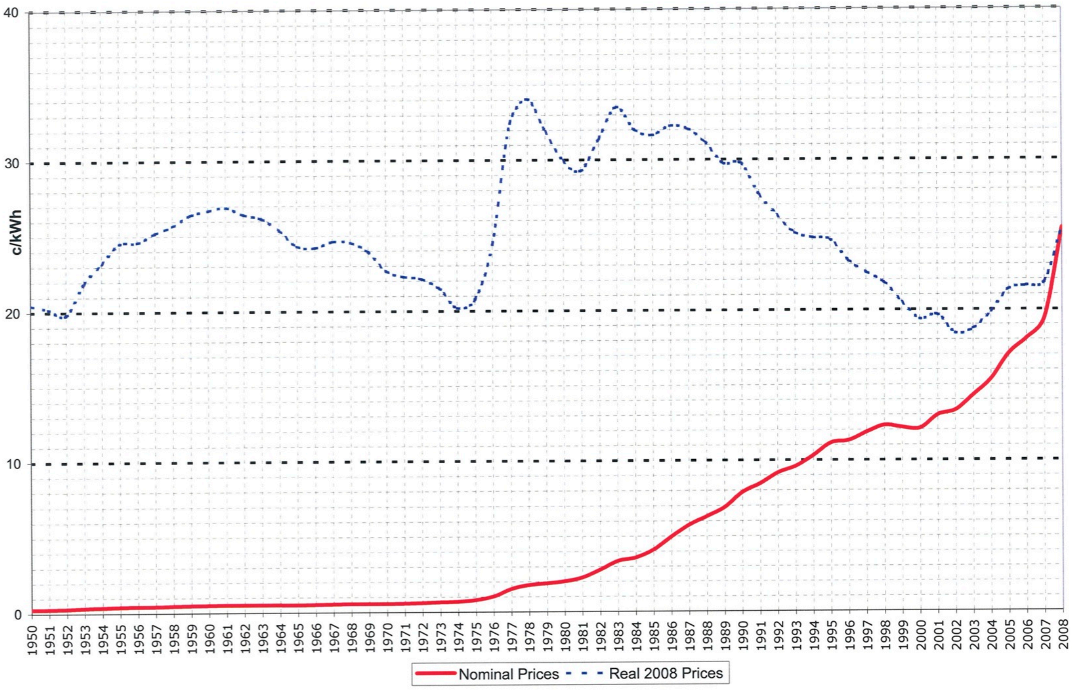


Figure 18- Historical Electricity Prices in South Africa from (ESKOM, 2012)

Demand Projections for South Africa

Informed by the past trends in South Africa's electricity consumption, we construct three scenarios for the aggregate residential energy consumption. South African electricity consumption per capita has only grown by approximately half a percent annually in the past twenty years; we use this rate for the low-growth scenario. The middle-growth scenario uses the statistical average of South African GDP growth since 1971—approximately two percent, which is also in line with the average growth South Africa has had in the past three years (IMF, 2013). In the high-growth case, we use the average GDP growth rate of the BRIC countries (Brazil, Russia, India, and China) over the past 20 years, which is 7% per year (IMF, 2013). These projections are found in

Figure 19.

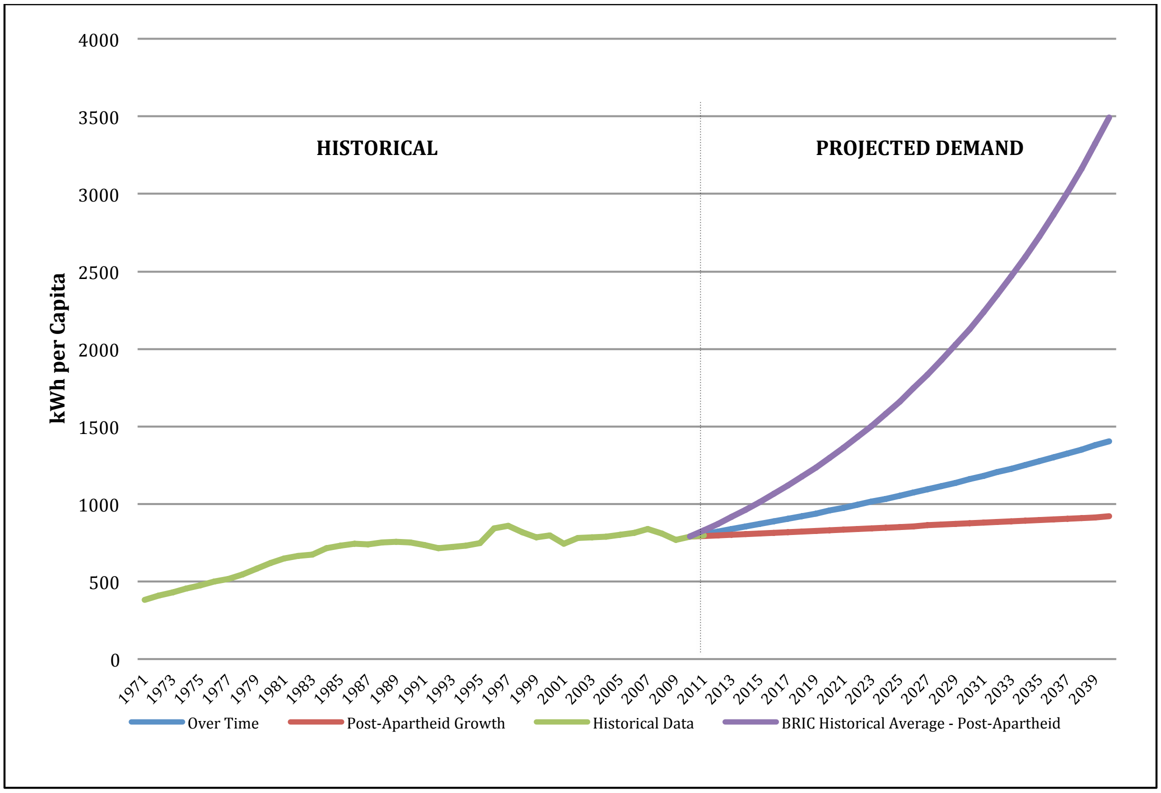


Figure 19 – Projections of per capita electricity demand in South Africa

These projections were calculated out to the year 2043 starting with the year 2013, and used to estimate the household demand over time. To project the population and the average number of people per household, we use the average trend since Apartheid. This calculation reflects the average decline in the number of people per household. Projected household electrical consumption over the 30-year period is shown in Figure 20.

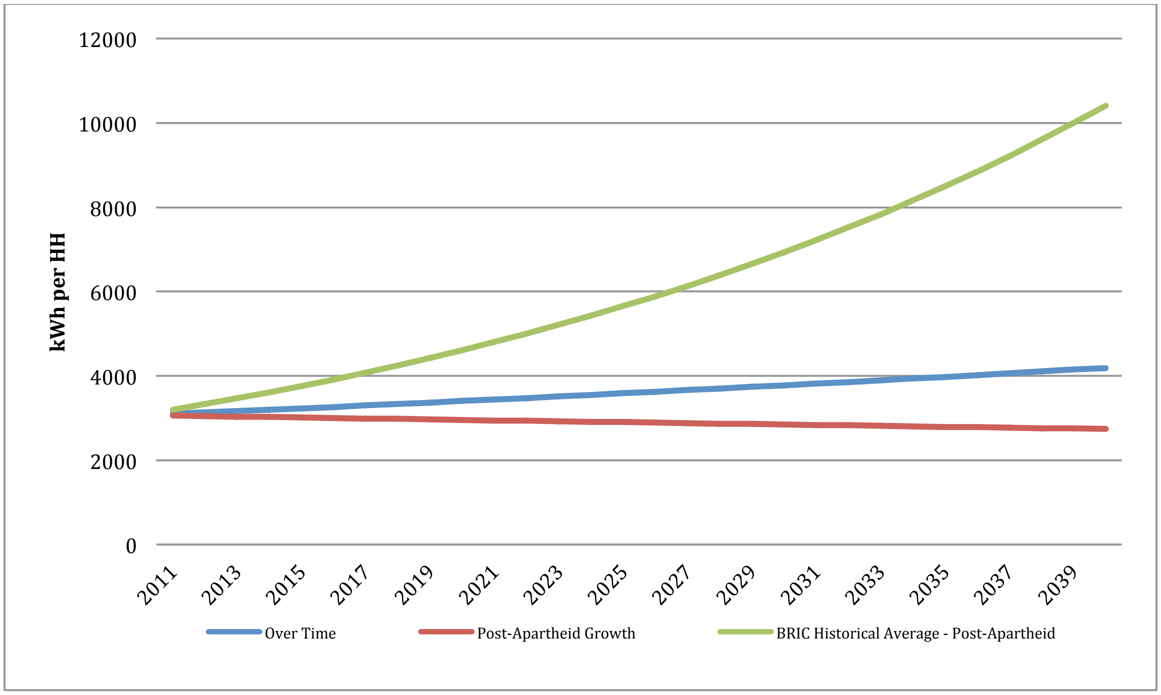


Figure 20 – Electricity Demand Projections Per Household in South Africa

Agent-based Model Framework

Agent-based models (ABMs) are computerized simulation models that include different decision-makers or agents who interact through prescribed rules (Farmer & Foley, 2009). Scholars have used these models to understand spatial and social interactions among different actors in a bounded setting (Jackson, 2010; Janssen & Ostrom, 2006; O'Sullivan & Haklay, 2000). The heterogeneous actors express the different behaviors and social processes of decision makers (Kiesling, Günther, Stummer, & Wakolbinger, 2012). ABM models can be empirical or equation-based in their logic structure. Many are equation-based, meaning that most of the agents derive their characteristics and/or action thresholds from equations. Equation-based models are more proof-of-concept models and do not rely on "real world" data. Empirical models can provide a better reflection of the beliefs and values of the population due to their use of data on actual preferences. Many of the energy ABM models are spatially explicit, addressing the connections between the spatial representation of the agents and the neighborhood (Hare & Deadman, 2004); thus, researchers could determine when agent decisions were influenced by the circumferential webs of neighborhood social networking.

Agent-based-model researchers have explored energy systems of different scales (Azar & Menassa, 2011; Ma & Nakamori, 2009; Weidlich & Veit, 2008), and have investigated consumer choices of alternative energy and energy-efficient products, particularly within the private vehicle market (Eppstein, Grover, Marshall, & Rizzo, 2011; Faber, Valente, & Janssen, 2010; Köhler et al., 2009; Maya Sopha, Klöckner, & Hertwich, 2011; Stephan & Sullivan, 2004). Agent-based models of the energy decisions and fuel choices of households at micro-levels were not found in the literature. To begin to fill this gap, we create an agent-based model that incorporates survey data on energy behaviors, perceptions, and willingness-to-pay into a fuel transition model.

Modeling Concept

We conceptualize a model that consists of heterogeneous agent households who have respective electricity demands and interact with other households. This model is created to explore the effects of electricity pricing and electricity demand while also evaluating rates of protest, pricing, and social networking; a schematic of the model is presented in Figure 21. The model is programmed in NetLogo 5.1.0 (Wilensky 1999).

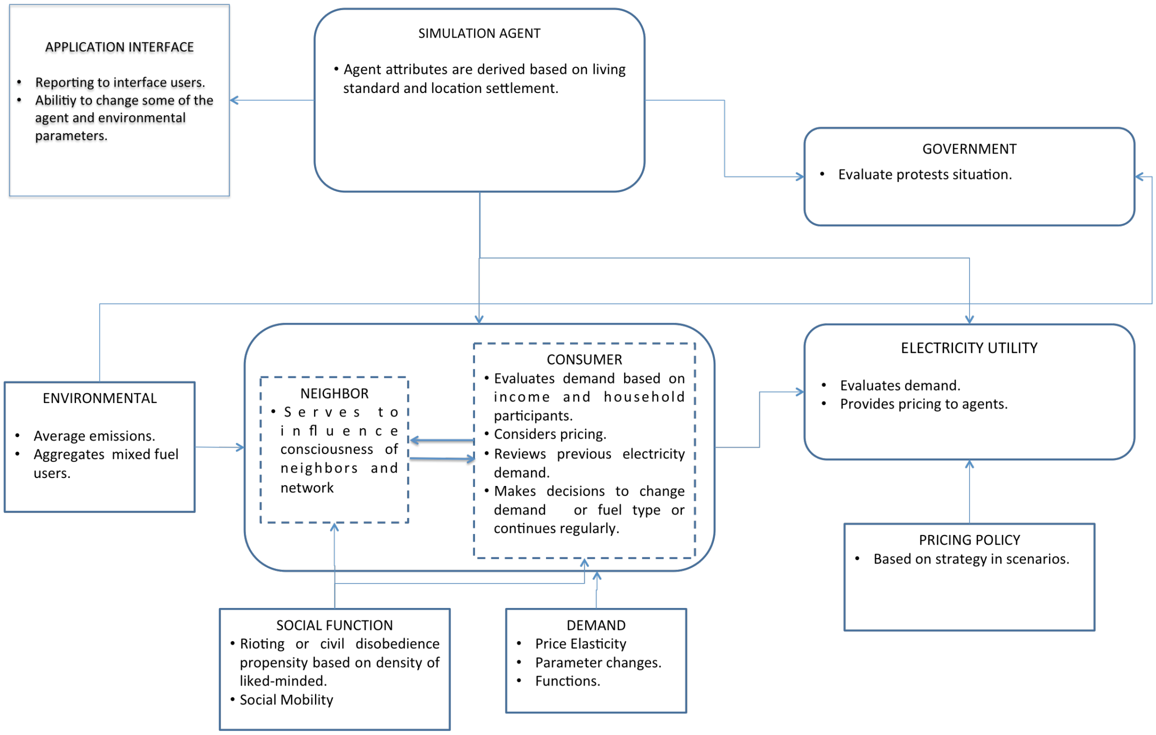


Figure 21 – Energy End-Use Agent-based Model Organization

Agent Decision-Making

Empirical agent-based models require data that supports the bottom-up structure of the model and is representative of the population under investigation. These models rely on stated or revealed preference data. Stated preference models rely on hypothetical data to evaluate consumer's willingness to pay *ex-ante*. These data are collected using experimentation or survey. Revealed preference models use observation data to evaluate consumer choices. We use stated preference data due to its availability and ease of collection in South Africa on energy behaviors.

These empirical data are used to initialize the characteristics of the agent population, based on location (*URBAN FORMAL, URBAN INFORMAL,* and *RURAL*) and living standard (*LOW, MID,* and *HIGH*). The agents are then randomly assigned quantitative and qualitative characteristics based on their location and living standard.

After initialization, each household evaluates their electricity demand and income expenditure on electricity. If the individual agent does not have access to electricity, the model automatically records no electricity demand from that agent. The agents network with other households in the spatial and class neighborhoods. This networking allows individual agents to evaluate their willingness to engage in electricity service protests considering their own grievances related to their income expenditure on electricity. Dependent upon the concentration of protest-ready agent households within their network, the agent will decide to be protest active or inactive. This is discussed further in the Consumer Agent Section.

The model, in preparation to go to the next time step, modifies the household characteristics of all of the agents. The model considers changing characteristics related to an agent's social class, income, fuel preferences and urban-rural location. The income growth per year is determined by the expected average GDP growth over the time period set by the user. Fuel preference changes are determined by the agent's income expenditure on electricity and their willingness to change to other fuels, which is evaluated using empirical data on stated preferences. This model considers the household electrification efforts of the developing country.

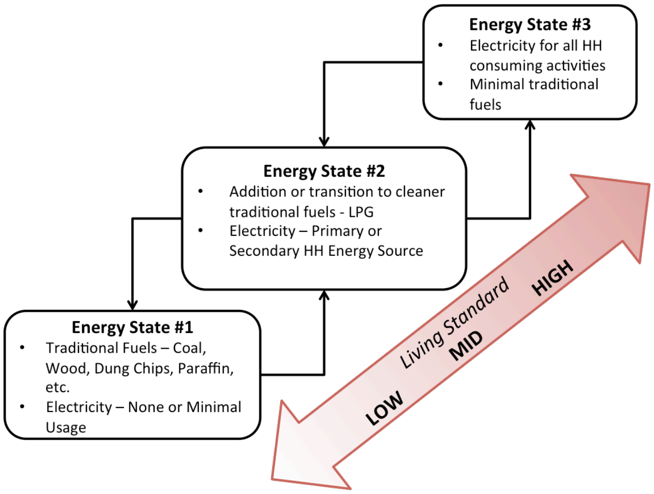


Figure 22 - Energy States of Consumers

Electricity is not the dominant fuel source in the some households due to its cost. Davis (1998a) found that low-income households will typically transition to cleaner fuel such as liquid petroleum gas (LPG) to replace traditional and more hazardous fuels such as paraffin, candles, wood, etc. Middle- and high-income households move from using these fuels to fuel stacking with better alternatives or using electricity completely (B. Campbell et al., 2003); a diagram of these transitions is shown in Figure 22.

We assume that there is a set of household agents having no access to electricity and being dependent on indigenous fuel sources; these agents are denoted as *NEMEU,* meaning non-electricity, multiple energy-source users. These agents may potentially transition to being either a multiple energy source user that has electricity, denoted as *MEU,* or an agent who uses only electricity denoted as a single energy source user, *SEU*.

All other parameters such as the agent's settlement location and class are changed at rates consistent to the socio-economic patterns of the country and are discussed in more detail in the following sections. The parameters are discussed further in the Consumer Agent Section. The electricity prices are calculated for the next time period and are changed based on the user set yearly increase in price.

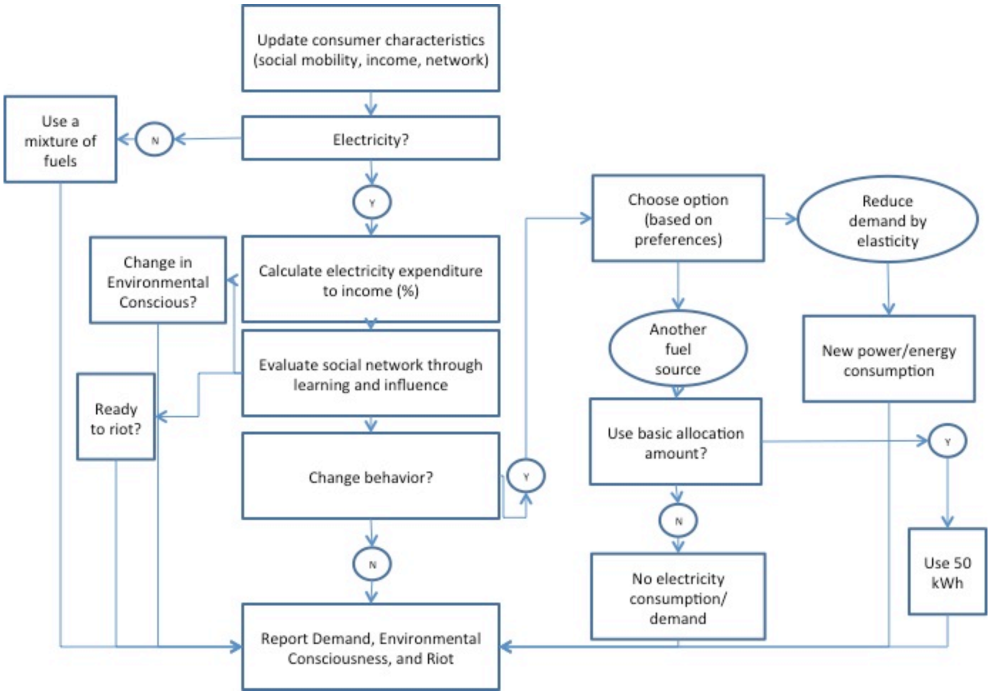


Figure 23 - Consumer Agent Decision Process

Consumer Agent

The model is built around the heterogeneity of the agents, their interactions within the community and social network, and their beliefs, as illustrated in Figure 23. The model establishes characteristics from the following sets for all consumer households:

- *Urban Formal/Urban Informal/Rural*
- *Low/Mid/High living standard*
- *Income*
- *Electrified/Unelectrified*
- *Social characteristics (i.e., environmental beliefs, social injustice response, etc.)*
- *Electricity price elasticities*
- *Energy awareness*

This model updates the characteristics each year based on changing circumstances in the agent's environment. Outside of any exogenous changes to the agent lifestyle, the agent's income is a direct function of the assumed GDP growth given by the user of the model and is compounded using an interest percentage drawn from a random normal distribution created from the historical GDP data of South Africa. This dynamic estimation of income over time in the case of South Africa is posited on the fact that income has this type of exponential trend since 1961 to the present. Based on World

Bank (2013b) data, the average yearly compounding factor for the GDP per capita growth is approximately 1.05. These data were fit to a normal distribution ($\mu = 3.15$, $\sigma = 1.66$), so that GDP growth year-over-year can be selected in the model. A wide distribution is expected due to the erratic growth in the four decades of data presented in Figure 17. A goodness-of-fit test (Kolmogrov-Smirnov Test, $p < 0.05$) found that the data fit the distribution. The distribution and histogram are shown in Figure 24. Table 9 provides the income classifications and ranges, based on data from Statistics South Africa (2010).

Table 9 - Monthly Income by Locale and Living Standard (in SA Rand)

RURAL	***Min***	***Middle***	***Max***
Low	289 R	793 R	1,265 R
Middle	1,265 R	2,080 R	3,940 R
High	3,940 R	7,067 R	9,630 R
URBAN INFORMAL			
Low	45 R	1,091 R	2,575 R
Middle	2,575 R	4,706 R	7,667 R
High	7,667 R	11,917 R	15,533 R
URBAN FORMAL			
Low	1,260 R	1,924 R	3,820 R
Middle	3,820 R	6,984 R	11,620 R
High	11,620 R	10,700 R	25,850 R

We employ a social class probability model in the form used by other researchers (McFarland, 1970; McGinnis, 1968). Carter and May (2001) defined a Markovian matrix for South Africa that explicitly states the probabilities of specific income groups transitioning to another income group. This is used to predict dynamic social class changes amongst the poor.

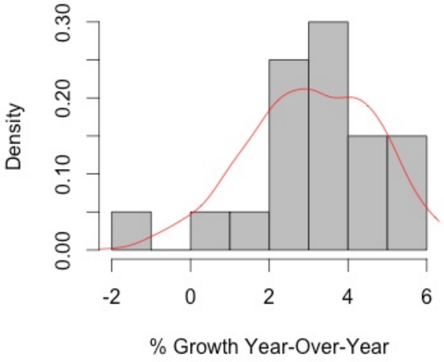


Figure 24 - GDP Distribution for South Africa over last 40 years

Each agent is assigned an initial location characteristic consisting of being in an urban formal, urban informal or rural settlement. The agents have both a social neighborhood network and a social class network (Athanasiadis, Mentes, Mitkas, & Mylopoulos, 2005; Eppstein et al., 2011). The social neighborhood network consists of other consumer agents within a random radius surrounding the observed agent. The social class network is a random number of consumer agents who are within the same class (living standard) as the agent of inspection. The social class network is created by initiating information linkages between a random set of agents of the same social class. A Poisson distribution $P(k)$ sets the degree of distribution between the different consumer agents' networks. A k of 3.29 is used for the distribution, derived from the meta-analysis of Albert and Barabási (2002), where they compile k (rates) for different types of networks; 3.29 is the average of the k rates of social (telephone) calling and Internet browsing, which we posit mirrors the influences of social interactions and social media.

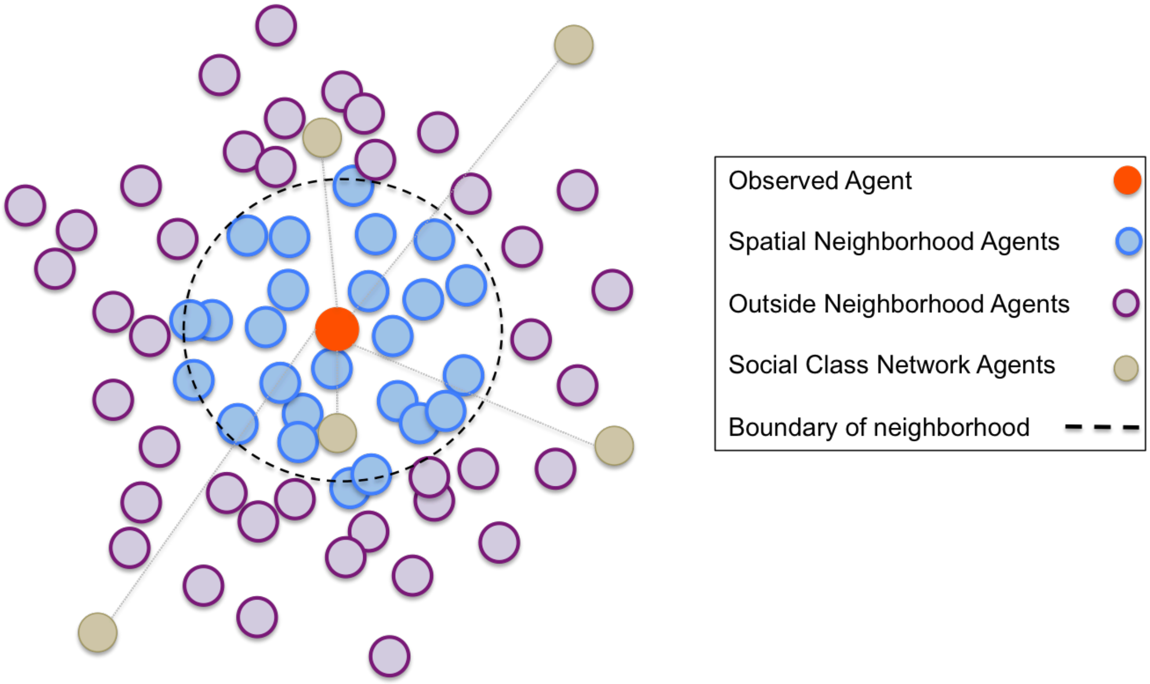


Figure 25 - Simulated Spatial Network of an Observed Agent

In both cases of the social network, the agents "socialize" with the observed agent, influencing his decisions on both rioting and energy. An example agent's surrounding environment is shown in Figure 25. The social class of the agent may change if the agent moves to a different class. If this occurs, the social class neighborhood is updated to reflect that change.

A social grievance indicator for rioting is embedded within the model. Agents have the ability to change their "rioting" status based on feelings within their social network and their economic hardships. Based on the research by Epstein (2002), a grievance function, G, is used to determine an agent's mindset toward the energy policy and pricing.

Equation 13 - Grievance Function

$$G = H \cdot (1 - L)$$

The function G relates to an individual's grievance toward the authority regarding their hardship, H, and the overall consensus of the legitimacy of the government, L. In this model, unlike Epstein (2002), hardship H is assigned by calculating the energy expenditure share of the agent's income; this assignment is bounded from 0 to 1. For a legitimate government with $L = 1$, there is no grievance suffered by the agents because they perceived no threat or corruption from the government (even in the case of high hardships). In the case of illegitimacy ($L \rightarrow 0$), the agents may have high grievances toward the government based on their individual hardships.

We assign legitimacy L to have a mean of 0.5, due to the current political climate of South Africa. This legitimacy parameter varies between the agents at each time period; legitimacy is assigned from a normal distribution with the aforementioned mean and a standard deviation equal to mean divided by the number of household agents within the simulation $\sim N(0.5, 1.67 \times 10^{-4})$.

An agent can either be riot active or quiescent; thus, an agent is ready to riot if there are others in their spatial neighborhood who are ready to riot or they remain out of any civil disturbances. An agent becomes active in relation to their arrest probability. We use Equation 14 to estimate a household agent's arrest probability, which is based on the number of police, P, and the number of citizens ready to riot, AC, in their spatial neighborhood. In this model, police are randomly placed throughout the grid at each time period.

Equation 14 – Arrest Probability Function

$$Prob(Arrest) = 1 - \exp\left(-2.3 \cdot \left(\frac{P}{AC + 1}\right)\right)$$

The agent's net risk is calculated by $N = R \cdot G$, which is a function of the household agent's risk aversion N and grievance level G. The agent's risk aversion is considered to be uniformly distributed, $U(0,1)$. If an agent is quiescent, the agent will evaluate if the difference between their grievance level G and the agent's risk aversion N is greater than the model's threshold of 0.25. If so, the agent becomes active. At each period, each household agent reevaluates the active status as their income, income expenditure on energy, and government legitimacy beliefs change.

Rioting consists of a concentrated area of people and counted as such in the model. If the concentration of active households within their spatial neighborhood surpasses a threshold of 90 percent, that area is considered to be a riot active area and is counted within the riot count.

ABM Data

South African Census and residential survey data are used to create an agent population representative of the South African population. The characteristics of the population are distributed based on collected data from the South African Department of Energy (2012). The geo-demographic data from the South African Census shape the sample surveyed in this study. Approximately 3,000 ($N = 3004$) people were surveyed on nearly fifty questions related to consumer beliefs about energy distribution and costs. The survey also questioned the consumers about their energy-efficiency beliefs and practice, environmental consciousness, beliefs about renewable energy, and their current household energy expenditures (costs per kWh, percent of income, etc.).

There are a few residential electricity demand log-linear models that estimate energy demand for households (Cassim et al., 2012; Louw et al., 2008). We follow the model of Louw et al. (2008), where the statistically significant variables of income and paraffin prices determine household electricity use. The equation for household-level electricity demand takes the form of Equation 15, where $P_{Electricity}$ is the price of electricity, Y_{Income} is the household income, $P_{Paraffin}$ is the price of paraffin and Φ_{HC} is a vector consisting of other household and physical environment characteristics such as household devices, climate, and physical environment.

Equation 15- Model for Household Electricity Demand

$$\ln E_t = \alpha + \beta \cdot \ln P_{Electricity} + \gamma \cdot \ln Y_{Income} + \delta \cdot \ln P_{Paraffin} + \Phi_{HC}$$

We use two distributions to approximate electricity demand in households: a log-linear method and the triangular distributions. The log-linear methods are used to characterize agents who use only electricity. Triangular distributions, appropriate to stochastically model parameters that have a high level of uncertainty and limited data (Hammonds, Hoffman, & Bartell, 1994), are used to characterize energy demand in households consuming both electricity and other fuels. A triangular distribution is formed to estimate MEU households in the low living standard stratification using a minimum of 600 (based on the EBSST Free Basic Electricity (50 kWh per month) and maximum of 1200 kWh. Middle- and high-living standard households have another distribution that uses the maximum value of the low- living standard distribution as its minimum value and a maximum value calculated from Ward (2002). The mean value of the distribution is calculated using data from Kehrer, Kuhn, Lemay, and Wells (2008).

Results

Scenario Design

To test the model, four scenarios were selected, with differences in middle class growth and year-over-year electricity tariff increase. The GDP was set to a random normal distribution that was fit to historical South African GDP data. The electrification rate of un-electrified households was kept constant within the four scenarios in order to simulate the continued electrification efforts within South Africa. Urbanization rate was also kept constant to reflect the South African trajectory. To evaluate rioting, a legitimacy level of 0.50 was set for all scenarios in line with the political environment of South Africa (Dolley, 2014; Ngwane, 2014). All scenarios and the respective parameters can be found in Table 10.

Table 10 - Selection of Initial Model Parameters

PARAMETERS	*Scenario #1*	*Scenario #2*	*Scenario #3*	*Scenario #4*
Middle Class Growth	*YES*	*YES*	*NO*	*NO*
Electricity Tariff Increase	*4 percent per year*	*7 percent per year*	*No Increase*	*7 percent per year*

Data were collected on electricity demand, rioting counts, income expenditure, and distribution of household energy-consuming types. The electricity demand results for each scenario are shown in Figure 26.

Scenarios 1 and 2 (S1 and S2) almost have the same trend over the 30-year simulation; at the ending year (year 2043), there was 3-percentage point difference between S1 and S2. Scenario 3 (S3) has the highest electricity demand growth over the 30-year period. With no electricity tariff increase, this result is expected; more income and cheaper electricity incentivizes more electricity demand. Scenario 4 (S4) had a lower slope than all of the other scenarios, as expected for a significant electricity price increase

(7 percent year-over-year increase) with no middle-class growth (unlike S1 and S2). However, there is a 10 percent difference between S3 and S4; these two scenarios are nearly similar except that S3 has no tariff increase. These results serve as a partial validation for the model as well as we can say that the results are consistent with plausible values.

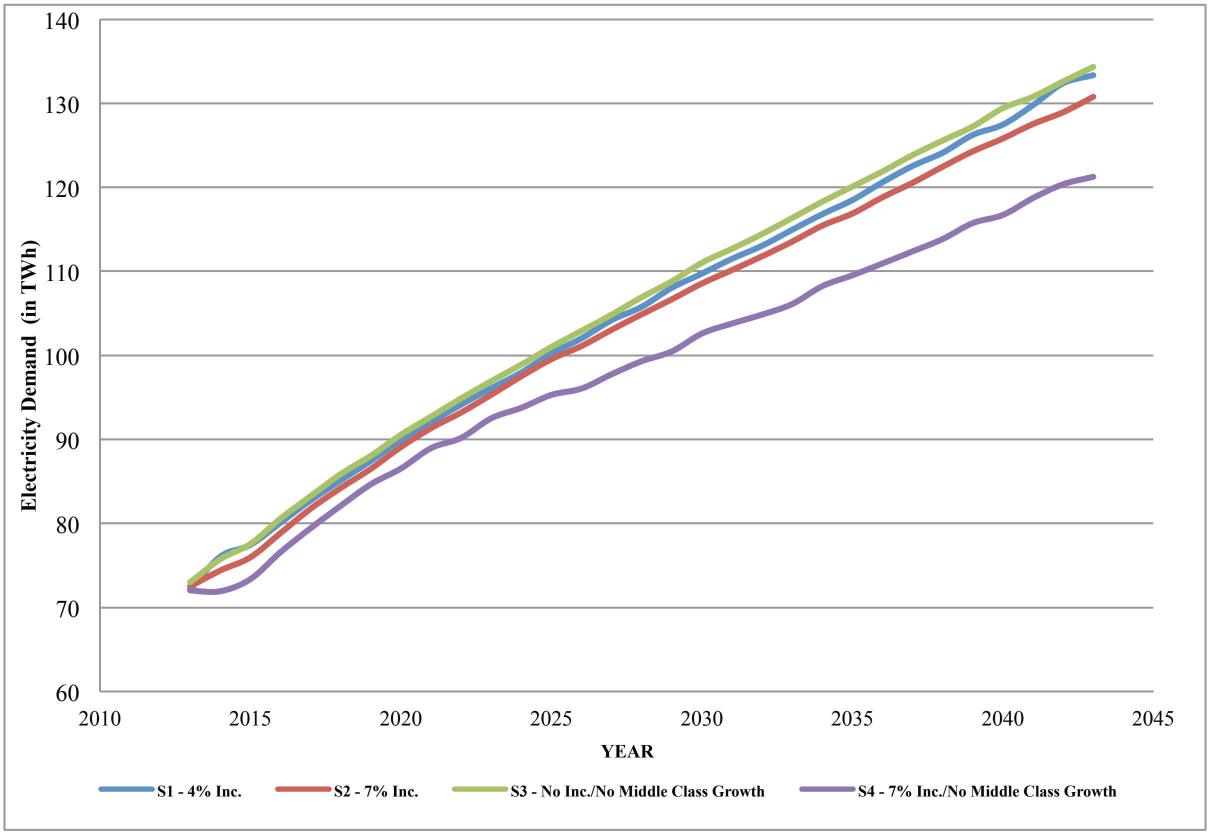


Figure 26 - Projected electricity demand for all scenarios

The propensity of agents to riot/civil disobedience was observed for all four scenarios. The results are shown in Figure 27; as electricity expenditure increases, more disturbances occur. The model produces an upward trend over the 30-year period for nearly all of the scenarios. Only in S3, with no increase in electricity tariffs, is there no increase in riots.

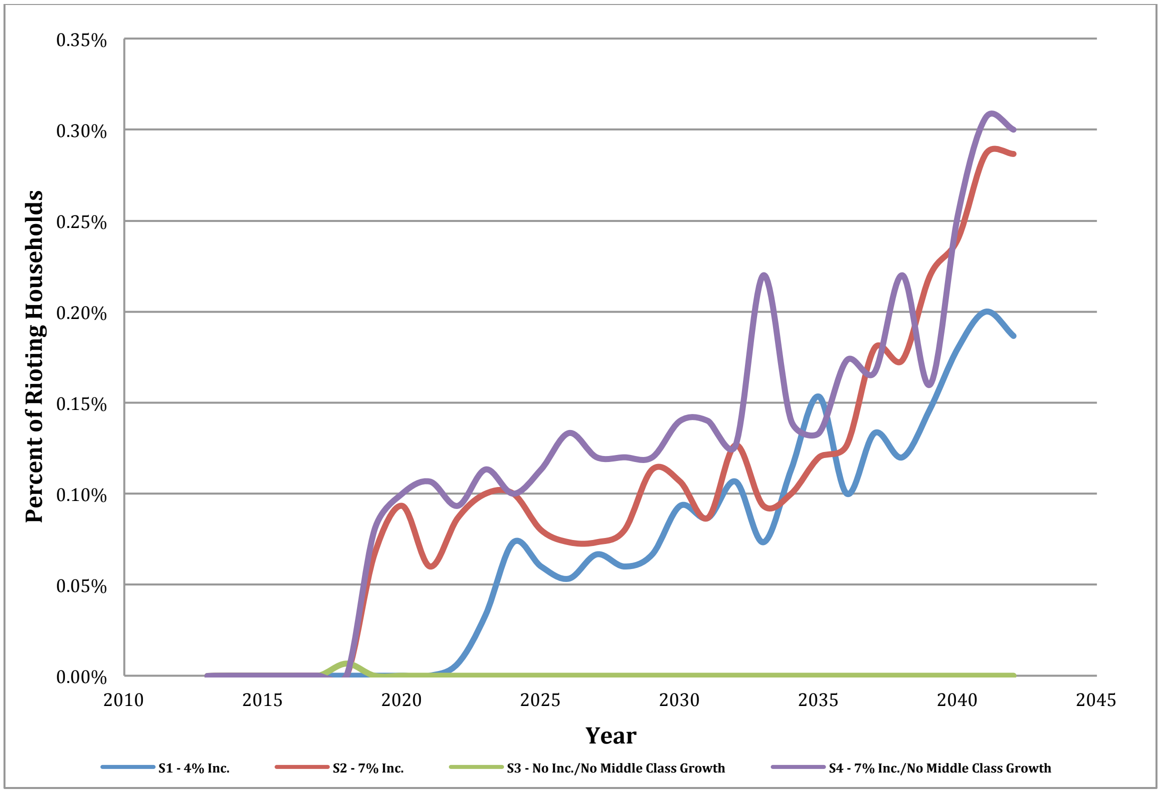


Figure 27 - Scenario Riot Count

There are distinct differences in the riot trends. S4 produces the greatest number of disturbances nearly every year. While S2 and S4 have the same tariff increase and nearly the same average agent expenditure, there was a 4-percent difference in the number of disturbances; however, there was no middle-class growth in S4. These two scenarios differ only in their inclusion of incorporating middle class growth at a rate of 0.289 percent year-over-year in the model. Thus, the results suggest that a 1-percent growth in the middle class would decrease energy expenditure-related riots by 15 percent.

The contrast between S1 and S4 is noteworthy, with nearly a 50-percent difference. This difference is most likely due to the inclusion of the middle class growth dynamic and a larger tariff increase in S4. However, the comparison of S1 and S2 is even more interesting as these two scenarios only have different increase in their initial tariff rate. A nearly 40-percent difference is found between the percentage of rioting households, with only a 3-percent difference in the tariff increase and all other parameters were constant. The results suggest a positive riot elasticity, where $\varepsilon = 13$. Hence, the results suggest an electricity tariff increase of one percent would potentially cause a 13-

percent increase in the number of riots related to energy costs. While this elasticity may seem high, it should be understood this increase would be relatively low in terms of the entire household population. The results show that less than 1-percent of households are involved in rioting at each time step in the model.

Overall, these large differences in riot activity between the scenarios are due to the number of agents that are displeased with energy services and are willing to engage in rioting. As income expenditure for energy increases (i.e., as energy becomes less affordable) for the entire population, more agents are displeased with energy delivery. If there is a critical number of agents who are actively displeased, willing to riot, and are in the spatial area surrounding of the observed agent, then the model registers that a civil disobedience occurs (Epstein, 2002). The behavior represented in these results is not linear in the tariff percentage increase.

A sinusoidal trend appears in the estimation of riots. These trends are shaped by concentrations of agents going to an inactive state after being active for a certain period within the model. Agents reevaluate their active status position at every period, and they may choose to go inactive due to a decrease in their electricity expenditure or a decline in the concentration of active agents around them.

The average portion of income expended on electricity - a factor in whether an agent decides to activate and become a part of a civil disobedience demonstration - is shown in Figure 28.

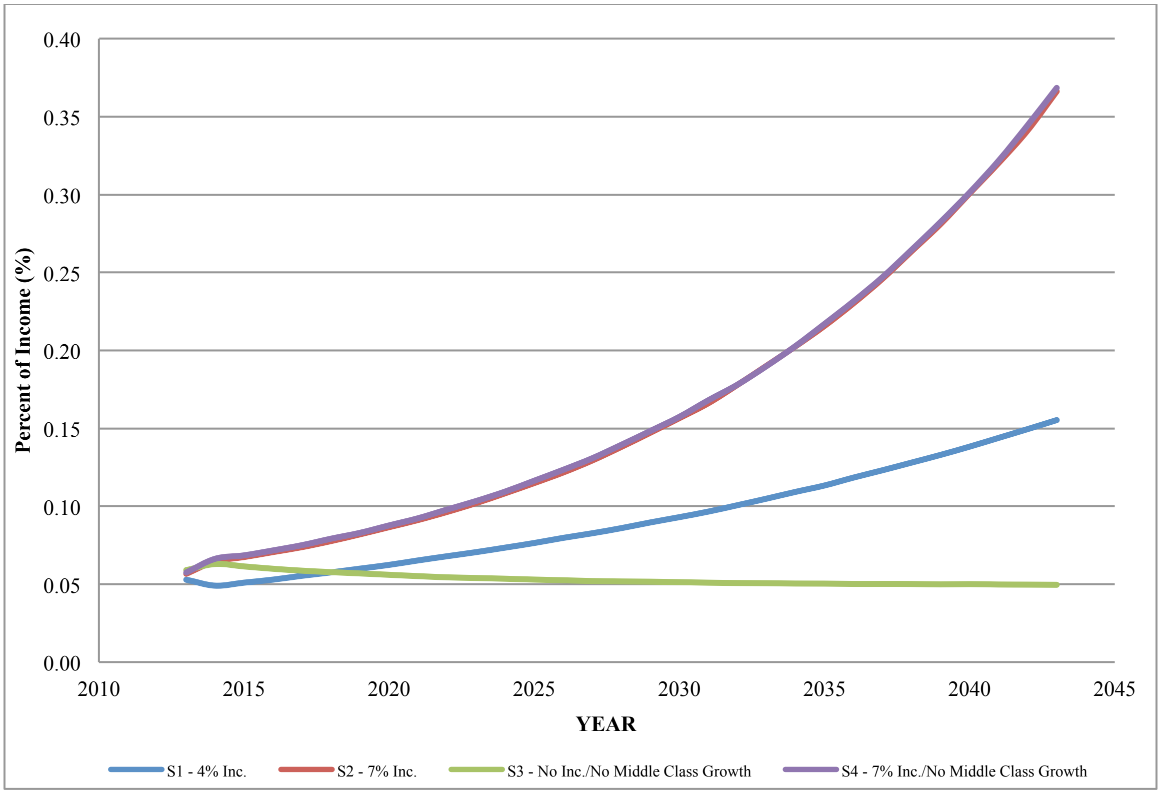
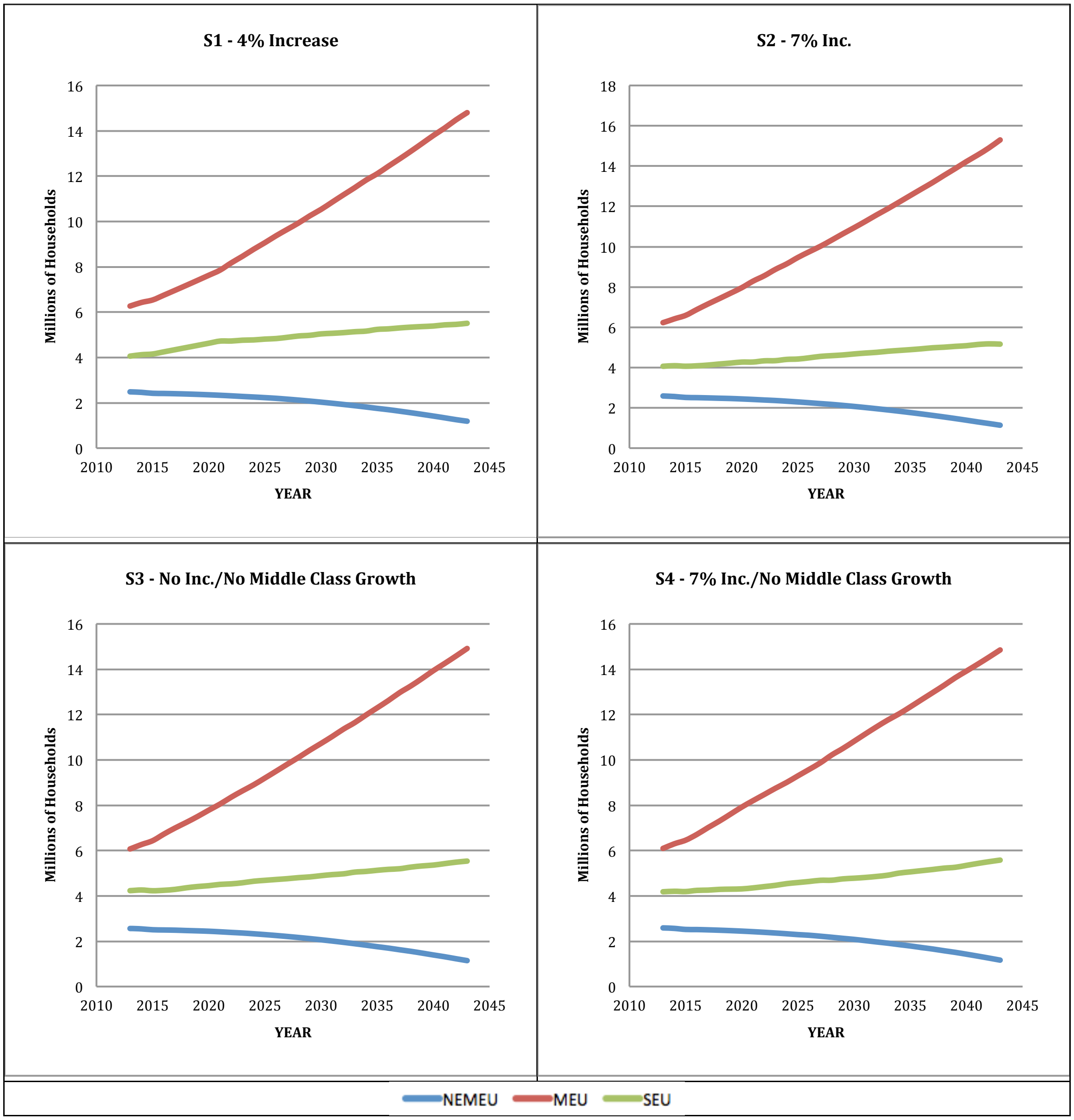


Figure 28 - Income Expenditure on Electricity by Scenario

The model tracks the number of all-electric (SEU), mixed energy (MEU), and non-electric mixed energy (NEMEU) agents and their transition to other energy states. The distributions are shown below in Figure 29. Particularly as the scenarios all had the same electrification rate, there are no major differences in these distributions between the scenarios. All scenarios result in a large fraction of households that are fuel stacking with traditional and electricity fuel sources.

Figure 29 - Distribution of HH Energy-consuming Types



Validation

Validation is challenging with stochastic-dynamic models using empirical data. These models contain non-linearities, non-trivial agent interactions, and dynamics that complicated the validation of the models (Fagiolo, Moneta, & Windrum, 2007). In this model, multiple phenomena are investigated in a transitioning economy that previously did not allow universal access to energy and economic markets (i.e., Apartheid). Thus, this study takes the validation approach that Eppstein et al. (2011) used.

To check for stability, the model parameters were set for no income growth, urbanization, or increase in electricity prices. The state of the economic and energy markets remained stable within the model and there was no real aggregate change in electricity demand or change in the household energy consumption stratification amongst the agents.

Discussion

Model Development

The model is a micro-simulation model of energy demand and consumer choice integrating social disobedience related to energy expenditure, with the ability to disaggregate energy users who are single-fuel and multi-fuel users.

This current work focuses on projecting the electricity usage within the household and subsequently the entire residential sector. Further model development could include the demands for all fuel types in the household and their respective greenhouse gas emissions. A challenge is that these fuel sources can be used in combination with other residential activities such as heating (water and space) and lighting.

Civil Disobedience Impacts

Basic service delivery of electricity, law enforcement, and water is one of the most contentious topics in South Africa and is a main cause for rioting. These riots and protests occur due to endogenous processes in residential communities, where one reactionary event causes a subsequent action of greater issue (Oliver, 1989). This model attempts to explore these endogenous processes that lead to civil disobedience and their relation to electricity pricing and income expenditure. The model pinpoints that while trying to maintain income growth related to GDP growth rioting still increases in all cases except S3, which had no tariff increases. This exploration may be beneficial to stakeholders, potentially improving understanding of the populous dynamics related to delivery of public services.

This model framework can be extended to investigate environmental and non-environmental policies that impose different burdens or costs onto society. Because protests can lead to violent riots, this model can assist in developing action plans to mitigate potential violence as well as differentiate between policies that anger their constituencies. Better socio-environmental data could further explore the beliefs associated with rioting, social networking, environmentalism and energy pricing. It is hoped that future investigations will collect these data and implement them into the model.

Potential Reduction In Greenhouse Gas Emissions

The results of the model were used to evaluate the greenhouse gas emissions from the residential sector over time. Resource planning scenarios and their subsequent emissions intensities were taken from the South African Integrated Resource Planning (IRP) for Electricity report (South African Department of Energy, 2010). The IRP represents the vision of the stakeholders with the South African Department of Energy and the executive branch of the South African government.

Four-generation investment schemes were investigated from the report in this analysis – *Base Case, Balanced Scenario, Carbon Tax*, and *Emissions Limited*. These scenarios have the following construction in the IRP report:

- *Base Case (case 1.0)* – This case combines Mozambique-imported hydropower, natural gas combined cycle gas turbines (CCGT), and fluidized bed combustion (FBC) coal for base-load capacity. Additional peaking capacity is provided by diesel-powered open-cycle gas turbines (OCGT). In this scenario, CO_2 emissions will grow, but at a lower rate due to older technologies being replaced during plant decommissioning.
- *Carbon Tax* – This scenario implements a carbon tax at R165 per MWh that increases to R332 per MWh in 2030 and R995 per MWh in 2040. The generation for this scenario includes low carbon-emitting technologies such as nuclear, wind power, Mozambique-imported hydropower, OCGT and CCGT with some FBC coal.
- *Emissions Limited (case 2.0)* – An emission limit of 275 million tons is applied in this scenario. It is imposed later in the investigated time period (year 2025). Nuclear and wind power plants are built to expand capacity along with the other technologies implemented in the Base Case scenario; older power stations are decommissioned.
- *Balanced Scenario* – This scenario was created considering divergent stakeholder expectations and key constraints and risks. It represents a trade-off between least-

investment cost, climate change mitigation, diversity of supply, localization and regional development.

Emissions data are applied to the model electricity demand estimates. The IRP data do not supply estimates for emissions after 20 years. Therefore, in this evaluation, the emissions intensities are assumed to be constant after 20 years. An additional scenario – Current Generation Scheme (*Current*) – is evaluated, which applies the current emissions intensity throughout time to show emissions reductions overall from the current baseline. This analysis is particularly relevant for South Africa due to the country's reliance on coal resources for electricity generation (used in over 90 percent of the generation) and the continually multi-year delays in electricity generation capacity expansion. The model results for Scenario 1 are applied to this scenario as the *Base Case* scenario. Scenario 4 results are applied to the *Balanced Scenario, Carbon Tax*, and *Emissions Limited* schemes. This represents perhaps a worst case cost scenario of 7% per year increases over the entire analysis period. The results are shown in Figure 30.

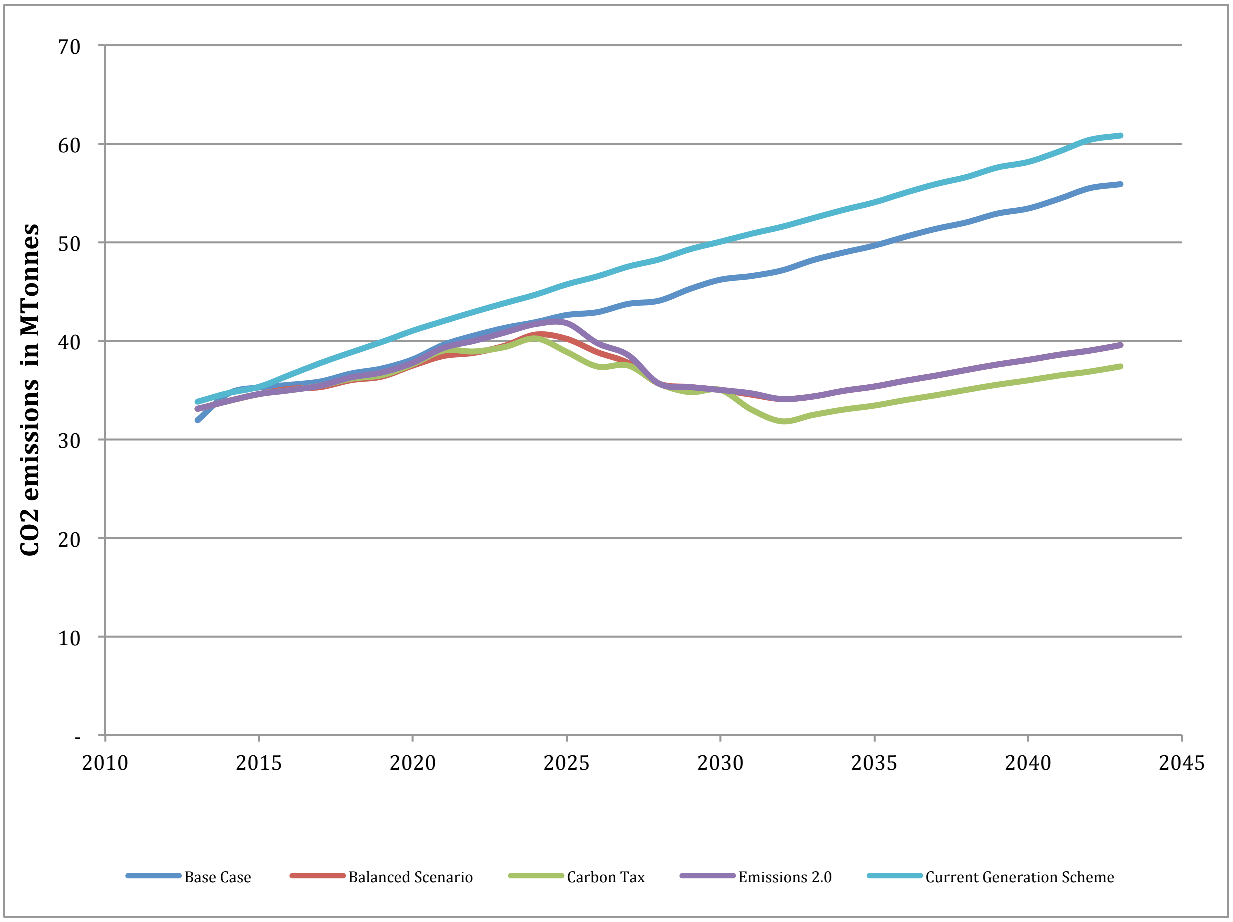


Figure 30 – Aggregate Residential Carbon Dioxide Emissions Model Results over 30 years

The *Base Case* shows a 10 percent reduction in CO_2 emissions from the *Current* scheme at the end of the 30-year period. There is a 34 percent reduction in emissions with the Carbon Tax scheme and 30 percent reduction in the other two schemes. This was not unexpected considering that the emissions intensity differential between the generation schemes. There is a 3 percent greenhouse gas emissions reduction benefit in the final year considering demand response to increased prices. That is to say, if the *Balanced Scenario, Carbon Tax*, and *Emissions Limited* are chosen and implemented, the model indicates a reduction of greenhouse gases, which is a benefit from reduced demand in the residential sector. This is a minimal improvement in emissions reduction. It shows that the various emissions schemes and subsequent electricity tariff increases may provide additional aggregate greenhouse gas reduction benefits from decreased use. And on the other hand there is potential for increased civil disturbance as indicated in Figure 27.

However, the decreased electricity demand is substituted with use of solid and liquid fuels in households. This agent-based model in all pricing and socio-economic scenarios exhibits a decrease in the number of fuel-stacking, non-electrified (NEMEU) users through the time period. This provides positive political, environmental, and public health benefits as people are happy using electricity, using more sustainable fuel sources, and are less at risk for smoke inhalation and household fires. However, these are rough estimates and the model only incorporate increases within the average costs and not the actual consumer tariff.

Health Impacts Of Renewable Energy and Energy Prices

Domestic pollution is connected to health and wellness of household participants, increasing susceptibility to pulmonary disease and tuberculosis (Fullerton, Bruce, & Gordon, 2008). Figure 29 displays a troubling aspect of this. The continued use of other fuel types in the future periods of the simulation means that toxic household environments will continue. The model indicates that there will be a significant population—over 30 percent of the population in all model scenarios—exposed to high-level indoor pollution and thus increased morbidity and mortality rates.

This type of evaluation provides important structural detail for analysis of energy development programs for developing countries, because air pollution in these households is many times higher than those in industrialized countries (Ezzati & Kammen, 2002). Haines, Kovats, Campbell-Lendrum, and Corvalán (2006) posited that climate change mitigation schemes that reduce fossil fuel use and increase renewable energy generation can improve health by reducing air pollution exposure. However, in the developing country case, the reduction has the potential to increase domestic pollution exposure among those who cannot afford the electricity prices for renewable energy generation. It is hoped that this model framework will support further investigations into energy poverty and health impacts of macro-enviro-economic policy.

Conclusion

The presented agent-based model estimates the aggregate energy demand from the residential sector over a 30-year period. This model distinguishes the number of single-energy (electricity) users as well as the number of multi-energy users who may or may not use electricity in their energy mix at each period. We address the questions of how demand changes in residential households as prices change, as well as the dynamic changes in residential energy end-use behavior among fuel consumers. Utilizing research on rioting and social networks, the analysis provides insight into the frequency of grievance.

This analysis provides a foundation for further research on civil disobedience, greenhouse gas reduction impacts on electricity demand, the health impacts of fuel transitions, and energy systems of developing countries. Although South Africa is more advanced than other African countries, it is not alone in its trials to reduce energy poverty and inequity as it moves toward greater economic development. Kenya, Angola, Nigeria, and India face some of the same issues of rapid urbanization, increased economic growth, and a rising middle class. All of these challenges intersect with having diverse communities with historically different energy needs. Aggregated linear demand models have limited application for these problems, and the agent-based approach developed here aims to capture some of the complexities and provide insight into the development of effective policy.

With our model, we do not claim to predict future development of electricity in South Africa. The model framework is suggested as an innovative tool for energy policy analysis in developing countries. We have developed the appropriate scenarios for South Africa to test the construction of this model, but these parameters can easily be revised to assist policy makers in other countries. Future work could potentially evolve this model for applications to different countries or to evaluate water demand dynamics within a watershed. It is our hope that policymakers will use this tool to evaluate the future social and economic impacts of sustainable development and possibly contrive policy interventions. It would also be interesting for this model to be extended so that household energy use can be evaluated considering the different primary energy-consuming activities of the household. Among a number of potential applications, the model could evaluate policies directed at energy efficiency or influencing cleaner fuel use.

CHAPTER 5

THE ROLE OF TRANSIT MOBILITY DEVELOPMENTS IN GREENHOUSE GAS EMISSIONS REDUCTION SCHEMES: A CASE STUDY OF THE ATLANTA BELTLINE

Introduction

Individual municipal governments are developing greenhouse gas emissions reduction plans that address the growing concern of climate change and its subsequent effects. Dodman (2009) argues that cities are the best suited to tackle these issues because they are responsible for land use and transportation planning, they have the best opportunity to implement new technological innovations, and they are the primary beneficiary of GHG reductions in the form of improved public health and air quality. These overall improvements lead cities to tackle not only the issues of improving density or energy efficiency, but to also engage in the broader issues of urban form and infrastructure development (Burgess, 2000).

Cities such as Atlanta (GA), Portland (OR), and New York City (NY) are creating inventories of the GHG emissions (scope 1 and 2) within their boundaries and are developing strategies for emissions reduction that develop (or redevelop) their urban landscapes. While cities have lower GHG emissions per capita than the countries in which they are located, these municipalities are using these inventories to create reduction targets and emissions abatement plans (Dodman, 2009). These inventories consider all major sources related to energy generation, waste/disposal, residential/commercial buildings, land use change, transport, and municipal services (i.e., water/wastewater processing) (Chandrappa, Gupta, & Kulshrestha, 2011). Considering these sources, the City of Atlanta has set various emissions targets for the coming years (CoA, 2014):

- Reduce greenhouse gas emissions within the City of Atlanta’s jurisdiction 25 percent by 2020, 40 percent by 2030, and 80 percent by 2050.

- Reduce, reuse and recycle 30 percent of the city's residential waste by 2013, 50 percent by 2015, and 90 percent by 2020.
- Provide a minimum of 10 acres of green space per 1,000 residents and protect and restore the city's tree canopy to 40 percent coverage.

The city is implementing programs that address urban ecological systems and urban redevelopment in formerly blighted/uninhabited or industrialized areas. One of the projects is the Atlanta BeltLine, which is a transit project that seeks to link various segments of the city through rail and bike paths as well as develop new residential and recreation areas. Some have criticized the BeltLine as a novelty project that will not bring benefit to the city or metropolitan region commensurate to the financial costs of the project. We investigate the benefit of this project through an analysis of the environmental and financial benefits of the system, acknowledging the many different challenges to cost-benefit analyses that include environmental metrics (Ackerman & Heinzerling, 2002; Greenstone, Kopits, & Wolverton, 2011; Sovacool, 2011) including:

- time-varying costs and benefits,
- identification and quantification of monetary costs and benefits to society, and
- pricing environmental protections and degradation.

The aim of this study is to evaluate the costs and benefits of such projects considering time-varying health and environmental benefits across the discount period. We also evaluate the total greenhouse gas emissions reduction from the system implementation and analyze its potential contribution towards reaching the municipal emissions goals.

This study is organized as follows: Sections 2 and 3 contain the literature review and general framework, respectively; Section 4 illustrates the characteristics of the Atlanta BeltLine; Section 5 presents the greenhouse (GHG) gas emissions savings from transit; Section 6 presents the GHG savings from reduced private car transport; Section 7 presents the methodology and results for household GHG emissions; Section 8 presents a cost-benefit analysis that integrates all previous results to show environmental benefits (or costs). Finally, Section 9 discusses the findings, their contribution to emissions targets, and their implications.

Literature Review

Cost-benefit analyses are the economic standard for determining the future success of public sector projects and programs, the importance of which is supported by a substantial volume of literature. Much of this literature has investigated direct costs as well as the indirect (social) costs. For governments, this is a daunting task, as it is difficult to include social costs, which cannot be priced or evaluated in the same way as manufactured goods (Ackerman & Heinzerling, 2002). However, as demonstrated in Section 1, government agencies over the last decade have been more inclusive of environmental costs in their calculations. This stance has been particularly controversial in transportation planning, due to the fact that some opponents do not see the need to recognize the cost associated with climate-changing air emissions and low-density development (Litman, 2011).

Although municipal governments and stakeholders are increasingly focusing attention and resources on reducing municipal greenhouse gas emissions, there is not yet a framework for developing cost-benefit analyses based on the life-cycle of the project. Some of the literature evaluates the generated emissions from the transit use and those mitigated from reduced car travel (Eliasson, 2009; Hensher, 2008; Rotaris, Danielis, Marcucci, & Massiani, 2010). However, these analyses have not evaluated the greenhouse gas emissions coming from residential or commercial development that directly stems from a public project such as transit. Additionally, past studies have not integrated energy-system changes within their analyses. These can be important in the case of electric-powered transit, as there may be significant changes in electricity generation over the next decades if coal-derived electricity decreases and other sources such as natural gas, renewable, nuclear, etc. are used in its place. These changes would not only result in changing emissions per kWh, but also changing costs per kWh (Choi & Thomas, 2012). Similarly, for roadway or transit projects, the changes over time in the emissions spectrum of the fleet of passenger cars should be accounted for within the analysis.

There is also a lack of cost-benefit analysis literature that substantively incorporates uncertainty and time-dependent parameters. Cost-benefit analyses have some degree of uncertainty due to the fact that it is not known what will happen in the future (e.g., in the case of transit, new car technology may advance such that it is more affordable; or roadway congestion pricing may make transit more affordable). We found no studies that seeks to quantify these variable social costs.

This investigation incorporates many of the internal and external costs and benefits a municipality would receive from project implementation within a reasonable time period. The findings provide a basis for public sector agencies and their stakeholders to evaluate these and other costs embedded within the development of public projects, with the consideration of time dependence.

General Methodology and Framework

Transit Greenhouse Gas Emissions Methodology

The per passenger-mile energy intensity of the proposed transit systems is estimated from data from similar systems, taking into account city structure and population density of the surrounding corridor (or urban area).. Using local data on greenhouse gas emissions intensity we evaluate the per passenger-mile greenhouse gas emissions per year. A multi-decade linearized electricity production optimization model for the State of Georgia is used to evaluate future electricity emissions and costs (Choi and Thomas 2012).

Residential Development Greenhouse Gas Emissions Methodology

Residential development greenhouse gas emissions are estimated by considering the potential population density and housing type distribution in the transit buffer zone. The estimated vehicle miles traveled by light-rail buffer residents are modeled based on data compiled by Brownstone and Golob (2009) and the corresponding greenhouse gas emissions are calculated based on the expected fuel economy of the private car fleet over the discount period. Estimated direct emissions from household energy use were generated using the methodology from Norman, MacLean, and Kennedy (2006), using local time-depending electricity greenhouse gas emissions per kWh.

Net Present Value Methodology

The costs and benefits for the municipality are presented in terms of the net present value (NPV) of the development, considering time-dependence and parameter variability. This model employs an "overnight" basis for costs; that is, we do not include the financing costs for loans and bonds that may be used to finance system construction. Also, for simplicity, we do not include the potential for system subsidies or long-term debt. We develop an expression for the present costs, PC, of building and operating the light rail system. Here, C is the capital cost per unit length of building the system, L is the length of the system, r is the discount rate, and T is the total expected lifetime of the system. The capital cost as a function of length *C(L)*. The total maintenance cost is taken to be a function of the system length. Maintenance cost can change over time depending on the age of the system; here we calculate it as a static cost over time period T, denoted as by $M(L) \cdot T$.

Lifecycle costs comprise the construction cost and other N system costs, ϕ_i where $i \epsilon (1, \dots, N)$. These costs can be fuel, environmental, societal cost (i.e., time), etc. We generalize the cost approach by denoting these costs (or benefits) as $\phi_i(\alpha_i)$ where α_i is a vector of inputs related to the i-th cost. Many cost benefit analysis studies use static cost across the time horizon. We use a more formal approach which incorporates dynamically changing values. These can be significant in in comparative analyses of transportation systems that face dramatically changing fleets, fuel composition, and costs in the coming years. While the capital and maintenance costs may not change over the time period T, we posit that other direct and indirect costs can be expected to change, due to demand changes (of infrastructure or fuel), policies, or constraints. Under these considerations, the lifecycle cost, LC, takes the following form, where the i-th cost, ϕ_i, is a function of environmental/system inputs, time t, and a vector $\bar{\theta}$. This vector $\bar{\theta}$ represents endogenous variables that relate to policies, demand scenarios, and constraints, which affect the representative price of the i-th cost at time t.

Equation 16

$$LC = C(L) + M(L,T) + \sum_{t=1}^{T}\sum_{i=1}^{N} \phi_i(\alpha_i, f(t,\bar{\theta}))$$

Considering the above, we use the following net present value (NPV) for this system by discounting at rate *r*.

Equation 17

$$NPV = C(L) + \sum_{t=1}^{T} \frac{(M(L) + \sum_{i=1}^{N} \phi_i(\alpha_i, f(t,\bar{\theta})))}{(1+r)^t}$$

Here, we include monetary and social costs, such as capital, maintenance and operating expenses, revenue, congestion costs, costs attributed to greenhouse gas emissions, the value of time saved or used in transportation, estimated health implications of transit use, and value added from real estate investment. These costs are quantified using the methodology discussed in the *CO_2 Emissions from Residential Development Energy Use* and *CO_2 Emissions from Residential Development Water Use* sections. The integration of these costs and their time-dependence in this case study are discussed in the Discussion. A diagram of the integration is shown in Figure 31. Different discount factors are used within a Monte Carlo analysis (MCA) to find the range of net present values and benefits-costs ratios for the development. Costs are then disaggregated to show which of the different variables has the most influence.

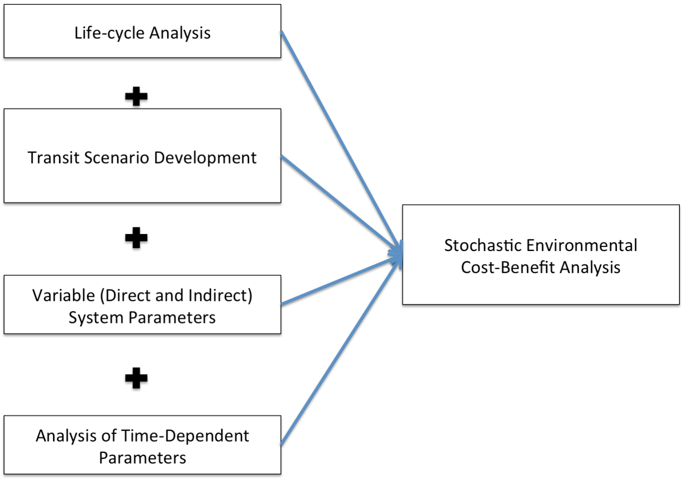


Figure 31. Model framework. This model incorporates transit-oriented scenarios and uncertainty into a stochastic cost-benefit analysis. The time-varying parameters incorporate significant changes in cost or environmental impacts over time.

Case Study: Atlanta BeltLine

Public transportation can reduce energy use, reduce greenhouse gas emissions, mitigate traffic congestion, and support the development of thriving neighborhoods. The Metropolitan Atlanta Rapid Transit Authority (MARTA) operates a system of heavy rail subway trains, a bus system, and a smaller demand-response system. Expansions to Atlanta's transit system are regularly planned and proposed. Prominent among these is the Atlanta BeltLine, a proposed 22-mile light-rail loop around Atlanta. This system is a large-scale, quasi-transit oriented development that will include the light-rail system, housing, parks and trails. The BeltLine plan is projected to provide community needs such as (non-transit and transit) mobility, recreation, economic development, workforce housing, and cultural resources (MARTA & Atlanta BeltLine Inc., 2009).

There are some challenges related to the feasibility and significance of the BeltLine. The transit corridor is routed along twenty-two miles of former or still in-use railroad right-of-way that provides circumferential mobility and recreation service to the Atlanta community. This corridor has the potential to connect job centers to people, and vice-versa. However, many of the areas adjacent to the BeltLine are sparsely populated and/or do not connect to large job centers. Only the northern and northwest corridors are adjacent to or connect to job and population centers. In an Atlanta Development Authority-sponsored feasibility study, a panel of researchers concluded that the BeltLine might suffer from low levels of ridership due to lack of connections and appropriate adjacent population density. In a MARTA study on the Feasibility of Transit, the Atlanta Regional Commission model forecast minimal improvements to transit with the model implementation of the BeltLine under current community conditions (C. Ross, Meyer, Dobbins, Jackson, & Millar, 2005). Other research, by Brown and Thompson (2008), shows that Atlanta's decentralization of jobs has been a major factor in the decline of patronage of the current MARTA system. In light of these studies, a key challenge is to increase housing and jobs development around the BeltLine facilities.

Land use and transportation are not independent of each other. For the Atlanta BeltLine, planners, strategists, and City of Atlanta officials must promote linear development of the spaces surrounding the BeltLine to increase ridership, improve system efficiency, and mitigate environmental impacts (Studio, 2002). These improvements will be driven by growth in density of jobs and people as well as increased transportation connectivity. Population and job growth in the past decade has occurred outside the boundaries of the City of Atlanta, and the appeal of location in Atlanta to current residents and businesses must be evaluated in the present and looking forward (Brown & Thompson, 2008). Atlanta is currently undergoing a renaissance as more people are beginning to move back within the Atlanta city limits, and in turn the city has become more engaged in supporting urban redevelopment efforts (Immergluck, 2009). There are potential benefits of building the Atlanta BeltLine, including neighborhood development, increases in tax receipts, and recreational value. These important factors shape our framework in the present study as we evaluate the potential financial benefits, energy savings, and greenhouse gas reductions of the BeltLine.

Energy and greenhouse gas implications of public transit in Atlanta

To provide context, we first consider the energy and greenhouse gas implications of existing transit in Atlanta. The heavy rail portion of the system runs on electricity and its buses run on natural gas and diesel. In 2010, the heavy rail portion consumed 95.3

million kWh of electricity while its buses consumed 6.2 million gallons of compressed natural gas[1] and 2.4 million gallons of diesel fuel (Federal Transit Administration, 2012). MARTA heavy rail had a ridership of 493 million passenger miles in 2010. The heavy rail alone expends 0.19 kWh per passenger mile. According to data provided by Georgia Power, the efficiency of electricity production and distribution is approximately 35% (approximately 9800 Btu/kWh$_e$), and the total primary energy consumption is 1.9 MJ or 1800 Btu per passenger mile. The bus system had a ridership of 273 million passenger miles, for a total energy use of 31.6 passenger miles per gallon, equal to 6.6 MJ or 6300 Btu per passenger mile.

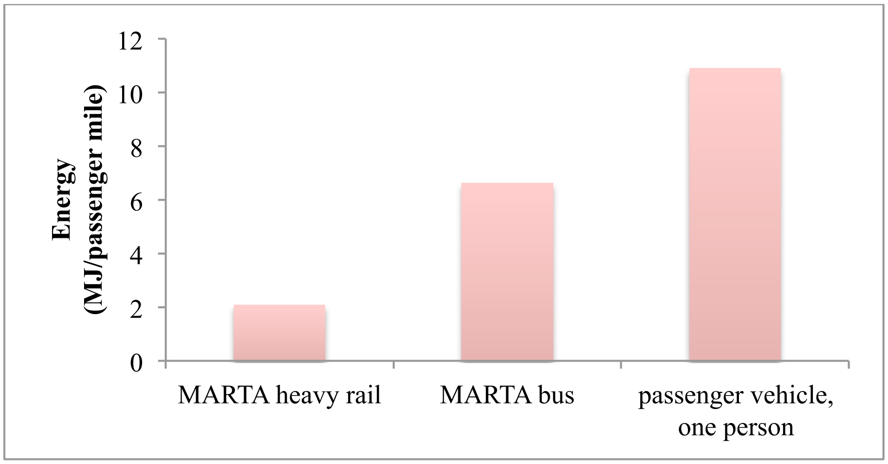


Figure 32. Average system energy use per passenger mile for Atlanta's MARTA heavy rail, MARTA buses, and a 20 mile per gallon (mpg) passenger vehicle. Data are from 2010.

Figure 32 shows these estimates of energy expenditure per passenger mile for MARTA heavy rail, MARTA buses, and passenger vehicles used by single persons. The figure shows both MARTA rail and MARTA buses as more energy efficient than the passenger vehicle. However, rail transport is shown to have the greater emissions reduction potential.

The greenhouse gas emissions from these systems depend on the emissions from electricity production, from the combustion of the natural gas and diesel fuel used for the buses, and from combustion of the gasoline used in cars and SUVs. As of 2010, the direct

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[1] This is reported as the energy equivalent gallons of diesel fuel or gasoline.

greenhouse gas emissions from electricity produced by Georgia Power was 0.65 kg CO_2 per kWh. Figure 33 shows greenhouse gas emissions per passenger mile. In comparing Figures 32 and 33, note that the emissions from the MARTA buses are relatively low compared to their energy use; this is due to the extensive use of natural gas, which has lower levels of greenhouse gas emissions compared with diesel fuel or gasoline.

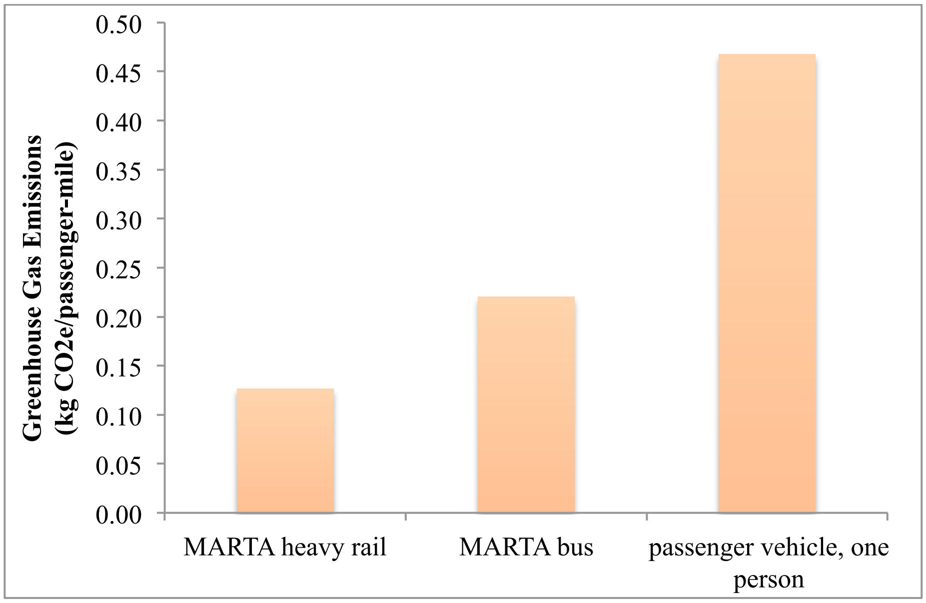


Figure 33. Greenhouse gas emissions per passenger mile from Atlanta MARTA heavy rail and buses, and a 20-mile per gallon passenger vehicle. Data are for 2010.

Direct Energy and Greenhouse Gas Implications

Figure 34 shows the proposed path of the Atlanta BeltLine light rail system, and the "BeltLine Study Area," the area about half a mile to either side of the BeltLine, which can be considered the main areas of residences and destinations to be served by the BeltLine light rail system. By the year 2030, the BeltLine is projected to provide 26.4 million rides to passengers annually, creating a travel savings of 145 million vehicle miles per year, equivalent to 5.5 vehicle miles avoided per boarding. These estimates were developed from the Atlanta Regional Commission's Travel Demand Model, and were used in the BeltLine Final Tier I Environmental Impact Statement as well as in the

Inner Core BeltLine Alternatives Analysis (MARTA, 2007 ; USDOTFTA & MARTA, 2012).

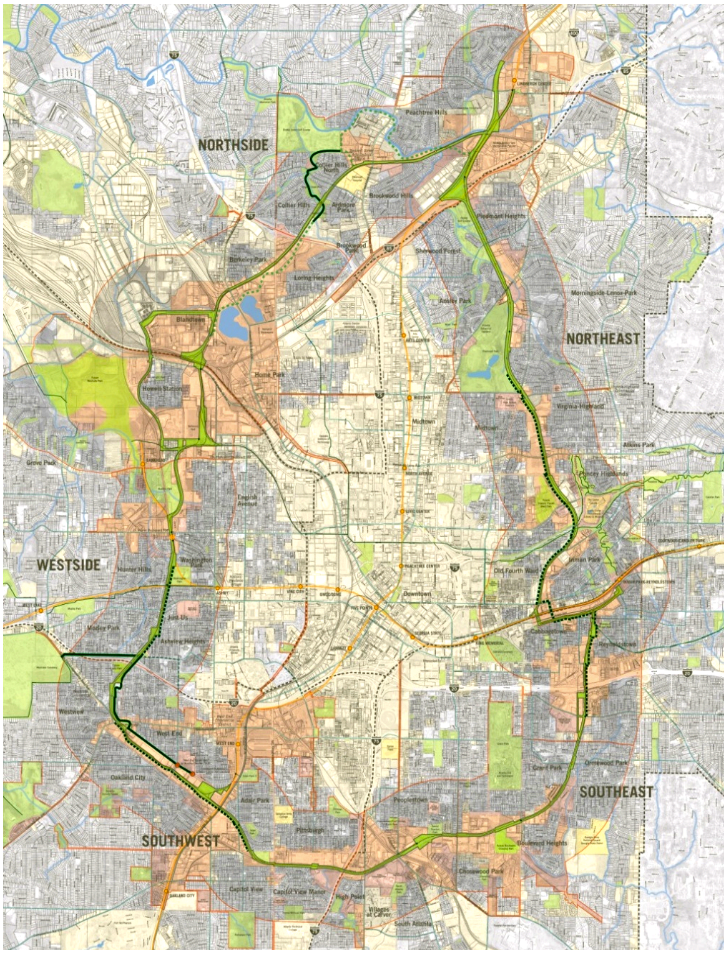


Figure 34. The Atlanta Beltline Study Area. Source: USDOTFTA and MARTA (2012).

The energy use per passenger mile will depend on the energy efficiency of the trains and the number of passenger miles. Public documents do not include estimates of the number of miles each passenger will travel on the BeltLine; we assume that the passenger miles on the BeltLine will be equal to the vehicle miles displaced, 5.5 miles per boarding.

There are no public estimates of the energy use of the BeltLine trains. Therefore we develop estimates from data on other US light rail systems. Table 1 shows data for several US urban light rail systems, where the electricity use per seat-mile varies from 0.18 kWh in Charlotte (NC), and Portland, to 0.3 kWh per seat-mile in Salt Lake City

(UT). Phoenix (AZ) and Portland (OR) have the lowest energy intensity per passenger, at 2,500 BTU. Portland achieves this efficiency by filling an average of 70% of seats; Phoenix achieves this efficiency filling 101% of seats on average (standing as well as seated passengers). Below we consider two scenarios: one in which the BeltLine achieves a high efficiency of 2,500 BTU per passenger mile, as in Phoenix or Portland, and another in which the BeltLine achieves a lower efficiency of 4,000 Btu per passenger mile, as in Charlotte or Salt Lake City.

Table 11 - Light rail system statistics for several US cities. Source data from (DOE, 2012) and (Federal Transit Administration, 2012).

City	Energy Intensity (BTU/pass-mi)	Seats per train	Population Density (ppl/sq. mi):	Electricity per train mile (kWh)	Electricity per seat-mile	Fraction of seats filled	Passengers per train
Charlotte	4000	68	2457	13	0.18	0.47	32
Dallas	6000	100	3518	24	0.24	0.43	43
Phoenix	2500	66	2798	16	0.24	1.01	67
Sacramento	4500	64	4764	21	0.33	0.78	50
Portland	2500	70	4375	13	0.18	0.70	49
Salt Lake City	4000	64	1678	19	0.30	0.73	47

The BeltLine ridership estimates are for the year 2030, so the energy use of the BeltLine in 2030 needs to be compared with the energy saved from avoided passenger vehicle travel in 2030. US fuel efficiency standards mandate average vehicle fuel efficiency to increase to reach 54.5 miles per gallon by model year 2030. However, clearly, not all cars on the road are new cars; the average fuel efficiency in 2030 can be expected to be higher than today but less than 54.5 miles per gallon. Choi et al. (2012) have modeled vehicle stocks and vehicle retirements in order to project the average fuel efficiency of the vehicles in use in 2030. As shown in Figure 34, by 2030 the average light duty vehicle in use is projected to have a fuel efficiency of 32 miles per gallon, or 3500 BTUs per vehicle mile. This projection differs from the assumptions of the BeltLine Final Environmental Impact Statement (USDOTFTA & MARTA, 2012), which uses 6,233 BTUs per vehicle mile, equivalent to 18.3 miles per gallon; that value is typical of today’s in-use vehicles, but by 2030 vehicle efficiencies can be expected to be considerably higher.

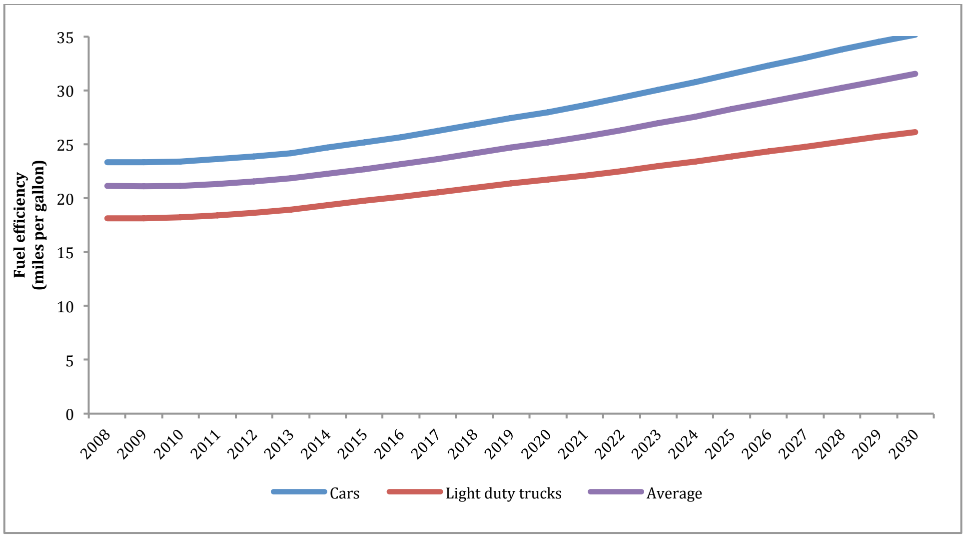


Figure 35 shows projected average fuel efficiency of in-use cars and light duty trucks. Data from Choi et al. (2012).

The greenhouse gas emissions from the BeltLine will depend on the amount of electricity used by the BeltLine trains and on the amount of greenhouse gas emissions emitted per kWh of electricity. As of 2010, greenhouse gas emissions from Georgia Power electricity were 0.65 kg CO_2 per kWh. A least-cost estimate considering power plants under construction and projected future demand and fuel costs indicates that by 2030 the emissions rate in Georgia will decrease to 0.56 g CO_2 per kWh, due both to the expected opening of two new nuclear power reactors, and to a partial shift toward natural gas, motivated by its lower cost (Choi & Thomas, 2012). This estimate is shown in Figure 36.

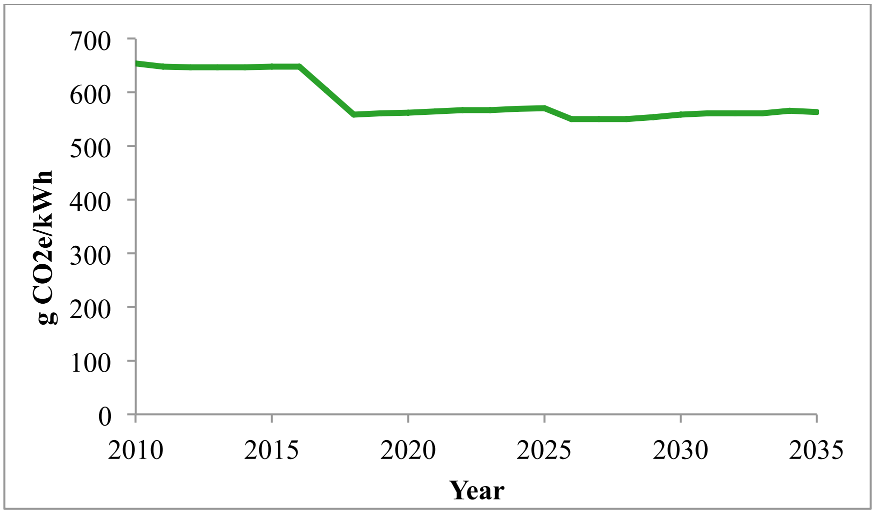


Figure 36. Future GHG emissions per kilowatt-hour estimates for Georgia based on Choi and Thomas (2012). These changes are due to expected increased nuclear and natural gas generation.

Figure 37 shows the resulting projection of net greenhouse gas emissions from the Atlanta BeltLine system in 2030. The first set of bars shows the total greenhouse gas emissions from the BeltLine in the high efficiency scenario (2,500 BTU per passenger mile) with lower emissions than the medium efficiency scenario (4,000 BTU per passenger mile). The second set of bars shows the energy savings from avoided car trips; the value is the same in both scenarios, and is based on BeltLine projections of avoided car travel and projections of vehicle efficiency in 2030. The third set of bars shows the difference between the emissions from operating the BeltLine system and the savings from avoided trips. Savings for the high efficiency train system are about 22 thousand tons of CO_2 per year; savings from the medium efficiency system are about 11 thousand tons of CO_2 per year.

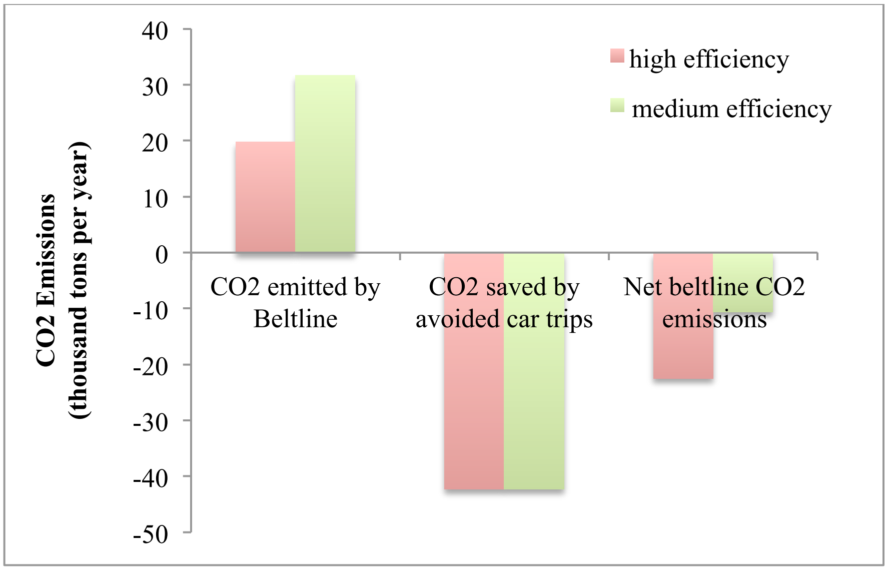


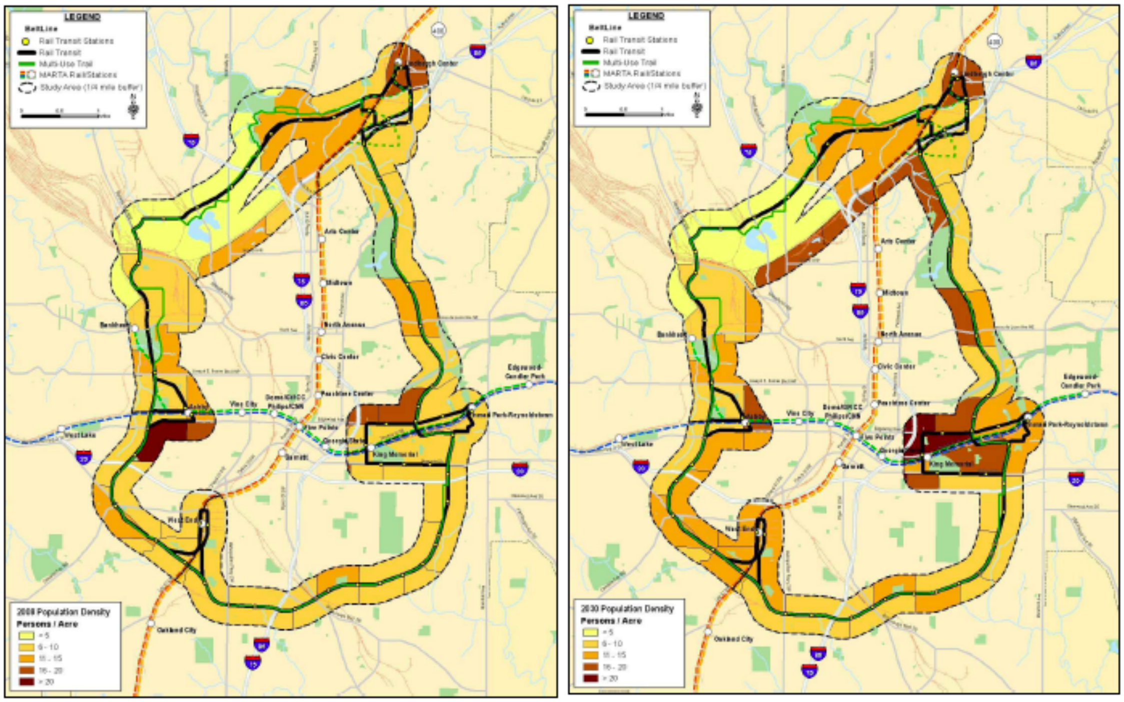
Figure 37. Estimate of greenhouse gas emissions from the BeltLine in 2030. The figure shows estimates CO_2 emissions from BeltLine operations; estimated CO_2 savings from new avoided vehicle travel, and the net savings is the difference between the two.

The estimated 22,000 tons of greenhouse gas emissions savings is less than 1% of the estimated 3 million tons of greenhouse gas emissions exuding from transportation in Atlanta by 2030 (Thomas et al. 2012). However, only a fraction of Atlanta's population is projected to live or work in the BeltLine Study Area. A more meaningful assessment of the BeltLine's transportation energy impact could instead be based on its effect on the residents of the BeltLine Study Area. As of 2008, 16% of Atlanta's population lives in the BeltLine Study Area; this fraction is projected to remain essentially constant to 2030, resulting in a BeltLine study population of 98,000 by 2030 (USDOTFTA & MARTA, 2012). There are few data on the typical daily vehicle miles traveled by Atlanta residents. In the overall Atlanta metropolitan statistical area, car travel has been estimated to be about 30 miles per day on average, but travel distances of people who live within the city limits of Atlanta may be smaller. In the Atlantic Station development in Midtown Atlanta, residents traveled an average of 14 miles per day by car in the first years after opening; this has since dropped to about 9.4 miles per day. Potentially, the current residents of the BeltLine Study Area could have similar driving habits; to develop a rough estimate we assume 11 miles per person per day for the residents of the BeltLine area, in the absence of BeltLine transit development. The projected use of the BeltLine - 26.4 million boardings per year - when combined with the projected population of the

BeltLine area, indicates that on average about a third of the BeltLine area residents would use the BeltLine on a daily basis, reducing their driving by 11 vehicle miles per person per day, resulting in an overall 25% decrease in driving by BeltLine area residents. This is a rough estimate yet it indicates that the BeltLine could substantially reduce the transportation energy use of BeltLine area residents.

Energy and Greenhouse Gas Savings from Residential Development

The BeltLine development plan includes new residential and non-residential development. In the transportation research literature, it is well established that use of transit systems increases as residential density increases. As shown in Figure 38, many places along the BeltLine, especially along the southwest and southeast corridor, have low residential densities, while the densities of the northeast corridor and northern endpoint are much larger. The figure shows that in much of the area, population density as of 2008 was between 6 and 15 people per acre, and that by 2030 population density is projected to increase somewhat. Overall a 29% growth is projected for the BeltLine study area from a 2008 population of 76,000 to a 2030 population of 98,000 (USDOTFTA & MARTA, 2012).



Source: U.S. Census Bureau, Census 2000, and ARC 2008 Regional Forecasts

Source: U.S. Census Bureau, Census 2000 and ARC 2008 Regional Forecasts

Figure 38a and 38b. Population density distribution in the Atlanta Beltline corridor, 2008 (a) and projection for 2030 (b). Source: USDOTFTA and MARTA (2012).

In the transportation literature, it has been argued that the minimum population density for light rail service is approximately 5,800 people per square mile, or 9 people per acre (Pushkarev, Zaupan, & Association, 1977). In a more recent publication, Zhang (2009) suggests that in order for travelers to switch from single-occupancy vehicles to transit, the density of the transit corridor should be approximately 8,300 people per square mile, or 13 people per acre. While some locations along the BeltLine route do have these high densities, the low density of other locations is a known challenge for the BeltLine system.

Other cities also face this issue of density to support light rail transit. All of the cities whose light rail systems are profiled in Table 11 have population densities of less than 5,000 people per square mile. The cities with the lowest population densities, Charlotte and Salt Lake City, which have densities similar to Atlanta's, have only moderately efficient systems in terms of overall energy use per passenger mile. In contrast, Phoenix is also a low-density city, and has managed to achieve high efficiency with its light rail transit system.

There is evidence that high density areas of cities have lower per-person transportation energy use (Norman et al., 2006). That is, aside from the availability of transit, people living in dense areas do not drive as many miles as people living in less dense areas. Using data on transportation energy use (Brownstone & Golob, 2009; Norman et al., 2006), we developed a model of the annual mileage and annual transportation fuel consumption as a function of residential housing density. For a population density increase from about 7 to 9 people per acre, corresponding to the projected population density increase by 2030, even without the Beltline transit system a 3% decrease in transportation energy use might be expected. The overall Atlanta population is projected to grow 26% from 2008 to 2030, from 477,000 to 603,000. Since the increase in the population density of the Atlanta BeltLine study area is not projected to be substantially greater than in Atlanta overall, no density savings should be attributed to the BeltLine per se; an approximate decrease of 3% in vehicle travel can be expected throughout Atlanta as its population grows to projected 2030 numbers. If the BeltLine in the future includes substantially higher density development, additional energy savings can be expected.

CO_2 Emissions from Residential Development Energy Use

US Census data were obtained to find the total number of housing units and the percentage of low-, middle-, and high-density housing. These data were delineated by seven different housing types: single unit (attached and detached), duplex, 3-4–unit buildings, 5-9–unit buildings, 10-49–unit buildings, and 50 and greater–unit buildings.

These housing types were aggregated into three density categories: low, middle and high. This aggregation was performed so that the fields for housing type in the Census are matched the housing types in the Residential Energy Consumption Survey (RECS) dataset (EIA, 2009). Single unit, both attached and detached, buildings were placed into the low-density housing category. The values for duplexes and 3 or 4 unit buildings were added under the middle-density housing. The 5 to 9 unit buildings, 10 to 49 unit buildings, and 50 or more unit buildings were aggregated as high-density. All other buildings were not aggregated and were not a significant percentage of units in the case of Atlanta (less than 1% of total buildings). The housing percentages for the three types were then calculated from the aggregated values.

RECS energy values for homes in the Southeastern US were used to estimate the per capita CO_2 intensity. The average electricity and natural gas usages for the three types of homes were available. The total CO_2 intensity per capita, HH_{CO_2}, were calculated using emission factors found in Thomas, Mlade, Borin, Tindall, and Okwo (2012). Data on the average number of residents per household are from the US Census (2013).

Equation 18

$$HH_{CO_2} = \frac{\left(\sum_1^n \lambda_n \cdot HH_{elec} \cdot EF_{elec} + \sum_1^n \lambda_n \cdot HH_{NG} \cdot EF_{NG} \right)}{HH_{resavg}}$$

Equation 18 calculates the household CO_2 intensity per capita where λ_n is the fraction of housing type n, HH_{elec} and HH_{NG} are the average electricity and natural gas usage for housing type n; EF_{elec} and EF_{NG} are the emissions factors for electricity and natural gas, and HH_{resavg} is the average number of residents per household.

CO_2 Emissions from Residential Development Water Use

Average per capita daily usages for single and multifamily residents are available by county (MNGWPD, 2009). We use the multifamily water usage rates in for the high-density housing. The middle-density housing usage was estimated to be the average between the single and multifamily usage.

Municipal water energy use data from Thomas et al. (2012) were used to calculate the average kWh per gallon for the city utility. In order to find the city water use, in this case, the percentage of city residents to total county population was used to find the amount of water attributable to the city. The energy use per gallon was calculated by dividing the water utility electricity usage by the total amount of municipal water produced.

The average per capita CO_2 intensity for water use, WTR_{CO_2}, for a specific housing mix is found using a linear combination similar to that in Equation 18.

Equation 19

$$WTR_{CO_2} = \frac{\left(\sum_1^n \lambda_n \cdot Water_{year} \cdot EL_{water} \cdot EF_{elec}\right)}{HH_{resavg}}$$

Equation 19 calculates the CO_2 intensity per capita attributed to water where λ_n is the percentage of housing type *n*, $Water_{year}$ is the total annual water use per capita. EL_{water} is the average electricity usage for housing type *n* electricity usage. EF_{elec} is the emissions factor and HH_{resavg} is the average number of residents per household.

CO_2 Emissions from Automobile Transportation of Corridor Residents

Considering results from other researchers in the field, we assume that density is the primary correlate of vehicle miles traveled (VMT). Brownstone and Golob (2009) analyzed the 2001 National Household Travel Survey data to understand the correlation between residential density and annual fuel usage (and mileage). Using these data, we developed a power function relating density to VMT, shown in Equation 20 where the area density (or city density), δ_{area}, is the independent variable and the average VMT, VMT_{est}, is the dependent variable. β and α are coefficient terms determined by the regression. The data and the power function are shown in Figure 39.

Equation 20

$$VMT_{est} = \beta e^{-\alpha \delta_{area}}$$

Equation 21

$$VMT_{CO2} = VMT_{est} \cdot MPG_{avg} \cdot EF_{trans}$$

The VMT per capita was calculated using the estimated VMT per household divided by the average number of people per household. Equation 21 calculates the CO_2 intensity per capita attributed to automobile transportation where MPG_{avg} is the overall average mile per gallon for automobiles and EF_{trans} is the emissions factor for transportation fuels.

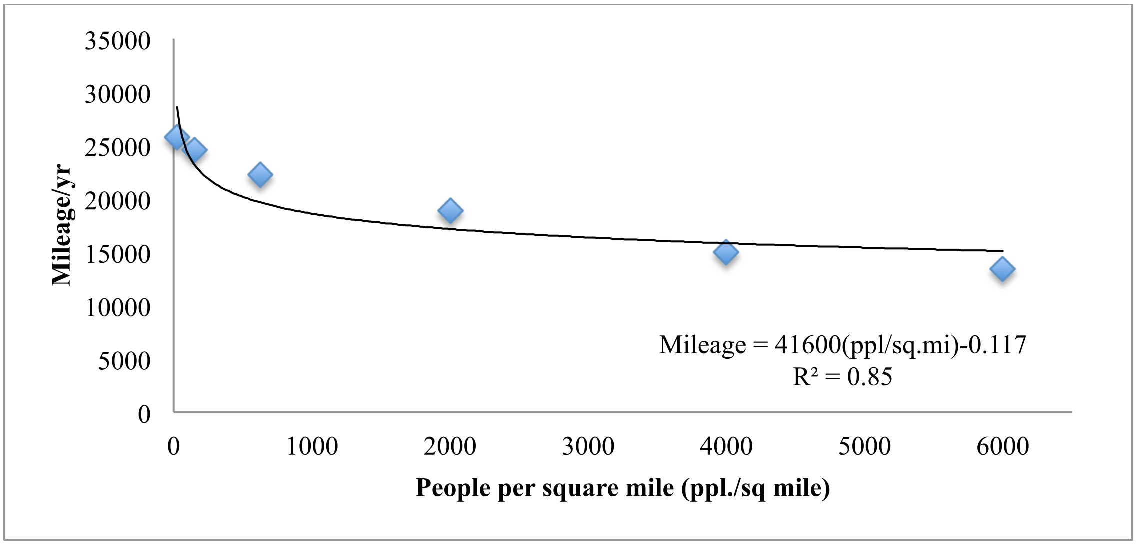


Figure 39. **Annual VMT per household and population density.**

In order to find the average transit trip distance, we used data from the American Public Transportation Association. We found the average trip distance by the total number of passenger-miles by dividing the total number of unlinked trips. The yearly average per capita CO_2 intensity attributed to transit was found by using the energy use per passenger-mile statistics found the 2011 Transportation Energy Data Book (DOE 2012). Equation 22 shows the calculation of the CO_2 intensity for transit, where, $D_{transit}$ is the average daily trip distance, $Transit_{energy}$ is the average energy usage per passenger-mile, and EPG_{diesel} is the energy per gallon of diesel fuel.

Equation 22

$$TR_{CO_2} = \frac{\mathrm{D}_{transit} \cdot \mathrm{Transit}_{energy} \cdot 365}{EPG_{diesel}}$$

We use the average population density of the City of Atlanta, 3,190 people per square mile, as the average BeltLine population density value. Considering the addition of more residents, approximately 115,000 people would need to move into the catchment area to achieve a density of 8,300 people per square mile (or 13 people per acre) that has been identified as sufficient to support light rail.

We use these values to calculate the residential footprint along the BeltLine; we compared the baseline density of 3,190 persons per square mile with the higher densities of 4,500 and 8,300 persons per square mile. We also investigated the housing distribution in each density category. Currently, the Atlanta housing mix primarily comprises single family homes (46 percent), with duplexes and buildings with more than 5 units comprising the remainder, at 9 and 45 percent, respectively (City of Atlanta, 2011). Since the BeltLine is focused on building transit-oriented housing where residents will live more compactly, a housing distribution of 50 percent middle-level density housing and 50 percent high-level density is investigated along with an even one-third even distribution between low-, mid- and high-level density. The results of the analysis can be found in Figure 10. The per capita emissions for Atlantic Station in 2035 show a nearly 50 percent reduction in the per capita emissions from the current (2010) City of Atlanta 2008 per capita emissions. The aforementioned scenarios of housing and mix (which are in line with the planned housing developments for the Beltline) are calculated to have a 30 to 40 percent reduction in per capita emissions from the 2010 baseline.

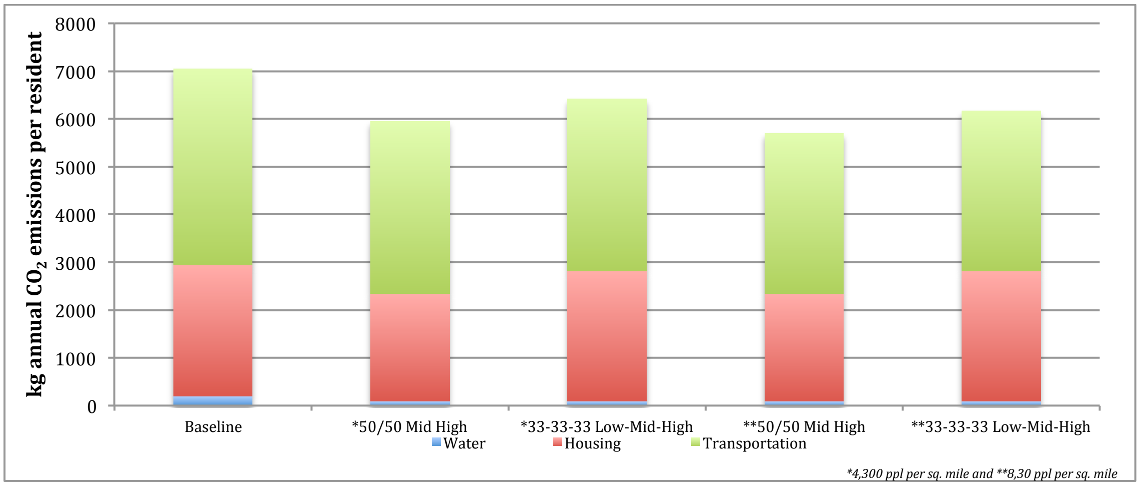


Figure 40. CO_2 emissions per resident-year considering residential densities of 4,500 and 8,300 persons per square mile. The projected per capita emissions for residents along the BeltLine are nearly 15 percent below the average City of Atlanta resident per capita emissions.

Figure 40 shows that the 50/50 distribution has the greatest savings potential. This is to be expected because higher density housing tends to have lower energy consumption. In the case of the 50/50 housing split with a residential density of 4,300 people per square mile, there is a savings of approximately 1,100 kg CO_2 per year per resident of the BeltLine corridor in comparison to the average of a current Atlanta resident. The 33/33/33 housing distribution had a lower saving of approximately 600 kg CO_2 per year for each BeltLine resident. Considering a density of 8,300 people per square mile, the 50/50 distribution will save 1,300 kg per year per resident of the BeltLine corridor. The 33/33/33 distribution is estimated to save almost 900 kg per year per resident of the BeltLine corridor.

The result is an average of 975 kg kg per resident-year per capita greenhouse gas emissions reduction of the BeltLine. The aggregate reduction is 2,730 tons per year for all households to be built on the BeltLine considering the current (2012) generation scheme and average fuel economy.

Lifecycle Cost Benefit Analysis

Capital Cost

The Atlanta BeltLine, Inc. has a reported capital cost of the system to be between $1.8 and $2.4 billion in 2012 dollars. However, other capital cost research, specifically the economic data related to the Charlotte LYNX system (GAO, 2001), indicates that the BeltLine may have cost as high as $5.7 billion in 2012 dollars. Moreover, the light-rail Metro in Los Angeles cost $790 million per mile in 2012 dollars, which corresponds to a total capital cost of over $17.4 billion for a system the size of the BeltLine (Guerra & Cervero, 2010). It must be noted that Atlanta does not have the high land and construction cost of Los Angeles. Using the meta-analysis of light rail capital expenditures by Zhang (2009), the Belt Line capital cost may range between $220 million and $2.0 billion with an average of nearly $620 million in 2012 dollars. We use the US average light rail construction cost of $43.1 million per mile, which is from the GAO (2001).

Maintenance and Operating Cost

The lifecycle operational costs of light rail systems have been investigated extensively over the last three decades (Allport, 1981; Castelazo & Garrett, 2004; Gomez-Ibanez, 1985; Tirachini, Hensher, & Jara-Díaz, 2010). These studies have argued primarily found that light rail systems carry significantly less cost than heavy rail systems, but were more costly than bus rapid transit. Much of this research models operational cost using data from major city networks (Bruun, 2005; Kim et al., 2010; Tirachini et al., 2010). For greater simplicity and potentially better accuracy we calculate the yearly maintenance cost for the BeltLine light rail segment using data from Dallas Area Rapid Transit (DART) light rail (GAO (2001), the system with the closest match to the demography of Atlanta. The 2012 dollar value of these data were calculated using (Bureau of Labor Statistics, 2014). The fuel costs were estimated from DART energy usage and the cost of electricity in that area (TCPA (1999); these values subtracted from the overall maintenance and operating costs. The result is an estimated \$2.68 per passenger mile, as shown in Table 12. The fuel savings for mitigated private vehicle use is included. This cost was calculated dividing the yearly fuel cost projections from EIA (2014) into the projected average fleet fuel economy from Choi et al. (2012). This savings at the initial (t = 0) is estimated to be \$0.13 per passenger-mile. Cost for trails and walkways are expected to be substantially smaller and are not accounted.

The maintenance and operations savings from mitigated private car travel are included in the analysis. The per passenger-mile savings was calculated using the average yearly household expenditure on vehicle maintenance, insurance, and car purchase from Ferdous, Pinjari, Bhat, and Pendyala (2010). This aggregate sum of household vehicle expenses was then divided by the average number of people per household and the average vehicle mile traveled per capita from Santos, McGuckin, Nakamoto, Gray, and Liss (2011). The result is an average maintenance and operations savings from mitigated private vehicle travel of \$0.26 in 2012 dollars.

Revenue

MARTA fares could be used to estimate the average revenue per passenger in the case of BeltLine since it will most likely be integrated into MARTA. The revenue from fares could be aggregated based on the number of riders that are projected to ride the BeltLine portion of the MARTA system However, these data points evaluate the entire revenues generated from an entire transit trip and do not explicitly denote the revenue generated from the (unlinked) trip on the BeltLine portion alone. The data on fare box revenue from the heavy rail portion of the MARTA as well as its heavy rail revenue passenger-miles from Federal Transit Administration (2012) is used to calculate the revenue per passenger-mile; the results is an average revenue of $0.12 per passenger-mile.

Congestion Cost

Roadway congestion costs have been computed in many different cost-benefit analyses covering tolling alternatives, roadway utilization, city size, social costing, parking, etc (Fosgerau & De Palma, 2013; Henderson, 1974; Hills & Evans, 1993; Livesey, 1973; Verhoef, Nijkamp, & Rietveld, 1996). These costs have typically been used to highlight the inefficiencies of the road system and have been computed by looking at the additional fuel and time costs of the road system users. This study uses the congestion cost cited by the 2012 Urban Mobility Report for the Atlanta metropolitan area, which is estimated to be $0.61 per passenger-mile. The congestion cost for the Atlanta metropolitan area is high relative to the US average of $0.47 per passenger-mile, but it does not outrank to the Seattle (WA), Boston (MA), and Los Angeles (CA) metropolitan areas.

Greenhouse Gas Emissions Costs

Carbon costs in many cost benefit analyses are considered to have a fixed value over time. Many studies make assessments utilizing a cost of $25–50 per ton over the discount period (Clinch & Healy, 2000; De Rus & Inglada, 1997). However, other studies have cost carbon and other pollutants in a more dynamic way by including increased cost of the pollutants over time. R. Clarkson, Deyes, and Britain (2002) discuss the optimality of pricing carbon equal to the marginal amount of damage it causes globally. They reason that the social cost of carbon varies over time; and that carbon cost can be considered constant only if its concentration in the atmosphere has stabilized. The analysis here uses social cost estimates issued by the White House and US EPA (White House et al., 2013) that consider 3 and 5% discount rates within different stochastic integrated assessment models. The model averages estimated for the next 40 years are shown in Figure 41. The social carbon dioxide cost per ton from White House et al. (2013) using a 3-percent discount factor are used in this analysis. We consider these values to be more in-line with social costs used in previous literature.

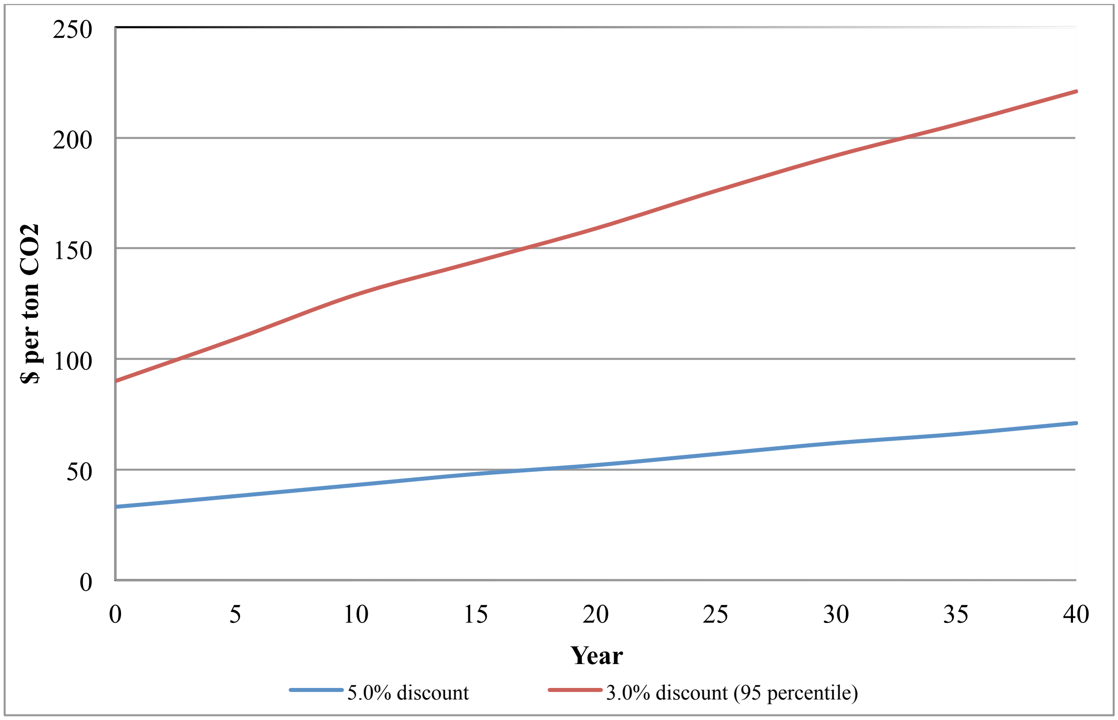


Figure 41. Estimated social carbon dioxide costs over the next 40 years (White House et al., 2013).

Greenhouse gas emissions from the light rail, residential, and reduced private car demand are evaluated as a part of the CO_2 costs. The per capita residential emissions analysis can be found in the *Energy and greenhouse gas implications of public transit in Atlanta* section. We consider the variability of these values when the housing distribution and densities are considered. A triangular distribution was used to evaluate the per capita residential emissions at each time step within the analysis; the mean of the distribution was found by averaging the emissions estimate for the different density and housing distribution scheme. We assume that the mean of the distribution has temporal variance due to electricity emissions per kWh decreasing each year throughout the time period. This projected GHG emissions rate is shown in Figure 36.

The Atlantic Station development energy and transportation metrics were used to estimate the minimum value of the triangular distribution.

This analysis accounts for the variation in the average private vehicle fleet fuel economy over the next 40 years shown in Figure 35.

Greenhouse gas emissions from the construction of the light rail are not considered within the model. An initial estimate indicated that they are relatively small, due to the transference of old railway corridors for use in the light rail system. The boundaries of this analysis are Scope 1 and do not include emissions from the construction or manufacturing of housing, rail stock or private vehicles.

We use an energy intensity of 1.12 kWh per passenger-mile for the BeltLine, which is the energy intensity of the Charlotte light rail system. Using the current emissions factor and the current social cost of carbon dioxide, an initial carbon dioxide cost per passenger-mile is $0.0168 per passenger-mile is found for our analysis.

Time Cost

This analysis computes the per passenger-mile time-savings by using the average wage for the Atlanta region of $23.21 per hour considering the travel speed differential between road transport and light rail transit (Bureau of Labor Statistics, 2013). The road transport costs are calculated using data from the Georgia Department of Transportation (DOT, 2014). A linear combination was used to find the average speed between peak and non-peak travel speed, considering the number of peak from Schrank, Eisele, and Lomax (2012). The average range of speed of light rail system was estimated using data on DART and was considered in the stochastic model, using triangular distributions. In most cases, it takes longer to take light rail than a private car, with a resulting average net time cost of $0.33 per passenger mile. In this study, we do not consider wait times. Wait times are dependent on the frequency of the transit cars, schedule reliability and the arrival times of the transit users; their evaluation is more tailored to approaches that use origin-destination network models (Bowman & Turnquist, 1981; Ferris, Watkins, & Borning, 2010; Pickrell, 1989; Spiess & Florian, 1989) and is beyond the scope of the present study.

Health and Hazard Costs

Health costs are important to consider in a transit system that includes modes of transportation (biking, walking, and rail) that get people out of their cars and active. These costs include the overall benefits related to the reduction of medical cost from staying active and willingness-to-pay for staying healthy.

The overall health costs and benefits of light rail development have been analyzed in Stokes, MacDonald, and Ridgeway (2008) where the medical (direct and indirect) and willingness-to-pay for weight loss costs over a period of 20 years for the Charlotte light rail system. The health savings are evaluated using conditional probabilities associated with the number of obese persons who use transit and will have over 30 minutes of physical activity. MacDonald, Stokes, Cohen, Kofner, and Ridgeway (2010) went on to analyze the reduction in body mass index and physical activity in relation to commuters' use of transit. The health impacts of the BeltLine have been investigated by C. L. Ross et al. (2012). These types of costs have also been evaluated with the contingent valuation method (Johannesson & Jönsson, 1991). In this study we use the average health savings costs per ride from (Stokes et al., 2008) analysis on light rail. However, it has been estimated that the percent of obese persons in the Georgia population will grow from 28 percent in 2011 to nearly 54 percent in 2030 (Levi et al., 2013). This rapid rate of increase in the number of obese persons is considered in averaging the savings generated from the BeltLine by a linear equation considering an average yearly growth of 1.3 percent in the number of obese persons in the Atlanta area. Further, we take into account to annual growth of medical expenses, approximately 5.5 percent year-over-year, through the annual percentage rate calculation (Center for Medicare & Medicaid Services, 2011; Cuckler et al., 2013; Hamel, Blumenthal, Stremikis, & Cutler, 2013).

The result from Stokes et al. (2008) of $99 per passenger-year is used as the health savings in the first year of the analysis.

There are other costs and benefits that may accrue to passengers, including the cost of the ticket versus the avoided costs of driving and of parking. These are not included in the analysis; they may largely cancel out, with the current ticket price of $2.50 versus the cost of driving 5.5 miles calculated with a per-mile cost of $0.6 coming to $3.30. By not including the net savings of taking transit rather than driving, the analysis may somewhat underestimate the benefits of the system.

Value Added Savings

The BeltLine system of trails, transit, and parks could provide increased benefit to the users, but also to the city. The city could reap financial benefit as property values around the BeltLine increases as homes on the corridor have access to newly develop parks and a secondary way of travel around the city. Value added costs (or savings) have been added only to a few cost-benefit analyses such as Cukier (1997). The value added benefit provides a direct monetary benefit to the city in the form of taxes. We compute the value added savings using data from previous studies on increased home value from transit and park development (Bartholomew & Ewing, 2011; Goetz, Ko, Hagar, & Hoang, 2009; Hess & Almeida, 2007). Considering a quarter-mile buffer around the light rail system and an additional $1636.45 in household value per 100 feet closer to transit from Nelson and Rabianski (1988), we estimate an added value of $20,455 in 2012 dollars per household added to the corridor.

Table 12 - Cost and Benefit Estimates for Belt Line (in 2012 USD)

BeltLine	***Initial Average Costs (time t=0)***
Capital Per Mile	$43,100,000.00
Light Rail Maintenance Per Passenger-Mile	$2.68
Vehicle Maintenance Savings Per Passenger-Mile	$0.26
Congestion Per Passenger-Mile	($0.61)
CO_2 cost Per Passenger-Mile	($0.0168)
Time Cost Per Passenger-Mile	$0.33
Light Rail Costs Per Passenger-Mile	$0.03
Vehicle Fuel Savings Per Passenger-Mile	$0.13
Value Added Per Home Built	$20,455
Health/Hazards Per Passenger-Year	$99.00
Revenue Per Passenger-Mile	$0.12
Average Miles Per Unlinked Trip	5.5
Daily Users	71,000
Discount Factor	7%
Annual GDP Increase	3%
Health Care Cost Increase Rate	5.5%
Annual Home Value Appreciation	5%
Annual Number of Homes to Corridor	224

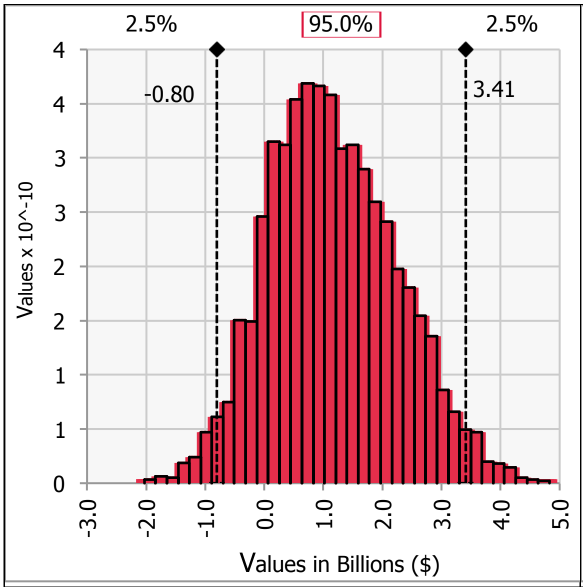
A Monte Carlo Analysis (MCA) over a 30-year discount period is used to derive a 95% Confidence Interval (CI) for the NPV of the system. This simulation considers variability and uncertainty amongst the capital, maintenance cost, health/hazards costs, time-savings, value added, and ridership. The other costs are not explicitly varied, but are calculated a function of the variable ridership.

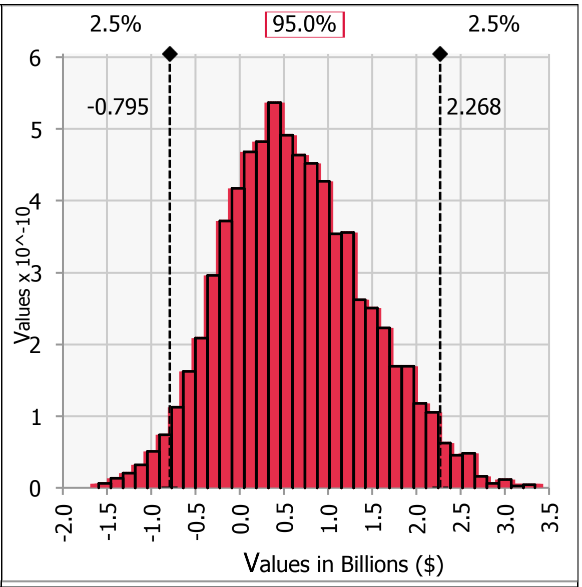
Table 13 - Monte Carlo Variable Distribution Characteristics

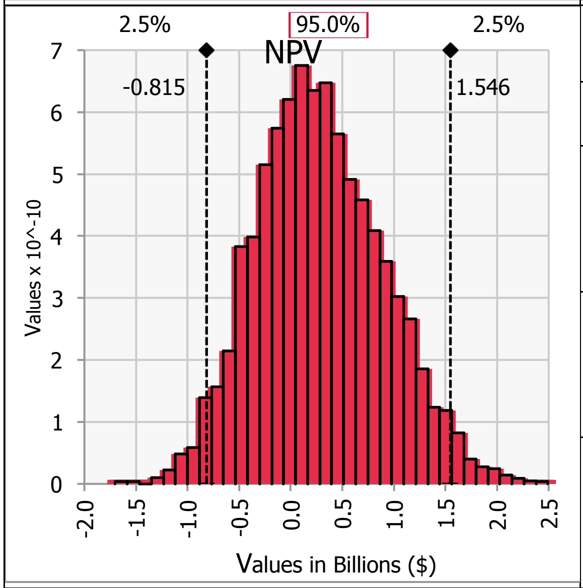
	Distribution	**Distribution Characteristics**	**Sources**
Capital	Erlang	$\Theta = \mu/k$, where μ is the average; $k = 5$	(Lichtenberg, 2000)
Maintenance/Operating	Triangular	Min = $0.90 \cdot \mu$, μ (mean), and Max=$1.50 \cdot \mu$	(Salling & Leleur, 2011)
Revenue	*(not varied; ridership dependent)*		
Congestion	*(not varied; ridership dependent)*		
CO_2 cost – Light Rail	*(not varied; ridership dependent)*		
CO_2 savings – Car	*(not varied; ridership dependent)*		
CO_2 cost – Residential	Triangular	Min, Mean, Max	*(Estimated in this analysis)*
Time Cost	Normal	$N(\mu, \sigma = (½ \cdot 0.15 * \mu))$	(De Jong et al., 2007)
Health/Hazards	Normal	$N(\mu, \sigma = (½ \cdot 0.47 * \mu))$	(Stokes et al., 2008)
Fuel Costs	*(not varied; derived via LP model)*		
Value Added	Normal	$N(\mu, \sigma = (½ \cdot 0.19 * \mu))$	
Ridership	Triangular	Min = $0.37 \cdot \mu$, μ (mean), and Max=$1.19 \cdot \mu$	(Pickrell, 1989);

An Erlang distribution is used for the capital cost estimation, based on the "successive principle" that (Lichtenberg, 1974) used in cost estimating and scheduling in the construction industry. The scale factor θ is the mean value while the shape parameter k is taken to be 5 based on (Lichtenberg, 2000). The maintenance costs are varied using a triangular distribution (Salling & Leleur, 2011); we assume the minimum of the distribution is 10 percent below the average and the maximum is 50 percent above the average. (De Jong et al., 2007) find that value of time has an uncertainty between 6 to 24 percent; we use the mid-point of ±15 percent to calculate the standard deviation of a normal distribution. In Stokes et al. (2008), uncertainty around health costs was found to be as large as 47 percent; we consider this level of variation with the standard deviation of Health/Hazards cost; the distribution is assumed to be normal. The value added per home is assumed to vary by 19 percent based on Bowes and Ihlanfeldt (2001) and its distribution is assumed to be normal.

Ridership uncertainty was assumed to be triangular. The minimum was assumed to be 63 percent below the projected ridership, based on. Pickrell (1989) analysis of ridership projections on the MARTA East-West corridor extension. There is little evidence in the historical data on other systems that points to underestimation, although, the new Charlotte light-rail system has ridership numbers nearly double the estimates at the opening of the system. Conservatively, we consider maximum of 10 percent above the projected average in this analysis. These distribution parameters are found in Table 13. We find the estimated range of the NPV to be -\$0.86 billion to \$3.7 billion considering all of the discount factors. The MCA distributions can be found in Figure 42.







95% Confidence Interval Range (in Billions)

Discount Factor	***Mean***	***Low***	***High***
3%	$1.17	$(0.80)	$3.4
5%	$0.63	$(0.80)	$2.2
7%	$.29	$(0.82)	$1.5

Figure 42. Results of Monte Carlo simulation used to find the distribution of NPVs of the Atlanta BeltLine. This analysis considers discount factors of 3, 5, and 7 percent, respectively. Maybe add a note as to why the Low column values are in parentheses

Discussion

Public transit in Atlanta is substantially more energy- and greenhouse gas–efficient than use of private vehicles. Increased availability and use of transit is a viable strategy for reducing greenhouse gas emissions from transportation; transit can also reduce traffic congestion and can support neighborhood and economic development in Atlanta.

The BeltLine light rail trains will use electricity for power, and will displace some car travel. The energy and greenhouse gas comparison will depend on the efficiency of electric power generation, the efficiency of the BeltLine trains, the efficiency of private vehicles, and the extent to which people choose to use the BeltLine rather than private vehicles. Using the ridership projections for 2030, BeltLine can be expected to provide about 22 thousand tons per year of greenhouse emissions reductions, if it uses efficient trains and achieves sufficiently high ridership, comparable to the most efficient light rail systems currently operating in the US. This corresponds to less than 1% savings of Atlanta's overall transportation greenhouse gas emissions, but could be roughly a 25% reduction in automobile use for the 16% of Atlanta residents projected to live in the BeltLine Study Area.

The Atlanta BeltLine development could provide additional energy savings and greenhouse gas reductions through an emphasis on energy efficiency in existing and new buildings. All new buildings will meet the new 2011 Georgia building energy code; the BeltLine Study Area also could embrace the potential to exceed the level of the rest of Atlanta by going beyond code with highly efficient new buildings, and by achieving energy upgrades in existing commercial and residential buildings.

Higher density of residences and workplaces along the BeltLine are recognized as important to the success of the BeltLine transit system. Higher density buildings tend to provide energy benefits, independent of energy efficiency measures, due to smaller size or shared walls, and people who live in areas of increased density drive less. Thus increased density supports the potential for increased BeltLine ridership, and will also support reduced energy use in buildings and for transportation overall. Current projections for residential development and employment within the BeltLine Study Area do show density increases by 2030. However, since the level of increased BeltLine density is about the same as the increases projected throughout Atlanta, we do not attribute energy savings through densification to the BeltLine. However, if the BeltLine area were to achieve substantially higher densities, the energy savings in buildings as well as in transportation could be substantial.

Atlantic Station currently has 3,300 residents, resulting in a population density of 15,296 people per square mile (or 23.9 per acre). It has not yet been built out to support its full capacity of 12,000 residents and thousands of jobs. Once it has been built out, the site will boast a population density of approximately 56,000 people per square mile (or 87 people per acre). The current results are promising and show that the City of Atlanta has the capacity, through smart development and innovation, to change behaviors and inspire change (MOA, 2010). Synthesizing emission per kWh, water, and transportation projections in the year 2035, we estimate that these developments will perform considerably due to the reductions in vehicle transport and electricity generation above in Figure 43. We use the housing and mobility data published by the Atlantic Station Development Authority to show even further reductions, compared with what has been modeled. The overall City of Atlanta per capita residential emissions rate is considered to be the maximum value for the distribution, due to most BeltLine development being new buildings in a layout that encourages transit use.

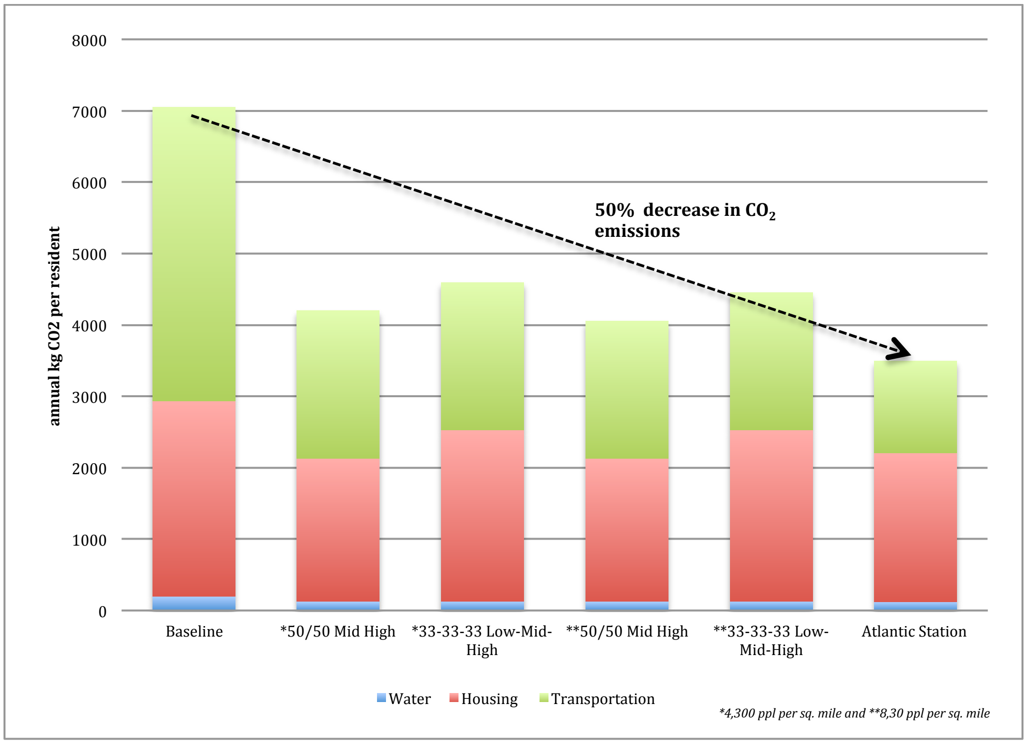


Figure 43. The 2035 Projected Per Capita Emissions of BeltLine Residents where the Baseline is the current emissions per capita and the rest of the values are 2035 projections. There is a 50 percent difference between the current (2010) average City of Atlanta per capita emissions and the Atlantic Station development considering the electricity emissions intensity in 2035.

As the BeltLine continues to be planned and developed, measurements of energy use –in terms of car travel, transit ridership, transit energy use, and building energy use– provide a useful baseline to chart the energy savings of the BeltLine.

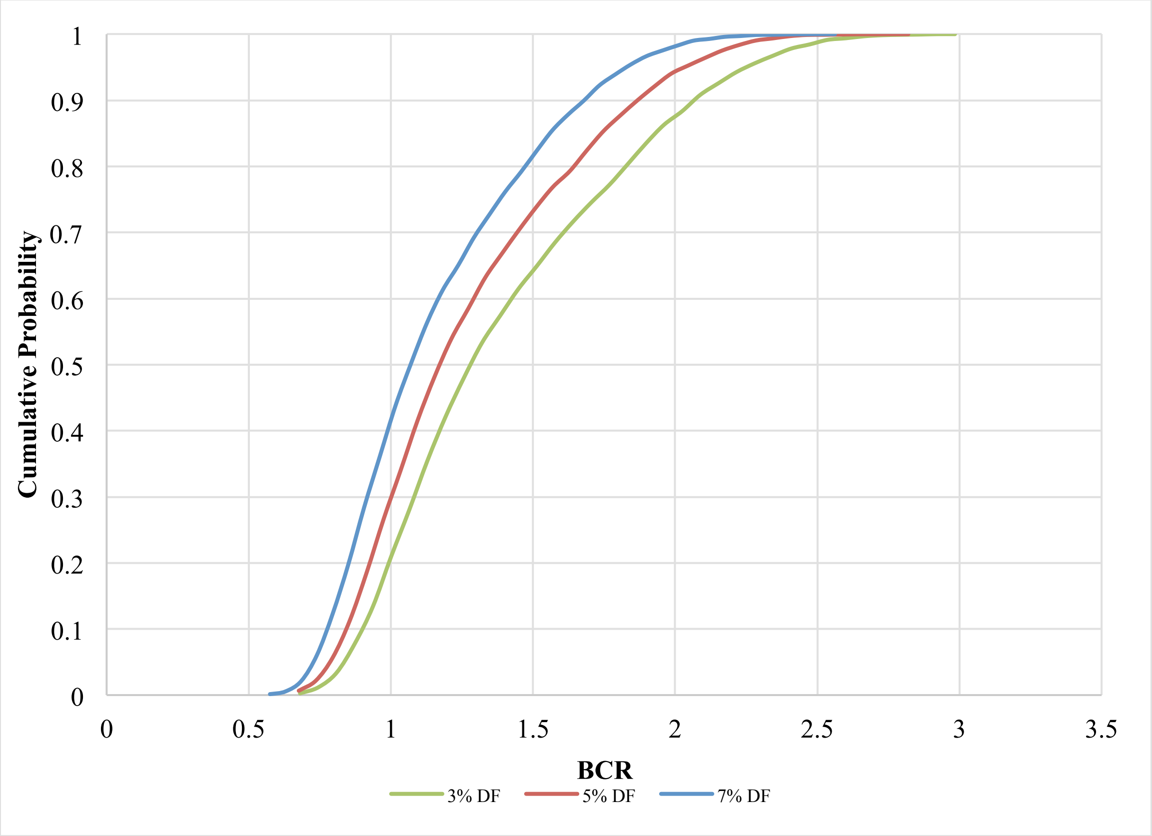


Figure 44. Accumulated Descending Graph for the Benefits-Costs Ratio (BCR) in the scenarios using a 3%, 5%, and 7% discount factor. The graph shows that in all cases there is a 30 percent probability that the system will have a BCR less than one, meaning that the system has no net benefit to the municipality. The dashline indicate the breakeven point where costs and benefits are equal.

A stochastic evaluation of the cost was performed in order to find the range of system financial benefits. In our analysis of the cost and benefits, we find positive net present values across the 95% confidence interval for the BeltLine over a 30-year period. This essentially means that the system has considerable value to the City of Atlanta. This indicates that the system can provide significant benefits to City as it helps to alleviate some highway and local traffic, create a new transportation corridor, provide health benefits, and help in emissions reductions. An accumulated graph in Figure 44 shows the likelihood of achieving various benefit-to-cost ratios (BCR). We find a range for the mean BCR of 1.1 to 1.4 indicating that the system may provide a positive economic benefit. Over the 95% confidence interval of all the discount factors, we find the range of BCR to be 0.75 to 2.25. Thus, there exist the possibility for a downside to developing the

BeltLine as the costs outweigh the benefits. Our model estimates show the 30 percent probability for the system providing no benefit.

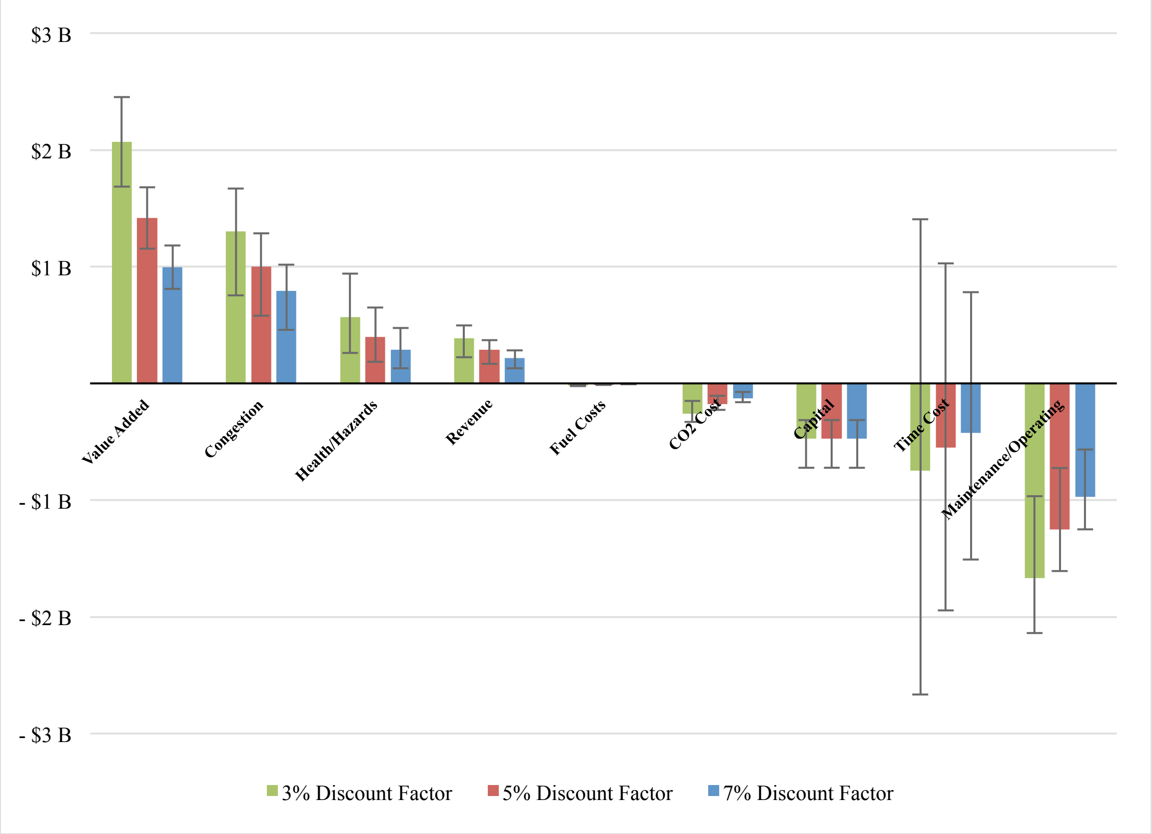


Figure 45. Disaggregated system costs for the BeltLine over a 30-year period. The value added savings and maintenance/operating costs are the largest benefit and cost; respectively, and hence drive the overall net present value.

Figure 45 shows the total costs over the discounting period from each of the different factors. Maintenance/operations costs and the value added savings have the largest absolute values within the cost-benefit analysis. The maintenance costs are in-line with expectations. The fuel cost have the smallest absolute value in the analysis. These fuel costs increase throughout the evaluation period; however, they were considerably less than all other costs. Interestingly enough, the model shows an aggregate fuel savings within the initial periods due to the savings from mitigated fuel expenses from passenger car travel. However, as electricity costs become more expensive and fuel economy increases in the future, it changes the aggregate value to a cost. Both the maintenance and fuel costs may be more due to underestimation of the ridership throughout the entire time period. If the BeltLine merges completely with MARTA system and there is considerable growth of the City of Atlanta population especially along adjacent corridors to the BeltLine, there would be potential for more riders than estimated. Thus, there will be higher energy costs as shorter headways are required and more trains are needed.

The added value cost from housing is surprisingly the highest savings. In the analysis, it is assumed that these households add not only value when they are built (or renovated) along the BeltLine, but they continually increase in value as home prices increase due to the development of the entire project and its proximity to public transit. This assumption was made from previous research on households that were in the buffer zones of public transit and their continual increase in value over time (Bartholomew & Ewing, 2011; Goetz et al., 2009; Hess & Almeida, 2007; Nelson & Rabianski, 1988). From the municipal standpoint, this is important to understand as tax value from home prices and city attractiveness to new residents provides additional revenue streams.

Congestion savings have the third highest absolute value and provide some insight into the importance of developing the BeltLine and other transit options. The mitigation of congestion or simply even users of the system provide the benefit of utilizing less municipal resources (i.e., police, ambulatory, traffic management, and fire services) and a decrease in cost to repair fatigued private car roadways.

This study takes an introductory approach to integrating health costs directly into the full cost benefit analysis by considering the probability of obese transit users receiving health benefits from walking to and from the system. There may be additional health factors that are beneficial or harmful to the system users, and should be investigated in future studies.

Carbon dioxide costs are the second smallest value of the analysis with a cost to the system of less than $300 million over the 30-year period. This is due to the inclusion of mitigated private vehicle costs. The overall emissions from the added 5,600 units of housing and the light rail system are projected to be nearly equal to those mitigated from private car use. It should be noted that this analysis assumes a 1-to-1 relationship of the travel distance. Hence, this benefit may be greater as there is a considerable amount of private car mileage that is not captured. Emissions from housing may be smaller as stricter energy building codes are implemented and older homes are brought to higher levels of energy efficiency. We did not include commercial costs here due to the lack of estimates of the number and type of businesses that may be along the corridor. The inclusion of major greenhouse emitting businesses or a large number of businesses may alter the overall emissions projections.

We evaluate the costs of generating greenhouse gas emissions considering all costs and benefits of the system. Bearing in mind all discount factors, we estimate the Beltline will generate an average savings of \$230 per ton of emitted CO_2, which is a positive benefit to the system. Its 95% confidence interval is found with an \$78 cost per ton and \$604 savings per ton CO_2.

The mean total time costs are moderate in comparison to other costs. However, the time costs of the users has the largest 95% confidence interval in the analysis and hence the largest variance. This large variance is due to the use of two different triangular distributions used to calculate the time-savings, where the average was evaluated to be time costs. Two distributions were used because there is significant variability in the average speed of the two modes. Private car usage on the city highways is estimated to be 55 mph normally, but is 40 mph during the peak times, which is a total of 8 hours each day. The light rail estimates were drawn from speed data from DART. The average travel speeds of DART were measured to be 25 to 30 mph, and thus were less than private car transport in Atlanta. We also estimated the time costs based on the actual work wage of users who have to make the valuation of whether they are gaining any benefit. This method is different than some previous analyses that consider user to have work and leisure travel time costs (Paulley et al., 2006).

While there are factors that may have been left out of this analysis in terms of origin-destination decisions, it is reasonable to assume that users consider these speed differences in contemplating different travel options in relation to their own preferences and personal utility accounting (Beirão & Sarsfield Cabral, 2007; Cesario, 1976; Reed, 1995). However, opposing literature finds that consumer preference will still choose transit options that are slower where quality transit service is provided in the current transit environment (Litman, 2011). This wide distribution for time-savings, at the minimum, speaks to the importance of the need for the system to operate with minimum headways and dependable service in order to attract users.

While the capital costs do not vary in the analyses using different discount factors, it should be noted that the projected construction costs of this analysis are in line with other findings in the literature. However, this study acknowledges the importance of capital costs in these analyses, especially where municipal authorities are the authors. Flyvbjerg, Holm, and Buhl (2002) find that most rail projects have a 40 percent cost escalation over the projected construction costs. It is believed that the capital cost interval, which we have found using this model, provides insight into and incorporates the potential capital cost over-escalation for the BeltLine project.

This study uses the best available data to evaluate the costs of the system. Traditionally, static values have been used in most NPV analyses that have environmental consideration. These values are not representative of either the increased environmental degradation or changes in society. We further the analysis by using Monte Carlo simulation to understand the deviation of the overall benefits over a 30-year period and attempt to avoid promoting financial costs that are not representative of the true capital costs to build these systems. Rail transit developments are typically estimated at nearly 30 percent below of their actual costs (Flyvbjerg et al., 2002). A highlight of this analysis is the adoption of a more advantageous technique of using time-varying environmental data and costs to the NPV calculation. This plays an important role in understanding the value of public works projects. This analysis includes time-varied costs for pollution and health as well as temporal changes in emissions, which have not generally been included in previous studies. The inclusion of health benefits from transit development, value added to the tax base, congestion mitigation, and time savings in this study supports the potential for governments taking a more holistic approach to create shared value – “the leveraging of unique [developments] to create economic value by creating social value” - for their constituencies, instead of considering economic expenditures alone (Porter & Kramer, 2011). In this case study, we show there is potential positive benefit to the development of the BeltLine.

The analysis takes into account the expected future changes in vehicle fuel efficiency and in greenhouse gas emissions from electricity production, as well as a number of other time-varying factors. Future improvements in vehicle fuel efficiency have the effect of reducing the greenhouse gas benefits of use of the transit system rather than driving. Future reductions in greenhouse gas emissions from the region's electricity system have the effect of increasing the greenhouse gas benefits of the system. By including detailed analysis of changes over time, some of these key issues are incorporated into the analysis, and the effective of additional time-variations can be readily incorporated into the analysis.

Conclusion

This study presents a framework that cities or urban stakeholders can use to evaluate the costs and environmental benefits of transit-oriented developments and their benefit to the overall municipal environmental goals. The overall analysis uses two models – a transportation model and residential lifecycle model and integrates them into a cost-benefit analysis model that incorporates temporal variance of model parameters. A case study of the city of Atlanta and its under-development transit-oriented development, the BeltLine, is used. The models were used in combination to assess the environmental and financial value of the Atlanta BeltLine project as well as its potential contribution to greenhouse emissions reductions. It is found that increasing the settlement density around the corridor is important if the municipality wants to use the transit-oriented development for greenhouse gas emission reduction. The overall emissions reductions are found to have no significant effect on reaching the emissions goals for the City. However, increased settlement and subsequent density play a large factor in decreasing the per capita emissions. A socio-environmental cost-benefit analysis is performed utilizing time varying environmental and costs data and stochastic measures in a Monte Carlo analysis. Considering environmental, health, transportation and capital costs data, the Atlanta BeltLine has strong potential –nearly 70 percent probability– to provide positive benefits to the municipality.

The primary contribution of this paper is its presentation and application of a cost-benefit analysis with time-varying parameters that lie outside the classical framework.

CHAPTER 6

This dissertation is a compilation of three investigations into sustainability. All of the respective case studies consider economic, ecological, and equity factors, which are pivotal in investigations of sustainability. In Chapters 2 and 3, corporate environmental performance analysis was investigated. Chapter 4 presented residential energy demand projections in South Africa. Chapter 5 contains the framework development and results from the cost-benefit analysis of the transit-oriented development, the Atlanta BeltLine. Conclusions and implications for each case are presented below.

Chapter 2 detailed the methodological framework for developing environmental performance models and the insight provided from the models. The development of large multi-facility databases on production, material and energy use, and environmental emissions from manufacturing facilities provided an opportunity to incorporate data analytics into sustainability analysis. This analytical approach provided rapid insight across hundreds of facilities, highlighted areas of concern within the manufacturer, and the potential for process improvement.

The question of how changes in the production mix may change environmental profiles was addressed. The research showed that the production composition within manufacturing facilities is an important factor in intra-facility environmental performance. This research makes a number of contributions to environmental sustainability and industrial ecology literature. To our knowledge, it was the first attempt to use this particular data transformation process for regression modeling in investigations of compositional data from manufacturing firms. Also, there is a dearth of literature that has investigated intra-firm environmental performance variations. This project was the first attempt to explain these variations. Additionally, this research showed the effects of geospatial dynamics and facility characteristics on environmental performance. This approach can be applied to other types of manufacturing, including electronics, clothing, and automotive, and the research may provide a useful approach for global multi-facility firms to find ongoing dynamic insight into environmental performance.

Using the models from Chapter 2, the climate change risks were investigated in Chapter 3. A methodological framework was created for this study of natural resource risk considering the firm's risk exposure, system vulnerabilities, and demand projections. From our best knowledge, this is one of the first approaches to understanding how changes in the production composition can alter the natural resource risk profile of firms. This analysis also adds to firms' ability to account for environmental performance and degradation as well as assess potential risk in regions where climate change may affect the availability of water and energy. This tool is a contribution to the literature in the area of risk assessment and mitigation.

In Chapter 4, an agent-based model created a set of heterogeneous households and modeled the effects of pricing and electricity demand in lieu of other household energy alternatives. Using research on rioting and social networks, the analysis provided insight into the frequency of grievance. This model distinguished the number of single-energy (electricity) users as well as the number of multi-energy users who may or may not use electricity in their energy mix at each period. The aggregate energy demand from the residential sector over a 30-year period was projected. With significant electricity price increases, electricity demand increased from its 2012 baseline. Thus, this shows that electricity is considered a basic need as more households gain access to it. However, there were still a considerable number of households that continued to use indigenous fuels in tandem with electricity.

This model is one of the first characterizations of household electricity demand response and fuel transitions related to energy pricing at the individual household level. Additionally, this was one of the first approaches to evaluating consumer grievance and rioting response to energy service delivery. The model framework is suggested as an innovative tool for energy policy analysis on civil disobedience, greenhouse gas reduction impacts on electricity demand, the health impacts of fuel transitions in the household, and energy choices at micro-scale in developing countries.

The overall analysis of the research project undertaken in Chapter 5 used two models: a transportation model and residential lifecycle model. These two models integrated them into a cost-benefit analysis model that incorporated temporal variance of model parameters. A Monte Carlo analysis was utilized to incorporate stochastic environmental and cost measures into the model.

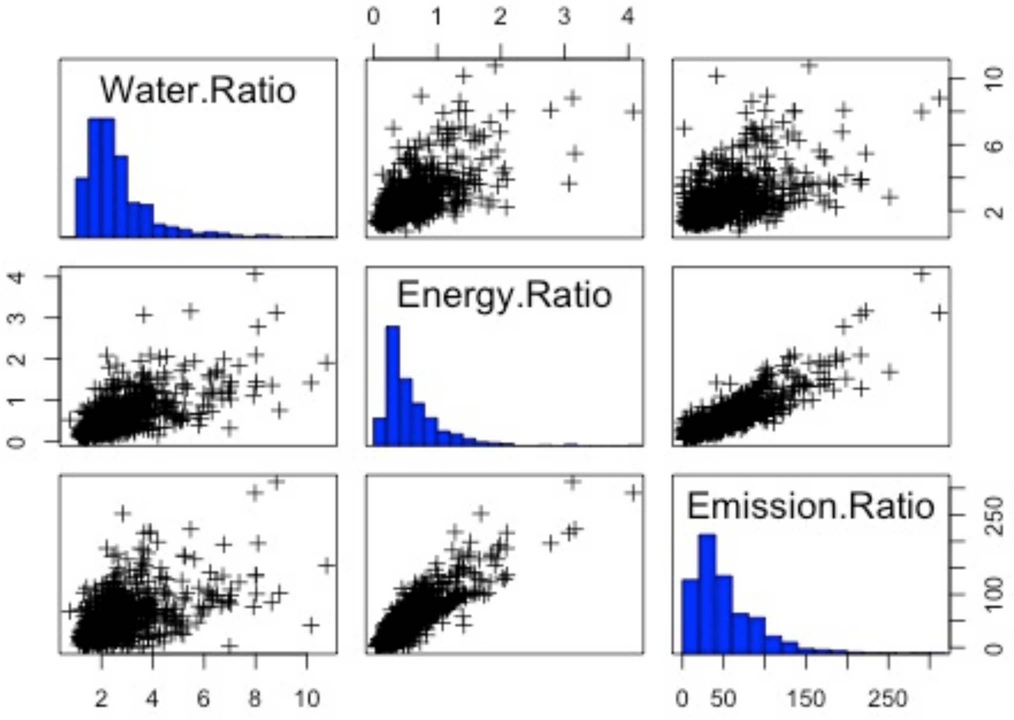
Increasing the settlement density around the corridor was important if the municipality wanted to use the transit-oriented development for greenhouse gas emission reduction. The overall emissions reductions were found to have no significant effect on reaching the emissions goals for the city of Atlanta. Considering environmental, health, transportation, and capital costs data, the Atlanta BeltLine has strong potential—nearly 70 percent probability—to provide positive benefits to the municipality. This study provided a framework for cities and other municipal stakeholders to use in the evaluation of the social costs and environmental benefits of transit-oriented developments and their benefit to the overall municipal environmental goals. The primary contribution of this research was its presentation and application of a cost-benefit analysis with time-varying parameters that lie outside the classical framework.

In conclusion, these research projects have investigated issues on multiple scales within the paradigm of “sustainable economic development” and “sustainable human development.” This research brought about a new lens on some of the dynamics of having balanced ecological-economic-equity development for all. While further issues will arise within the spectrum of sustainable development, this research postulated new frameworks and methods to investigate our current environmental problems in hopes of curtailing malignancies in our environment’s future.

APPENDIX A

CHAPTER 2

Figure 46: Correlations between Water, Energy and Emissions Per Unit Product



Bivariate scatterplots were found between the 3 EPIs from the facility data. The only correlation was found between energy and emissions. This correlation was expected since emissions are a direct result from energy inputs and most countries use fossil fuels as a dominant fuel source. However, it is understood that the scattering within this case is due to differences between energy inputs at the facility level and the aggregate electricity production mix at the country level.

Figure 47 - HDI Values and Facility Energy ratio

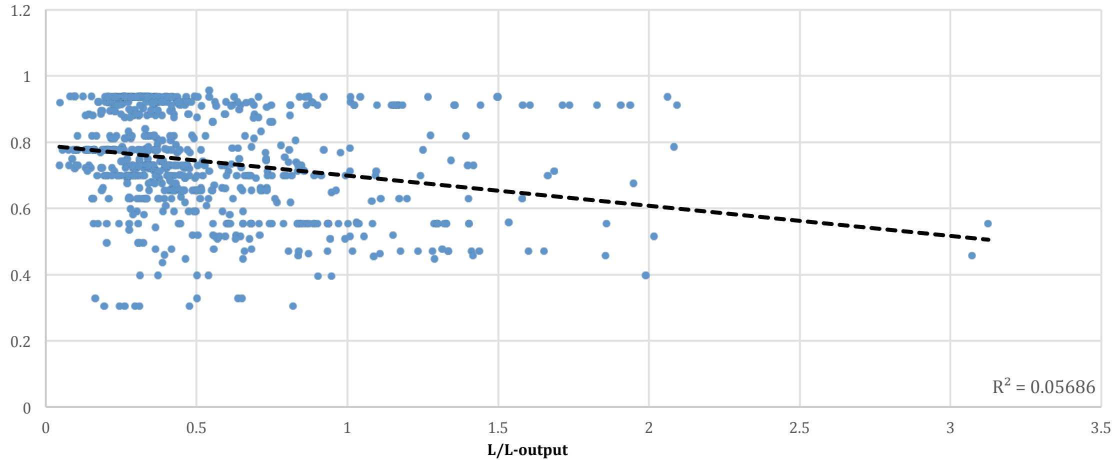
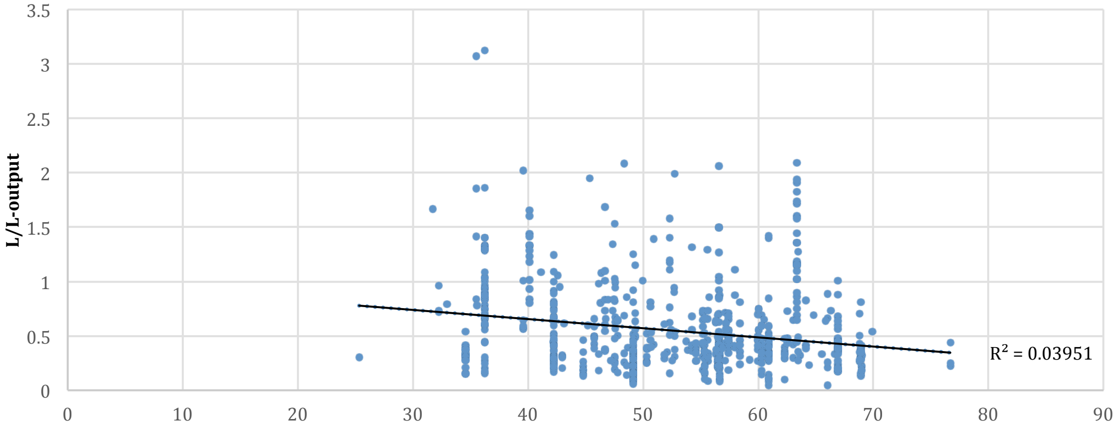


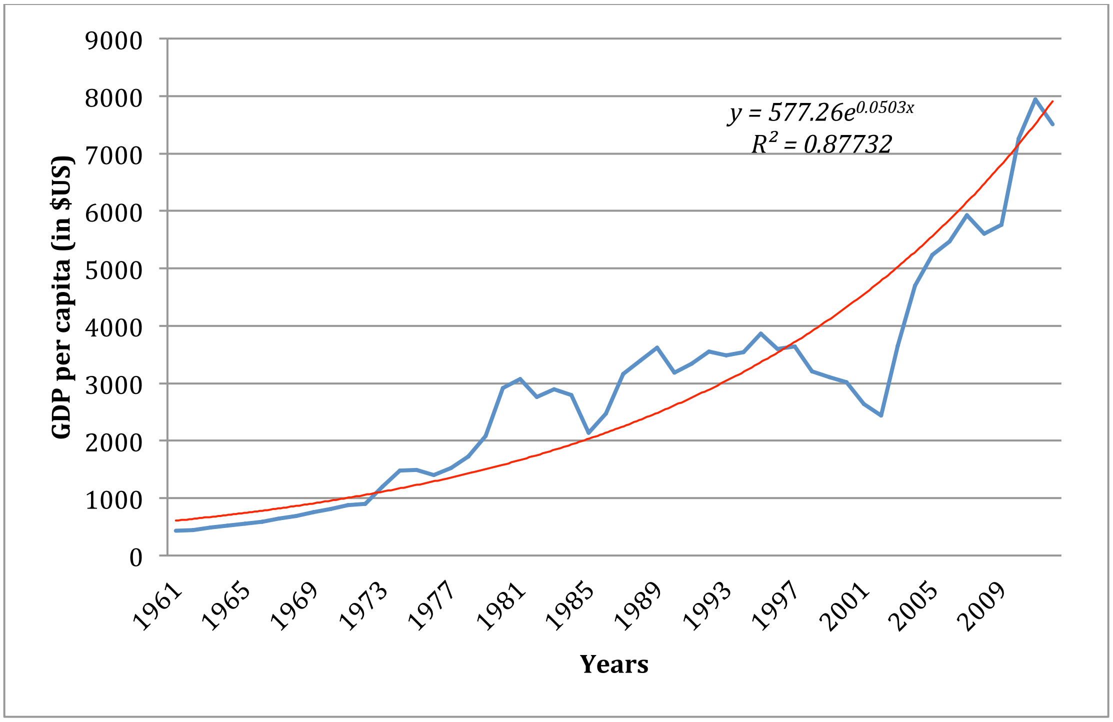
Figure 48 - Energy Ratio and EPIs



APPENDIX B

CHAPTER 4

Figure 49 - Growth of GDP Per Capita



REFERENCES

Abayomi, K., Luo, D., & Thomas, V. (2010). Statistical evaluation of the effect of ethanol in us corn production: A flexible test for independence on a constrained sum. *International Journal of Ecological Economics and Statistics, 22*(S11), 105-126.

Abdelaziz, E., Saidur, R., & Mekhilef, S. (2011). A review on energy saving strategies in industrial sector. *Renewable and Sustainable Energy Reviews, 15*(1), 150-168.

Ackerman, F., & Heinzerling, L. (2002). Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection. *University of Pennsylvania Law Review, 150*(5), 1553-1584. doi: 10.2307/3312947

Adger, W. N. (2006). Vulnerability. *Global environmental change, 16*(3), 268-281.

Aguinis, H., & Glavas, A. (2012). What we know and don't know about corporate social responsibility a review and research agenda. *Journal of management, 38*(4), 932-968.

Aitchison, J. (1981). A new approach to null correlations of proportions. *Journal of the International Association for Mathematical Geology, 13*(2), 175-189.

Aitchison, J. (1986). *The Statistical Analysis of Compositional Data*. London: Chapman Hall.

Al-Ghandoor, A., Al-Hinti, I., Jaber, J., & Sawalha, S. (2008). Electricity consumption and associated GHG emissions of the Jordanian industrial sector: empirical analysis and future projection. *Energy Policy, 36*(1), 258-267.

Albert, R., & Barabási, A.-L. (2002). Statistical mechanics of complex networks. *Reviews of modern physics, 74*(1), 47.

Allport, R. J. (1981). The costing of bus, light rail transit and metro public transport systems. *Traffic Engineering & Control, 22*(HS-032 837).

Amusa, H., Amusa, K., & Mabugu, R. (2009). Aggregate demand for electricity in South Africa: an analysis using the bounds testing approach to cointegration. *Energy Policy, 37*(10), 4167-4175.

Antea Group, & BIER. (2012). Water Use Benchmarking in the Beverage Industry: Trends and Observations 2012: Beverage Industry Environmental Roundtable.

Athanasiadis, I. N., Mentes, A. K., Mitkas, P. A., & Mylopoulos, Y. A. (2005). A hybrid agent-based model for estimating residential water demand. *Simulation, 81*(3), 175-187.

Azar, E., & Menassa, C. C. (2011). Agent-based modeling of occupants and their impact on energy use in commercial buildings. *Journal of Computing in Civil Engineering, 26*(4), 506-518.

Backlund, S., Thollander, P., Palm, J., & Ottosson, M. (2012). Extending the energy efficiency gap. *Energy Policy, 51*, 392-396.

Barney, J. B., Ketchen Jr, D. J., & Wright, M. (2011). The Future of Resource-Based Theory Revitalization or Decline? *Journal of management, 37*(5), 1299-1315.

Bartholomew, K., & Ewing, R. (2011). Hedonic price effects of pedestrian-and transit-oriented development. *Journal of Planning Literature, 26*(1), 18-34.

Basu, K., & Palazzo, G. (2008). Corporate social responsibility: A process model of sensemaking. *Academy of management review, 33*(1), 122-136.

Beirão, G., & Sarsfield Cabral, J. A. (2007). Understanding attitudes towards public transport and private car: A qualitative study. *Transport Policy, 14*(6), 478-489. doi: http://dx.doi.org/10.1016/j.tranpol.2007.04.009

Berazneva, J., & Lee, D. R. (2013). Explaining the African food riots of 2007–2008: An empirical analysis. *Food Policy, 39*, 28-39.

Berchicci, L., Dowell, G., & King, A. A. (2012). Environmental capabilities and corporate strategy: Exploring acquisitions among US manufacturing firms. *Strategic management journal, 33*(9), 1053-1071.

Berenguer, J., Corraliza, J. A., & Martín, R. (2005). Rural-Urban Differences in Environmental Concern, Attitudes, and Actions. *European Journal of Psychological Assessment, 21*(2), 128.

Berry, M. A., & Rondinelli, D. A. (1998). Proactive corporate environmental management: A new industrial revolution. *The Academy of Management Executive, 12*(2), 38-50.

Bettencourt, L. M., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences, 104*(17), 7301-7306.

Biro, A. (2012). Water wars by other means: virtual water and global economic restructuring. *Global Environmental Politics, 12*(4), 86-103.

Blackhurst, B. M., Hendrickson, C., & Vidal, J. S. i. (2010). Direct and indirect water withdrawals for US industrial sectors. *Environmental Science & Technology, 44*(6), 2126-2130.

Blom, J. E. (2009). *Hedging revenues with weather derivatives: a literature review of weather derivatives & a case study of Ringnes AS.* (Master of Science in Financial Economics Master Thesis), NORGES HANDELSHØYSKOLE, Bergen, Norway.

Bowes, D. R., & Ihlanfeldt, K. R. (2001). Identifying the Impacts of Rail Transit Stations on Residential Property Values. *Journal of Urban Economics, 50*(1), 1-25. doi: http://dx.doi.org/10.1006/juec.2001.2214

Bowman, L. A., & Turnquist, M. A. (1981). Service frequency, schedule reliability and passenger wait times at transit stops. *Transportation Research Part A: General, 15*(6), 465-471.

Brown, J. R., & Thompson, G. L. (2008). The Relationship between Transit Ridership and Urban Decentralisation: Insights from Atlanta. *Urban Studies, 45*(5 and 6), 1119-1139.

Brownstone, D., & Golob, T. F. (2009). The impact of residential density on vehicle usage and energy consumption. *Journal of Urban Economics, 65*(1), 91-98. doi: 10.1016/j.jue.2008.09.002

Bruun, E. (2005). Bus rapid transit and light rail: comparing operating costs with a parametric cost model. *Transportation Research Record: Journal of the Transportation Research Board, 1927*(1), 11-21.

Bureau of Labor Statistics. (2013). *Occupational Employment Statistics - 2013 Metropolitan and Nonmetropolitan Area Occupational Employment and Wage Estimates*. Washington D.C.,: Retrieved from http://www.bls.gov/oes/current/oes_12060.htm.

Bureau of Labor Statistics. (2014). CPI Inflation Calculator. 2014, from http://www.bls.gov/data/inflation_calculator.htm

Burgess, R. (2000). The compact city debate: A global perspective. *Compact cities: Sustainable urban forms for developing countries*, 9-24.

Cagno, E., & Trianni, A. (2013). Exploring drivers for energy efficiency within small-and medium-sized enterprises: first evidences from Italian manufacturing enterprises. *Applied Energy, 104*, 276-285.

Campbell, B., Vermeulen, S., Mangono, J., & Mabugu, R. (2003). The energy transition in action: urban domestic fuel choices in a changing Zimbabwe. *Energy Policy, 31*(6), 553-562.

Campbell, S. (1996). Green Cities, Growing Cities, Just Cities?: Urban Planning and the Contradictions of Sustainable Development. *Journal of the American Planning Association, 62*(3), 296-312. doi: 10.1080/01944369608975696

Carter, M. R., & May, J. (2001). One kind of freedom: Poverty dynamics in post-apartheid South Africa. *World development, 29*(12), 1987-2006.

Cassim, A., Ewinyu, A., & Sithebe, T. (2012). *Weighing up the effect of current electricity pricing and additional environmental regulation on household electricity expenditure*. Paper presented at the Economic Regulators Conference Johannesburg, South Africa.

Castelazo, M. D., & Garrett, T. A. (2004). Light rail: boon or boondoggle. *The Regional Economist, 1*, 12-13.

Center for Medicare & Medicaid Services. (2011). *Heatlh Expenditures by State of Residence*. Retrieved from http://www.cms.gov/NationalHealthExpendData/downloads/resident-state-estimates.zip.

Cesario, F. J. (1976). Value of time in recreation benefit studies. *Land economics*, 32-41.

Chandrappa, R., Gupta, S., & Kulshrestha, U. (2011). Greenhouse Gas Inventory *Coping with Climate Change* (pp. 69-88): Springer Berlin Heidelberg.

Chetty, L.-R. (2013, 13 February 2013). The realities of social mobility in South Africa. *Mail & Guardian*. Retrieved from http://www.thoughtleader.co.za/leeroychetty/2013/02/16/the-realities-of-social-mobility-in-south-africa/

Choi, D. G., & Thomas, V. M. (2012). An electricity generation planning model incorporating demand response. *Energy Policy, 42*, 429-441.

Chou, Y.-C., & Hong, L. H. (2000). A methodology for product mix planning in semiconductor foundry manufacturing. *Semiconductor Manufacturing, IEEE Transactions on, 13*(3), 278-285 %@ 0894-6507.

City of Atlanta. (2011). *Comprehensive Development Plan*. Atlanta, GA: Retrieved from http://www.atlantaga.gov/index.aspx?page=376.

Clark, D. P., Kaserman, D. L., & Mayo, J. W. (1990). Barriers to trade and the import vulnerability of US manufacturing industries. *The Journal of Industrial Economics*, 433-447.

Clarkson, P. M., Li, Y., Richardson, G. D., & Vasvari, F. P. (2011). Does it really pay to be green? Determinants and consequences of proactive environmental strategies. *Journal of Accounting and Public Policy, 30*(2), 122-144.

Clarkson, R., Deyes, K., & Britain, G. (2002). Estimating the social cost of carbon emissions. *Government economic service working paper %@ 0141-5158.*

Clinch, J. P., & Healy, J. D. (2000). Cost-benefit analysis of domestic energy efficiency. *Energy Policy, 29*(2), 113-124 %@ 0301-4215.

Cohen, B. (2006). Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. *Technology in society, 28*(1), 63-80.

Crichton, D. (2001). The implications of climate change for the insurance industry. *Building Research Establishment, Watford, England.*

Cuckler, G. A., Sisko, A. M., Keehan, S. P., Smith, S. D., Madison, A. J., Poisal, J. A., . . . Stone, D. A. (2013). National health expenditure projections, 2012–22: slow growth until coverage expands and economy improves. *Health Affairs, 32*(10), 1820-1831.

Cukier, J. (1997). Cost-benefit analysis of telelearning: Developing a methodology framework. *Distance education, 18*(1), 137-152.

Curran, M. A. (1993). Broad-based environmental life cycle assessment. *Environmental Science & Technology, 27*(3), 430-436 %@ 0013-0936X.

Dasgupta, S., Hettige, H., & Wheeler, D. (2000). What improves environmental compliance? Evidence from Mexican industry. *Journal of Environmental Economics and Management, 39*(1), 39-66.

Davis, M. (1998a). Rural household energy consumption: The effects of access to electricity—evidence from South Africa. *Energy Policy, 26*(3), 207-217. doi: http://dx.doi.org/10.1016/S0301-4215(97)00100-6

Davis, M. (1998b). Rural household energy consumption: the effects of access to electricity,Äîevidence from South Africa. *Energy Policy, 26*(3), 207-217.

De Jong, G., Daly, A., Pieters, M., Miller, S., Plasmeijer, R., & Hofman, F. (2007). Uncertainty in traffic forecasts: literature review and new results for The Netherlands. *Transportation, 34*(4), 375-395.

De Rus, G. s., & Inglada, V. (1997). Cost-benefit analysis of the high-speed train in Spain. *The Annals of Regional Science, 31*(2), 175-188 %@ 0570-1864.

Deloitte. (2013). Deloitte on Africa - The Rise and Rise of the African Middle Class. In D. Touche (Ed.): Deloitte & Touche.

Dodman, D. (2009). Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization, 21*(1), 185-201.

DOE. (2012). *Transportation Energy Data Book* Oak Ridge, TN.

Dolley, C. (2014, 7 February 2014). Nation gripped by protests. *Cape Times*. Retrieved from http://www.iol.co.za/capetimes/nation-gripped-by-protests-1.1643310 - .Uyr6nXlQa1E

DOT, G. (2014). Metro Atlanta Highway Morning Peak Hour Speeds. 2014, from http://www.dot.ga.gov/informationcenter/statistics/performance/Pages/PeakSpeedsAM.aspx

Dou, Y., & Sarkis, J. (2010). A joint location and outsourcing sustainability analysis for a strategic offshoring decision. *International Journal of Production Research, 48*(2), 567-592 %@ 0020-7543.

Dyllick, T., & Hockerts, K. (2002). Beyond the business case for corporate sustainability. *Business strategy and the environment, 11*(2), 130-141.

EIA. (2009). *Residential Energy Consumption Survey*. Washington, D.C.: US Department of Energy Retrieved from http://www.eia.gov/consumption/residential/data/2009/.

EIA. (2013). International Energy Outlook (Department of Energy, Trans.). In e. I. Agency (Ed.). Washingtion, D.C.: Department of Energy,.

EIA. (2014). *Energy Prices by source and sector - United States*. Washington, D.C.: Retrieved from http://www.eia.gov/oiaf/aeo.

Eliasson, J. (2009). A cost–benefit analysis of the Stockholm congestion charging system. *Transportation Research Part A: Policy and Practice, 43*(4), 468-480.

Energy Research Centre. (2009). *Energy Security in South Africa*.

Eppstein, M. J., Grover, D. K., Marshall, J. S., & Rizzo, D. M. (2011). An agent-based model to study market penetration of plug-in hybrid electric vehicles. *Energy Policy, 39*(6), 3789-3802.

Epstein, J. M. (2002). Modeling civil violence: An agent-based computational approach. *Proceedings of the National Academy of Sciences of the United States of America, 99*(Suppl 3), 7243-7250.

Ercin, A. E., Aldaya, M. M., & Hoekstra, A. Y. (2011). Corporate water footprint accounting and impact assessment: the case of the water footprint of a sugar-containing carbonated beverage. *Water Resources Management, 25*(2), 721-741.

ESKOM. (2012). Historic Eskom Average Selling Price c/kWh. In E. H. Prices (Ed.). Eskom.com.

Esterl, M. (2013, January 18, 2013). Is This the End of the Soft-Drink Era? *The Wall Street Journal* Retrieved from http://online.wsj.com/news/articles/SB10001424127887323783704578245973076636056 - printMode

Ezzati, M., & Kammen, D. M. (2002). The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental Health Perspectives, 110*(11), 1057-1068.

Faber, A., Valente, M., & Janssen, P. (2010). Exploring domestic micro-cogeneration in the Netherlands: An agent-based demand model for technology diffusion. *Energy Policy, 38*(6), 2763-2775.

Fagiolo, G., Moneta, A., & Windrum, P. (2007). A critical guide to empirical validation of agent-based models in economics: Methodologies, procedures, and open problems. *Computational Economics, 30*(3), 195-226.

Farmer, J. D., & Foley, D. (2009). The economy needs agent-based modelling. *Nature, 460*(7256), 685-686.

Federal Transit Administration. (2012). *National Transit Database*. Table 17-20. Retrieved from: http://www.ntdprogram.gov

Ferdous, N., Pinjari, A. R., Bhat, C. R., & Pendyala, R. M. (2010). A comprehensive analysis of household transportation expenditures relative to other goods and services: an application to United States consumer expenditure data. *Transportation, 37*(3), 363-390.

Ferris, B., Watkins, K., & Borning, A. (2010). *OneBusAway: results from providing real-time arrival information for public transit.* Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

Flyvbjerg, B., Holm, M. S., & Buhl, S. (2002). Underestimating costs in public works projects: Error or lie? *Journal of the American Planning Association, 68*(3), 279-295.

Fosgerau, M., & De Palma, A. (2013). The dynamics of urban traffic congestion and the price of parking. *Journal of Public Economics, 105*, 106-115.

Fry, J. M., Fry, T. R., & McLaren, K. R. (2000). Compositional data analysis and zeros in micro data. *Applied Economics, 32*(8), 953-959.

Fullerton, D. G., Bruce, N., & Gordon, S. B. (2008). Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Transactions of the Royal Society of Tropical Medicine and Hygiene, 102*(9), 843-851.

GAO. (2001). *MASS TRANSIT: Bus Rapid Transit Shows Promise*. (GAO-01-984). Washington, D.C.: Retrieved from http://www.gao.gov/products/GAO-01-984.

Global Environmental Management Initiative. (1998). Measuring environmental performance: A primer and survey of metrics in use.

Goetz, E., Ko, K., Hagar, A., & Hoang, T. (2009). *Differential Impact of Hiawatha Light-Rail Line on Property Values in Minneapolis.* Paper presented at the Transportation Research Board 88th Annual Meeting.

Gomez-Ibanez, J. A. (1985). A dark side to light rail? The experience of three new transit systems. *Journal of the American Planning Association, 51*(3), 337-351.

Greenstone, M., Kopits, E., & Wolverton, A. (2011). Estimating the social cost of carbon for use in us federal rulemakings: A summary and interpretation: National Bureau of Economic Research.

Guerra, E., & Cervero, R. (2010). Cost of a Ride: The Effects of Densities on Fixed-Guideway Transit Ridership and Capital Costs.

Haines, A., Kovats, R. S., Campbell-Lendrum, D., & Corvalán, C. (2006). Climate change and human health: Impacts, vulnerability and public health. *Public health, 120*(7), 585-596.

Hamel, M. B., Blumenthal, D., Stremikis, K., & Cutler, D. (2013). Health Care Spending—A Giant Slain or Sleeping? *New England Journal of Medicine, 369*(26), 2551-2557.

Hammond, G. P., & Norman, J. B. (2012). Decomposition analysis of energy-related carbon emissions from UK manufacturing. *Energy, 41*(1), 220-227. doi: http://dx.doi.org/10.1016/j.energy.2011.06.035

Hammonds, J., Hoffman, F., & Bartell, S. (1994). An introductory guide to uncertainty analysis in environmental and health risk assessment. *Technical Rep. No. ES/ER/TM-35 R, 1*.

Hare, M., & Deadman, P. (2004). Further towards a taxonomy of agent-based simulation models in environmental management. *Mathematics and Computers in Simulation, 64*(1), 25-40. doi: http://dx.doi.org/10.1016/S0378-4754(03)00118-6

Hart, S. L. (1995). A natural-resource-based view of the firm. *Academy of management review*, 986-1014.

Haywood, M., & Peck, H. (2003). *Improving the management of supply chain vulnerability in UK aerospace manufacturing.* Paper presented at the Proceedings of the 1st EUROMA/POMs Conference.

Henderson, J. V. (1974). Road congestion: a reconsideration of pricing theory. *Journal of Urban Economics, 1*(3), 346-365.

Hensher, D. A. (2008). Climate change, enhanced greenhouse gas emissions and passenger transport–What can we do to make a difference? *Transportation Research Part D: Transport and Environment, 13*(2), 95-111.

Hermann, B., Kroeze, C., & Jawjit, W. (2007). Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. *Journal of Cleaner Production, 15*(18), 1787-1796.

Hess, D. B., & Almeida, T. M. (2007). Impact of proximity to light rail rapid transit on station-area property values in Buffalo, New York. *Urban Studies, 44*(5-6), 1041-1068.

Heyman, R. E., & Slep, A. M. S. (2001). The Hazards of Predicting Divorce Without Crossvalidation. *Journal of Marriage and Family, 63*(2), 473-479. doi: 10.1111/j.1741-3737.2001.00473.x

Hills, P., & Evans, A. W. (1993). Road Congestion Pricing: When Is It a Good Policy?(Comment and Rejoinder). *Journal of Transport Economics and Policy*, 91-105.

Huchzermeyer, M., & Karam, A. (2006). *Informal settlements: a perpetual challenge?* : jutaonline. co. za.

IEA. (2012). CO2 emissions from fuel combustion-highlights *IEA Statistics* (2012 Edition ed.). Paris, France: International Energy Agency.

IESS. (2008). Townships *International Encyclopedia of the Social Sciences* (2 ed., pp. 405-407).

IMF. (2013). IMF Country Report - South Africa. In IMF (Ed.): International Monetary Fund (IMF).

Immergluck, D. (2009). Large redevelopment initiatives, housing values and gentrification: the case of the Atlanta Beltline. *Urban Studies, 46*(8), 1723-1745.

Inglesi, R. (2010). Aggregate electricity demand in South Africa: Conditional forecasts to 2030. *Applied Energy, 87*(1), 197-204. doi: http://dx.doi.org/10.1016/j.apenergy.2009.08.017

J.W. Emerson, A. H., M. A. Levy, A. de Sherbinin, V. Mara, D.C. Etsy, M. Jaiteh. (2012). 2012 Environmental Performance Index and Pilot Trend Environmental Performance Index. New Haven: Yale Center for Environmental Law and Policy.

Jackson, J. (2010). Improving energy efficiency and smart grid program analysis with agent-based end-use forecasting models. *Energy Policy, 38*(7), 3771-3780.

Janssen, M. A., & Ostrom, E. (2006). Empirically based, agent-based models. *Ecology and Society, 11*(2), 37.

Jasch, C. (2000). Environmental performance evaluation and indicators. *Journal of Cleaner Production, 8*(1), 79-88 %@ 0959-6526.

Jeswani, H. K., & Azapagic, A. (2011). Water footprint: methodologies and a case study for assessing the impacts of water use. *Journal of Cleaner Production, 19*(12), 1288-1299.

Johannesson, M., & Jönsson, B. (1991). Economic evaluation in health care: is there a role for cost-benefit analysis? *Health policy, 17*(1), 1-23.

Kee, R., & Schmidt, C. (2000). A comparative analysis of utilizing activity-based costing and the theory of constraints for making product-mix decisions. *International Journal of Production Economics, 63*(1), 1-17 %@ 0925-5273.

Kehrer, P., Kuhn, B., Lemay, J., & Wells, C. (2008). *Developing Energy Solutions for a South African Informal Settlement.* (BS), Worcester Polytechnic Institute.

Khanna, M., & Rao, N. D. (2009). Supply and demand of electricity in the developing world. *Annu. Rev. Resour. Econ., 1*(1), 567-596.

Kiesling, E., Günther, M., Stummer, C., & Wakolbinger, L. M. (2012). Agent-based simulation of innovation diffusion: a review. *Central European Journal of Operations Research, 20*(2), 183-230.

Kim, G.-T., Kim, K.-T., Lee, D.-H., Han, C.-H., Kim, H.-B., & Jun, J.-T. (2010). Development of a life cycle cost estimate system for structures of light rail transit infrastructure. *Automation in Construction, 19*(3), 308-325.

Kituyi, E., Marufu, L., Huber, B., O Wandiga, S., O Jumba, I., O Andreae, M., & Helas, G. (2001). Biofuel consumption rates and patterns in Kenya. *Biomass and Bioenergy, 20*(2), 83-99.

Köhler, J., Whitmarsh, L., Nykvist, B., Schilperoord, M., Bergman, N., & Haxeltine, A. (2009). A transitions model for sustainable mobility. *Ecological Economics, 68*(12), 2985-2995.

Krasimirov, A. (2013, 17 Feb 2013). Tens of thousands join electricity protests across Bulgaria. *Reuters*. Retrieved from http://www.reuters.com/article/2013/02/17/us-bulgaria-protests-electricity-idUSBRE91G0C520130217

Kundzewicz, Z., Mata, L., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., . . . Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management.

Lahdelma, R., Salminen, P., & Hokkanen, J. (2002). Locating a waste treatment facility by using stochastic multicriteria acceptability analysis with ordinal criteria. *European Journal of Operational Research, 142*(2), 345-356 %@ 0377-2217.

Leke, A., Lund, S., Roxburgh, C., & van Wamelen, A. (2010). What's driving Africa's growth. *McKinsey Quarterly, June*.

Levi, J., Segal, L., Thomas, K., Laurent, R. S., Lang, A., & Rayburn, J. (2013). F as in Fat: How Obesity Threatens America's Future: Robert Wood Johnson Foundation.

Lévová, T., & Hauschild, M. Z. (2011). Assessing the impacts of industrial water use in life cycle assessment. *CIRP Annals-Manufacturing Technology, 60*(1), 29-32.

Liaskas, K., Mavrotas, G., Mandaraka, M., & Diakoulaki, D. (2000). Decomposition of industrial CO2 emissions:: The case of European Union. *Energy Economics, 22*(4), 383-394. doi: http://dx.doi.org/10.1016/S0140-9883(99)00035-3

Lichtenberg, S. (1974). *The successive principle.* Paper presented at the proceedings, International PMI* Symposium.

Lichtenberg, S. (2000). *Proactive management of uncertainty using the successive principle: a practical way to manage opportunities and risks*: Polyteknisk Press.

Lim, H.-J., Yoo, S.-H., & Kwak, S.-J. (2009). Industrial CO2 emissions from energy use in Korea: A structural decomposition analysis. *Energy Policy, 37*(2), 686-698. doi: http://dx.doi.org/10.1016/j.enpol.2008.10.025

Litman, T. (2011). Evaluating public transit benefits and costs. *Victoria Transport Policy Institute, 65*.

Livesey, D. A. (1973). Optimum city size: a minimum congestion cost approach. *Journal of Economic Theory, 6*(2), 144-161.

Louw, K., Conradie, B., Howells, M., & Dekenah, M. (2008). Determinants of electricity demand for newly electrified low-income African households. *Energy Policy, 36*(8), 2812-2818.

Luger, M. I., & Evans, W. N. (1988). Geographic differences in production technology. *Regional Science and Urban Economics, 18*(3), 399-424.

Ma, T., & Nakamori, Y. (2009). Modeling technological change in energy systems–from optimization to agent-based modeling. *Energy, 34*(7), 873-879.

MacDonald, J. M., Stokes, R. J., Cohen, D. A., Kofner, A., & Ridgeway, G. K. (2010). The effect of light rail transit on body mass index and physical activity. *American journal of preventive medicine, 39*(2), 105-112.

Madlener, R., & Sunak, Y. (2011). Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? *Sustainable Cities and Society, 1*(1), 45-53.

Madubansi, M., & Shackleton, C. (2006). Changing energy profiles and consumption patterns following electrification in five rural villages, South Africa. *Energy Policy, 34*(18), 4081-4092.

Mandal, S. K., & Madheswaran, S. (2011). Energy use efficiency of Indian cement companies: a data envelopment analysis. *Energy Efficiency, 4*(1), 57-73.

MARTA. (2007). *Inner Core Beltline Alternatives Analysis Detailed Screening Results*. Atlanta, GA: MARTA Retrieved from http://www.itsmarta.com/beltline-documents.aspx

MARTA, & Atlanta BeltLine Inc. (2009). BeltLine Corridor Environmental Study. *Environmental Effects Report Public Hearing* [Powerpoint]. Atlanta.

Martínez-Zarzoso, I., & Maruotti, A. (2011). The impact of urbanization on CO< sub> 2</sub> emissions: Evidence from developing countries. *Ecological Economics, 70*(7), 1344-1353.

Mason, J., Dixon, J., & Redwood, J. (1994). *Making Development Sustainable*. Washington D.C.

Maxime, D., Marcotte, M. l., & Arcand, Y. (2006). Development of eco-efficiency indicators for the Canadian food and beverage industry. *Journal of Cleaner Production, 14*(6), 636-648.

Maya Sopha, B., Klöckner, C. A., & Hertwich, E. G. (2011). Exploring policy options for a transition to sustainable heating system diffusion using an agent-based simulation. *Energy Policy, 39*(5), 2722-2729.

McFarland, D. D. (1970). Intragenerational Social Mobility as a Markov Process: Including a Time- Stationary Mark-Ovian Model that Explains Observed Declines in Mobility Rates Over Time. *American Sociological Review, 35*(3), 463-476. doi: 10.2307/2092989

McGinnis, R. (1968). A stochastic model of social mobility. *American Sociological Review*, 712-722.

McKenna Jr, J. E. (2003). An enhanced cluster analysis program with bootstrap significance testing for ecological community analysis. *Environmental Modelling & Software, 18*(3), 205-220. doi: http://dx.doi.org/10.1016/S1364-8152(02)00094-4

Mehlwana, A. M. (1997). The anthropology of fuels: situational analysis and energy use in urban low-income townships of South Africa. *Energy for sustainable development, 3*(5), 5-15.

Mirasgedis, S., Georgopoulou, E., Sarafidis, Y., Papagiannaki, K., & Lalas, D. (2013). The Impact of Climate Change on the Pattern of Demand for Bottled Water and Non-Alcoholic Beverages. *Business strategy and the environment*.

MNGWPD. (2009). *Water Supply and Water Conservation Management Plan*.

MOA. (2010). *Transportation Control Measure 2010 Performance Update*. Atlanta, GA: Atlantic Station Master Owner's Association (MOA) Retrieved from http://www.atlanticstation.com.

Molina-Morales, F. X. (2002). European industrial districts: Influence of geographic concentration on performance of the firm. *Journal of International Management, 7*(4), 277-294.

NASA, CIESIN, & CIAT. (2005). Gridded Population of the World, Version 3 (GPWv3): Population Density Grid, Future Estimates. Retrieved 20140606, from NASA Socioeconomic Data and Applications Center (SEDAC), Center for International Earth Science Information Network (CESIN), Centro Internacional de Agricultura Tropical (CIAT) http://dx.doi.org/10.7927/H4ST7MRB

National Resarch Council of the National Academies. (2011). *Climate stabilization targets: emissions, concentrations, and impacts over decades to millennia*. Washington, D.C.: National Academies Press.

Natural Earth. (2009). *World Urban Areas*. Retrieved from: https://koordinates.com/layer/1285-world-urban-areas-110-million/

Nelson, T. R., & Rabianski, J. (1988). Consumer Preferences in Housing Market Analysis: An Application of Multidimensional Scaling Techniques. *Real Estate Economics, 16*(2), 138-159. doi: 10.1111/1540-6229.00451

Neumayer, E. (2012). Human development and sustainability. *Journal of Human Development and Capabilities, 13*(4), 561-579.

Ngwane, T. (2014). 'Protest Nation': What's Driving the Demonstrations on the Streets of South Africa? In F. Farouk (Ed.). SACSIS.com: South African Civil Society Information Service.

Norman, J., MacLean, H. L., & Kennedy, C. A. (2006). Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions. *Journal of Urban Planning and Development, 132*(1), 10-21.

O'Sullivan, D., & Haklay, M. (2000). Agent-based models and individualism: is the world agent-based? *Environ Plann A, 32*(8), 1409-1425.

Oliver, P. E. (1989). Bringing the crowd back in: The nonorganizational elements of social movements. *Research in social movements, conflict and change, 11*(1989), 1-30.

Özler, B. (2007). Not Separate, Not Equal: Poverty and Inequality in Post-apartheid South Africa. *Economic Development and Cultural Change, 55*(3), 487-529.

Paulley, N., Balcombe, R., Mackett, R., Titheridge, H., Preston, J., Wardman, M., . . . White, P. (2006). The demand for public transport: The effects of fares, quality of service, income and car ownership. *Transport Policy, 13*(4), 295-306. doi: http://dx.doi.org/10.1016/j.tranpol.2005.12.004

Pawlowsky-Glahn, V., & Egozcue, J. (2006). Compositional data and their analysis: an introduction. *Geological Society, London, Special Publications, 264*(1), 1-10.

Peters, G. P., Marland, G., Le Quere, C., Boden, T., Canadell, J. G., & Raupach, M. R. (2012). Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. *Nature Clim. Change, 2*(1), 2-4. doi: http://www.nature.com/nclimate/journal/v2/n1/abs/nclimate1332.html - supplementary-information

Pezzoli, K. (1997). Sustainable Development: A Transdisciplinary Overview of the Literature. *Journal of Environmental Planning and Management, 40*(5), 549-574. doi: 10.1080/09640569711949

Pickrell, D. H. (1989). Urban rail transit projects: forecast versus actual ridership and costs. Final Report.

Plambeck, E. L. (2012). Reducing greenhouse gas emissions through operations and supply chain management. *Energy Economics, 34, Supplement 1*(0), S64-S74. doi: http://dx.doi.org/10.1016/j.eneco.2012.08.031

Porter, M., & Kramer, M. R. (2011). The big idea: creating shared value. *Harvard Business Review, 89*(1), 2.

Praetorius, B., & Bleyl, J. W. (2006). Improving the institutional structures for disseminating energy efficiency in emerging nations: a case study for energy agencies in South Africa. *Energy Policy, 34*(13), 1520-1531. doi: http://dx.doi.org/10.1016/j.enpol.2004.11.012

Pushkarev, B., Zaupan, J. M., & Association, R. P. (1977). *Public transportation and land use policy*: Indiana University Press.

Reed, T. B. (1995). *Reduction in the burden of waiting for public transit due to real-time schedule information: a conjoint analysis study.* Paper presented at the Vehicle Navigation and Information Systems Conference, 1995. Proceedings. In conjunction with the Pacific Rim TransTech Conference. 6th International VNIS.'A Ride into the Future'.

Reig, P., Shiao, T., & Gassert, F. (2013). Aqueduct Water Risk Framework. Washington, D.C. : World Resources Institute.

ReSEP. (2013). The emergent South African middle class [Press release]. Retrieved from http://resep.sun.ac.za/index.php/projects/emergent-middle-class-in-south-africa/

Roberts, B. H. (2004). The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an Australian case study. *Journal of Cleaner Production, 12*(8), 997-1010 %@ 0959-6526.

Ross, C., Meyer, M., Dobbins, M., Jackson, T., & Millar, W. (2005). The Atlanta BeltLine: Transit Feasibility White Paper. Atlanta: Atlanta Development Authority.

Ross, C. L., Leone de Nie, K., Dannenberg, A. L., Beck, L. F., Marcus, M. J., & Barringer, J. (2012). Health Impact Assessment of the Atlanta BeltLine. *American journal of preventive medicine, 42*(3), 203-213.

Rotaris, L., Danielis, R., Marcucci, E., & Massiani, J. (2010). The urban road pricing scheme to curb pollution in Milan, Italy: Description, impacts and preliminary cost–benefit analysis assessment. *Transportation Research Part A: Policy and Practice, 44*(5), 359-375.

Rulli, M. C., Saviori, A., & D'Odorico, P. (2013). Global land and water grabbing. *Proceedings of the National Academy of Sciences, 110*(3), 892-897.

SA Department of Environmental Affairs. (2011). *National Strategy for Sustainable Development and Action Plan 2011-2014(NSSD 1)*.

SA Department of Minerals and Energy. (2009). *National Energy Efficiency Strategy of the Republic of South Africa*.

Sadorsky, P. (2013). Do urbanization and industrialization affect energy intensity in developing countries? *Energy Economics, 37*(0), 52-59. doi: http://dx.doi.org/10.1016/j.eneco.2013.01.009

SAinfo. (2012). South Africa's plan for a better future. Retrieved August 27, 2013, from http://www.southafrica.info/business/economy/policies/ndp2030.htm - .UhzI7bQuid4%23ixzz2dBVt95IA

Salling, K. B., & Leleur, S. (2011). Transport appraisal and Monte Carlo simulation by use of the CBA-DK model. *Transport Policy, 18*(1), 236-245.

Santos, A., McGuckin, N., Nakamoto, H. Y., Gray, D., & Liss, S. (2011). *Summary of travel trends: 2009 national household travel survey*. (FHWA-PL-11-022). Washington, D.C. .

Sapountzaki, K. (2005). Coping with seismic vulnerability: small manufacturing firms in western Athens. *Disasters, 29*(2), 195-212.

Schrank, D., Eisele, B., & Lomax, T. (2012). Urban Mobility Report: Texas A&M Transportation Institute. T.

Shrestha, S., & Kazama, F. (2007). Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environmental Modelling & Software, 22*(4), 464-475.

Sikdar, S. K. (2004). Sustainable development and sustainability metrics. *AIChE journal, 49*(8), 1928-1932.

South African Department of Energy. (2010). Integrated Resource Plan for Electricity Department of Energy.

South African Department of Energy. (2012). *A survey of energy-related behavior and perceptions in South Africa - The Residential Sector*.

Sovacool, B. K. (2011). The policy challenges of tradable credits: A critical review of eight markets. *Energy Policy, 39*(2), 575-585.

Sowers, J., & Weinthal, E. (2010). Climate Change Adaptation in the Middle East and North Africa: Challenges and Opportunities: Harvard Kennedy School

Dubai School of Government.

Soytas, U., & Sari, R. (2007). The relationship between energy and production: evidence from Turkish manufacturing industry. *Energy Economics, 29*(6), 1151-1165.

Spiess, H., & Florian, M. (1989). Optimal strategies: a new assignment model for transit networks. *Transportation Research Part B: Methodological, 23*(2), 83-102.

Statistics South Africa. (2010). *Monthly earnings of South Africans*. (P0211.2). Retrieved from https://http://www.statssa.gov.za/Publications/P02112/P021122010.pdf.

Stephan, C., & Sullivan, J. (2004). *An agent-based hydrogen vehicle/infrastructure model.* Paper presented at the Evolutionary Computation, 2004. CEC2004. Congress on.

Steurer, R., Langer, M. E., Konrad, A., & Martinuzzi, A. (2005). Corporations, Stakeholders and Sustainable Development I: A Theoretical Exploration of Business-Society Relations. *Journal of Business Ethics, 61*(3), 263-281. doi: 10.2307/25123621

Stokes, R. J., MacDonald, J., & Ridgeway, G. (2008). Estimating the effects of light rail transit on health care costs. *Health & Place, 14*(1), 45-58.

Studio, R. L. U. (2002). Alternative Land Use Futures - Metropolitan Atlanta 2025 (C. a. R. P. P.-C. o. Architecture, Trans.). Atlanta: Georgia Institute of Technology

Suri, V., & Chapman, D. (1998). Economic growth, trade and energy: implications for the environmental Kuznets curve. *Ecological Economics, 25*(2), 195-208. doi: http://dx.doi.org/10.1016/S0921-8009(97)00180-8

Tabachnick, B. G., Fidell, L. S., & Osterlind, S. J. (2001). Using multivariate statistics.

TCPA. (1999). The Energy Report. In S. Combs (Ed.), (pp. Chapter 27,): Texas Comptroller of Public Accountants,.

Thollander, P., & Ottosson, M. (2010). Energy management practices in Swedish energy-intensive industries. *Journal of Cleaner Production, 18*(12), 1125-1133. doi: http://dx.doi.org/10.1016/j.jclepro.2010.04.011

Thom, C. (2000). Use of grid electricity by rural households in South Africa. *Energy for sustainable development, 4*(4), 36-43.

Thomas, V., Mlade, J., Borin, S., Tindall, N., & Okwo, A. (2012). Reducing Greenhouse Gas Emissions in Atlanta. Atlanta, GA: Georgia Institute of Technology.

Tirachini, A., Hensher, D. A., & Jara-Díaz, S. R. (2010). Comparing operator and users costs of light rail, heavy rail and bus rapid transit over a radial public transport network. *Research in transportation economics, 29*(1), 231-242.

Turok, I. (2012). Urbanisation and Development in South Africa: Economic Imperatives, Spatial Distortions and Strategic Responses: IIED Working Paper, 23 October.

UN-Habitat, U. (2010). State of African Cities 2010. *Governance, Inequalities and Urban Land Markets., UNEP, Nairobi*.

US Census. (2013). *State and County QuickFacts*. Online: Retrieved from http://quickfacts.census.gov/qfd/states/13/1304000.html.

USDOTFTA, & MARTA. (2012). *Fulton County GA Tier 1 Final Environmental Impact Statement*. Atlanta, GA: Retrieved from http://beltlineorg.wpengine.netdna-cdn.com/wp-content/uploads/2012/05/ABI-FEIS-4f-FINAL-042012.pdf

Verhoef, E., Nijkamp, P., & Rietveld, P. (1996). Second-best congestion pricing: the case of an untolled alternative. *Journal of Urban Economics, 40*(3), 279-302.

Wagner, S. M., & Neshat, N. (2010). Assessing the vulnerability of supply chains using graph theory. *International Journal of Production Economics, 126*(1), 121-129.

Ward, S. (2002). *The energy book for urban development in South Africa*: Sustainable Energy Africa.

Weidlich, A., & Veit, D. (2008). A critical survey of agent-based wholesale electricity market models. *Energy Economics, 30*(4), 1728-1759.

Weissmann, J. (2012, May 2015). The End of Soda? *The Atlantic*.

White House, Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, . . . Department of the Treasury. (2013). *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. Washington, D.C.: Retrieved from http://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

Winston, A. (2014). Resilience in a hotter world. *Harvard Business Review, 92*(4), 56-64, 132.

Wolde-Rufael, Y. (2006). Electricity consumption and economic growth: a time series experience for 17 African countries. *Energy Policy, 34*(10), 1106-1114.

World Bank. (2013a). Adaptation to Climate Change in the Middle East and North Africa Region. Retrieved 9 July 2014, from http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/MENAEXT/0,,contentMDK:21596766~pagePK:146736~piPK:146830~theSitePK:256299,00.html

World Bank. (2013b). *World Bank DataBank*.

Worrell, E., Price, L., & Martin, N. (2001). Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. *Energy, 26*(5), 513-536.

Z News. (2014, 17 July 2014). AAP protest against power tariff hike. *Z News*. Retrieved from http://zeenews.india.com/news/delhi/aap-protest-against-power-tariff-hike_948207.html

Zhang, M. (2009). Bus Versus Rail. *Transportation Research Record: Journal of the Transportation Research Board, 2110*(-1), 87-95. doi: 10.3141/2110-11

Zhong, R. (2014, 11 June 2014). Scorching Heat Exposes India's Power Woes. *The Wall Street Journal*. Retrieved from http://online.wsj.com/articles/scorching-heat-exposes-indias-power-woes-1402491922

Ziramba, E. (2008). The demand for residential electricity in South Africa. *Energy Policy, 36*(9), 3460-3466.

Zopounidis, C., & Doumpos, M. (2002). Multicriteria classification and sorting methods: A literature review. *European Journal of Operational Research, 138*(2), 229-246 %@ 0377-2217.

VITA

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