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Life of Sugar: Developing Lifecycle Methods to Evaluate
the Energy and Environmental Impacts of Sugarcane Biofuels

By

Anand Raja Gopal

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Energy and Resources

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Daniel Kammen, Chair

Professor Michael O'Hare

Professor Robert Dibble

Fall 2011

Life of Sugar: Developing Lifecycle Methods to Evaluate the Energy and Environmental Impacts of Sugarcane Biofuels

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Abstract

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Doctor of Philosophy in Energy and Resources

University of California, Berkeley

Professor Daniel Kammen, Chair

Lifecycle Assessment (LCA) is undergoing a period of rapid change as it strives to become more policy-relevant. Attributional LCA, the traditional LCA category, is beginning to be seen as particularly ill-equipped to assess the consequences of a policy. This has given birth to a new category of LCA known as Consequential LCA that is designed for use in LCA-based policies but is still largely unknown, even to LCA experts, and suffers from a lack of well developed methods. As a result, many LCA-based policies, like the California Low Carbon Fuel Standard (LCFS), use poor LCA methods that are both scientifically suspect and unable to model many biofuels, especially ones manufactured from byproduct feedstocks. Biofuels made from byproduct feedstocks, primarily molasses ethanol from Asia and the Caribbean, can contribute significantly to LCFS' carbon intensity targets in the near-term at low costs, a desperate need for the policy ever since US corn ethanol was rated as having a worse global warming impact than gasoline.

In this dissertation, I develop the first fully consequential lifecycle assessment of a byproduct-based biofuel using a partial equilibrium foundation. I find that the lifecycle carbon content of Indian molasses ethanol is just **5 gCO₂/MJ** using this method, making it one of the cleanest first generation biofuels in the LCFS. I also show that Indian molasses ethanol remains one of the cleanest first-generation biofuels even when using the flawed methodology ratified for the LCFS, with a lifecycle carbon content of **24 gCO₂/MJ**. My fully consequential LCA model also shows that India's Ethanol Blending program, which currently subsidizes blending of molasses ethanol and gasoline for domestic consumption, can meet its objective of supporting domestic agriculture more cost-effectively by helping producers export their molasses ethanol to fuel markets that value carbon. However, this objective will be achieved at a significant cost to the poor who will face a **39% increase in the price of sorghum** because of the policy.

Keywords: Consequential Lifecycle Assessment · Biofuels · Sugarcane · Molasses · Low Carbon Fuel Standard · India · Indirect Land Use Change · Greenhouse Gas Emissions.

For my wife Elizabeth, step-daughter Jessica and my parents Malathi and Rajagopalan.

Life would be nowhere as enriching without the presence of all of you in my life and I definitely would not be writing a dedication page in a doctoral dissertation without your support.

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List of Acronyms

| | |
|----------|--|
| AB32 | Assembly Bill No. 32, California's Climate Mitigation Law |
| AEZ | Agro-ecological Zone |
| ALCA | Attributional Lifecycle Assessment |
| CARB | California Air Resources Board |
| CDE | Constant-Difference of Elasticity |
| CES | Constant Elasticity of Substitution |
| CGE | Computable General Equilibrium |
| CLCA | Consequential Lifecycle Assessment |
| DDGS | Dried Distiller's Grains and Solubles |
| DGS | Distiller's Grains and Solubles |
| EBP | Ethanol Blending Program |
| EIOLCA | Economic Input-Output Lifecycle Assessment |
| EPA | Environmental Protection Agency |
| EtOH | Ethanol |
| GHG | Greenhouse Gases |
| REET | Greenhouse Gas, Regulated Emissions and Energy Use in Transportation |
| GTAP | Global Trade Analysis Project |
| GTAP-BIO | Global Trade Analysis Project for Biofuels Model |
| GTAP-E | Global Trade Analysis Project for Energy Model |
| GWI | Global Warming Impact |

ILUC Indirect Land Use Change
INR Indian Rupee
IO Input-Output
ISO International Standards Organization
LCA Lifecycle Assessment
LCFS Low Carbon Fuel Standard
LCI Lifecycle Inventory
OECD Organisation for Economic Co-operation and Development
OPEC Organization of Petroleum Exporting Countries
PE Partial Equilibrium
PM Particulate Matter
REACH Registration, Evaluation, Authorization and Restriction of Chemical Substances
REPA Resource and Environmental Profile Analysis
RFA Renewable Fuels Association
RFS Renewable Fuel Standard
RFS2 Renewable Fuel Standard 2, the successor to the Renewable Fuel Standard
SAM Social Accounting Matrix
SETAC Society of Environmental Toxicology and Chemistry

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Chapter 1

Introduction

1.1 Motivation

The transportation sector is responsible for 13.5% of all anthropogenic greenhouse gas (GHG) emissions which is equivalent to 23% of all GHG emissions from the energy sector [Ins, 2007]. In OECD countries transport's share of GHG emissions rises to 30% of all anthropogenic emissions due to the high usage of road transport and diminished emissions from land use change [OECD, 2008]. Further, the marginal cost of abating carbon from the transport sector is substantially higher when compared to the electric power sector

[Vuuren et al., 2007, Wing, 2006], making it that much harder to achieve the deep emissions reductions that are necessary from the transport sector to stabilize the climate. Under these circumstances, climate mitigation policies have focused mainly on the electricity sector in the near term and policymakers have tended to table the discussion on transport until substantial technological breakthroughs occur. However, there is growing consensus that transport cannot be completely ignored even in the near term due to various reasons, chief among them being the role that the fossil fuel infrastructure plays in deepening a path dependence that will make it harder for clean transportation technologies to make the leap to commercialization [Sperling and Yeh, 2009].

In 2007, the California Assembly passed AB32, a bill that required the reduction of greenhouse gases across several sectors including transportation [Commission, 2007]. In designing the policy to implement the law it became clear that, the point and mode of regulation, as well as the setting of GHG targets for liquid transportation fuels had to be different from the electricity sector primarily due to structural differences between the sectors and the fossil fuel alternatives available to each [Farrell and Sperling, 2007b]. For the electricity sector the end-user of the fuel, the power plant, is the logical point of regulation but in the case of transportation fuels, regulators are forced to regulate further upstream since the end-users of fuel are vehicles which are numerous and mobile. In fact, policymakers are forced to make more substantive changes relative to the electric sector in the setting of GHG targets and in the mode of regulation. The anticipated high marginal cost of reducing GHG emissions from transport relative to electricity has led policymakers to more confidently set absolute carbon caps on electricity while only setting intensity targets for transportation which is the case in California's climate change law. The bulk of the GHG emissions associated with the production, processing and use of all fossil fuels, whether for power or transportation, occur at the point of end-use [Gopal and Kammen, 2010]. Given jurisdictional and other constraints, simply counting the carbon released at the end use as the sum total of all GHG emissions for fossil fuels results in only a minor error and hence is optimal for policy design. If this fact held true for all non-fossil fuels used in either sector or if the full lifecycle GHG emissions of the alternative fuels were negligible, then just counting the final carbon emissions would be optimal for any fuel in the entire sector. For the power sector these criteria hold but for the transport sector they do not; necessitating vastly different climate policy designs for each sector.

For several reasons, primarily due to the existing transportation infrastructure and lower costs of production, the most likely near- to medium-term alternatives to petroleum in the transport sector are biofuels from various feedstocks [Farrell and Sperling, 2007a]. Unlike power sector alternatives like solar PV, solar CSP or Wind, biofuels do not have negligible lifecycle GHG emissions upstream of the final use. In fact, even when you just consider the biofuel supply chain,

the majority of GHG emissions that can be associated with them occur due to the application of agricultural inputs for growing the crop [Farrell et al., 2006, Mascia et al., 2010, Wang et al., 2006, Wang et al., 2008]. Faced with this unusual emissions profile, the consensus among policy experts in the latter half of this decade was that lifecycle assessment (LCA) based policies were the best approach to regulate transportation fuels for carbon [CARB, 2009d]. Under such a policy the regulator adopts an approved LCA methodology and calculates default fuel carbon content ratings for each fuel utilized in the program. An average of all the LCA fuel carbon ratings weighted by the quantity of each type of fuel utilized is then calculated to determine the fuel carbon intensity of the entire jurisdiction. Implicit in such an approach are the following assumptions:

1. The lifecycle GHG rating of each transport fuel can be determined using established lifecycle assessment methodologies.
2. The lifecycle GHG rating so derived can be precise enough to accurately quantify the actual greenhouse gas impact of using the transportation fuel to meet the policy requirement.
3. An entity within the jurisdiction of the regulator (like a fuel wholesaler in California), can effectively track and affect the entire supply chain of the fuel purchased.

The transportation fuels part of AB32, known as the Low Carbon Fuel Standard (LCFS), was designed in 2007 assuming the above assumptions hold true. Since then, questions have been raised regarding the validity of all three and addressing each can be a dissertation of its own. Within a few months of the enactment of the LCFS, the first assumption above was proved to be very wrong; existing LCA methods were woefully inadequate to determine the lifecycle GHG emissions of fuels used in a low carbon fuel policy. The need for better methods to calculate the lifecycle GHG footprint of transportation fuels for use in LCA based policies was one of the main motivations for my dissertation.

The LCAs for the LCFS were expected to be performed by the dominant LCA methodology at the time, Attributional Lifecycle Assessment (ALCA). In fact one of the reasons policymakers confidently adopted an LCA based policy for the LCFS was due to the presence of a widely used and tested LCA tool for transportation fuels known as GREET (Greenhouse Gas, Regulated Emissions and Energy Use in Transportation). The ALCA approach, which is implemented in GREET, assumes that the material and energy flows associated with the lifecycle of a product are static relative to the economy. This reduces the problem to studying the supply chain and allocating the material and energy flows appropriately to the products of interest. In February 2008, Tim Searchinger and his team of researchers at Princeton published a paper in Science [Searchinger et al., 2008], that quantified an effect that came to be known as indirect land use change (ILUC) emissions. In simple terms, the paper posits that GHG emissions that occur due to land use change far removed from the biofuel supply chain but caused by the biofuel policy are so high that the lifecycle GHG emissions attributable to each biofuel could have a higher global warming impact (GWI) than gasoline and diesel [Searchinger et al., 2008]. This ILUC concept has since been widely accepted by academics, policymakers and other transport fuel stakeholders as real and significant [Parliament, 2009, O'Hare et al., 2010, Biofuels, 2010], and all major fuel

policies regulating carbon have agreed that ILUC needs to be incorporated into their policy in some form. However, established ALCA tools such as GREET are not designed to estimate ILUC, leaving policymakers scrambling to find other methods or metrics to quantify ILUC. The methods developed have been unsatisfactory thus far. Further, ILUC itself is only one “indirect” effect of a fuel policy and there are others that also result in a net change in GHG emissions as I show in Chapter 5. Hence, there is a great need for the development of lifecycle assessment methods and tools to determine the lifecycle GHG rating of transportation fuels for policies like the LCFS. In this dissertation I develop a new LCA tool, which falls under the rubric of consequential lifecycle assessment (CLCA), that improves LCA modeling for fuel policies.

As I mentioned before, due to the substantial transportation infrastructure built around liquid fuels, any near term fuel carbon reduction strategy will depend heavily on first generation biofuels (i.e. biofuels made from starch and sugar based feedstocks) that can be reliably proven to reduce GWI relative to fossil fuels. The menu of such options has dwindled considerably since the incorporation of ILUC. The efficacy of US corn ethanol, the most abundantly produced biofuel today, to reduce GWI relative to gasoline is in serious doubt [CARB, 2009b]. This situation should have led to an exhaustive search for as many commercially available biofuels as can be found to meet the requirements of low carbon fuel policies but somewhat surprisingly, plainly visible options have been ignored. Large volumes of biofuels made from byproduct feedstocks can be manufactured cheaply and the use of these in programs like the LCFS can go a long way toward meeting the programs’ carbon targets over the next 3 to 4 years. Ethanol from molasses, a byproduct of sugar production, is one of the most abundantly available byproduct biofuels with approximately 8 billion liters of annual production capacity [Licht, 2011]. The current LCA modeling tools and methods ratified by the major low carbon fuel programs cannot be used to calculate the lifecycle GHG footprint of molasses ethanol thereby shutting the product out of these markets when it can play a major role in reducing the costs of program compliance in the near term. In this dissertation, I develop several pioneering and innovative LCA models of molasses ethanol followed by recommendations on which approach is best suited for LCA based policies.

India, the world’s largest producer of molasses ethanol, enacted a biofuel blending mandate known as the Ethanol Blending Program (EBP) in 2003 that demanded large amounts of domestically produced molasses ethanol. The policy was enacted with little analysis of its ability to meet its stated objectives of reducing foreign oil dependence and supporting domestic agriculture or the costs at which these goals would be achieved. In this dissertation, I apply my newly developed LCA methods to calculate the LCA GHG emissions of Indian molasses ethanol, to see if the results can provide valuable insights into the efficacy of the EBP. I provide some suggestions on how the program could be redesigned to meet one of its objectives more cost effectively.

1.2 Research Questions and Contributions

The motivations for the dissertation discussed above can be summarized by a set of research questions I set out to answer. All the research questions listed below were answered as corollaries to the following specific question that I set out to answer directly.

What are the lifecycle GHG emissions of molasses ethanol using new attributional and consequential methods?

My research based on this question neatly allowed me to answer all of the following larger questions.

- How can we build better models and approaches to improve the efficacy of LCA-based fuel policies?
- Can Attributional and Consequential LCAs for biofuels made from byproducts be developed for use in LCA-based GHG fuel policies?
- Can molasses ethanol be a significant near-term contributor to reducing GHG emissions from the transport sector?
- What are appropriate applications each for Attributional and Consequential LCA and what are implications for the LCFS which uses both?
- Is there a better policy than the Ethanol Blending Program in its current form for India to achieve one or both of its objectives of boosting domestic agriculture and reducing foreign oil dependence?

This dissertation has a wide mix of theoretical, empirical and policy relevant contributions. The major contributions are listed below.

- I show that current modeling approaches ratified by the California Air Resources Board (CARB) for the LCFS are a scientifically incoherent mix of Attributional and Consequential LCAs that cannot capture the actual GHG impact of using a fuel in the policy.
- Based on the above finding, I develop the first fully consequential lifecycle assessment of molasses ethanol based on a bottom-up partial equilibrium model. This method is the best current approach to calculate the actual GHG impact of molasses ethanol in the LCFS.
- The partial equilibrium modeling tool substantially improves consequential LCA methodology, which in turn, is essential to improve the efficacy of LCA-based fuel GHG policies.
- I develop the most comprehensive attributional lifecycle model of a sugarcane factory that flexibly co-produces sugar and ethanol. So far, lifecycle assessment studies of sugarcane ethanol have narrowly focused on specific regions and factory-types primarily in Brazil. This model has been adopted by CARB to rate molasses ethanol that will be sold under the LCFS.
- By studying the same product using both Attributional and Consequential LCA, I compare the two approaches in depth and provide greater clarity regarding the relevance, strengths and limitations of each in various applications.

- I find that India's Ethanol Blending Program can be redesigned to use taxpayer money much more efficiently to boost the domestic sugarcane sector and that domestic molasses fuel ethanol is not the best option to reduce India's foreign oil dependence.
- I find that molasses ethanol can indeed be a significant option to meet the near-term targets of California's LCFS cost effectively.

1.3 Dissertation Overview

This dissertation consists of seven chapters including this introduction. Following the introduction, in Chapter 2, I introduce the theory of Attributional and Consequential Lifecycle Assessment, a review of seminal papers in each method and a detailed discussion on the premise and applications of each. In Chapter 3, I present the attributional LCA model of sugarcane factories that are fully flexible in sugar and ethanol production and present the results of the model when applied to a typical Indian sugarcane factory. This model is the first in published literature to explore the issue of co-product allocation between sugar and molasses in depth. In Chapter 4, I use the GTAP model, which is currently the only model ratified by California to estimate the indirect land use change emissions of all fuels used in the LCFS, to derive the consequential LCA GHG emissions of Indian molasses ethanol and highlight its inability to do this for any byproduct based biofuels. In Chapter 5, I develop a bottom-up partial equilibrium model of molasses and related markets in India to derive the full consequential lifecycle GHG emissions of Indian molasses ethanol. This is not just the first consequential LCA of molasses ethanol but also the first attempt to analyze India's Ethanol Blending Policy. The results of the model strongly point toward the redesign of the policy. In Chapter 6, I discuss the feasibility of LCA based fuel policies based on my model results. I also present a menu of options that policymakers should consider to improve current LCA based policies. In the final chapter, I present my opinion on how biofuels should be treated in existing low carbon fuel policies and conclude with a discussion of how this work can be extended.

Chapter 2

Theory and Evolution of Lifecycle Assessment

2.1 Chapter Summary

Lifecycle Assessment (LCA) is a fairly young field of study. Consequential lifecycle assessment is the newest category of lifecycle assessment. It is so new that many LCA experts do not know how to clearly define it. In this chapter, I define Attributional LCA (ALCA) and Consequential LCA (CLCA), discuss the main methods used in both and highlight the lack of widespread understanding of the distinction between the two with examples where they are mixed incoherently. I also discuss other hot-button LCA issues in depth and finish with a summary of the main contributions my dissertation makes to the field of LCA.

2.2 Definition and History of Lifecycle Assessment

Definition of Lifecycle Assessment: According to the International Standards Organization (ISO) Standards, Lifecycle assessment (LCA) is a tool to help assess the total resource use and environmental effects associated with products throughout their entire life cycle, from raw materials extraction, through production, transportation, use, and disposal [ISO, 2006a].

The first lifecycle assessment in the USA, known at the time as a Resource and Environmental Profile Analysis (REPA) was commissioned by the Coca-Cola Company in 1969 to help inform a decision regarding the manufacture of beverage cans [Hunt et al., 1996]. The company wanted to understand the full lifecycle resource and environmental implications of self-manufacturing beverage cans. This study led to subsequent REPAs in the 1970s being viewed as a tool to be used by private sector clients to reduce the environmental impact of their supply chain with the solid waste consequences of packaging being the key variable of interest. However, with corporate interests at stake, neither the methodology nor the results of any of the studies were made public, leading to little widespread interest in LCA as a field of academic and political inquiry. In 1972, the Environmental Protection Agency (EPA) commissioned a REPA to compare refillable glass bottles and disposable cans with the aim of designing policy and regulations for them. After an exhaustive study and an extensive peer review, the first publicly available LCA study was released as an EPA report in 1974 [Hunt et al., 1996]. The OPEC Oil Embargo drew attention to energy consumption in REPAs, resulting in a set of studies that came to be known as energy profile analyses. However, toward the latter half of the decade, interest in REPAs faded because of two reasons. Oil prices crashed, reducing public interest in energy and the EPA decided that regulation based on REPAs was inferior to directly regulating pollution and solid waste at the end of the chain [Hunt et al., 1996]. Inability to control actors throughout the supply chain is a recurring problem in LCA based regulation and one that is central to the LCFS.

Public sector and academic interest in LCA remained low until 1988 when a renewal of public concern about solid waste and toxic releases by companies led to an explosion of government and academic studies on the lifecycle effects of solid waste disposal options like landfilling, recycling, reusing, etc. In August 1990, the Society of Environmental Toxicology and Chemistry (SETAC) convened its first meeting to discuss REPA methodology and christened it with the new name: Lifecycle Assessment [Hunt et al., 1996]. Rebirth of LCA in the US, which was mostly

concurrent with gaining popularity of the method in Europe, was driven by an interest in using the tool in public policy design and analysis. Most LCAs from that time were unable to shed any light on social outcomes, a primary concern of policymakers, and studied environmental outcomes as though they were unaffected by socio-economic factors. LCAs that take such an approach came to be known as Attributional LCAs (ALCA). It was only in the late 1990s when LCA methods that explicitly attempt to quantify the effect of a decision¹ on environmental outcomes started to be developed. LCAs with such an objective came to be known as Consequential LCAs (CLCA). ALCA and CLCA are two distinct LCA categories which start out by asking completely different questions of the same product.

2.3 Categories of Lifecycle Assessment

2.3.1 Attributional LCA

From the first Coca-Cola REPA² to most studies performed today, the dominant approach to LCAs is *Attributional*. An ALCA³ inventories and analyzes the direct environmental effects of some quantity of a particular product or service, recursively including the direct effects of all required inputs across the supply chain, as well as the recursive direct effects of using and disposing of the product [ISO, 2006b]. Phrased differently, an ALCA attempts to answer the following question:

What are the environmental effects of making a unit of something from scratch, relative to the world being otherwise exactly the same and the good not made at all?

An ALCA is performed in the following steps [ISO, 2006b, Guinée, 2001, Pedersen Weidema, 1993]:

1. Define the product to be studied (e.g. Corn ethanol manufactured from corn grown in the US Midwest)
2. Decide on the functional unit of study (e.g. 1 MJ of corn ethanol)
3. Decide which environmental parameters to quantify (e.g. GHG emissions, fossil energy consumed)
4. Assemble the Lifecycle Inventory (LCI), which is all the material, process and environmental data that are inputs to the LCA

¹The decision so analyzed is usually a public policy decision

²The Coca-Cola study was used to inform a decision as are almost all LCAs and an ALCA is innately incapable of helping inform the outcomes of decisions

³Until the mid-1990s ALCA was the only category of LCA. From the mid-1990s to 2004, ALCA was rechristened as Retrospective LCA. It was only in 2004 that the current two categories of ALCA and CLCA were named as such.

5. Determine the ALCA methodology to be employed (e.g. EIOLCA, Process-based, hybrid, etc)
6. Apply the chosen ALCA method to the LCI and generate a result
7. Perform an uncertainty analysis or provide an argument for not performing one
8. Interpret the result based on the objective and redo any earlier steps if necessary

While the steps above appear to be fairly straightforward, areas of disagreement and subjectivity are widespread in LCA, especially in steps 4, 5 and 6. As a result, two studies that study the same product with the same objective rarely arrive at the same lifecycle result. I discuss some of the hot-button issues and controversies in LCA later in the chapter. For now, I provide an overview of methods employed to solve ALCA problems.

2.3.1.1 ALCA Methodology

Process Analysis

In this method, the processes involved in the production, use and disposal of the product are mapped out and analyzed in detail. The material and energy flows along with the environmental impacts of each process in the full production tree required to produce the product are *linearly* scaled to the functional unit being studied. The environmental variable of interest is then tracked throughout the boundaries of the problem and summed to obtain the LCA result. GREET employs such an approach for the fuel sector to derive the well-to-tank and well-to-wheel LCA impacts of various environmental metrics associated with transportation fuels.

The processes that need to be modeled to perform a comprehensive LCA extend beyond just the ones that are directly associated with the product of study. It is necessary to recursively model processes further up the supply chain and during the use and disposal phases as well. In the case of petroleum this may include processes directly dealing with oil production like drilling, with gasoline production like refining, with gasoline delivery like transportation and with gasoline use like combustion but for the study to be an LCA it also needs to include any process linked to this first level of processes and any processes linked to the second level and so on. In a highly interlinked global economy, this can frequently lead to a situation where almost any process in the global economy should be included in the LCA of the product being studied. In practice when implementing this method, the process diagram pyramid is usually truncated after the first one or two levels under the assumption that processes further removed from the final product will probably have a negligible impact on the LCA of the final product [Suh et al., 2004, Ekvall and Weidema, 2004]. The vast majority of LCAs performed to date, including the one I perform in Chapter 3, use the Process method [Hendrickson et al., 2006].

Economic Input-Output LCA (EIO LCA)

In order to relieve the analyst from arbitrarily having to decide where to truncate the process diagram and draw a system boundary [Suh et al., 2004], a team of researchers at Carnegie Mellon's Green Design Institute developed the Economic Input-Output (EIO LCA) method to solve LCA problems [Hendrickson et al., 2006]. The EIO LCA method uses economic input-output (IO) tables⁴ of entire economies linked with environmental impact tables that map onto the original IO tables. In this way, all economic activity in a region linked to a product are captured. To extend the system boundary to encompass the entire economy, the EIO LCA method ends up aggregating several processes into one and is forced, because of the structure of SAMs, to connect environmental impacts linearly to financial flows. Importantly due to its coarse resolution, new technologies or processes cannot be studied using EIO LCA since these will either not be included in the IO tables or their innovations will be lost in the noise. Also, EIO LCAs tend to become grossly inaccurate if a significant proportion of the materials and energy associated with a good is imported, since the IO tables are usually just available for specific countries.

Hybrid

Suh et al (2004) [Suh et al., 2004], proposed a hybrid approach that combines the strengths of the Process and EIO LCA methods while minimizing their weaknesses. This is possible because the strengths and weaknesses of the two methods occur at complementary parts of the analysis. They argue that Process LCAs provide the most insight if applied at the level directly associated with the product under study beyond which process modeling provides rapidly diminishing returns. So, they recommend the use of EIO LCA beyond the first or second level of process modeling to obtain the LCA result in a hybrid manner.

2.3.1.2 ALCA Today

ALCA was the original LCA category and continues to be the most dominant one used today. There is now substantial disagreement on its efficacy when it comes to prospective or consequential analyses [Reap et al., 2008a, Delucchi, 2004, Ekvall and Weidema, 2004, TILLMAN, 2000, Weidema, 2000b], especially in the realm of public policy, but ALCAs continue to be used for such purposes.

2.3.2 Consequential LCA

The revival of LCA in Europe and the US in the late 1980s was primarily driven by the need to take action to reduce solid waste production and toxic discharges, in most cases through public policy action. It soon became clear to some LCA practitioners that a simple static study of the supply, use and disposal chains does not provide any insights into the environmental impacts that

⁴This type of IO tables are also known as Social Accounting Matrices (SAMs).

will result from changes caused by policy actions to the production patterns of the main product and its related products [Pedersen Weidema, 1993]. As an example, if the Government decides to ban the use of wood pencils in order to save forests it will probably result in the increased consumption of plastic pens that will increase oil production⁵ and the solid waste burden⁶. If an ALCA was used to quantify the policy effect, the environmental impacts of the increased pen consumption will simply be ignored since that is not part of the supply, use and disposal chain of pencils and the policy will appear to be an unqualified success. It was not until the mid-1990s when a group of Scandinavian scientists coalesced several methods that would have shed insight on the higher pen consumption that will result from the pencil ban into a new category of LCA which they named Prospective LCA [TILLMAN, 2000]. Prospective LCA was renamed as Consequential LCA in 2001 and the original LCA approach was rechristened as ALCA at the same conference in Cincinnati [Ekvall and Weidema, 2004].

A CLCA estimates the environmental impact of a new decision that changes the quantity produced or the technology employed for a product over its entire lifecycle. A CLCA attempts to answer the following question:

What are the full lifecycle environmental effects of a change in some aspect of a product's production, use or disposal?

The original proponents of CLCA, envisioned it to be a support tool for decision analysis [Ekvall and Weidema, 2004] which naturally implied that it was well suited to inform policy decisions. While there is substantial doubt regarding the usefulness of CLCA as a tool in policy analysis, CLCA can attempt to inform policy decisions while ALCA simply cannot because it asks a different question at the outset. Given these vastly different starting points, the methods employed to perform CLCAs are also very different from ALCAs.

2.3.2.1 CLCA Methodology

To perform a CLCA well, it is necessary to describe the world⁷ before and after the change in the product that is the centerpiece of the study. Hence, it is almost always necessary to use models to perform CLCAs as opposed to ALCAs where IO matrices could suffice. If the change or decision in question has already occurred and been studied before, it is probably best to use statistically or econometrically estimated models to isolate the effect of the change. However, such a scenario is very unlikely because if the particular decision or change has already occurred there is probably no need for a CLCA. Given that CLCAs are most relevant for decisions or changes that have never been made before it is necessary to have a model that can predict the causal environmental effects of a decision.

Partial Equilibrium Models: Partial Equilibrium (PE) Models are economic models that describe the interactions of a select set of markets and regions and treat the rest of the world as

⁵Petroleum is a major input in plastics production

⁶Plastics are non-biodegradable while wood is biodegradable

⁷Usually just a subset of the world where the greatest impact is expected

exogenous. PE Models are generally used for academic and policy applications and hence tend to delineate markets and regions in accordance with the jurisdiction of major policymaking entities. For example, a popular PE model known as FAPRI is an agricultural sector PE model with nations as the regional unit. PE Models were built to assess social and economic welfare changes caused by policy decisions on issues like trade, subsidies, etc. Although they do not contain any environmental information, they frequently serve as the backbone of CLCAs because they exist to quantify the supply and demand responses to structural or policy changes in the market⁸. Outputs from a PE model are then combined with an environmental database to compute CLCA results.

General Equilibrium Models: General Equilibrium (CGE⁹) models were born in response to the truncated system boundary in PEs which ignore the global economy outside of the few markets they focus on. CGE models typically encompass all economic activity in the world but they are able to do so and remain computationally feasible by having coarser resolutions on markets and regions. Using a CGE Model as the backbone of a CLCA instead of a PE model is analogous to choosing the EIOLCA method instead of the Process method for an ALCA. In both cases, the system boundary truncation is eliminated in return for coarser resolution. CGE models are beginning to be widely employed for CLCAs, particularly for performing biofuel LCAs [Mascia et al., 2010].

One of the main reasons for the paucity of CLCA studies is the complexity of determining baseline and decision outcomes. When PE and CGE models are used to define baseline and decision scenarios, the resulting uncertainty is substantial and in some cases, irreducible. Perhaps in an attempt to avoid complexity, most CLCAs do not perform any sort of economic modeling and hence consider only one consequential effect which is identified through expert knowledge of a sector or region [Plevin, 2010]. However, this simply results in false precision and unquantifiable inaccuracy.

2.4 Hot-Button Issues in LCA

In both ALCA and CLCA, a wide range of issues are controversial, identified as areas needing improvement or standardization, or seen as unresolvable. The persistence of controversies and issues led to the formulation of ISO Standards for LCA in order to narrow the differences between studies of the same product and to create best practice guidelines [Guinée, 2001]. Despite these Standards, a substantial number of LCA issues remain unresolved and lack consensus. I discuss here the state of discourse on the major LCA issues, with an emphasis on biofuel LCAs.

2.4.1 Extensive Data Needs

Both ALCA and CLCA require substantial amounts of data to be performed defensibly. In the case of the Process method of ALCA, material and energy data for almost all processes in an

⁸Since products have to exist in a market, changes in product quantity and technology are captured by PE models

⁹General Equilibrium Models are generally called Computable General Equilibrium Models or CGE Models

economy could be relevant to the product studied if the LCA has to be comprehensive. Assembling the Social Accounting Matrices (SAMs) to build national and regional IO tables used in an EIOLCA takes years and hence by the time one is completed, it is already out of date. In the case of CLCAs the data intensity is even higher; detailed market and balance of trade data are needed in addition to the material and energy flows discussed above. Gathering this amount of data is usually infeasible for any study and so an early step in any LCA is to assess the optimal amount of data that needs to be gathered to still provide a reasonably accurate or insightful result [Reap et al., 2008b]. However, drawing the system boundaries with the aim of keeping the result useful is more art than science since you can never clearly show that influences from outside your system boundary do not have a substantial impact on your LCA result [Zamagni et al., 2008]. In general, most LCAs, including those in this dissertation, assume that second and third order effects¹⁰, technologies or flows do not affect the final result significantly, and articles that challenge this assumption [Reap et al., 2008b, Reap et al., 2008a, Suh et al., 2004] do not suggest any alternative approaches. Note that an LCA can have burdensome data needs even if the system boundaries only include first- and second-order effects. In my analyses, I make the same constrained optimization decision on relevant data based on their contexts and objectives as other analysts have done.

2.4.2 System Boundaries

While data burdens seem to be the only driver in determining system boundaries, it is sometimes not even the main driver, especially in the case of CLCAs [Ekvall and Weidema, 2004]. In the case of ALCAs, the primary determinant of system boundaries is the balance between the time and effort burden of analyzing all related effects and the ability to obtain a defensible and accurate result. When using the Process method, analysts usually draw their system boundary around the first-order level of processes¹¹ [Plevin, 2010, Wang, 2001], and do not count the environmental impacts further removed under the assumption that only a small fraction of the impacts occur outside the first-order. Several researchers questioned the validity of this assumption [Reap et al., 2008b, Suh et al., 2004] and used it as motivation to develop the EIOLCA method. While the EIOLCA method does expand the system boundary considerably, in practice even this method suffers from arbitrary system boundary truncation since the IO tables used usually do not encompass the entire global economy.

To perform a comprehensive CLCA, the system analyzed usually needs to be the entire global economy and environment as in the case of ALCAs but in addition, CLCAs also need to forecast the time evolution of the environmental parameter of interest in decision and baseline scenarios. As discussed in Section 2.3.2.1 above, CGE models have been offered as an option to feasibly expand the system boundary to the entire economy. However, their coarse resolution results in huge, hard-to-quantify uncertainty and they are simply ill-equipped to handle many different products as I show in Chapter 4. Hence, a CLCA analyst frequently prefers to choose a smaller

¹⁰This includes consequential effects that are outside the supply chain but can still be categorized as first-, second- and third-order effects

¹¹First-order refers to any processes that are directly necessary to produce the product being studied.

subsystem for analysis where most of the effects can be captured while keeping the model feasible. Up to this point, the system boundary problem is driven by the data burden similar to ALCAs but unlike an ALCA, the subsystem that is analyzed need not be centered on the supply chain of a product.

To perform a CLCA, both a product and a decision need to be defined. As a result, the subsystem that you choose to analyze can be different for the same product based on the decision that is taken. As an example, when performing a CLCA of increasing Brazilian sugarcane ethanol production to meet demand from the US Renewable Fuel Standard (RFS), the subsystem is centered on increasing sugarcane acreage in Brazil and the analysis is centered on land and agricultural markets within Brazil. If we instead want to perform a CLCA of the introduction of a production tariff on Brazilian sugarcane ethanol, the subsystem analyzed is likely to be centered on US corn ethanol and its related land and agricultural markets because the tariff will make corn ethanol cost competitive and result in exports from the US to Brazil. Hence, to perform CLCAs feasibly and credibly, the section of the global economy and resources where you expect to see the maximum environmental effects from the product and decision needs to be identified first. The key factor to note here is that this subsystem may be well removed from the supply chain of the product being studied, like in the second instance of the example above.

The data burden and the drawing of system boundaries are correlated but not perfectly so. The decision regarding both issues in every study is subjective and difficult to universalize and hence it is left to the analyst to justify his or her choice of problem resolution and system boundary. In this dissertation I develop some guidelines on making these choices for both Attributional and Consequential LCAs of biofuels made from low-value byproducts.

2.4.3 Co-product Treatment

Co-product treatment is perhaps the most controversial issue in ALCA [Ekvall, 2001]. In the case of CLCAs, methodologies to deal with co-products is less in dispute. Hence the discussion in this section primarily deals with co-product treatment for ALCAs. Co-products here refer to all the products produced from the same process or facility as the product being studied. When performing an ALCA on such a system, the LCA analyst needs to make a decision regarding if and how the main product being studied gets credited since other useful products are co-produced. There are several methods to address this in an ALCA but controversies arise because it is hard to prescribe objective, universal methods for co-product treatment. In this section I will discuss all the possible co-product treatment approaches when it comes to biofuel LCAs except for the system expansion method which I will discuss in a different context later in the chapter.

2.4.3.1 Mass-based Allocation

In the mass-based allocation approach, the LCA environmental or energy burden upstream of the production process is allocated to each co-product based on its mass-output share. Mass-based allocation is the most commonly used co-product treatment method in LCAs to date but it is not

very common in the case of biofuel LCAs. For this approach to make sense, all the co-products need to have actual mass (e.g. cannot be electricity) and the values of the co-products should ideally be correlated to their mass share. These two rarely hold true in the case of biofuel LCAs and hence the mass-based method is rarely considered acceptable in the case of most biofuel LCAs.

2.4.3.2 Energy-based Allocation

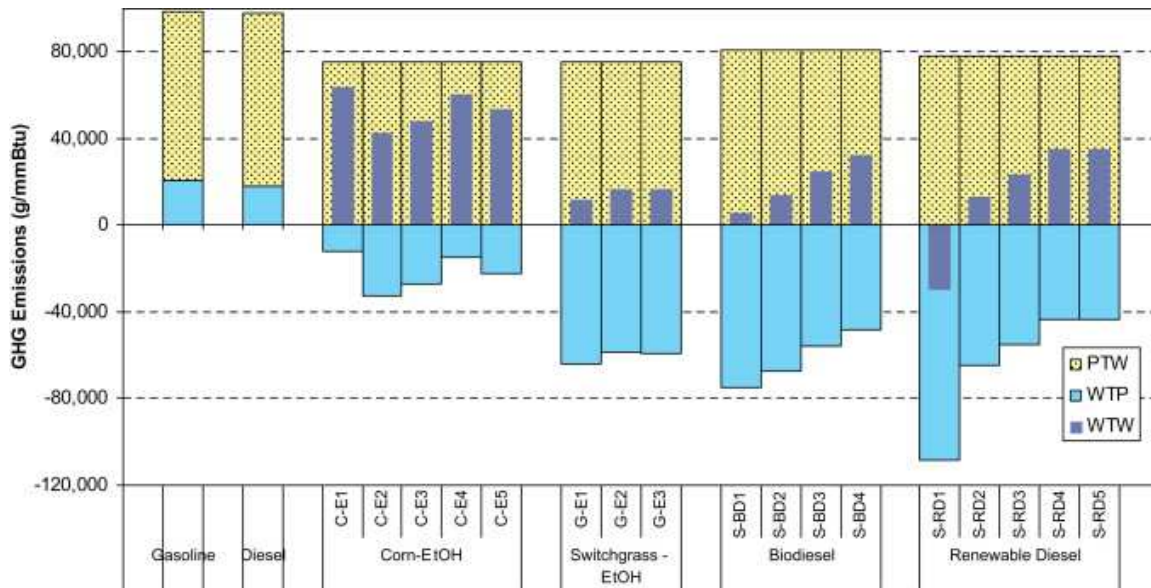
When studying any energy generation or fuel production technology useful products like electricity and heat that have no mass are produced. The energy-based allocation method overcomes that shortcoming of the mass-based approach. In this method, the LCA environmental or energy burden upstream of the production process is allocated to each co-product based on its energy output share. Energy output is usually measured as heat content for materials and joules or kWh for energy products. LCAs of oil refineries and power plants almost always use this method since most of the products are intended as energy products. This method is difficult to justify if one or more of the co-products are not valued for their energy content which is common for biofuel LCAs because some of the co-products produced are usually not energy products.

2.4.3.3 Market value-based Allocation

In market value-based allocation approach, the upstream environmental or energy burden is allocated to the output products based on their share of revenue to the facility. This method avoids the problems of the two previous methods when there is a heterogeneous mix of co-products. Further, this method is useful when the LCA should attribute a greater share of the environmental effects to the primary product than the byproducts [Gopal and Kammen, 2009]. The primary product will most probably have the largest revenue share [Wang et al., 2010]. For example, the LCFS encourages the use of low-value feedstocks to produce biofuels and hence the use of the market value method to determine the LCA GHG emissions of a feedstock will help meet this objective [Gopal and Kammen, 2009]. This is one of the primary reasons that I use the market value-based allocation method in the ALCA of molasses ethanol that I describe in Chapter 3.

2.4.3.4 Process-purpose-based Allocation

When the use of equipment and resources at all stages of the lifecycle can clearly be partitioned for different products then the process-purpose based approach is best. This is akin to being able to separate all stages of the lifecycle into single product pathways which when possible usually means that each product is manufactured at separate facilities, eliminating the need for co-product allocation. In most biofuel cases, multiple products are produced from the same process in fixed proportions making it impossible to identify processes separately for each product. Hence, rarely do we get the opportunity to use the process-purpose-based allocation method.



Source: [Wang et al., 2010]

Figure 2.1: LCA GHG Emissions of Biofuels using various Co-product Treatment Methods. The figure shows LCA GHG emissions of various biofuels and how the results are affected by changing co-product allocation methods.

Co-product treatment in practice

The ISO attempted to set guidelines for co-product treatment [ISO, 2006b] in the hope that the methods would be standardized. Instead, the guidelines were simply not applicable to a variety of cases and the use of any of the co-product treatment methods could prove reasonable depending on the context [Wang et al., 2010, Edwards et al., 2007a]. With the disputes showing no signs of abating, some authors published studies that applied all the co-product treatment methods to the same product to show that the results did not vary significantly [Wang et al., 2010, Curran, 2007, Shapouri and Duffield, 2003]. However, these studies could not prove that the agreement between results using different co-product treatment methods were anything other than sheer coincidence. In fact, in many more cases, changing co-product treatment method can radically change the LCA result [Zamagni et al., 2008, Wang et al., 2004].

The co-product treatment disputes are no less heated in the case of biofuel LCAs and in some cases are more heated since LCAs are used to set biofuel policy and fuel producers stand to gain or lose a lot of money based on their LCA fuel rating. Figure 2.1, taken from Wang et al (2010) [Wang et al., 2010] shows the LCA GHG emissions of Corn Ethanol, Switchgrass Ethanol, Soy Biodiesel, and Soy Green Diesel using multiple co-product allocation methods for each. The figure shows that the relative LCA ranking of each product can change based on the co-product method chosen. Hence, the choice of co-product method has significant revenue implications for fuel producers.

2.4.4 Uncertainty in LCA

It should be clear from all the categories of LCA, the methods and issues discussed in this chapter that no LCA, Attributional or Consequential, can be performed with both precision and accuracy. Uncertainty, both parametric and epistemic, is inevitable in all LCA studies but few studies nor the ISO standards address uncertainty systematically [Plevin, 2010, ISO, 2006a]. One of the main reasons for this is the lack of methods to address uncertainty in LCA as well as the possibility that a time consuming uncertainty analysis may produce no new insights. Uncertainty analyses on LCAs are almost always extremely complex, time-consuming, data hungry and demanding of computing resources. Any LCA method requires large volumes of data where most parameters are uncertain so Monte Carlo simulations are the primary uncertainty analysis method for LCAs. When it comes to CLCAs, the uncertainty becomes substantially larger because these require a large socio-economic model in addition to the same level of data for ALCAs. Numerous researchers argue that uncertainty in LCA is intractable but the results are still insightful and useful [Melillo et al., 2009] while others argue that uncertainty is so large that point-estimate LCA results are meaningless [Plevin, 2010].

When an LCA is used in regulation of policies, I agree that an uncertainty analysis must be performed. In fact, developing a consistent framework to characterize uncertainty in LCAs is an urgent need where some excellent work has already been done [Plevin et al., 2010, Plevin, 2010] but more needs to be. However, methods to build CLCAs are still so underdeveloped that I believe that there is also substantial room to improve these and therefore better CLCA methods should be developed in parallel with better uncertainty quantification methods. In my dissertation I focus on the former.

2.4.5 Mixing ALCA and CLCA

There are several areas and issues in LCA where an ALCA approach is blended with a CLCA approach including in the ISO Standards [ISO, 2006b, ISO, 2006a]. Since these two categories ask orthogonally different questions right at the outset, blending of the two categories at any level is scientifically incoherent but is widely prevalent. This is perhaps a testament to the slow evolution of LCA from its original attributional roots toward being policy relevant. System expansion co-product crediting and the LCA GHG rating methodology used by the CA LCFS are both examples of blended ALCA and CLCA.

2.4.5.1 System Expansion

System expansion, which is also known as the *substitution* method as well as the *displacement* method, is a co-product treatment method that is applied in an ALCA. In fact, the ISO Standards recommend the use of the System Expansion method as the preferred co-product treatment approach in any LCA where a decision on co-product treatment has to be made [ISO, 2006b]. I use Figure 2.2 as a reference to show how system expansion is implemented in an ALCA.

1. Designate the product whose LCA is sought as the primary co-product which, in this case, is ethanol made from corn.
2. Assign 100% of the ALCA GHG emissions (assume that this is the environmental parameter being studied) calculated to ethanol.
3. Identify all secondary co-products, which in this case, is only Distillers' Grains and Solubles (DGS).
4. For the byproduct DGS, ask the question; What currently produced product will be replaced by the introduction of DGS into the world?¹² Here, this replaced product is Soy Meal.
5. Decide the ratio in which DGS replaces Soy Meal (assume that 1 kg of DGS replaces 1 kg of Soy Meal).
6. Calculate the GHG emissions avoided by the termination of production of 1 kg of Soy Meal.
7. Convert the GHG value calculated in step 6 to ethanol heating value equivalents and subtract this value from the original ALCA GHG emission of corn ethanol calculated in step 2 to obtain the ALCA GHG emissions of corn ethanol using system expansion co-product treatment.

The main scientific inconsistency in the system expansion method is that it sums one LCA impact derived using an ALCA method (i.e Corn ethanol) and a second LCA impact derived using a (poorly performed) CLCA method (i.e DGS). System expansion is promoted by numerous LCA practitioners as the preferred co-product treatment method in an ALCA without addressing this incoherence in the approach. In fact, I have seen instances where peer-reviewed publications conflate system expansion applied to an ALCA as equivalent to a complete CLCA [Thomassen et al., 2008] which is a sign of deep misunderstanding of these concepts at a systemic level. Finally, by assuming that DGS, will successfully replace a *single* marginal product, Soymeal, and that all the GHG emissions saved by the production of DGS will only occur in the Soymeal supply chain, system expansion is in fact a *very poor* application of CLCA. If it were somehow justifiable to use CLCA only for co-product treatment rather than for the entire problem (which it is not), the GHG consequences of DGS production should not be assumed to occur only from the supply chain of Soymeal. A properly performed CLCA will allow for the replacement of DGS in several markets, a possible increase in demand for cattle feed due to the lower price of DGS and, the possible reversion of cropland to forest due to the reduced production of soy. Hence the net GHG consequence of DGS introduction can, and most probably will, extend way beyond the Soymeal supply chain.

¹²This question is very similar in intent to the CLCA question where instead of simply assuming that one single marginal product will be replaced due to a decision to produce another product, the researcher is interested in the total global change in GHG emissions due to the introduction of the new product no matter how many different products are replaced and in consequential emissions that occur where no production occurs.

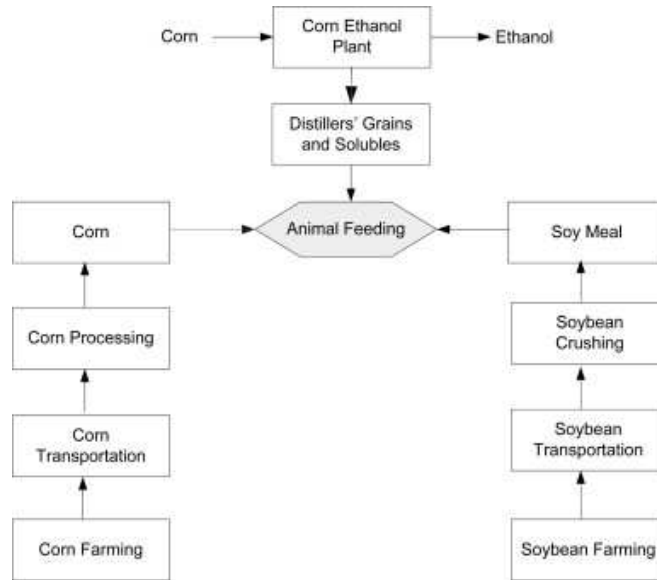


Figure 2.2: System Expansion Co-Product Treatment in a Corn Ethanol LCA. The figure shows how system expansion is applied to a corn ethanol ALCA. The method reasons that soymeal production and all its GHG emissions will be avoided if DDGS enters the market.

2.4.5.2 Indirect Land Use Change Emissions from Biofuels

Since the publication of Searchinger et al (2008) and Fargione et al (2008) [Searchinger et al., 2008, Fargione et al., 2008] and the coining of the term ILUC, there has been furious, heated debate on land use change and biofuels [Mascia et al., 2010]. The debate, however, has centered on *land use* alone without much understanding of the consequential LCA mode of thought that led to the recognition that land use change emissions could be causally assigned to the decision to produce crop-based biofuels. This has led to the generation of the following concepts that are simply false.

1. Land use change emissions are the only source of GHG emissions that can occur outside the biofuel supply chain when a biofuel policy is enacted.
2. It is scientifically sound to perform an ALCA to assign a carbon rating to a biofuel for use in a policy for all aspects except for land use change which is separately calculated using a CLCA approach. The LCA results obtained from these two methods can then be summed to obtain a total lifecycle rating for the fuel.

The above myths are so widely accepted that the first fuel policy that counts carbon, the CA LCFS, rates its fuels based on the sum of a Process ALCA for the supply chain and a CLCA for land use change emissions [CARB, 2009d]. Interestingly, the California Air Resources Board (CARB) has been assailed by critics on how poorly their land use change emissions calculations are performed but there has been very little criticism of the more fundamental error in the policy design; its incoherent mix of ALCA and CLCA. In subsequent policies, especially for the US

Renewable Fuel Standard 2 (RFS2), the LCA analysts substantially improved their approach and adopted more complete CLCAs to derive LCA ratings for fuels [USEPA, 2009].

In this dissertation I develop an analysis for molasses ethanol that can be directly used to rate the fuel in the CA LCFS. While I developed the model primarily for its immediate policy value, I also juxtapose it with the first fully consequential LCA of a byproduct-based biofuel to highlight the differences in methodology and intent between the two LCA categories.

2.5 Contributions to LCA in this Dissertation

Chains of causality are ignored in an ALCA. If the decision to manufacture a product results in a change in environmental impacts it will not be captured in an ALCA. In the dissertation I argue through a demonstration of an ALCA, a partial CLCA for land use change, and a full CLCA of the same product, that CLCA is the only LCA category that should be used in biofuel policy if the policymaker determines that an LCA based policy is the best approach to the problem¹³.

I built the ALCA model of any mix of cane juice and molasses ethanol described in Chapter 3 to add a lifecycle pathway for the product that would fit within the framework of the CA LCFS. After working with CARB for almost two years, this pathway is about to be ratified by them for use by molasses ethanol producers to sell fuel under the LCFS.

I estimate the consequential land use change emissions from molasses ethanol using Global Trade Analysis Project (GTAP), the CGE model used by CARB for the LCFS, to demonstrate the structural limitations of the CGE approach to CLCA when attempting to model byproduct-based biofuels thereby highlighting the absence of any methods to perform a CLCA of byproduct-based biofuels. In Chapter 5, I develop the first full CLCA of a byproduct-based biofuel, using a bottom-up PE model method that can be replicated in concept for other byproduct based biofuels. In Chapter 6, I present my perspective on whether LCA based biofuel policies should be employed at all and how to design them better if such a policy design makes sense.

¹³In a later chapter, I argue that LCA-based regulation should not be a first-choice option for fuel regulation

Chapter 3

Attributional Lifecycle Model of Sugarcane and Molasses Ethanol

3.1 Why we need an ALCA of Molasses Ethanol

The production of raw cane sugar from sugarcane juice results in the formation of molasses, a byproduct that contains minerals regarded as impurities in raw sugar [Hugot and Jenkins, 1986]. The sugar production process results in the loss of some high value disaccharides and monosaccharides from the final raw sugar product that end up in the molasses. The fermentable sugar content of molasses varies inversely with the efficiency of the sugar-making process. Molasses is a low-value product that is used as a cattle-feed supplement, as a feedstock for beverage alcohol, in specialized yeast propagation or as a flavoring agent in some foods [Troiani and Gopal, 2009b]. Although the sucrose in the molasses cannot be further upgraded to raw sugar, it can be converted to ethanol in a distillery. Hence, integrated sugarcane factories that have sugar manufacturing co-located with an ethanol distillery can use both molasses and fresh, mill-pressed cane juice as feedstocks for ethanol production. A significant number of sugarcane factories in Brazil and several hundreds of others around the world are of this type [Szwarc and Gopal, 2009]. Since molasses has a substantially lower opportunity cost than raw cane juice, ethanol manufactured from it needs a different attributional lifecycle assessment (ALCA) model than the one for sugarcane ethanol. The current GREET model for sugarcane ethanol does not include this pathway [Wang and Gopal, 2009, CARB, 2009a].

In this chapter, I build a model that uses GREET as the backbone to calculate attributional lifecycle greenhouse gas (GHG) emissions for integrated sugarcane factories that use any proportion of molasses and cane juice to make ethanol. I present the model results for a typical Indian sugarcane factory that is assumed to have full flexibility in using its cane for either ethanol or sugar production¹. I find that an Indian distillery that uses only molasses as a feedstock has farm-to-pump ALCA GHG emissions of just **22 gCO₂-eq/MJ**, making it one of the cleanest first generation biofuels in the Low Carbon Fuel Standard (LCFS). As I mentioned in earlier chapters, I built this model primarily for molasses ethanol to receive a lifecycle carbon content rating under the LCFS because almost 2 billion liters of molasses ethanol can feasibly be used to meet LCFS targets [Licht, 2006]. As I write this chapter, the California Air Resources Board (CARB) is about to approve this model (with some modifications) as the default molasses ethanol fuel rating method.

3.2 The Integrated Sugar and Ethanol Factory Process

Sugarcane factories can be broadly classified into three categories:

1. Factories that produce only raw table sugar (hereby referred to as raw sugar)
2. Factories that produce only ethanol
3. Integrated factories that produce both raw sugar and ethanol

¹Flex factories currently exist only in Brazil. Even they do not 100% flexibility but could vary the cane juice share for either process between 30 and 70% of the total juice

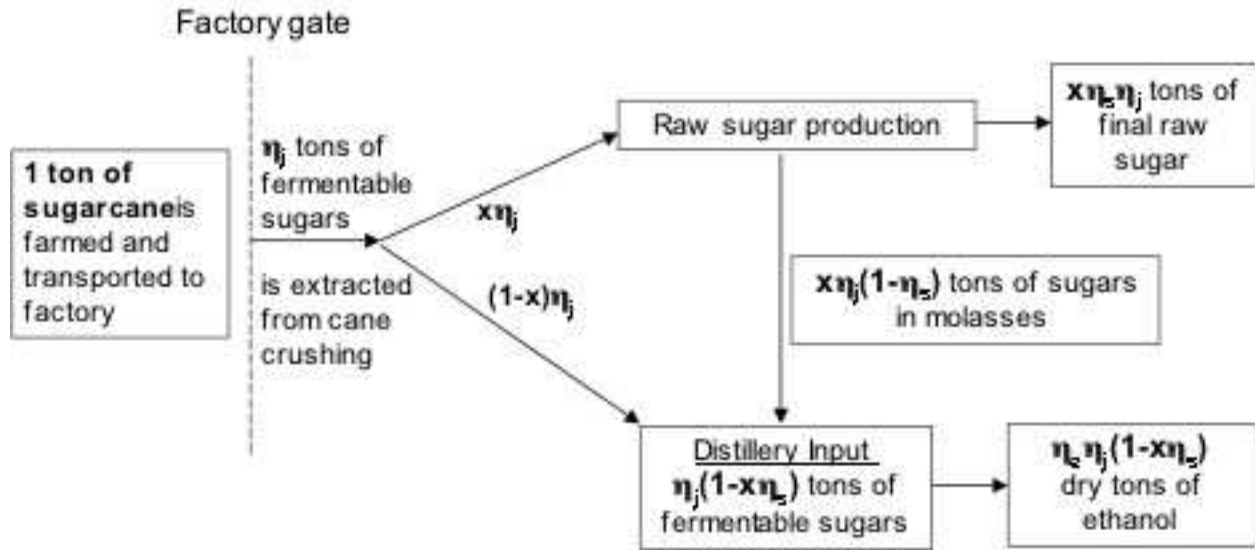


Figure 3.1: Mass and Process Flow of an Integrated, Fully Flexible Sugarcane Factory.

This figure is a process and mass flow diagram of an integrated sugar and ethanol factory that shows the quantities of intermediate and final products produced from the crushing of 1 wet ton of sugarcane.

Approximately 80% of the factories in Brazil belong to the third category [BNDES, 2008]. In other countries, large factories (crushing more than five hundred thousand tons of sugarcane each season), also overwhelmingly belong to the third category [Troiani and Gopal, 2008]. The use of both molasses and sugarcane juice to produce ethanol is only possible in factories belonging to the third category. Typically all three types of sugarcane factories meet their process energy demand by burning bagasse, the ligno-cellulosic fiber that is a byproduct of sugarcane crushing. Figure 3.1 is a process and mass flow diagram of an integrated sugar and ethanol factory that shows the quantities of intermediate and final products produced from the crushing of 1 wet ton of sugarcane.

In Figure 3.1:

x = fraction of cane juice sent to manufacture raw sugar

η_j = cane crushing yield (tons of fermentable sugars in cane juice / ton of sugarcane)

η_s = raw sugar manufacturing efficiency (tons of sucrose in final sugar / ton of sucrose entering sugar section)

η_e = ethanol distillery efficiency (dry tons of EtOH / ton of sucrose entering distillery)

In integrated factories, sugarcane is crushed at a mill that produces both sugarcane juice, which is rich in sucrose, and bagasse, which is used to meet the energy demand of the entire factory. Factories could then split the juice into two streams sending one part for raw sugar production and the other part to the ethanol distillery. Currently, most factories in India are sized to maximize sugar production, and are inflexible, so all the cane juice is first sent to sugar factory. It is likely though if sugarcane ethanol becomes more valuable in Indian markets that factories will be made flexible. Molasses, which is a byproduct of raw sugar production is then sent as additional

feedstock to the distillery. The yield of ethanol from fermentable sugars in molasses is almost identical to the yield from fermentable sugars in cane juice [Troiani and Gopal, 2009a].

3.3 ALCA Model of Ethanol from Fully Flexible Sugarcane Factories

GHG emissions upstream of the factory are already well described in GREET. The sugarcane factory process calculations, however assume that only cane juice is used as a feedstock. I use GREET to model the processes upstream of the sugarcane factory and then build my process ALCA model of the factory, ethanol transportation and distribution and final use. The factory model includes a key parameter x that is currently implicitly set to a value of 0 in GREET, which is the fraction of sugarcane juice by mass that is sent to manufacture raw sugar. All emissions associated with raw sugar manufacturing need to be allocated between raw sugar, the primary product, and molasses, the byproduct. I choose to make this co-product allocation based on the market value method. Since, as discussed in Chapter 2, co-product allocation is a hotly debated issue in ALCA, especially in the case of biofuels, I discuss the system expansion and market value methodologies in detail within the context of this paper and present my reasoning for the one I choose. Note that co-product allocation based on the energy content of sugar and molasses would lead to a solution identical to that of GREET's sugarcane ethanol model where cane juice and molasses are indistinguishable from an LCA standpoint.

3.3.1 Co-product Treatment by System Expansion

Recall from Chapter 2 that using system expansion to deal with co-products is an incoherent mix of ALCA and consequential lifecycle assessment (CLCA) methods. Those are sufficient grounds, in my opinion, to disqualify the use of system expansion in any ALCA. However, given that one of the goals of this model is to have it used in the LCFS, which along with the ISO Standards [ISO, 2006a, CARB, 2009d] prefers that researchers use the system expansion method where possible, I considered applying it here as a first choice but found that the market value approach is more appropriate here.

Molasses is used in several applications in addition to ethanol production and, in each case is easily substituted by a variety of other products. It is commonly used as a feed supplement for both feedlot and pasture cattle where it normally constitutes 4% of the feed mix [Fox et al., 2001] and is highly substitutable with products made from corn, wheat or barley [Surry and Moschini, 1984]. Further, it is difficult to store and transport and hence only about 15% of the molasses sold worldwide is traded internationally [Feed, 2002]. Molasses has three further uses where the total demand for it is insignificant when compared to the volume demanded by the cattle feed industry. It functions as a substrate in the propagation of yeast, as a flavoring or coloring agent in some food products, and a highly concentrated form of it called high-test molasses is sold for use in baking. Due to all these factors demand for molasses is

highly elastic. Perhaps more importantly, molasses serves as substitute for several products across several industries making it nearly impossible to isolate a single marginal product that it will substitute in the market.

Note that using system expansion for molasses is the reverse of the more typical application of the method for the DGS co-product from corn ethanol. In the latter case, an *output* of the process of interest (ethanol production) is the co-product (DGS) that replaces soymeal on the market. In the molasses case, the *input* to the process of interest is the co-product of another process (sugar production). Here, an application of system expansion would involve finding the marginal product that enters the market to replace molasses. This is such a rare occurrence in ALCA and, system expansion is so narrowly defined that such an application is not considered to be system expansion even though all the theoretical underpinnings are exactly identical. Hence, in a strict sense, system expansion is undefined for molasses ethanol.

3.3.2 Market Value-based Allocation

The strongest criticism of co-product allocation based on market value is that it does not represent environmental outcomes. While this criticism of the market value method holds true here, it is also true that for reasons described above, the system expansion method is both undefined and difficult to apply and will result in grossly inaccurate results in this case. Further, a major motivation for this model and the LCFS is to reward producers for the use of a waste or low-value biofuel feedstock. While not perfect, price is the most responsive and best available indicator of how much of a waste product molasses is. If there is a surge in demand for molasses by ethanol producers looking to take advantage of the better lifecycle rating, the price of molasses will rise relative to sugar to a point where it can no longer be considered a waste or low-value product. The system expansion method will be blind to such an effect but if the regulation is set based on the market value method, this relative price increase will reduce the lifecycle GHG advantage of molasses ethanol. In fact, if the relative price increase is large enough, we will reach a breakeven point where molasses and cane juice ethanol are indistinguishable from a lifecycle GHG perspective. This is shown in Figure 3.5. The potential for better policy design is also the primary reasoning of Nguyen and Gheewala (2008) [Nguyen and Gheewala, 2008] for adopting the market value allocation method for sugar and molasses.

3.3.3 Model Derivation

I estimate the lifecycle emissions of ethanol from any combination of molasses and cane juice using three steps. First I estimate total GHG emissions per ton of sugarcane input based on mass flow estimates as shown in Figure 3.1 followed by an aggregation of associated individual process emissions. Next I calculate the ethanol yield per ton of cane input, which then is used to estimate GHG emissions per MJ of ethanol produced. Finally, I add the emissions associated with the transportation and distribution, and the final use of ethanol. Equations 3.1, 3.2 and 3.3 represent each of the above steps.

The Total LCA GHG Emissions of the Ethanol produced prior to shipping from the distillery is given by Equation 3.1.

$$LCA_D = U(1-x) + x(U+S) \left[\frac{\{(1-\eta_s)/m_m\} P_m}{\{(1-\eta_s)/m_m\} P_m + (\eta_s/m_s) P_s} \right] + [(1-x\eta_s)(E \times LHV_{anhyd} \times \eta_e \eta_j)] \quad (3.1)$$

where

LHV_{anhyd} = Lower Heating Value of Anhydrous Ethanol

U = All GHG emissions upstream of factory calculated by GREET

S = Raw Sugar Production Emissions

E = Ethanol Production Emissions

P_s = 18-month moving average price of raw sugar on the market

m_s = Mass fraction of sucrose in final sugar product

P_m = 18-month moving average price of standard molasses on the market

m_m = Mass fraction of fermentable sugars in standard molasses

GREET assumes a fixed ethanol yield of 24 gallons of hydrous ethanol per ton of cane which is reasonably accurate when cane juice is the only feedstock. However, when molasses is also used as a feedstock, the ethanol yield depends on the fraction of cane juice sent to raw sugar production as well as the process efficiencies of each production stage. The efficiency of the distillery in converting fermentable sugars to ethanol is effectively the same for molasses and cane juice. The lower concentration of fermentable sugars in molasses does not affect the performance of the distillery.

The distillery's ethanol yield in MJ of Anhydrous Ethanol per ton of cane processed is given by Equation 3.2.

$$EtOH_{yield} = LHV_{anhyd} \times \eta_e \eta_j [(1-x\eta_s)] \times \frac{10^6}{947.8} \quad (3.2)$$

To obtain the total farm-to-pump² lifecycle greenhouse gas emissions for ethanol from any combination of molasses and cane juice in GREET equivalent units of gCO₂-eq / MJ of anhydrous ethanol, I divide Equation 3.1 by equation 3.2 and add emissions due to transportation and distribution of the fuel. This calculation includes transportation of anhydrous, denatured ethanol by rail and truck within India and then by ocean tanker to California. Once in California, the ethanol is blended with gasoline and then transported and distributed by truck, which is also included in the term T in equation 3.3. The dehydration and denaturing are assumed to be done at the distillery in India.

$$LCA_T = \frac{Equation3.1}{Equation3.2} + T \quad (3.3)$$

where

T = GHG emissions due to transportation and distribution of Ethanol

²The pump here is a gasoline station in California

Table 3.1: ALCA Molasses Model Parameter Values

| Parameter | Unit | Value |
|-----------|--|-------------|
| η_s | tons of sucrose in final sugar / ton of sucrose entering sugar section | 0.86 |
| η_e | dry tons of EtOH / ton of sucrose entering distillery | 0.48 |
| η_j | tons of fermentable sugars in cane juice / ton of sugarcane | 0.13 |
| U | gCO ₂ -eq / ton of cane | 88630 |
| E | gCO ₂ -eq / mmBtu of anhydrous ethanol | 2430 |
| S | gCO ₂ -eq / ton of cane | 3700 |
| T | gCO ₂ -eq / MJ of anhydrous ethanol | 3.1 |
| P_s | Indian Rupees (INR) / ton of raw sugar | Rs. 17, 865 |
| P_m | INR / ton of standard molasses | Rs. 2, 478 |

3.4 Results

Based on my field research and published data from sugarcane factories in India, I determined average values for each of the efficiency parameters in the equations above. These are shown in Table 3.1. GREET ignores raw sugar production and hence does not report raw sugar process emissions. I estimate raw sugar process emissions by assuming that all of it is due to the non-CO₂ emissions from bagasse combustion, which, in reality, does make up the majority of sugar production emissions. Additives like lime and flocculant that are consumed in the sugar production process make up the rest of the emissions, which is a very small part of the total emissions for sugar production.

The farm-to-pump ALCA GHG emissions of Indian molasses ethanol delivered to California are **22 gCO₂-eq/MJ**. Table 3.2 shows that the LCA GHG emissions value will increase non-linearly if the Indian factory could increase the share of cane juice relative to molasses as the ethanol feedstock. When $x = 0$, we get the GREET calculated ALCA GHG emissions for Indian sugarcane juice ethanol. Such a result is applicable if the Indian factory operated in a Brazilian configuration where only cane juice is used to make ethanol. You can also see from Table 3.2 that only emissions upstream of the distillery vary based on the relative mix of cane juice and molasses. The ethanol processing, transportation and distribution emissions are unchanged. Figure 3.2 shows the non-linear relationship between x and the ALCA GHG Emissions as is evident from Equation 3.3 where x features both in the numerator and denominator.

Figure 3.3 shows that the yield of ethanol and sugar are linearly variant with respect to x . However, you can also see from Figure 3.3 that there is always feedstock available to produce ethanol even if you choose to maximize sugar production.

Figure 3.4 compares the 100% molasses and 100% cane juice ethanol ALCA emissions for Brazil and India. Indian cane juice ethanol has a substantially higher carbon footprint compared to Brazilian cane juice ethanol. However, Indian molasses ethanol has lower lifecycle GHG emissions than Brazilian sugarcane ethanol and since India only produces molasses ethanol, this is the key comparison from the perspective of the LCFS. Brazil has very little molasses feedstock but even if some Brazilian producers switched to 100% molasses, their ALCA GHG rating only

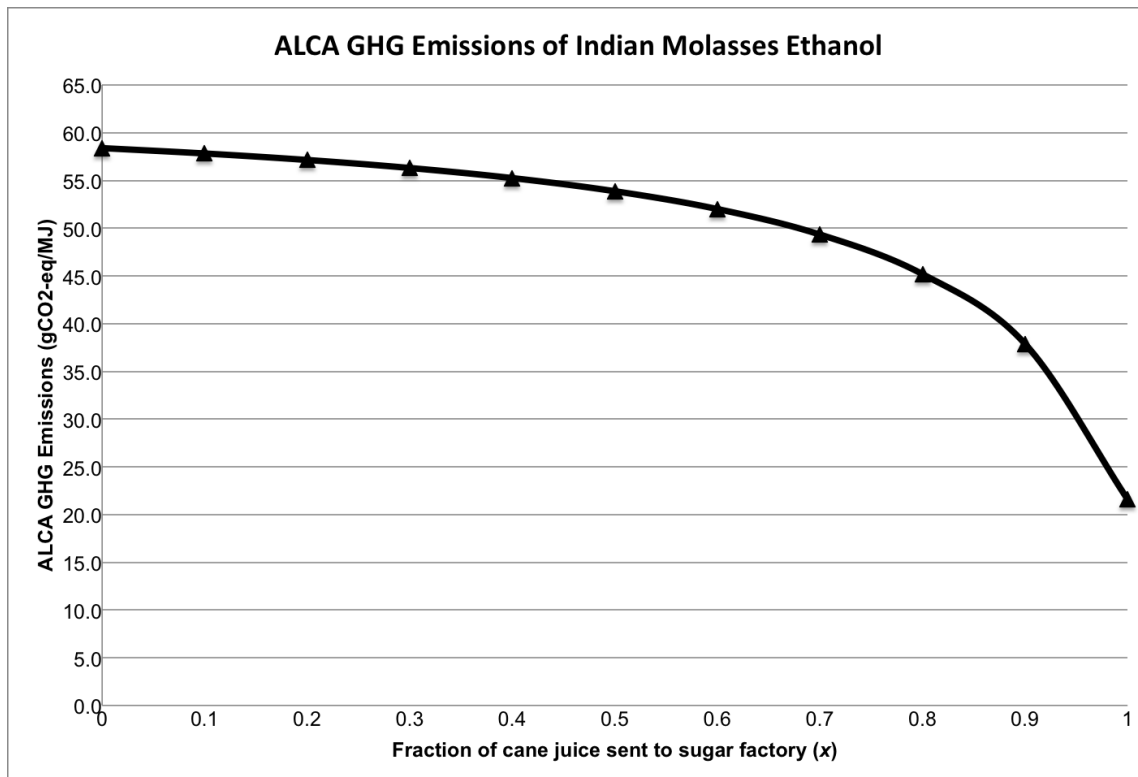


Figure 3.2: ALCA GHG Emissions of Indian Ethanol based on feedstock mix. The figure shows the relationship between the fraction of cane juice used for sugar in a factory and the ALCA GHG emissions of the ethanol produced. Unless the factory primarily exists to make sugar, with a little bit of ethanol on the side, it has little to gain on a lifecycle carbon rating basis when compared to an ethanol-only sugarcane factory.

Table 3.2: Farm-to-Pump ALCA GHG Emissions of Indian Ethanol Produced from a Mix of Cane juice and Molasses

| Fraction of cane juice sent to Sugar Factory (For India = 1) | ALCA GHG Emissions upstream of distillery (gCO ₂ -eq/MJ) | Ethanol Processing Emissions (gCO ₂ -eq/MJ) | Transportation and Distribution Emissions (gCO ₂ -eq/MJ) | Total ALCA GHG Emissions (gCO ₂ -eq/MJ) |
|--|---|--|---|--|
| 1.0 | 16.2 | 2.3 | 3.1 | 21.6 |
| 0.9 | 32.5 | 2.3 | 3.1 | 37.9 |
| 0.8 | 39.8 | 2.3 | 3.1 | 45.2 |
| 0.7 | 43.9 | 2.3 | 3.1 | 49.3 |
| 0.6 | 46.6 | 2.3 | 3.1 | 52.0 |
| 0.5 | 48.5 | 2.3 | 3.1 | 53.9 |
| 0.4 | 49.9 | 2.3 | 3.1 | 55.2 |
| 0.3 | 50.9 | 2.3 | 3.1 | 56.3 |
| 0.2 | 51.8 | 2.3 | 3.1 | 57.1 |
| 0.1 | 52.4 | 2.3 | 3.1 | 57.8 |
| 0.0 | 53.0 | 2.3 | 3.1 | 58.4 |

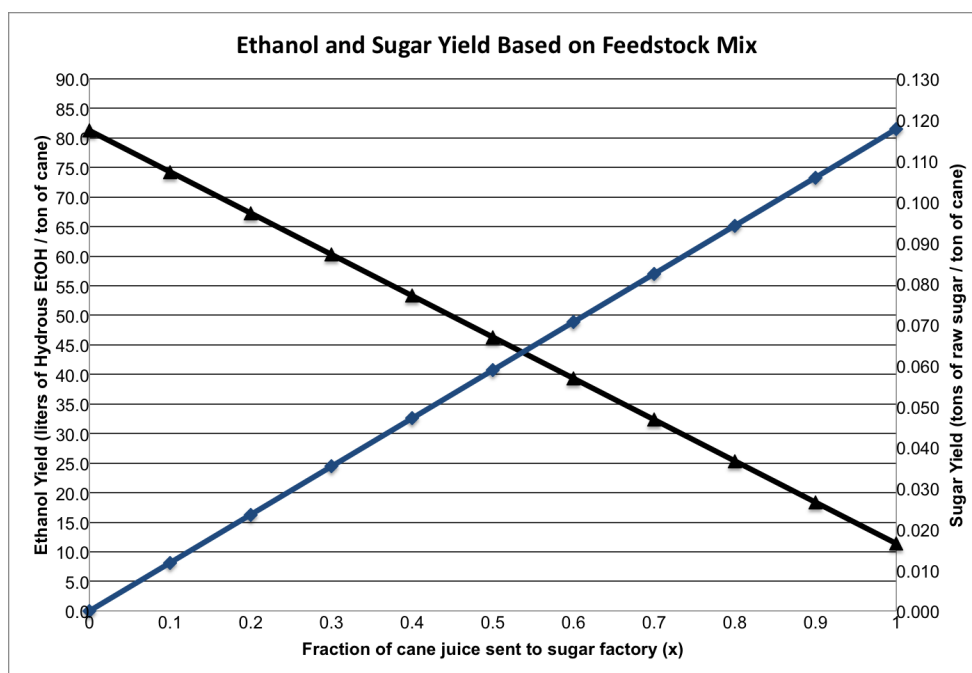


Figure 3.3: Ethanol and Sugar Yield Based on Feedstock Mix.

The figure shows the linear relationship between ethanol and sugar yield and the fraction of cane juice sent to make sugar. Even if 100% of the cane juice was sent to make sugar, molasses is still produced which can be used to make ethanol.

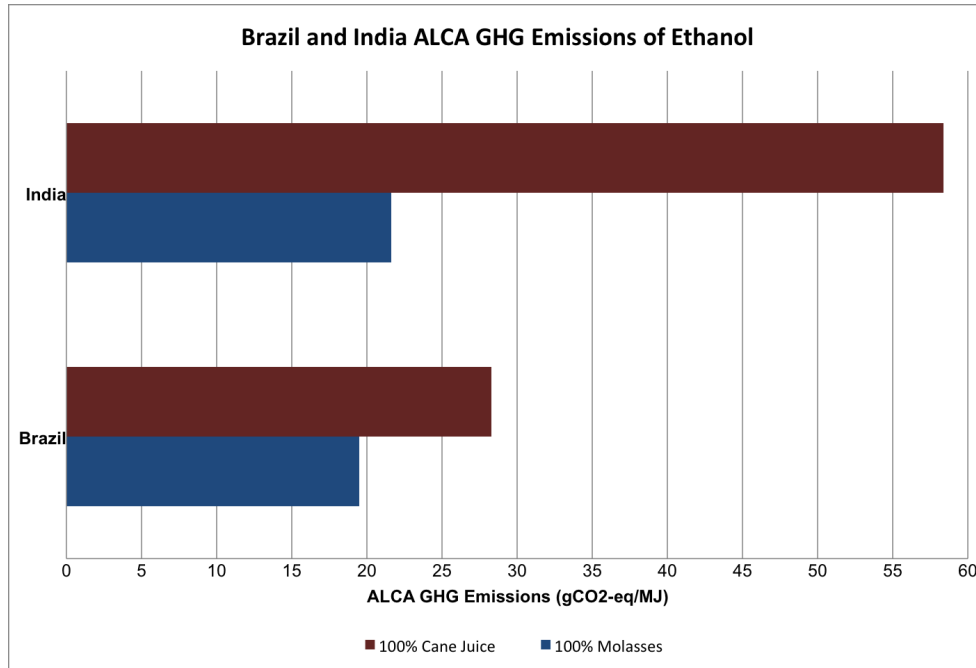


Figure 3.4: Comparison of Indian and Brazilian Ethanol.

The figure shows the ALCA GHG emissions of sugarcane and molasses ethanol for Brazilian and Indian cases. Brazilian sugarcane ethanol has a higher ALCA carbon rating than Indian molasses ethanol.

drops from 28 gCO₂-eq/MJ to 20 gCO₂-eq/MJ. This is because, unlike India which has a protected sugar market, Brazil has an open sugar market that results in a lower sugar to molasses price spread. From an LCFS point of view, a molasses rating provides little marginal benefit to a Brazilian producer when compared to an Indian producer.

The key parameter of interest in this model is the ratio of sugar price to ethanol price (P_s/P_m). In Figure 3.5, I show the sensitivity of the results to this parameter for a factory that uses only molasses as feedstock. Based on the average sugar and molasses prices in the Indian market over the last 18 months, the LCA GHG emissions of 100% Indian molasses ethanol is 22 gCO₂-eq/MJ. The red dashed line in Figure 3.5 represents the farm-to-pump GHG emissions for 100% Indian cane juice ethanol. Note that once the sugar to molasses price ratio drops below the point where the red and black lines intersect, it is worse, from a lifecycle GHG standpoint, to produce molasses ethanol than cane juice ethanol.

3.5 Issues in Applying the Model to the LCFS

This model works with GREET's current outputs and hence can initially be applied on the same scale, using a single value for many producers over a region. If used in this manner, all the parameters and inputs to my model and in GREET would just be an aggregate central tendency measure for all the factories in the area of regulation. Without any modification of the model, it

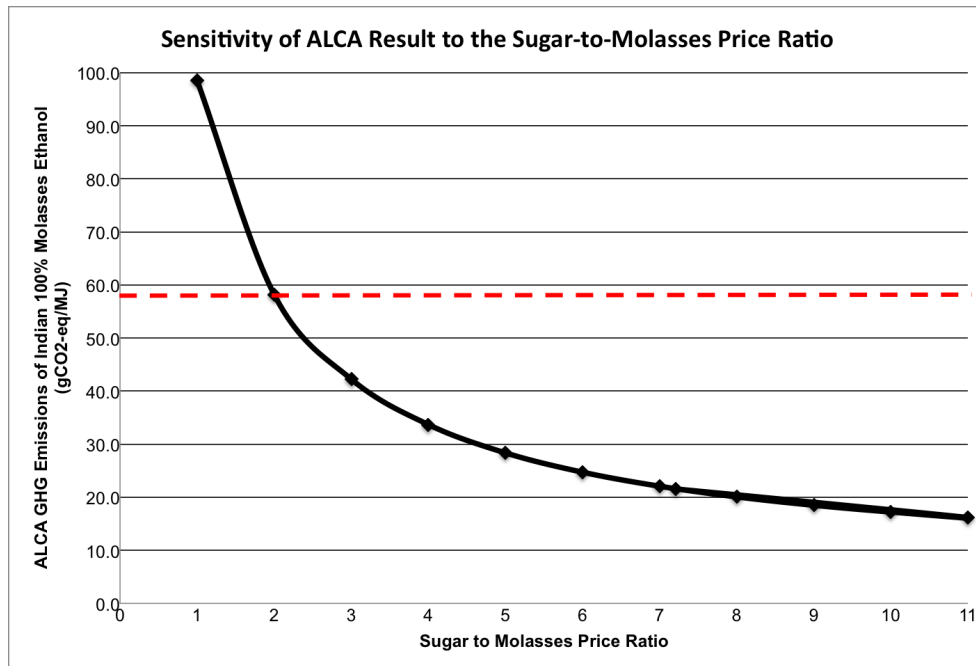


Figure 3.5: Sensitivity of ALCA Result to changes in the Sugar-to-Molasses Price Ratio. The figure shows the sensitivity of the results to the sugar-molasses price ratio. When the ratio drops below 2, molasses ethanol becomes 'dirtier' than sugarcane ethanol.

can also be applied at the factory level to determine an individual ALCA. This is the first, complete farm-to-pump ALCA of sugarcane ethanol when molasses is used as any fraction of the feedstock. It was built to be used in a plug and play manner to derive an LCFS rating. In the case of Brazil, most integrated factories tend to favor ethanol production over raw sugar and hence are likely to see very little improvement in their rating over the current value. However, for producers in India, Indonesia, Thailand, Guatemala and several other countries, molasses is the majority feedstock for ethanol production. Many producers in these regions have both the interest and the capacity to export their ethanol to California and this model will more accurately describe their fuel. In fact, after I developed this model, the Sugar Group Companies, with whom I worked during the development phase, has applied to CARB for a carbon rating for their molasses ethanol.

A number of concerns exist if firms are given credit for the use of molasses. First, firms may begin using more and more molasses to make ethanol, diminishing its status as a low-value product. This is the strongest argument for doing the co-product allocation based on revenue ratio as I have, since higher molasses demand will simply raise its price relative to sugar, which will result in increased fuel lifecycle GHG emissions.

Second, firms may re-engineer their process as to direct more cane juice to the raw sugar factory but deliberately produce raw sugar less efficiently leaving more fermentable sugars in the molasses (also known as intermediate molasses) which they will then use to make ethanol. Such re-engineering will need substantial capital investment in factories that are operating at full capacity to allow the sugar factory to handle a greater throughput of cane juice than its original

design capacity. A vast majority of sugarcane factories worldwide operate at full capacity since their sugar and ethanol markets are predictable and, they do not want to under-utilize capital. The additional revenue gained from their improved GHG rating is unlikely to justify such investment. So, even a sporadic audit of molasses ethanol firms should be sufficient to prevent any fraud. Several Brazilian factories do have additional sugar and ethanol capacity but production of intermediate molasses is still non-trivial due to the machinery used in sugar production and can only be done on the time-scale of several months. Brazilian factories, however, have little to gain from using molasses so such actions on their part are unlikely.

If this model is to be used in regulation, it will be important to examine the volatility of sugar and molasses prices in order to determine how often the fuel lifecycle rating should be adjusted. If the prices are too volatile relative to each other, the prices may have to be averaged over longer time scales in order to make the regulation feasible in practice. While it is impossible to predict future trends in molasses and raw sugar prices, I analyzed the price trends of the two commodities over the entire 2006-07 harvest season on the Indian market. Figure 3.6 shows Indian prices for standard molasses and raw sugar from Oct 2006 to Sep 2007. From the figure we can see that there is enough relative volatility in the spot price that it will be better to employ moving averages for regulation, but not so much volatility to make it infeasible to use this model in regulation. I concede that past trends are no indication of the future and the criticism that the market value method could result in volatile ALCA calculations is not refuted in this case.

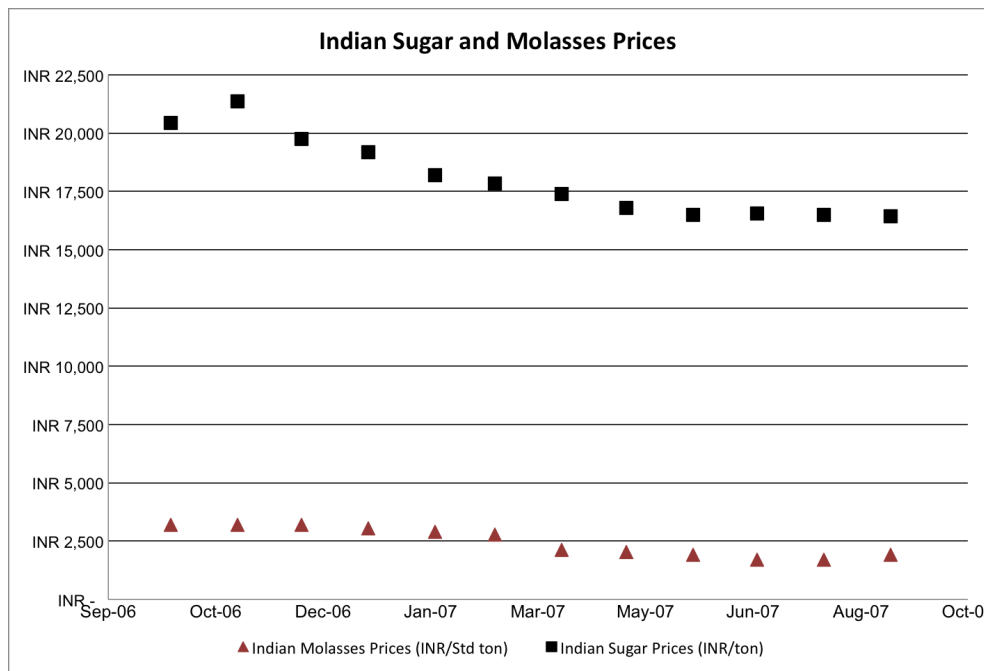


Figure 3.6: Sugar and Molasses Prices in India for 2006-07 harvest season. The figure shows molasses and sugar prices in the Indian market. The trends are reasonably correlated keeping the market-value allocation stable.

3.6 Conclusion

From my perspective, this ALCA model of molasses ethanol serves two major objectives:

1. Molasses ethanol is inexpensive and abundant, with 8 billion liters of it being produced annually in 2010 [Licht, 2011]. It is a much superior bridge to second-generation biofuels than corn ethanol in terms of costs as well as GHG emissions. The LCFS and the RFS2 can now use my model to rate molasses ethanol for use in their respective programs.
2. This ALCA model of a byproduct-based biofuel allows me to highlight the differences in methodology and approach with the CLCA models I develop for subsequent chapters.

I have been working with CARB for the last year to ratify this model as the molasses ethanol pathway for the LCFS and they are about to do so. The immediate, practical relevance of the molasses ALCA model does not mean that this is the right model or method for the use of molasses in a fuel carbon policy. In fact, I argue in subsequent chapters that it is not. However, the entire regulatory methodology of the LCFS needs to be revamped before better methods of rating molasses ethanol can be used under that program.

Chapter 4

Consequential LCA of Indian Molasses Ethanol using General Equilibrium Analysis

4.1 Chapter Summary

I find that the consequential land use change emissions of Indian molasses ethanol used for the Low Carbon Fuel Standard (LCFS) is just **1.2 gCO₂-eq/MJ** using the computable general equilibrium (CGE) model, GTAP-BIO. I use this method, which is the only one ratified to calculate indirect land use change (ILUC) emissions in the LCFS, to highlight the numerous shortcomings of the GTAP-BIO model¹ in estimating the ILUC of molasses ethanol. I conclude by highlighting that even though CARB would use this exact method to assess ILUC for molasses ethanol, the use of CGE models to perform CLCAs of biofuels manufactured from byproducts is inappropriate without substantial improvements in these models.

4.2 Computable General Equilibrium Models and CLCAs

4.2.1 General Equilibrium Basics

A market for a single homogeneous good is said to be in equilibrium when its price is at a point where neither producers nor consumers have any incentive to alter their decisions. This equilibrium price is also the price at which the supply and demand curves for that one good intersect. An economy is said to be in general equilibrium (GE) when all markets operate at their equilibrium price simultaneously. Since demand for any good is dependent on the demand for every other good, with the same being true for supply, a change in the equilibrium price in one market will typically result in changes in the equilibrium prices in all other markets with some markets more affected than others. Eventually, the economy will resettle at a new equilibrium point.

This expectation of general equilibrium is governed by Walras' Law which states that in an economy of 'n' markets, if 'n-1' are in equilibrium then the last market also has to be in equilibrium. In mathematical terms, Walras' Law hinges on the fact that the sum of excess market demands and the sum of excess market supplies both equal zero. Hence, GE is a fundamental part of microeconomic theory and is a state that can describe an entire economy at any given moment. One of the main applications of the GE concept is to assess welfare on an economy-wide basis and changes to welfare from policy decisions and other structural alterations of the economy.

4.2.2 Purpose and Scope of CGE Models

CGE Models are constructed primarily to assess the welfare effects of policies and other changes in the economy (such as innovation, anti-competitive behavior, etc). Therefore, at a minimum they model the economic behavior of consumers, producers and the government. By definition, CGE models have to cover and model all financial flows in the global economy. Many models, however, achieve this wide coverage by sacrificing detail. Most CGE models, including the one I

¹Many other CGE models share the same shortcomings as GTAP

use in this analysis, primarily aim to describe the effects of trade policy and so are strong in characterizing the costs of trading. CGE models are usually static and are benchmarked to the specific year from which all the financial or physical flows are obtained from. In addition to a financial or physical flow database, CGE models characterize the behavior of actors in the economy by using parameters derived from econometric studies and government databases.

In summary, CGE models are very data intensive and require substantial computing power. Their primary purpose is to describe the economic implications of a decision regarding the economy. However, CGE models by themselves do not contain much environmental information aside from quantities of natural resources used for production.

4.2.3 CGE Models for CLCAs

CGE models help us understand the consequences of a decision taken within the economic system. Since the environmental consequences of a decision usually get filtered through markets and the economic system, CGE models are a promising starting tool to perform consequential lifecycle assessments (CLCAs) [Weidema and Ekvall, 2009]. As I discussed in Chapter 2, they eliminate the system boundary truncation problem by covering the entire global economy but do so by having less detail at the microeconomic level. This and other reasons in favor of CGEs led to the adoption of a CGE framework by CARB to assess ILUC for biofuels in the LCFS. Such a ratification of CGE models for the land use aspect of CLCAs by a high-profile policymaking body has led to an explosion in the use of CGE models to perform CLCAs [CARB, 2009d, Al-Riffai et al., 2010].

A frequent hurdle in the use of CGE models for CLCAs occurs at the second stage; finding an environmental database or model that can use the outputs of the CGE model to calculate an environmental impact. Environmental databases usually do not map onto the sectors and regions of a CGE very well thereby rendering large parts of a CGE result unusable for a CLCA. The GTAP-BIO model which I use in this chapter, was built to estimate the only the land use related environmental consequences of biofuel policies [Birur et al., 2008a]. There is no feasible way, short of compiling an LCI for each sector in each region of a CGE model, to estimate other environmental consequences of biofuel policies like increased fertilizer demand² or rebounded gasoline demand³, using CGE models. An even more frequent issue, which occurs in my analysis, is when the particular decision of interest simply cannot be simulated satisfactorily by a CGE model. This can occur because products, regions and sectors are too aggregated or because the magnitude of the decision is too small for the model to pick up. As discussed in Chapter 2, the choice of CLCA methodology is very context dependent and the CGE approach is the best in some circumstances but not in all.

²Fertilizer demand increase because farmers strive to get higher yields because crop prices have risen.

³Increased use of biofuels in the US because of the RFS2, reduces US gasoline demand, which, drops oil price, which, results in higher gasoline demand in the rest of the world. This is known as the rebound effect in economics.

4.3 The GTAP Model

The Global Trade Analysis Project (GTAP) model is widely regarded as one of the best CGE models of the global economy. The model is a collaborative initiative of Purdue University's Agricultural Economics Department and Monash University. Dr. Tom Hertel, Professor of Economics at Purdue, created GTAP to have an open-source model and database to improve transparency and verifiability in the CGE modeling community [Abo,]. This was an essential step in improving the credibility of CGE models because their immense data needs and complexity frequently result in counter-intuitive results that skeptical audiences found difficult to digest without detailed explanations. This open-source design of GTAP is, in my opinion, the biggest reason for GTAP's popularity relative to other CGE models.

The backbone of the GTAP model is the GTAP Data Base. The GTAP Data Base describes bilateral trade flows, production, consumption and intermediate use of commodities and services. The database is in the form of social accounting matrices (SAMs), which are denominated in US Dollar flows. A new version of the database is released approximately every 4 years and on each occasion, more regions and commodities are added. The latest release, GTAP Data Base 7, consists of SAMs for 113 regions and 57 commodities with a base year of 2004 [GTA,]. Note here that the development of the database is so cumbersome that the base year is usually 4 to 5 years earlier than the release year. If major structural changes occur in the global economy in the interim, the database is already out of date when released. This is a major drawback of comparative static CGE models like GTAP. They cannot be used to model new commodities, regions or technologies.

The GTAP database is linked to the GTAP model which describes the interactions between actors in the economy. Demand is modeled through a Regional Household which in turn consists of private consumption, government consumption and savings. Supply is modeled through a Producer who can use imports, domestic intermediates, imported intermediates and primary factors to produce goods. All the main flows captured in the model are shown in Figure 4.1.

Private Household demand is modeled assuming that preferences follow a constant-difference of elasticity (CDE) implicit expenditure function. Government consumption is modeled assuming a Cobb-Douglas Utility function. A third component of demand is savings which are all reinvested by an omniscient Global Bank. Production is modeled assuming constant returns to scale and each sector is restricted to producing one output⁴. The production structure consists of several sub-trees each of which has a constant elasticity of substitution (CES) functional form [Hertel, 1997]. GTAP assumes that technology is weakly separable from primary factors and that firms decide their mix of primary factors before deciding on intermediate inputs [Brockmeier, 2001, Hertel, 1997]. The most restrictive aspects of the production structure in GTAP, pertinent to my dissertation are the fact that sectors have production functions that have limited adaptability and are designed to produce only one product. GTAP experts have modified the model for co-products from biofuel sectors but this requires substantial modification of the model. Trade is a key component of GTAP but its detailed mechanics are beyond the scope of this chapter.

⁴Co-products cannot be included in GTAP without substantial reprogramming of the original model.

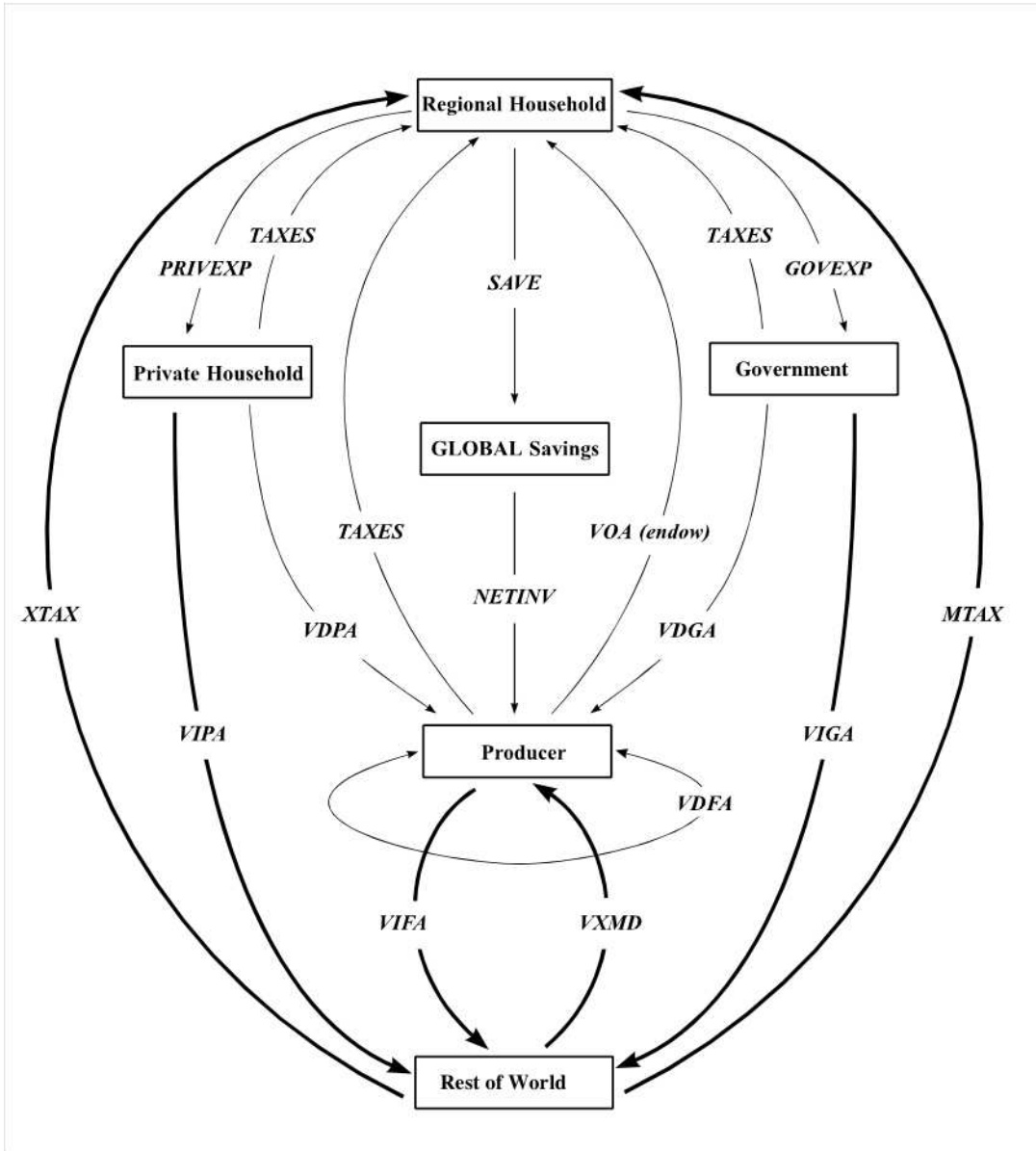


Figure 4.1: Flows and Actors in the GTAP Model (Source [Brockmeier, 2001]).
The figure shows the major financial flows in the GTAP model.

GTAP is a comparative static CGE model and hence the economy does not undergo structural change in the model and therefore there is no time component. All model results use the base year of the GTAP Data Base in the simulation as the starting point. Hence, researchers are constrained when explaining the meaning of a model result that implies changes occurring over time.

No biofuel commodities are in the original version of even the latest GTAP data base. Corn ethanol, sugarcane ethanol and soybean biodiesel were introduced into GTAP Data Base 6, forming the new GTAP-BIO Data Base, using a GTAP software utility called SplitCom. SplitCom creates a new commodity by scaling input-output tables of some other commodity already in the model that is surmised by the researcher to be most similar in structure to the new commodity. This means that none of the biofuel commodities are based on real data but are simply an adaptation of other sectors already in GTAP.

To further highlight the lack of detail in production, corn ethanol in GTAP can use any coarse grain as feedstock because corn does not exist as a separate commodity in GTAP. The corn ethanol sector itself is derived from the input-output database and production structure of the *food processing sector* [Taheripour et al., 2008], which was the chosen sector by GTAP experts as the input to SplitCom to create the corn ethanol sector. I will argue later that GTAP, in any of its current variations, is incapable of modeling biofuels from byproducts but note that even though non-byproduct feedstocks like corn could be modeled in GTAP, even their biofuel sectors are only built by expert judgement and not with real data.

Sugarcane and sugar are included as separate sectors in GTAP Data Base 6 but no sector existed for sugarcane ethanol. For GTAP-BIO, the sugarcane ethanol sector was also built using SplitCom in a procedure similar to corn ethanol. For sugarcane ethanol the IO data and production structure are derived from the *chemicals, rubber and plastics* sector [Taheripour et al., 2008]. Similarly, soybean biodiesel is derived from the *vegetables and oilseeds* sector. I do not highlight how these sectors were constructed to criticize GTAP-BIO, but simply to question its efficacy as a tool in performing CLCAs of biofuels.

Most importantly from the perspective of this dissertation, while coarse grains and sugarcane are commodities included in the original GTAP model even if their conversion to biofuel is not, molasses and any commodity that is a byproduct are completely excluded from the GTAP model and Data Base. In any CLCA, the model should include substitutes for the product under study since they are likely to be the marginal products that replace it. No substitute for molasses⁵ is in the GTAP Data Base.

4.4 CLCA of Indian Molasses Ethanol using GTAP-BIO

4.4.1 Origin and Purpose of the GTAP-BIO Model

In order to examine welfare questions surrounding climate policy, Burniaux and Truong (2002) [Burniaux and Truong, 2002] improved the representation of energy in the original GTAP

⁵Examples are sorghum in beverage alcohol production and citrus pulp as cattle feed supplement

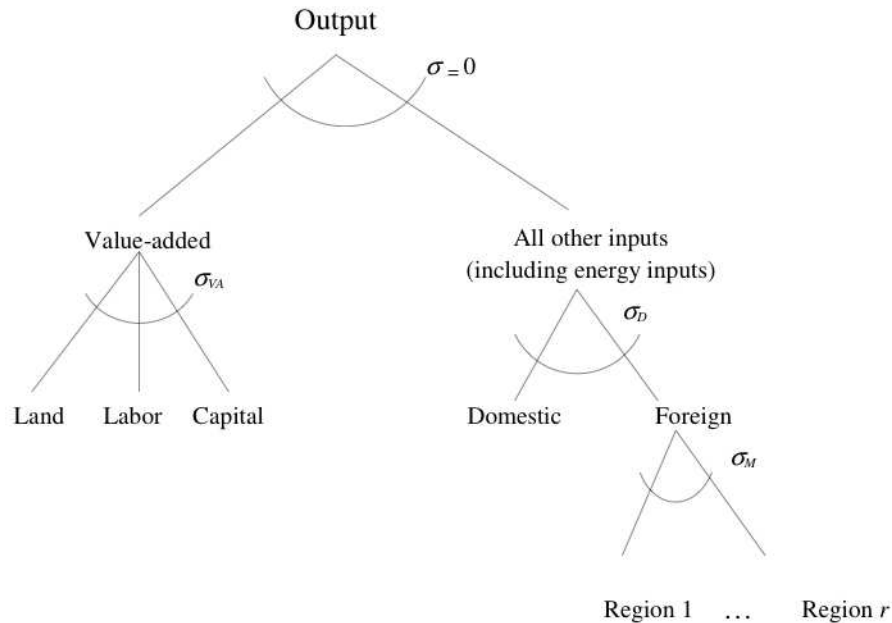


Figure 4.2: The Standard GTAP Production Structure (Source: [Brockmeier, 2001]). The figure shows the structure of the production tree for all sectors in the original GTAP model. Each sub-tree is a CES production function.

production structure and added GHG emissions to develop the GTAP-E model. The production tree for all industries in the standard GTAP model is shown in Figure 4.2. This production structure only allows for substitution among all intermediates and among primary factors with both these categories being weakly separated. In the GTAP-E model, a capital-energy composite is added to the primary factors tree and all non-energy intermediates remain in the intermediates tree as shown in Figure 4.3. This capital-energy composite itself has a sub-production tree that models the energy sector in some detail as shown in Figure 4.4.

Birur et al (2008) [Birur et al., 2008b] extended the GTAP-E production structure to include biofuels from corn, sugarcane and soy. They also modified demand to include these new commodities which they introduced into the GTAP Data Base 6 using SplitCom as described in Section 4.3. Further, Taheriour et al (2008) [Taheripour et al., 2008] introduced the co-products DDGS and soymeal to the corn ethanol and soybean biodiesel industries respectively. Finally, land supply was improved with separation of land into 18 Agro-ecological zones (AEZs) and also into forestry, pasture and cropland within each AEZ. This modified database and model, whose production structure is shown in figure 4.5, was christened the GTAP-BIO model and was built explicitly to model the consequential land use change caused by biofuel policies [Birur et al., 2008a].

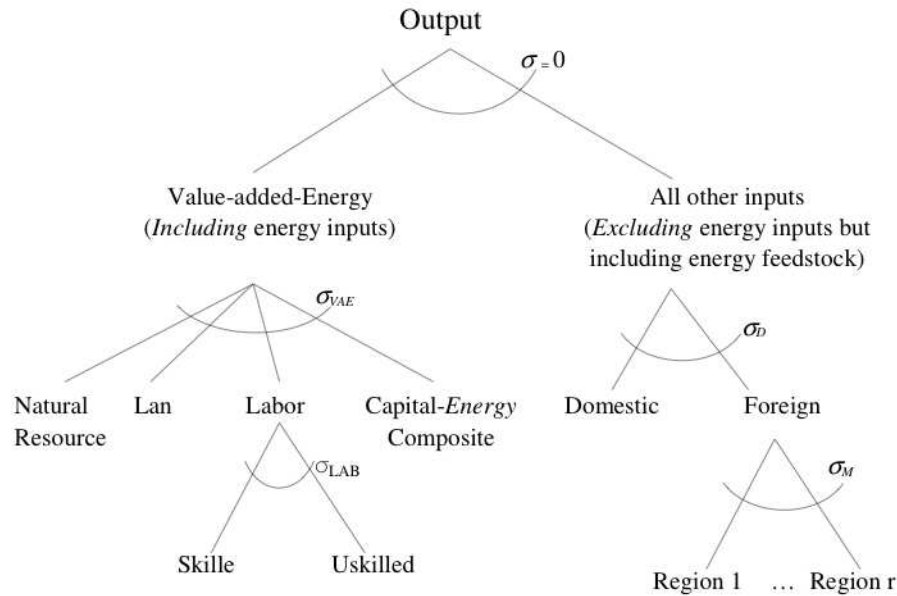


Figure 4.3: The GTAP-E Production Structure (Source: [Burniaux and Truong, 2002]). The figure shows the additional sub-trees added in GTAP-E. Energy gets moved to the value-added sub-tree.

4.4.2 Method, Inputs and Reasoning

4.4.2.1 Commodity Modeled and Shock Applied

A CGE simulation involves the application of a 'shock' once the database, model version, parameters and closure are defined. The 'shock' is the change in the economy whose economic effects the researcher is interested in modeling. More specifically, in GTAP, the modeler applies a shock to an exogenous variable that best describes the initial change caused by the policy or decision of interest. The effects of the shock are allowed to reverberate throughout the economy and the final results reflect the new equilibrium point of the economy and therefore the full economic consequences of the decision.

Usually, the main policy lever for biofuels is a quantity mandate or the policy is designed in a way that allows us to estimate the quantity of a particular type of biofuel that will be produced in a region to meet the policy requirements. If two different policies are expected to demand approximately the same biofuel volume, then the results of the simulation can be interpreted as the consequential effect of either policy by itself but not together. Here, the production of Indian molasses ethanol for either the Indian Ethanol Blending Program (EBP) or the LCFS is expected to be approximately **1.5 billion liters** higher than the actual production in my chosen base year of 2006-07 [Aradhey, 2010]. The reasons for the choice of the base year and the shock quantity are explained in the next Chapter.

As shown in Table 4.1, in GTAP-BIO, neither the right commodity nor the right shock could be modeled in this case. GTAP-BIO does not include molasses as a commodity and it cannot even be

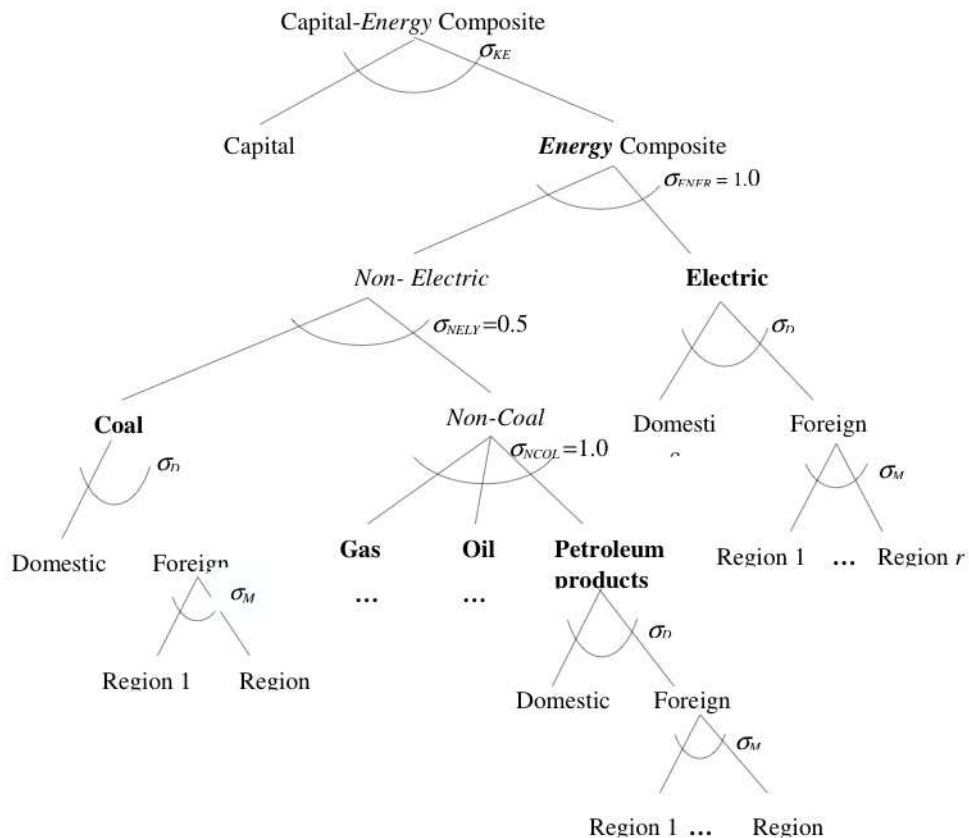


Figure 4.4: The Capital-Energy Composite Sub-Tree (Source: [McDougall and Golub, 2007]). The figure shows how detailed the capital-energy composite sub-tree is. This was done to permit GTAP-E to assess climate policy better.

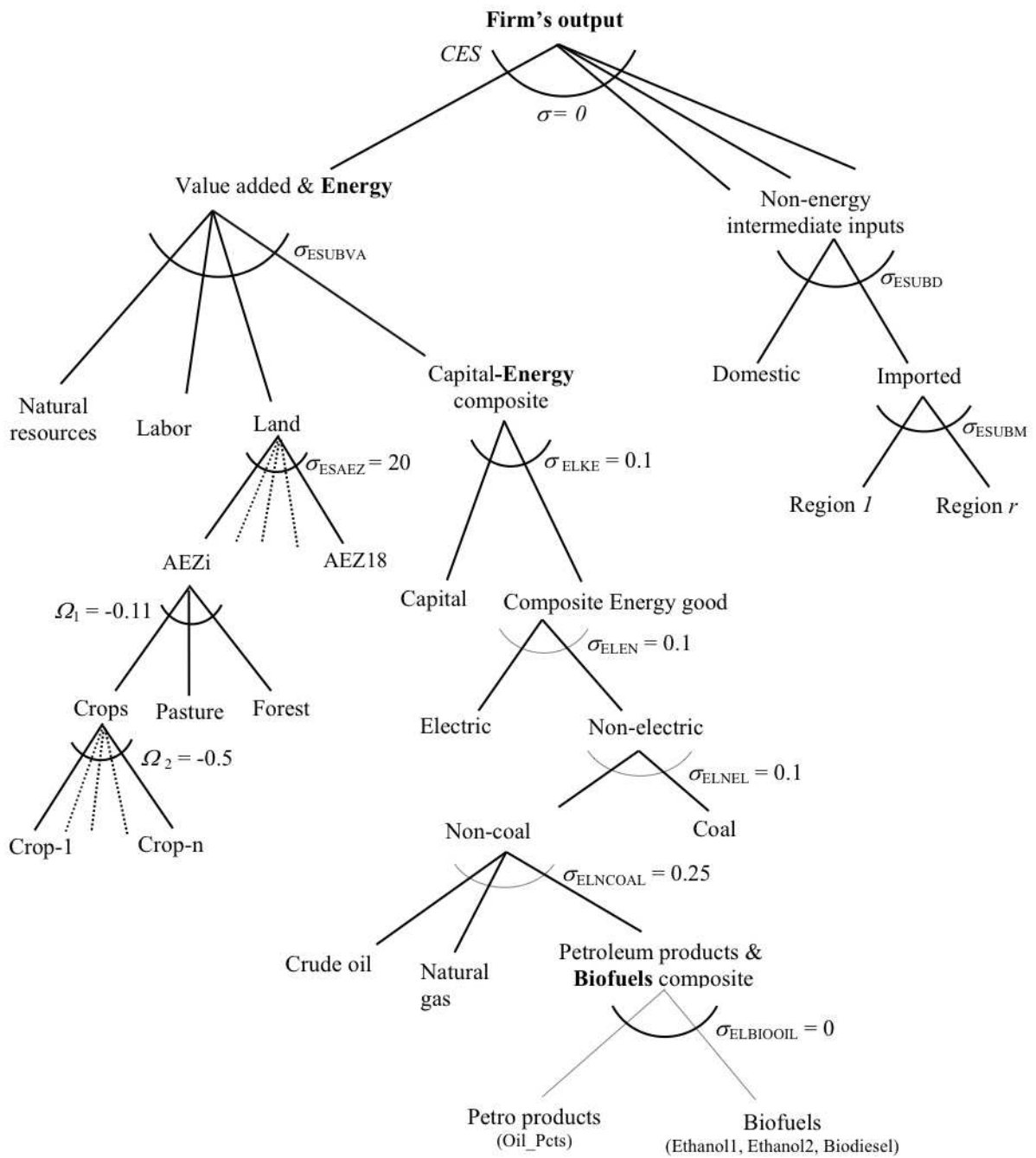


Figure 4.5: GTAP-BIO Production Structure (Source: [Birur et al., 2008b]).
 The figure shows how GTAP-BIO extends the GTAP-E production structure to include biofuels.

Table 4.1: Commodity and Shock Modeled in GTAP-BIO

| | What should have been modeled | What was modeled in GTAP-BIO |
|------------------------------|-------------------------------|------------------------------|
| Commodity | Molasses Ethanol | Sugarcane Ethanol |
| Production Quantity Increase | 1,500 million liters | 24 million liters |

added using the SplitCom tool because it is a byproduct of sugar production. Hence, I model sugarcane ethanol with GTAP-BIO and apply a post-processing correction for molasses. When SplitCom was used to construct the GTAP-BIO database for sugarcane ethanol, the primary goal was to scale the secondary data to ensure that Brazilian production in 2001 was correct since the estimation of ILUC for Brazilian ethanol was the immediate goal. As a result, actual sugarcane fuel ethanol production in every other region was not verified and the value in the database for Indian production is just 1.2 million liters, when the actual production was almost 50 million liters [Licht, 2006]. GTAP’s solver fails to converge when applying a shock of 1.5 billion additional liters to a base production of just 1.2 million liters. The maximum shock that I could feasibly apply was an increase of 24 million liters. Hence by reporting emission factor results, I am implicitly assuming that the CLCA GHG emissions scale linearly for Indian molasses ethanol from 24 million liters all the way to 1.5 billion liters. This is clearly unlikely to occur in reality which is another reason the GTAP approach is inappropriate for this particular problem.

4.4.2.2 Economic Parameters Modeled

The GTAP model contains a large number of economic parameters, mostly elasticities. Examples are elasticity of supply, elasticity of demand, elasticity of substitution in the production tree and thousands more. Many of these are econometrically estimated where possible but many more are simply best guesses since no studies estimate them. In any GTAP simulation, the result is more sensitive to some parameters than others depending on the context of the simulation. In a GTAP-BIO analysis of ILUC caused by biofuel policy, the result is most sensitive to parameters related to land supply, marginal land productivity and yield response to price [Berry, 2011]. Unfortunately, there are no conclusive econometric studies estimating these in each region. Therefore, I simulated five scenarios with each key parameter set to the same values chosen by the GTAP expert modeling team when performing the sugarcane ethanol analysis for the LCFS. The parameters and values are shown in Table 4.2.

4.4.2.3 Biofuel Production Time Horizon and Amortization of Emissions

As I discussed in Chapter 2, a key issue to be addressed in CLCAs is the question of how long the effects of a decision are expected to last. This problem arises in CLCAs because some environmental impacts are step functions. The clearest example of this is the immediate release of GHG emissions when forest is converted to cropland as a consequence of a biofuel policy. How this concentrated environmental impact is then incorporated into the CLCA is dependent on our

Table 4.2: Economic Parameters by Scenario

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|------------|------------|------------|------------|-----------------------|
| Productivity of Marginal Land over Average Land | 0.50 | 0.75 | 0.50 | 0.50 | India=0.8, Others=0.5 |
| Yield elasticity with respect to price | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Elasticity of transformation for land cover | 0.20 | 0.20 | 0.30 | 0.10 | 0.20 |
| Elasticity of transformation for crop areas | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |

expectation of how much of the new biofuel will be produced in total. The question facing the analyst is, if a particular environmental impact in the CLCA is not a function of the quantity of the product being produced, then how should it be attributed to the product? This is similar to a net-present value financial cash flow analysis where an up-front investment or loan needs to be amortized over the life of the project. The starting points of such a cash-flow analysis is to decide the lifetime of the project and the discount rate to apply. The equivalent starting points in the ILUC example are to decide how long the biofuel production will continue (and therefore how much biofuel will be produced in total) and how the environmental damage from the up-front emissions should be valued over time. There is significant controversy regarding both [MO'Hare et al., 2009].

The Searchinger et al (2008) [Searchinger et al., 2008] article, which was the first to estimate ILUC caused by biofuel policy, arbitrarily assumed that the new biofuel will continue to be produced for 30 years. Many have argued, on either side, that the authors offered no defense of this choice and that the assumed production period should either be longer or shorter depending on their point of view. Some have said that biofuels are not likely to survive without policy support, and so the production period should be no longer than the life of the policy that encourages biofuel production. Others with a pro-biofuels stance, like the Renewable Fuels Association (RFA), have said that once a biofuel plantation is established it will continue to produce for 100 years regardless of the policy environment. No consensus has been reached nor a convincing argument given yet for the right method to decide on the biofuel production time period. In the absence of such consensus, the early precedent of 30 years set by Searchinger et al (2008) [Searchinger et al., 2008], has been adopted by California policymakers for the LCFS. Since I want my analysis to be relevant to the LCFS and allow for easy comparison to other LCFS analyses, I also choose the same 30 year production period.

Searchinger et al (2008) [Searchinger et al., 2008] also set a precedent on amortizing emissions by assuming that any GHG emissions today cause the same climate damage as GHG emissions in the future. Unlike the production period issue, amortization has, in my opinion, been scientifically

improved from the original assumption. O'Hare et al (2009) [MO'Hare et al., 2009], convert GHG emissions over time to their climate forcing effect over time and find that early emissions cause substantially more climate damage than later emissions which implies that the up-front ILUC release needs to be assigned an interest rate over the production period. Once again, however, CARB has adopted the Searchinger precedent for the LCFS and so I also take a no-discounting approach for the up-front ILUC emissions in this analysis.

4.5 Results

The CLCA of Indian molasses ethanol for use in the LCFS using the CGE approach only yields *consequential land use change GHG emissions* for reasons already outlined in Section 4.2.3. As I described in Section 4.4.2.2, I ran 5 scenarios and averaged the result to estimate the ILUC GHG emissions of Indian sugarcane ethanol. I followed this with 2 post-processing steps to obtain the ILUC GHG emissions of Indian molasses ethanol.

4.5.1 Post-processing Adjustment for Indian Sugarcane Yield Changes from 2001 - 2007

The base year for the GTAP-BIO database is 2001 and hence the sugarcane yields correspond to that year. Short of updating the entire database to my base year of 2006-07, I adjust the results for any yield changes in sugarcane in a post-processing step. For Brazil, there has been substantial yield gains in the last decade and so the original GTAP-BIO result would have been reduced correspondingly. Figure 4.6 shows that Indian sugarcane on the other hand has had a rocky decade with no net yield improvement between 2001 and 2007 [FAO,]. Hence, I determined that there was no need to adjust the GTAP-BIO result for improved sugarcane yields.

4.5.2 Post-processing Adjustment from Sugarcane Ethanol to Molasses Ethanol

Since the simulation only estimates the ILUC GHG emissions of sugarcane ethanol, I also had to develop a post-processing adjustment to account for the feedstock change. Approximately 14% of the fermentable sugars in the sugarcane plant remain in the molasses to make ethanol so I attribute 14% of the ILUC GHG result of sugarcane to molasses. This post-processing adjustment is a very weak attempt to correct for the inability to model molasses as a commodity which is one of my main arguments against the use of GTAP here. So, I present the results both prior to and after the adjustment in Table 4.3.

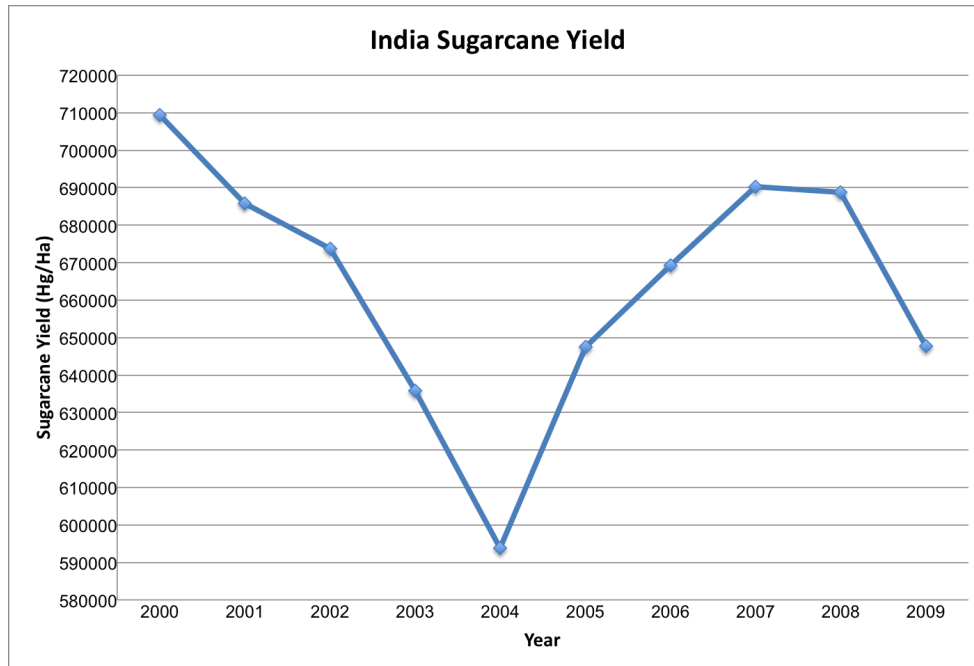


Figure 4.6: Indian Sugarcane Yield from 2001 to 2009 (Source: [FAO,]).

The figure shows the annual average sugarcane yield in India from 2001 to 2009. Unlike Brazil, there is no clear upward trend but a more cyclical trend.

4.5.3 Indian Molasses Ethanol CLCA GHG Emissions Factor

Prior to the feedstock post-processing adjustment, Table 4.3 shows that the average ILUC GHG emissions of the 5 scenarios is **8.5 gCO₂-eq/MJ** for Indian **sugarcane** ethanol when its production is caused by the LCFS. After the feedstock adjustment, the ILUC GHG emissions factor of Indian **molasses** ethanol is just **1.2 gCO₂-eq/MJ**. Indian sugarcane ethanol has a substantially lower ILUC GHG emissions factor than the mean GTAP-BIO simulation for Brazilian sugarcane ethanol, which was **46 gCO₂-eq/MJ** [CARB, 2009c].

4.5.4 Landcover Changes

The main factors driving the difference in the result between Indian and Brazilian sugarcane are sugar policy, the carbon content of forest in each country and the total forest area in each country. India has an extremely protective sugar market that effectively isolates Indian sugar price from the rest of the world, while Brazil has an open market that practically determines the world sugar price. So, farmers within India are the only ones who receive a strong price signal to plant more sugarcane as a result of which most of the land conversion to cropland occurs within India itself. Since both the total forest area and the carbon content of that forest cover are lower in India compared to Brazil, the carbon released from conversion to cropland in India is substantially lower. In fact, in all 5 scenarios, India is pretty much the only region where cropland grows at the

Table 4.3: ILUC GHG Emissions Factors for Indian Sugarcane and Molasses Ethanol

| | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 4 | Scen. 5 | Avg |
|--|---------|---------|---------|---------|---------|------------|
| CLCA GHG Emissions Factor for Indian sugarcane ethanol (gCO ₂ -eq/MJ) | 9.8 | 7.5 | 12.6 | 6.3 | 6.5 | 8.5 |
| CLCA GHG Emissions Factor for Indian molasses ethanol (gCO ₂ -eq/MJ) | 1.4 | 1.0 | 1.8 | 0.9 | 0.9 | 1.2 |

expense of forest and pasture. In the Brazilian analysis, on the other hand, forest and pasture are lost to cropland within Brazil and all over the world [CARB, 2009c].

4.6 Limitations of CGE Models for CLCAs of Byproduct-based Biofuels

CGE models initially appear to be the ideal tool to estimate consequential economic effects for CLCAs. On closer scrutiny, however, there are several situations in which they are the wrong tool to assist in a CLCA as I discuss throughout this Chapter. In summary, CGE models need substantial improvement before they can be used for CLCAs of byproduct-based biofuels:

1. CGE models need to model both the production and demand of *co-products* in all sectors, especially agricultural sectors.
2. CGE models need to have sufficient low-level detail to be able to meaningfully model the weak signals originating from byproduct markets.
3. CGE models need to map onto LCIs that can calculate the environmental impact of sectors other than land.

In the next chapter I develop a bottom-up partial equilibrium (PE) model to develop the CLCA of molasses ethanol from India that overcomes all of the shortcomings of CGE models listed here.

Chapter 5

Full Consequential LCA of Indian Molasses Ethanol

5.1 Chapter Summary

I perform the first full consequential LCA of the greenhouse gas (GHG) emissions of Indian molasses ethanol for use in the Low Carbon Fuel Standard (LCFS) and find that it is **5 gCO₂-eq/MJ**. I develop a bottom-up partial equilibrium (PE) model to do this analysis, an approach that I argue is substantially superior to the GTAP-based approach ratified by the California Air Resources Board (CARB). The results also confirm that molasses ethanol is one of the cleanest first-generation biofuels from a carbon perspective. This is entirely expected since the economic and environmental consequences of higher demand for a *low-value product* like molasses are not substantial. Finally, I find that using molasses ethanol domestically will do little to reduce India's foreign oil imports. A far more effective way of achieving the Ethanol Blending Program's goal of boosting domestic agriculture is to support the export of molasses ethanol to fuel markets that price carbon.

5.2 Motivation for Developing this CLCA Method

The CLCA method I develop in this chapter is the most significant contribution of this dissertation, although the attributional LCA (ALCA) of molasses ethanol developed in Chapter 3 has been adopted for the LCFS while this approach is unlikely to be adopted similarly. This is because CARB strictly restricts the LCA modeling methods permitted to rate fuels in the program. However, for both CLCA methodology improvement and better policy design, the modeling approach I develop here is a substantial leap from what has been done in this field previously. Here are my main motivations for developing this PE-based CLCA method for Indian molasses ethanol.

- In the last chapter I highlighted the various ways in which CGE models are ill-equipped to perform a CLCA of molasses ethanol. Here, I develop a PE-based approach that overcomes many of the main weaknesses of the CGE approach, and allows me to analyze important aspects of both the Indian Ethanol Blending Policy and the LCFS.
 - The PE model focuses closely on molasses and related markets to model their responses in great detail.
 - This model produces a *fully consequential* LCA unlike GTAP-BIO which only models consequential land use change.
 - There are no arbitrary restrictions on sectors producing co-products.
- As I have pointed out in this dissertation before, biofuels made from byproduct feedstocks like molasses ethanol and soybean biodiesel are abundant but are invisible to low carbon fuel programs because there is no methodology to determine a lifecycle carbon rating for them. The method I develop in this chapter, although specific to molasses ethanol, can be easily used as the theoretical basis to develop CLCA methods for any product manufactured from a byproduct.

- CLCA is a powerful concept that should be the default approach when LCAs need to be used in policies but so little effort has gone into developing CLCA methods. One of the reasons that ALCAs continue to be used in such applications where they are entirely inappropriate is due to the lack of established, reliable CLCA methods. While it is a far cry from being a perfect or even the best CLCA method, the model I develop here aims to inject some momentum into CLCA theory and method development and to spur other researchers to improve on it.
- India's Ethanol Blending Program (EBP) was enacted with no analysis of the policy and its implications. Both the results of the PE model by itself and the CLCA as a whole provide great insight into the effectiveness of the policy as it is and how it could be redesigned to better serve Indian agriculture and the Indian taxpayer.
- The molasses ethanol model I developed in Chapter 3, and now ratified by CARB, showed that the state's policymakers were ignoring a clean, commercially available biofuel that is produced in large enough volumes to help feasibly meet LCFS targets prior to the commercialization of second generation biofuels. In addition to simply easing the tight supply of low carbon fuels, molasses ethanol holds promise in being the biofuel with the lowest cost of carbon mitigated since it is produced from a byproduct. My PE model is the first to determine if this is indeed the case by calculating the marginal cost of Indian molasses ethanol to meet LCFS demand. This result only applies within the range of my analysis where molasses fuel ethanol production in India is increased by 1.5 billion liters. If the low carbon rating drives molasses ethanol production much higher than the 1.5 billion liter increase, then it may no longer be the biofuel with the lowest cost of carbon mitigated.

This chapter is organized as follows. I first derive the PE model which is the front-end of the CLCA and report the major assumptions implied in it. I then publish the emissions factors which are linked to the PE model results to obtain the full CLCA GHG emissions. Next, I walk through the steps involved in solving the model which includes a discussion on how I deal with land use change emissions. Next, I report the PE and CLCA results and discuss their implications for Indian biofuel policy.

5.3 Model Derivation

In a decision similar to the one an analyst has to make in a process ALCA, I first had to decide which markets to include in my PE model and where to draw the analysis boundary. The immediate effects of an increase in the production of molasses ethanol will be felt in the molasses market and the fuel market. However, the 1.5 billion liter increase in molasses ethanol that I model will have little impact on the fuel market but a substantial impact on the molasses market. This is because that volume of molasses ethanol is barely 4% of total gasoline demand in energy equivalent terms [India, 2010] but will need 88% of domestic molasses to produce. Hence, the

strongest consequences of a molasses ethanol mandate will occur in the molasses market and all the markets where molasses is currently demanded¹. The three main uses of molasses are:

1. Feedstock for fuel ethanol.
2. Feedstock for industrial and beverage alcohol which is also known as rectified spirits in India.
3. Cattle or poultry feed supplement, not as a source of calories but to make the feed more palatable, to keep dust down and to catalyze cellulosic digestion in ruminants.

In India, however, molasses is not used as a feed supplement and is mainly used for only the other two purposes. Hence, my PE model of the Indian molasses ethanol mandate models the following markets:

1. Fuel ethanol
2. Rectified Spirits
3. Molasses
4. Molasses substitute in Rectified Spirit Production, which as I determine in section 5.3.3 is grain sorghum.

The full model includes the cattle feed market and the market for citrus pulp, which is a substitute for molasses in cattle feed. In this chapter, however, I only derive the model relevant to Indian molasses ethanol.

5.3.1 Model of the Molasses Market

The molasses market is one of the trickiest to model primarily because it is a byproduct and because there is no end-use demand for it. I account for molasses demand by modeling its derived demand in other markets where it is an input to production.

The supply curve of molasses, shown in figure 5.1, is complex and consists of 3 separate sections. Before the total capacity of molasses production is reached, its supply curve is flat where price will equal the marginal cost of storage, transport and distribution of molasses, which is C_{MT} in figure 5.1. Q_{CAP} is determined by the total installed sugar production capacity in India. It is the amount of molasses that will be produced if all the sugar factories operated at capacity. If more than Q_{CAP} tons of molasses are demanded, the price will rise to keep demand constant since sugar factories will not respond by producing more molasses yet. For the purposes of this dissertation as well as any conceivable real-world scenario, these are the only two parts of the molasses

¹There is almost no private consumption of molasses. In all of its uses, molasses is an intermediate input in a production process.



Figure 5.1: Molasses Supply Curve in India.

The figure shows the supply curve of Indian molasses. Its odd shape reflects the fact that it is a byproduct subject to capacity constraints.

supply curve that are relevant. If, the molasses price reaches P_{SAM} , which is the price of sugar adjusted to molasses equivalent terms based on sucrose content, then molasses becomes a more valuable commodity than sugar. This is unlikely to ever happen but if it does, the third and final section of the molasses supply curve will be positively sloped and sugar factories owners will make supply decisions based on molasses price.

One important thing to keep in mind is that all the molasses manufactured in India is demanded by just two sectors, rectified spirits and fuel ethanol. Further, I assume that once a fuel ethanol mandate or policy is in place, all produced molasses will be used. So, the supply and demand of molasses is given by equation 5.1.

$$Q_{CAP} = Q_{MSFE} + Q_{MSBE} \quad (5.1)$$

The marginal cost, price and capacity of molasses in my simulation base year of 2006-07² are shown in Table 5.1.

5.3.2 Model of the Fuel Ethanol Market

For the purposes of this model, the fuel ethanol market does not need to be modeled in its entirety. I only need to model *molasses* fuel ethanol production and demand. Molasses fuel ethanol production is quite accurately described by a fixed proportions production function, which is the functional form I employ. The yield of anhydrous fuel ethanol per ton of molasses is 214 liters per

²2006-07 here corresponds to the sugarcane harvest season which starts in October and ends in June but some distilleries continue to process molasses until September.

Table 5.1: Molasses market parameter values in the base year

| | |
|--|------|
| Molasses Price P_m^0 (Rs/ton) | 2478 |
| Cost of storage, transportation and distribution of molasses C_{MT} (Rs/ton) | 250 |
| Total molasses production capacity Q_{CAP} (million tons/yr) | 10.7 |
| Molasses demanded by rectified spirits Q_{MSBE}^0 (million tons/yr) | 9.4 |
| Molasses demanded by fuel ethanol Q_{MSFE}^0 (million tons/yr) | 1.3 |

Sources: [Licht, 2011, Gunatilake, 2011]

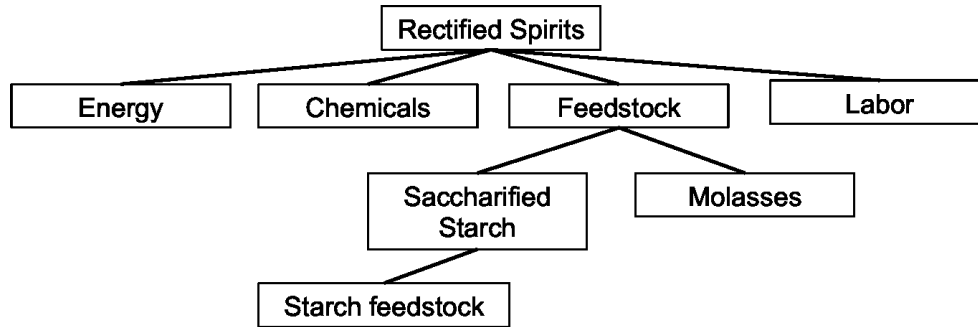


Figure 5.2: Production Tree for Rectified Spirits in India.

The figure shows the way I model production of Rectified Spirits in India. It is a fixed-proportions production function.

ton of molasses [Verma, 2010]. The marginal cost of all inputs other than molasses are assumed to be independent of the volume of ethanol produced by each factory and it has a value of Rs. 10.5 per liter of anhydrous ethanol [Gunatilake, 2011]. The volume of molasses fuel ethanol produced in India is the variable I use to shock the PE model and is denoted by Q_{MSFE} . In a post-processing step, I calculate the marginal cost of Indian molasses fuel ethanol.

5.3.3 Model of the Rectified Spirits Market

India's rectified spirits market is dominated by molasses as the main feedstock. So, increased demand for molasses from fuel ethanol will have substantial impacts on this market. The supply of rectified spirits is also governed by a fixed proportions production function with molasses being replaced by a perfect substitute based on cost. Figure 5.2 shows the way I model rectified spirits production.

A key step in solving this CLCA was to determine what product will be the molasses substitute for the rectified spirits industry. The options included several starch and sugar feedstocks such as sugarcane, rice, wheat, barley, corn, millet and sorghum. I used data from the Indian Ministry of Agriculture to arrange all of these feedstocks in ascending order of their average price in 2006-07 [India, a]. Millet and sorghum were priced much lower than the rest with sorghum having a slightly lower annual average price. I deduce that sorghum will be the molasses substitute from the following factors.

- Several sorghum based alcohol plants already exist in India with a total production capacity of 500 million liters per year [India, 2011]. Millet could also be used as a feedstock in these plants but the cost of saccharification is higher for millet [Verma, 2010].
- All the existing grain-based distillery capacity in India is in the state of Maharashtra, which is also the main sorghum growing region. This was caused by a state policy to subsidize grain ethanol production that was initiated in 2003 and discontinued in 2006 in the face of widespread protests.

Once I was able to determine that sorghum would be the molasses substitute, I looked at several studies to obtain its supply elasticity in India. Kumar et al [Kumar et al., 2010], study all of India's major crops and econometrically determine their supply elasticities from 2001-08 and derive a value of 0.35 for sorghum. I use this value after cross-checking with the IFPRI elasticity database for sorghum supply elasticity worldwide, which was 0.3.

The final step in having a complete model of the rectified spirits market is to estimate its demand elasticity in the Indian market. Rectified spirits are used both in industrial applications and as the base for alcoholic beverages. In India, the split between the two uses has been approximately equal throughout the last decade [Aradhey, 2010, Singh, 2009]. In my simulation base year of 2006-07, 1 billion liters of rectified spirits went to industrial use and approximately the same amount went to beverage production [Gunatilake, 2011]. Industrial alcohol demand is normally measured to be more price elastic than beverage alcohol demand which can be an addictive good. While there are several studies looking at each demand elasticity separately, there is only one that estimates the demand elasticity of rectified spirits in India combined for both uses [Mino, 2010]. Mino [Mino, 2010], estimates a value of -0.55, which I use in my model.

5.3.4 Emissions Factors

The PE model described above calculates the change in equilibrium quantities and prices for all the commodities but does not furnish any environmental information. Calculating the environmental impact (GHG emissions in this case) requires a second model that uses the PE results as inputs. The marginal emissions changes could be non-linear in more sectors than land use. For example, the introduction of the fuel ethanol program will, in all likelihood require the construction of ethanol dehydration plants, which results in up-front emissions that need to be amortized over the lifetime of the plant. If any of the industries that supply materials or services to the fuel ethanol industry are close to a capacity constraint then the policy will necessitate

Table 5.2: Emissions Factors used in Analysis

| Product | Process Emissions (gCO₂-eq/anhydrous liter) |
|---|---|
| Molasses Fuel Ethanol | 115 |
| Molasses Rectified Spirits | 110 |
| Sorghum Rectified Spirits [no land use change] | 995 |

Sources: [Menichetti et al., 2009, Gopal and Kammen, 2009]

additional capital investment, which in turn, will likely lead to up-front emissions. Exploring all such possibilities is extremely time consuming and data intensive but I did examine many of these sectors in detail. Very little data is available but I was able to determine, to the best of my efforts, that non-linear effects are unlikely to be significant since the changes in quantities of sorghum, fuel ethanol and rectified spirits were small relative to the size of the industries that provide material inputs and services to them. The only case where non-linear effects seemed likely, as is common with any agricultural markets, was in land use change from one type to another to accommodate higher sorghum demand. I discuss my land use modeling later in sections 5.5.1 and 5.6 but table 5.2 shows the emissions factors for all others and their sources.

5.4 Model Assumptions

My PE-based CLCA model for Indian molasses ethanol includes numerous assumptions. I list the most important ones here and verify the validity of each where possible.

1. All the markets modeled propagate prices only within India and are sufficiently isolated from world markets for the same commodities. Table 5.3 shows that the import tariffs for all cereals that could be used for alcohol production, on rectified spirits, on sugar and on molasses are all very high in India.

Table 5.3: Indian Import Tariffs for all Markets Modeled

| Commodity | Import Tariff (ad-valorem %) |
|-----------------------------------|------------------------------------|
| Sorghum bicolor | 70 |
| Pearl Millet | 70 |
| Broken Rice | 80 |
| Spirits (ethanol volume > 80%) | 150 |
| Liquors (ethanol volume < 80%) | 150 |
| Sugar | 100 |
| Molasses | 30 |

Indian agricultural policy fiercely protects domestic producers of these commodities and the Government has frequently adjusted the tariffs to prevent imports in the past. It would be reasonable to assume that such actions would be taken again, upholding my assumptions.

2. The production function for rectified spirits and fuel ethanol are assumed to be of fixed-proportion between inputs and outputs in my model. From data that I have collected from distilleries in Indonesia and India [Troiani and Gopal, 2008], this assumption is very close to reality for both the feedstock and other supplements.
3. I assume that no significant consequential GHG emissions occur outside of the markets that I model. In a situation similar to the process LCA system boundary decision, it is impossible to prove this is true without actually expanding the system boundary infinitely. For example, sorghum in Maharashtra may displace rice, an inelastic staple in India, for which forests may be cleared in southern India to expand rice acreage. Such an occurrence is conceivable but unlikely.
4. Finally, I assume that the molasses fuel ethanol policy does not cause a structural change in the economy even in the long-run. For example, one may expect that sustained high prices for sorghum could spur the development of higher yielding varieties and lower other costs.

5.5 Solving the Model

Prior to simulating the policy scenario, I had to:

1. Choose the base year and,
2. Benchmark the model to the base year.

I chose the base year for the simulation to be from Oct 2006 to Sep 2007 which is the latest sugarcane season when all the required data was available and the sugarcane factories operated close to capacity throughout the season. The capacity factor of sugarcane factories was an important criterion because the fuel ethanol policy is likely to improve capacity factors due to the increased revenues accruing to the sugarcane sector. Hence, we can expect to see high capacity factors in the long-run if a molasses fuel ethanol policy is instituted.

I used data from the Indian Government, FO Licht's Interactive Molasses and Feed Ingredients Database and the USDA's India Biofuels Annual reports to obtain the price, quantity and land use data for all commodities in 2006-07

[India, b, India, 2011, India, a, Licht, 2011, Singh, 2009, Aradhey, 2010]. I parameterized the supply curve for sorghum and the demand for rectified spirits using base year data. The total molasses production for the year and the amount of ethanol used for fuel ethanol production were both calculated using the model and verified to match the actual production values closely. I solved the entire PE model after calibration and found that the results closely matched actual production and prices for the base year.

To simulate the molasses fuel ethanol policy scenario, I had to decide which variable to shock in the PE model. Both the Indian EBP and the LCFS translate most appropriately into a molasses fuel ethanol mandate. I chose a fuel ethanol production increase of **1.5 billion liters per year**, a value that neatly simulates the EBP or the use of the fuel under the LCFS. The EBP mandates that molasses ethanol should constitute 5% of gasoline supply by volume in 2010 which corresponds to approximately 1.5 billion liters per year. If all of the demand only originated from the LCFS, that would also only result in approximately the same production increase since 1.5 billion liters per year will consume 88% of India's molasses supply and any further demand for fuel production will create a molasses shortage that the Government will move to ameliorate.

I introduced a molasses fuel ethanol production shock of 1.5 billion liters and solved the non-linear PE model using MATLAB (source code in Appendix). I multiplied the change in production of molasses fuel ethanol, molasses rectified spirits and sorghum rectified spirits with their corresponding emissions factors from table 5.2. In the final step I calculated land use change emissions from the additional sorghum cultivation.

5.5.1 Land Use Change for Sorghum

All ILUC studies of biofuels published to date agree that higher prices for an agricultural commodity cause two separable effects related to land use shown in figure 5.3; intensification and extensification.

Intensification is the higher yield that is the outcome of a farmer's response to higher crop prices.

Extensification is the increase in the cultivated area of a crop because of higher demand for it.

The studies also agree that the intensification effect occurs first, because farmers initially try to grow more from existing land and avoid the transaction costs associated with extensification.

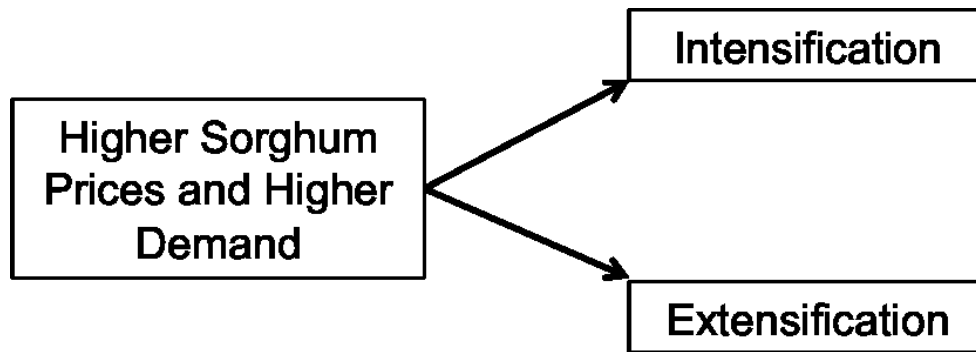


Figure 5.3: Land Use Consequences of Higher Sorghum Prices

Additional demand beyond that fulfilled by intensification is met from new, extensified land that is assumed to have lower yields. Unfortunately, while most resource economists agree qualitatively on these dynamics, there is a real scarcity of studies that quantify intensification and extensification. The few studies that do estimate yield elasticity with respect to price focus on the US and Europe. I could find no studies that estimate sorghum yield elasticity with respect to price specifically in India. Recently, some economists have also challenged the assumption that new lands have lower yields. They argue that conversion of highly productive forests or pastureland, like those in Brazil, to cropland may not result in any yield drop [Barr et al., 2010, Nassar et al., 2011, Berry, 2011].

5.5.1.1 Intensification

With no studies that estimate intensification for Indian sorghum, I looked for studies that estimate it for sorghum grown anywhere. Keeney and Hertel (2008) [Keeney and Hertel, 2008], reference a 1997 study that estimates the yield response to price for sorghum grown in the Southeastern US to be 0.19. Sorghum yields in India are some of the lowest of any world region. India's average sorghum yield in 2006 was just 800 kg/ha, compared to a global average of 4000 kg/ha [ICRISAT, 2010]. Indian resource economists argue that the main cause for poor yields is sorghum's low price because several higher yielding cultivars are widely available in India at modestly higher prices than the dominant sorghum bicolor variety planted today. This claim is backed by data that shows Indian sorghum yield following fluctuations in price [ICRISAT, 2010]. Given this evidence and the lack of yield response estimates of Indian sorghum, I chose to use Keeney et al's reasonably high value of 0.19 in my analysis.

5.5.1.2 Extensification

CGE models generally do a poor job of modeling land use dynamics because of many reasons discussed in Chapter 4 but they have one advantage relative to PE models. Since they include almost all of the world's land, their post-simulation land allocation is internally consistent and ensures that total land supply does not grow or shrink. My PE model only includes land supply

for sorghum and the simulation tells me how much additional sorghum land is needed in India but the model is incapable of deciding where this expansion would occur. Fortunately, sorghum acreage has been shrinking in India and recent years from a peak of 16 million ha in 1984 to just 8.5 million ha in 2006 [ICRISAT, 2010]. I looked at a historical time series of maps of sorghum land from the Indian government and was able to determine that sorghum has mostly been replaced by millet and tropical corn [India, a]. Higher sorghum prices will likely first re-occupy lands ceded to millet since it currently fetches only a slightly higher price than sorghum and because these millet lands are in Maharashtra, the only state with distilleries that can accept sorghum. The displacement of millet will cause two effects: (1) intensification and (2) reduced millet consumption because of its increased price. These two effects absorb much of the demand for new millet land resulting in much less millet extensification than the original millet acreage displaced. Every subsequent cropland displacement will result in diminished extensification each time. If we assume that intensification and demand reductions are the first responses to crop area displacements then it is possible for the economy to reach a new equilibrium after a small³ sorghum extensification without any net increase in total cropland. I argue that this is the case in my results in section 5.6 because the extensification demand for sorghum after the mandate is less than 0.01% of India's cropland. In most cases, conversion of cropland from one crop to another will not result in any net carbon release [Fargione et al., 2008] hence a new equilibrium without any net change in total cropland implies no net GHG emissions due to land use change.

5.6 Results

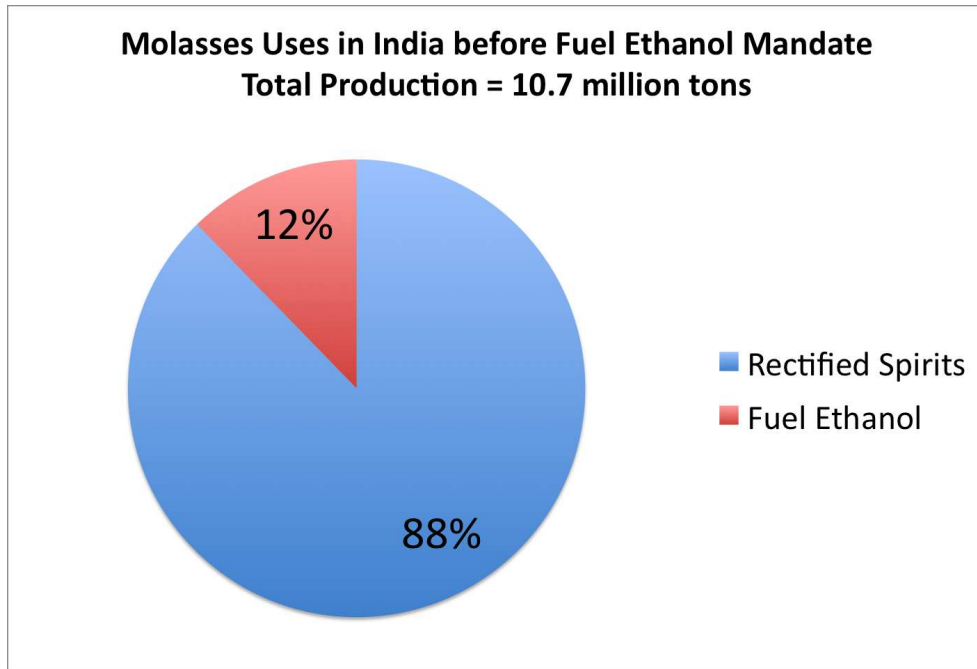
5.6.1 Full CLCA GHG Emissions

An increase of 1.5 billion liters in molasses fuel ethanol production in India does not cause additional molasses production but substantially alters the share of end-uses for the commodity. Figure 5.4a shows that 88% of Indian molasses was used to manufacture rectified spirits while 12% was used to manufacture fuel, in 2006-07. After the fuel ethanol mandate, this share is reversed (Figure 5.4b), with 81% going to fuel production and 19% going to rectified spirit production.

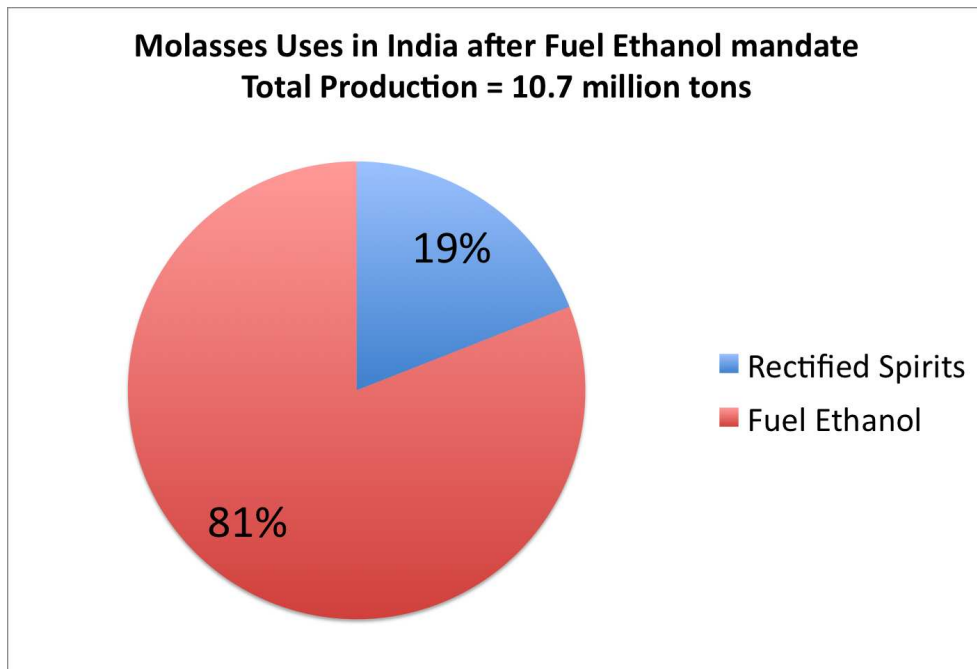
The full consequential lifecycle GHG emissions of Indian molasses ethanol using my PE-based approach are **5 gCO₂-eq/MJ**. The consequences in emissions terms of the 1.5 billion liter increase in molasses fuel ethanol production in each affected sector is shown in table 5.4. It is important to note that not all consequences result in increased GHG emissions, a fact usually not highlighted in biofuel LCAs. The cutback in molasses rectified spirits production results in savings of 5.5 gCO₂/MJ. However, the added production of sorghum rectified spirits and molasses fuel ethanol more than outweighs those savings. The emissions associated with sorghum rectified spirits shown in table 5.4 include the added fertilizer application associated with intensification.

The total additional sorghum demand induced by the fuel ethanol policy is 0.5 million tons of which 98% is absorbed by intensification. The intensification effect from increased sorghum

³“small” is subjective but anything less than 1% of total Indian cropland applies here



(a) Molasses End-use Shares Prior to Mandate.



(b) Molasses End-use Share After Mandate.

Figure 5.4: Molasses End-uses in India before and after the molasses fuel ethanol mandate. The figures show the substantial diversion of molasses from the rectified spirits industry to the fuel ethanol industry after the molasses fuel ethanol mandate.

Table 5.4: Full Consequential LCA GHG emissions of Indian Molasses Ethanol

| | |
|---|-----------------------------|
| Consequential emissions due to molasses fuel ethanol production | +4.5 gCO ₂ /MJ |
| Consequential emissions due to reduced demand for molasses rectified spirits | -5.5 gCO ₂ /MJ |
| Consequential emissions due to sorghum intensification and production processes | 6.0 gCO ₂ /MJ |
| Consequential land use extensification emissions | negligible |
| Total CLCA GHG emissions | 5 gCO₂/MJ |

prices and demand raises Indian sorghum yield from 0.87 tons/ha to 0.93 tons/ha. As a result, the extensification demand is just **9200 ha**, which is **0.01%** of India's total cropland area. I apply the argument outlined in section 5.5.1.2 to argue that there will be no land type changes other than the conversion of cropland from one crop to another. Hence the consequential land use change extensification emissions for Indian molasses ethanol are *negligible*.

To derive this result, I use linear (scale independent) emissions factors because I assume that a production increase of 1.5 billion liters is not enough to push any of the markets I model into a non-linear step change. An example of such a non-linear change would be if fertilizer supply was at capacity prior to the molasses ethanol mandate, the higher demand for fertilizer because of the mandate caused the construction of a new fertilizer plant. All the emissions associated with the construction of the new fertilizer plant would have to be included in my CLCA since it's construction is a consequence of the mandate. It is beyond the scope of this work for me to explore every affected market to check if my linear emissions factors assumption would be violated in any of them even with a 1.5 billion liter molasses fuel ethanol increase. However, the chance of emissions factors being non-linear, which increases with higher molasses fuel ethanol production, introduces an important caveat in my result. The CLCA carbon rating for Indian molasses ethanol derived is only valid as long as the emissions factors in table 5.2 remain linearly dependent on the quantity of molasses fuel ethanol produced.

5.6.2 Economic Impacts

Important outputs of PE model are the equilibrium quantities and prices of commodities. Price and cost increases caused by the fuel ethanol mandate in all commodities are summarized in table 5.5. The biggest beneficiary of the fuel ethanol mandate, whether used for India's EBP or the LCFS, is the sugarcane industry which more than triples its revenues from molasses sales. However, it is not clear how much of this additional revenue will filter down to the sugarcane farmer, who is intended to be one of the beneficiaries of India's EBP. If the design of the EBP remains as it is, the 119% increase in the marginal cost of molasses fuel ethanol would be

Table 5.5: Price and Cost Increases caused by the Fuel Ethanol Mandate

| | |
|-------------------------------|---------------|
| Price of Sorghum | 39% increase |
| Marginal Cost of Fuel Ethanol | 119% increase |
| Price of Rectified Spirits | 125% increase |
| Price of Molasses | 221% increase |

absorbed by the taxpayer since the government guarantees an ethanol price to refiners. Perhaps the result with the most significance to the poor is the 39% projected price increase for sorghum. Sorghum is overwhelmingly consumed by the poor since it is a cheap substitute for wheat. So, while the CLCA GHG emissions may be low, showing Indian molasses ethanol to be a clean fuel, its use as a fuel comes at a real social cost by stretching the food budgets of the poor.

5.7 Implications for India’s Ethanol Blending Program

The EBP was instituted in 2003 with two main objectives which are identical to the initial objectives of Brazil’s 185 Proalcool program and of the US’s Energy Policy Act of 2005.

1. The Indian Government wanted to increase the blend of biofuels in the transportation fuel mix in order to reduce India’s foreign oil imports.
2. The government also wanted to boost domestic agriculture in the process.

My analysis provides insight into how well or poorly the policy can achieve both these objectives. The government decided to have only molasses ethanol under the EBP because it anticipated an outcry if it allowed any food crops to be used for fuel. Although my analysis shows that even a molasses ethanol mandate can raise food prices, such indirect effects are usually not detected and so are not a political liability. However, even if all the molasses in India is used to make fuel, only 4.5% of national gasoline demand will be displaced [India, 2010]. So, by restricting the EBP to molasses, almost no significant reductions are made in oil imports. The EBP needs to be redesigned radically in order to meet its first objective.

As I mention in section 5.6.2, under the current design of the EBP, the government guarantees a price ceiling to refiners and covers the difference with taxpayer funds. Even with a much more modest increase in molasses ethanol production than 1.5 billion liters, producers are already pricing ethanol higher than the price ceiling [India, 2011]. My model estimates that even if producers price competitively at marginal cost, a 1.5 billion liter boost in molasses fuel ethanol production will drive its price up by 119%, that will increase the already heavy taxpayer burden on this program.

A lifecycle carbon rating of 5 gCO₂/MJ makes molasses ethanol the cleanest first generation biofuel of all currently rated on a lifecycle basis. Fuel programs that explicitly favor low carbon fuels like the LCFS, the EU RED and the RFS2, are natural sources of demand for Indian

molasses ethanol once the fuel is rated by the regulating authority. In all of these programs, and in the case of the LCFS in particular, price premiums commanded are inversely proportional to the fuel's carbon rating. So, a clean fuel like Indian molasses ethanol will need no government support if sold in these markets. Based on the CLCA and economic results I have presented, the Government can meet the second objective of the EBP much more cost-effectively by assisting molasses ethanol producers in getting their fuel rated and in exporting the product to California, the US and Europe.

Chapter 6

LCA-Based Climate Policies: When they are a Good Idea and How to Make them Better

6.1 Chapter Summary

Current LCA-based fuel policies, the Low Carbon Fuel Standard (LCFS) and the Renewable Fuel Standard 2 (RFS2), are very problematic due to the use of wrong LCA approaches and because of the large parametric and epistemic uncertainty in the LCA models employed. In this chapter I portray the ideal way to regulate the global warming impact (GWI) of fuels, a regulatory regime that has no need for LCAs. However, this ideal scenario is politically infeasible at this time, necessitating the use of LCAs to meet some fuel policy objectives. Given that, I present my suggestions, drawn from previous chapters and developed independently, on how to improve LCA-based climate policies in general and fuel carbon policies in particular. These suggestions can be summarized in two main points. When designing an LCA-based climate policy:

1. Make sure that the policy is entirely CLCA-based, and,
2. Do not use CLCA point estimates as a performance metric but produce stochastic CLCA results that can help develop risk profiles for the product's ability to meet the policy's objectives.

6.2 LCA-based Policies are only Required in a Second-best World

6.2.1 The Ideal Scenario for GWI Regulation

The monetary cost of a fuel or, any product for that matter, reflects the prices of every service and input that was used in its manufacture no matter where in the world each supply chain activity occurred. This happens because every business in the supply chain only provides the demanded service or input for the fuel if they get paid. If the global warming externality was priced for all economic activities, the GWI caused by the fuel from cradle to combustion would already be paid for, since the GWI would be passed through as a monetary cost in every transaction leading up to and including combustion. Hence, the ideal way to regulate transportation fuels for their GWI is not through a fuel carbon policy at all, but through global, all-sectoral climate regulation.

In other words, if greenhouse gas (GHG) emitting activities¹ in all sectors and all regions of the world were regulated, there would be no need for highly uncertain LCA calculations because GHG emissions would be measured and priced everywhere. In this ideal scenario, all of the following must hold true:

- Every nation must agree to regulate climate change in every sector, including the most controversial of all; land use.

¹Even more ideally, non-GHG climate changing activity like albedo changes should also be regulated according to their climate forcing effect, but leaving non-GHG activities out will not introduce too much error, certainly not of the scale of LCA-based policies.

- All the policies regulating GHG emissions should be equivalent across regions and sectors. For example, we cannot have the Chinese power sector regulated on an intensity basis while the US power sector operates under a carbon tax. Carbon tax based regulation can be reconciled with a cap-and-trade regulation. Ideally, there will be just a single global policy for regulating all anthropogenic climate change instead of national or continental ones.
- The policy should be designed so that the global warming externality is priced correctly. This means that the tax or carbon price lies at the intersection of the marginal abatement cost curve and the marginal abatement benefit curve. This is not an easy task since neither curve is easy to determine in many cases.

It is important to note that even in this ideal scenario which substantially reduces uncertainty relative to that seen in CLCAs, uncertainties are not eliminated. One source of uncertainty is whether the damages caused by climate changing activities are correctly monetized as discussed above. A second source of uncertainty is in the measurement of GHG emissions. While, emissions from smokestacks and tailpipes can be measured accurately, NO_x emissions from land use changes are difficult to measure and therefore are uncertain [De Klein et al., 2006b, De Klein et al., 2006a, Winiwarter, 2007]. Despite these uncertainties, if such a regulatory regime existed, it would be far superior to LCA-based fuel policies.

This type of global, all-sectoral climate policy regime is unlikely even in the distant future. The UN climate talks, which have stalled, propose nothing that goes this far. According to current negotiations, in a global climate agreement, developing countries are not expected to meet any absolute GHG reduction targets and there is no proposal for land use GHG emissions to be part of the same regulatory regime as the energy sector. Hence, in the absence of a coordinated global effort, entities with smaller jurisdictions, like California, that want to regulate for GHG emissions must turn to alternative policy designs.

6.2.2 Rationale for LCA-based Policies: From the Perspective of the LCFS

When only some jurisdictions in the world try to regulate for global pollutants like GHGs, policy design options are numerous but littered with pitfalls. The most popular area of research is in the design of carbon tax or cap-and-trade programs and how to avoid the many pitfalls associated with them [Jaffe and Stavins, 2008, Stavins, 2008]. Numerous articles deal with these issues, with some focusing specifically on California's planned cap-and-trade program for the electricity sector [Bushnell et al., 2008, Bushnell, 2008]. I will focus my discussion on when LCA-based climate policies make sense and some of the factors that have emerged from the LCFS that make them problematic, atleast in the case of fuels.

An LCA-based climate policy should only be considered if the policymaker needs to regulate:

1. Climate changing activity outside his/her jurisdiction for the policy to be effective
2. Climate changing activity that is not regulated by any other body

Point 1 above is really important because if only the second were true and if a climate policy can be effective even if GHG emissions occur outside the jurisdiction, then a carbon tax or cap-and-trade policy would be preferable to an LCA-based policy. As I point out in Chapter 1, simply counting GHG emissions from the final combustion of fossil fuels accounts for around 85% of GHG emissions associated with the fuel [Gopal and Kammen, 2010], hence point 1 does not hold if only fossil fuels are regulated for GWI. If the non-fossil fuel options also cause limited GHG emissions outside the jurisdiction like solar PV and Wind power, then point 1 still does not hold and there will be no need for LCA-based policy. This is why no one proposes the use of an LCA-based policy for the electricity sector. For alternatives to petroleum in transportation fuels, and especially in the case of biofuels, point 1 is unequivocally true [Farrell et al., 2006, Gopal and Kammen, 2010, Mascia et al., 2010, Wang et al., 2008, Wang et al., 2006]. There are other sectors like food where point 1 holds but none of these are currently being considered for climate regulation.

When LCFS policy was being designed, the designers rejected a carbon tax or cap-and-trade for the reasons mentioned above and because the LCFS was an intensity standard that does not lend itself easily to a carbon tax policy. Further, the only way to know if the LCFS was met, was by calculating the lifecycle carbon intensity of all transportation fuel used in California. Hence, it was natural to design the LCFS as an LCA-based policy because an LCA result was required to know if the state was in compliance.

When an LCA-based policy was recommended and accepted by the State, all participants in the process assumed that:

1. An ALCA was an appropriate LCA approach to calculate the fuel carbon content, and
2. The LCA results would yield point estimates of actual lifecycle fuel carbon content with little uncertainty.

Two issues were overlooked by the initial LCFS designers even before the publication of Searchinger et al (2008) [Searchinger et al., 2008] sent everyone back to adjust course as I describe in Chapter 1.

1. More than a decade after the birth of CLCA, all the LCA experts involved in the original design of the LCFS still did not clearly understand the different purpose of each LCA type.
2. Even if ALCA was accepted as appropriate for the LCFS, ALCA results are still too uncertain to be assumed to provide accurate deterministic results.

These two false assumptions and the mid-course correction prompted by the emergence of ILUC highlighted the most problematic aspects of the LCFS design and would apply to any other LCA-based climate policy designed similarly. First, it is scientifically untenable to have an LCA-based policy that sums the result of an ALCA and a CLCA. Second, even if the right LCA category was used, the policy should not have been designed on the expectation of accurate point estimate results.

6.3 Uncertain Science and Policy

Uncertain science has been used in policy before although, as I discuss in this section, scientific uncertainty does not mix well with politics. However, the magnitude of the uncertainty for the LCFS is higher than other policies based on uncertain science and unlike other successful policies it explicitly refuses to acknowledge uncertainty. Here are some examples of how policies address uncertainty.

In some policies, uncertainty can be reduced by better measurement. In the Acid Rain program, the main source of uncertainty is the quantity of SO₂ and NO_x emitted from power plant smokestacks which is reduced by using continuous monitoring systems and more precise instruments. Another source of uncertainty arises if the proxy that is regulated does not meet the policy objectives perfectly. The mechanism by which acid rain is caused is well understood and limiting SO₂ and NO_x meets the objective of the program with little proxy uncertainty.

In the regulation of Particulate Matter (PM) concentrations under the Clean Air Act, the public health burden of PM is understood but a little uncertain. Hence, the Clean Air Act explicitly uses a probability distribution function of PM concentrations over 24 hour periods. The law requires that the 98th percentile of PM concentrations in a 24 hour period must not exceed 35 $\mu\text{g}/\text{m}^3$, instead of using a central tendency value like a mean or median. Hence such a policy accounts for uncertainty using a scientific method and prefers to reduce Type I errors (the chance that PMs have a worse human health impact than thought) at the cost of increased Type II errors (the chance that PM concentrations could be higher without adversely affecting human health).

When uncertainty is much higher, especially with regard to critical outcomes like public health, the burden of proof may be reversed in a policy. This is the case with the European Union's Registration, Evaluation, Authorization and Restriction of Chemical Substances (REACH) approach to industrial chemicals. REACH requires that manufacturers of industrial chemicals demonstrate that their products pose no undue risks to public health and the environment. Such an approach is warranted when meeting the policy objective with accuracy is critical even at a high cost or when it is determined that the product poses a substantial enough risk that its use will cause the policy to fail. In my opinion, which I express in detail in the next Chapter, many crop-based biofuels do present a substantial enough risk to LCFS efficacy that the burden of proof should be placed on the producers.

6.3.1 Politics and Science

While the examples above are of successful policies based on uncertain science, there are many occasions when uncertainty results in political disagreement that adversely affects a policy. The LCFS, for example, has faced a severe backlash because its lack of acknowledgement of huge uncertainties has provided fertile grounds for the politically powerful corn ethanol industry to attack it. Van der Sluijs (2005) [van der Sluijs, 2005] uses the metaphor of *monsters* to describe the four main ways in which stakeholders respond to uncertainty in the science-policy interface. In this case, a monster is a hard to tame phenomenon that fits into two categories that are usually

considered to be mutually exclusive such as objective v subjective, facts v values, knowledge v ignorance, etc. A monster arises in the science-policy interface when a policy is predicated on complex science that is uncertain. Van der Sluijs (2005) places the response of stakeholders to this monster in four categories which I explain in the context of the LCFS.

Monster Exorcism. In this response, certain stakeholders believe that uncertainty can be reduced enough through research to better inform and defend the policy. By developing a new CLCA method that I believe improves on the current CGE framework used by the California Air Resources Board (CARB), I hold the belief that the new method will tamp down criticism of some aspects of the modeling and hence can be seen as falling in this category. However, the monster-exorcists are convinced that using the scientific method alone will reduce uncertainty to a non-controversial level, which I disagree with. With the policy as it is, no foreseeable breakthroughs in thought or methods will eliminate uncertainty-driven controversy in the LCFS.

Monster Adaptation. In this response, stakeholders believe that the best approach to solving the controversy is by quantifying uncertainties or producing different model results based on scenarios that depend on value judgements. This has been the response of the Global Trade Analysis Project (GTAP) modeling team and CARB staff where various scenarios are run in GTAP and the mean result is taken as one that has accounted for uncertainty. However, their choice of using just a subset of scenarios based on value judgements has left them open to the criticism that many other “important” scenarios were not considered.

Monster Embracement. In this response, the corn ethanol lobby cites uncertainty as the reason to delay any action that penalizes their fuel under the LCFS. This manifests itself as a “scientization” of politics [Doremus, 2005], where the biofuel lobby and its supporters in government ask for a delay in instituting the LCFS or the RFS2 until the “science” has progressed enough for the uncertainty to be eliminated. The goal of the biofuel lobby is to push for a desired political outcome by falsely presenting themselves as purveyors of the scientific view. Plevin et al. (2010) [Plevin et al., 2010] have shown that if the lobby really wanted to pay heed to science, then they should in fact be asking that corn ethanol be *excluded* from use in the LCFS while we wait for the uncertainty to be reduced. This is because, the article shows that the uncertainty in the LCA GHG emissions of corn ethanol are heavily skewed toward much higher values than previously thought. Doremus (2005) [Doremus, 2005] also points out that the use of monster embracement to argue against environmental regulation was a repeated tactic of the Bush Administration.

Monster Assimilation. In this response, the uncertainty is given an explicit place as a factor in policymaking. This outcome is portrayed by van der Sluijs as the best of the four but there is no sign that the LCFS or the RFS2 are inclined to move in this direction.

The uncertainty in the LCA modeling for the LCFS and the RFS2 have resulted in a worse political outcome than in the case of some other similar policies because the uncertainties in the LCFS are irreducibly large and the policy itself made no plans on how to deal with them. The positive aspect of all the attacks on the policy is that it has brought the huge uncertainties inherent in LCA into the spotlight and will not permit LCA experts to leave them unacknowledged in the future. Importantly, any future LCA-based policy will likely be designed very differently after the experience of the LCFS.

6.4 Guidelines for Designing LCA-based Policies

First and foremost, as I have already argued in this chapter, an LCA-based policy should not be considered unless other options with less uncertainty are eliminated. In the event that an LCA-based policy is determined to be the best approach, I have drawn on my research to develop a set of guidelines to design such policies.

- Any LCA-based policy should employ *fully consequential methods* to perform the LCA. It is possible that the consequences of a policy will only result in linear marginal effects in which case an ALCA can approximate to a CLCA but if this was the case, then policy is itself likely to be inconsequential. It is important to recognize that CLCA methods are still in their infancy and LCA and other interdisciplinary researchers should be provided with incentives to develop better methods, given its immediate policy relevance in many contexts.
- No LCA-based policy should be designed assuming that an LCA will provide accurate and precise results. As a result, the policy should not determine quantitative performance metrics or metrics for compliance expecting deterministic results from the LCA. The LCFS does exactly this by calculating the average fuel carbon intensity of fuels in the state using LCA-based fuel carbon ratings.
- Do not use an LCA-based policy if the environmental impact that you are regulating has geographically variable impacts like fertilizer runoffs, air pollution, etc. LCAs are not well designed to translate this geographic variation into a useful environmental impact metric. LCA-based policies work best when applied to well-mixed global pollutants like GHGs.
- If the uncertainty in the CLCA is quantifiable and you are able to produce probability distribution functions of the results, these need to be explicitly taken into the policy design. As in the case of the Clean Air Act, the policymaker could then decide if Type I or Type II errors are more important and set the compliance threshold in stochastic terms rather than simply choosing a central tendency estimator. If there are multiple criteria with stochastic outputs, then these can be used to develop a risk rating for the product that is then used as the main decision variable for the policy.
- In many cases, uncertainty in CLCA results is simply irreducible. All CGE models are abstractions of reality and their results can never actually be verified. Hence, it is impossible to build probability distribution functions for any structural assumptions in the model. If this is the case, a policy that uses the model should be designed to accommodate uncertainty that is not quantifiable. The policymaker could ask each individual producer to undertake actions that bypass the LCA. An example is a solution for a biofuel producer to be granted exemption from the ILUC penalty that I heard first from my advisor, Dr. Michael O'Hare. A Brazilian sugarcane ethanol producer will be granted a waiver of its ILUC penalty if it purchases pastureland in Brazil and intensifies the number of cattle heads per acre by an amount specified by CARB.

Chapter 7

Conclusion

7.1 Contributions to LCA

Many LCA experts still do not understand the theoretical and practical differences between attributional LCA (ALCA) and consequential LCA (CLCA) as evidenced by the poor design of the Low Carbon Fuel Standard (LCFS) and the continued use of ALCA to inform policy decisions. This dissertation clearly differentiates ALCA from CLCA, the theoretical foundations of each and which approach applies in specific situations. The prevalence of such widespread confusion even among experts regarding the two approaches makes this clear separation of ALCA and CLCA, the primary contribution of this dissertation to the field of LCA. Perhaps the most important rule that emerges from my study of the theoretical foundation and purpose of the two approaches is:

Only Consequential LCA should be used for LCA-based policies

The CLCA model developed in Chapter 5 is one of the few fully consequential LCA studies employing an economic model that have been developed for any product and the first one for a byproduct-based biofuel. Early development of methodology in any field is much more difficult but also provides a much larger marginal benefit to the field than later additions. The model in chapter 5 is an example of such an early methodological improvement in CLCA. My initial motivation, however, was to develop a method that can rate byproduct-based biofuels in low carbon fuel programs and this dissertation makes two specific contributions in this regard.

1. I develop a modeling framework, a partial equilibrium (PE) foundation linked to emission factors, that can serve as the basis to solve CLCAs for any byproduct-based biofuels.
2. I show that a partial equilibrium model is a much superior foundation for a CLCA model of byproduct-based biofuels than a computable general equilibrium model.

7.2 Official LCA Rating Method for Molasses Ethanol in the LCFS

When I started work on this project, I found it astounding that the California Air Resources Board (CARB) did not know what molasses ethanol is, even though 8 billion liters of it was being manufactured annually. Worse, they and other policymakers mistook molasses ethanol to be the same as sugarcane ethanol. I developed the ALCA model in Chapter 3 and the GTAP-based approach in Chapter 4 primarily for the immediate policy relevance of the results that would make it possible for the cost of complying with the LCFS to be lowered substantially in the near- to medium-term. The biggest contributions of the LCA studies in Chapters 3 and 4 are their immediate, practical relevance to the LCFS.

1. The models from Chapters 3 and 4 have been ratified by CARB as official methods to be used in rating molasses ethanol for the LCFS. The results have been adopted as the default ratings for the fuel.

2. The ALCA model in Chapter 3 is the first LCA model that actually recognizes that sugarcane factories can use two different feedstocks, molasses and cane juice, to make ethanol. Hence, for the first time, molasses ethanol is clearly distinguished from sugarcane ethanol in the eyes of policymakers.
3. The ALCA model in Chapter 3 is also the first to calculate the LCA GHG emissions of a fully flexible sugarcane factory.
4. Molasses ethanol has a similar LCFS rating to cellulosic ethanol but is much cheaper and already commercial. Hence, my work has started a process that could lower the cost of compliance for the LCFS at least until molasses ethanol capacity limits are reached.

A second reason I performed the analysis of molasses ethanol within CARB's methodological constraints was to highlight:

1. The LCFS' fuel carbon rating method is poor and needs to be changed irrespective of what is decided regarding how it deals with indirect land use change (ILUC),
2. GTAP cannot be realistically used as it is or feasibly modified to estimate ILUC for molasses ethanol and,
3. CARB had no methods to rate byproduct based biofuels like molasses ethanol and soybean biodiesel.

7.3 Full CLCA of Indian Molasses Ethanol

The fully consequential LCA of Indian molasses ethanol that I develop in Chapter 5 has many direct uses and indirect implications. The model serves to demonstrate that a full consequential LCA can be done for biofuels and that methodological difficulties should not be put forth as a reason to keep the LCFS unchanged. In short, if the LCFS continues to be an LCA-based policy, using fully consequential methods for fuel ratings are a much superior and more scientifically defensible approach than the current one. On a practical level, the CLCA results provide numerous insights into Indian molasses ethanol and India's Ethanol Blending Program.

1. The CLCA model shows that Indian molasses ethanol is one of the cleanest first generation biofuels from a consequential lifecycle carbon perspective.
2. After molasses fuel ethanol production is ramped up in India to meet policy demand, my PE model predicts that the marginal cost of the fuel will increase by 119%. Based on current molasses ethanol prices, that increase implies a post-mandate marginal cost of approximately **\$1 per liter**. While this does not make Indian molasses ethanol cheaper than corn ethanol, it still becomes **one of the cheapest LCFS fuels on the basis of cost per ton of carbon abated**.

3. The use of Indian molasses fuel ethanol either for the EBP or the LCFS does come at a cost to the poor. My PE model projects that the policy alone will **raise sorghum prices by 39%**.
4. Domestic molasses ethanol will not make a significant contribution to reducing India's oil imports because even if all the domestic molasses capacity was used to make fuel, only 4.5% of the nation's gasoline demand would be displaced.
5. Domestic agriculture can be boosted most cost-effectively by encouraging producers to get their fuel rated by low carbon fuel programs like the LCFS and export their fuel to these markets. Forcing domestic use of molasses ethanol is expensive and does not help reduce foreign oil dependence.

7.4 My View on the use of Biofuels in Low Carbon Fuel Programs

In this section, I elaborate on the opinion I stated in Chapter 6 that crop-based biofuel producers should bear the burden of proof on the use of their fuel in low carbon fuel programs. First and foremost, even if you are of the view that carbon fuel programs should be concerned with GWI alone, Plevin et al (2010) [Plevin et al., 2010] have shown that the probability distribution of ILUC GHG emissions of crop-based biofuels are skewed heavily to the right making them much more likely to be worse than currently assumed. If you agree, like I do, that the LCFS and similar programs while remaining primarily concerned with carbon, should consider other environmental and social impacts when deciding how to deal with uncertainty surrounding a biofuel, then there are other compelling reasons to make biofuel producers bear the burden of proof for allowing their product into the LCFS.

The ecological impacts of biofuels extend far beyond ILUC climate damage [Fargione and Plevin, 2010]. Their water demand is substantial and sometimes result in very polluted runoff [Fingerman et al., 2010, Fargione and Plevin, 2010]. Specifically, the demand for irrigation of first generation biofuel crops is higher on average than many grain crops [Service, 2009]. Biorefineries also emit substantial quantities of air pollutants even if these are not of the same magnitude as oil refineries.

Recent research has claimed that many cellulosic biofuel crops like miscanthus and switchgrass show a high propensity to become invasive species [BARNEY and DITOMASO, 2008, Buddenhagen et al., 2009]. When this is coupled with the fact that both first and second generation biofuel crops are associated with reduced levels of biodiversity [Groom et al., 2008], purpose grown energy crops appear to be just as bad for the local environment as any other crop.

Finally, while the economic effects of increased land competition are much less certain than the environmental impacts described above, a large scale diversion of land from food to energy crops will inevitably result in higher food prices. When even the use of molasses ethanol, a non-crop-based biofuel can indirectly raise sorghum prices, it is hard to imagine how direct competition for land by biofuel crops will not have a worse effect.

7.5 Next Research Steps

I have formed a collaborative partnership with Dr. Sergio Pacca at the University of Sao Paulo to extend this work in two ways. Dr. Pacca and I are building an economic optimization model of the entire Sao Paulo sugarcane sector that predicts the production quantities of sugar, hydrous ethanol and anhydrous ethanol of each factory based on the prices of all three commodities. The model will also be able to calculate the share of molasses and cane juice used for ethanol production based on prices for sugar and ethanol. I plan to couple my ALCA model with this to obtain an ALCA GHG emissions factor for each factory's ethanol simply based on sugar and ethanol prices. Since prices are public information, this model will be a useful tool for the regulator to perform a first-order audit of each firm. Dr. Pacca and I are also going to extend the same model to stochastically predict investment decisions in the Brazilian sugarcane sector.

I am also working with Dr. David Laborde and his team at IFPRI who are the developers of the MIRAGE model, which is a dynamic CGE model with a focus on agricultural policy and trade. We plan to include molasses as one of the commodities in MIRAGE or to couple my PE model with MIRAGE so we can have a model that has the granularity of PE and the completeness of CGE.

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Appendix A

ALCA Model Excel Worksheets

Table A.1: Indian Ethanol GREET Outputs and Calculations

| India Sugarcane ethanol results from CA-GREET | | | | |
|--|---|---|--|--|
| | LCA results from sugarcane farming before applying downstream loss factor cells EtOH' AI197-210' with region as SE Asia (g/mmBtu Anhyd) | LCA results from sugarcane farming after applying downstream loss factor cells EtOH' AI197-210' with region as CA Petroleum (g/mmBtu Anhyd) | LCA results from Ethanol manufacturing, transportation and distribution cells EtOH' AJ197-210' with region as CA Petroleum (g/mmBtu Anhyd) | LCA results from ethanol storage and transportation only (g/mmBtu Anhyd) |
| Loss factor | 1.0 | | | |
| VOC | 446.6 | 447.1 | 57.5 | 2.3 |
| CO | 5723.6 | 5729.4 | 93.5 | 6.5 |
| NOx | 303.6 | 303.9 | 144.3 | 57.6 |
| PM10 | 490.6 | 491.1 | 113.7 | 4.3 |
| PM2.5 | 246.4 | 246.7 | 54.2 | 3.2 |
| SOx | 68.0 | 68.1 | 18.9 | 14.2 |
| CH4 | 206.0 | 206.2 | 39.3 | 3.4 |
| N2O | 30.4 | 30.4 | 4.9 | 0.1 |
| CO2 | 34173.9 | 34208.1 | 3251.5 | 3148.9 |
| Total GHGs (gCO2-eq/mmBtu) | 48382.6 | 48431.0 | 5680.6 | 3255.3 |
| Calculation of Gopal-Kammen Model parameters | | | | |
| U (gCO2-eq/ton of cane) - lifecycle GHG emissions upstream of sugarcane factory | 88633.1 | | | |
| E (gCO2-eq/mmBtu anhyd EtOH) - lifecycle GHG emissions from ethanol production only | 2425.3 | | | |
| T (gCO2-eq/MJ anhyd EtOH) - lifecycle GHG emissions from the transportation and distribution of ethanol only | 3.1 | | | |

Table A.2: ALCA Model Parameters for Indian Flex Sugarcane Factory

| Gopal-Kammen Model Parameters for India ALCA | | | |
|---|---------------|---|------|
| U (gCO ₂ -eq/ton of cane) | 88633.1 | η_j (tons of fermentable sugars in juice/ton of cane) | 0.13 |
| S (g CO ₂ -eq/ton cane) - not from CA-GREET, see paper for source | 3700.0 | η_s (tons of sucrose in final sugar/ton of sucrose into sugar factory) | 0.86 |
| E (gCO ₂ -eq/mmBtu of anhyd EtOH) | 2425.3 | η_e (dry tons of EtOH/ton of fermentable sugars into distillery) | 0.48 |
| T (gCO ₂ -eq/MJ of anhyd EtOH) | 3.1 | Lower heating value of anhyd EtOH (mmBtu/dry ton EtOH) | 25.4 |
| Average P _s (INR/ton of sugar) in Indian Market for 06-07 season | INR 17,864.49 | m _s (tons of sucrose in final sugar/ton of final sugar product) | 0.95 |
| Average P _m (INR/ton of standard molasses) in India for 06-07 season | INR 2,477.90 | m _m (tons of fermentable sugars in std molasses/ton of std molasses) | 0.50 |

Table A.3: Sugar, Molasses and Ethanol Yields from a Fully Flexible Indian Factory

| Yield of raw sugar, standard molasses and Hydrous Ethanol in response to fraction of cane juice sent to make sugar | | | |
|--|---|--|--|
| Fraction of cane juice sent to make sugar with rest going directly to EtOH distillery (for India = 1) | Raw Sugar Yield (tons of raw sugar/ton of cane) | Molasses Yield (tons of standard molasses/ton of cane) | EtOH yield (liters of hyd EtOH/ton cane) |
| 1 | 0.118 | 0.036 | 11.4 |
| 0.9 | 0.106 | 0.033 | 18.4 |
| 0.8 | 0.094 | 0.029 | 25.4 |
| 0.7 | 0.082 | 0.025 | 32.3 |
| 0.6 | 0.071 | 0.022 | 39.3 |
| 0.5 | 0.059 | 0.018 | 46.3 |
| 0.4 | 0.047 | 0.015 | 53.3 |
| 0.3 | 0.035 | 0.011 | 60.3 |
| 0.2 | 0.024 | 0.007 | 67.3 |
| 0.1 | 0.012 | 0.004 | 74.3 |
| 0 | 0.000 | 0.000 | 81.3 |

Table A.4: Brazilian Ethanol GREET Outputs and Calculations

| Brazil results from CA-GREET | | | | |
|--|---|---|--|--|
| | LCA results from sugarcane farming before applying downstream loss factor cells EtOH' AI197-210' with region as SE Asia (g/mmBtu Anhyd) | LCA results from sugarcane farming after applying downstream loss factor cells EtOH' AI197-210' with region as CA Petroleum (g/mmBtu Anhyd) | LCA results from Ethanol manufacturing, transportation and distribution cells EtOH' AJ197-210' with region as CA Petroleum (g/mmBtu Anhyd) | LCA results from ethanol storage and transportation only (g/mmBtu Anhyd) |
| Loss factor | 1.001 | | | |
| VOC | 734.1 | 734.8 | 57.6 | 2.7 |
| CO | 9606.5 | 9616.1 | 91.8 | 8.1 |
| NOx | 301.8 | 302.1 | 149.0 | 65.7 |
| PM10 | 813.5 | 814.4 | 110.1 | 4.5 |
| PM2.5 | 406.9 | 407.3 | 52.5 | 3.4 |
| SOx | 47.5 | 47.6 | 19.2 | 14.7 |
| CH4 | 291.1 | 291.4 | 39.2 | 4.6 |
| N2O | 21.5 | 21.5 | 4.7 | 0.1 |
| CO2 | 8340.6 | 8349.0 | 3818.4 | 3707.3 |
| Total GHGs (gCO2-eq/mmBtu) | 22033.6 | 22055.6 | 6193.4 | 3848.8 |
| Calculation of Gopal-Kammen Model parameters | | | | |
| U (gCO2-eq/ton of cane) - lifecycle GHG emissions upstream of sugarcane factory | 40404.2 | | | |
| E (gCO2-eq/mmBtu anhyd EtOH) - lifecycle GHG emissions from ethanol production only | 2344.6 | | | |
| T (gCO2-eq/MJ anhyd EtOH) - lifecycle GHG emissions from the transportation and distribution of ethanol only | 3.6 | | | |

Table A.5: ALCA Model Parameters for Flex Brazilian Factory

| Gopal-Kammen Model Parameters for Flex Brazilian Factory | | | |
|---|----------|---|------|
| U (gCO ₂ -eq/ton of cane) | 40404.2 | η_j (tons of fermentable sugars in juice/ton of cane) | 0.14 |
| S (g CO ₂ -eq/ton cane) - not from CA-GREET, see paper for source | 3700.0 | η_s (tons of sucrose in final sugar/ton of sucrose into sugar factory) | 0.86 |
| E (gCO ₂ -eq/mmBtu of anhyd EtOH) | 2344.6 | η_e (dry tons of EtOH/ton of fermentable sugars into distillery) | 0.48 |
| T (gCO ₂ -eq/MJ of anhyd EtOH) | 3.6 | Lower heating value of anhyd EtOH (mmBtu/dry ton EtOH) | 25.4 |
| Ps (US\$/ton of sugar in Sao Paulo Mercantile Exchange) | \$330.00 | ms (tons of sucrose in final sugar/ton of final sugar product) | 0.95 |
| Pm (US\$/ton of standard molasses) | \$90.00 | mm (tons of fermentable sugars in std molasses/ton of std molasses) | 0.50 |

Table A.6: Sugar, Molasses and Ethanol Yields for Flex Brazilian Factory

| Yield of raw sugar, standard molasses and Hydrous Ethanol in response to fraction of cane juice sent to make sugar | | | |
|--|---|--|--|
| Fraction of cane juice sent to make sugar with rest going directly to EtOH distillery (for Sugar Group = 1) | Raw Sugar Yield (tons of raw sugar/ton of cane) | Molasses Yield (tons of standard molasses/ton of cane) | EtOH yield (liters of hyd EtOH/ton cane) |
| 1 | 0.127 | 0.039 | 12.3 |
| 0.9 | 0.114 | 0.035 | 19.8 |
| 0.8 | 0.101 | 0.031 | 27.3 |
| 0.7 | 0.089 | 0.027 | 34.8 |
| 0.6 | 0.076 | 0.024 | 42.4 |
| 0.5 | 0.063 | 0.020 | 49.9 |
| 0.4 | 0.051 | 0.016 | 57.4 |
| 0.3 | 0.038 | 0.012 | 64.9 |
| 0.2 | 0.025 | 0.008 | 72.5 |
| 0.1 | 0.013 | 0.004 | 80.0 |
| 0 | 0.000 | 0.000 | 87.5 |

Appendix B

Full CLCA Model MATLAB Source Code

B.1 The PE Model Function Code

```
function F = pemodv2( moletghg,Qm0607,Qfem,Jmfe,Jmsbe,Chg,Jgbe,Cbenf,Qgto)
%pemod PE Model of molasses related markets in India
F = [moletghg(1) - Qm0607;
moletghg(2) - (Qfem/Jmfe);
moletghg(1) - moletghg(2) - moletghg(3);
moletghg(4) - Jmsbe*moletghg(3) - Jgbe*moletghg(5); (moletghg(6)+Chg)/Jgbe -
moletghg(7)/Jmsbe;
(moletghg(6)+Chg)/Jgbe + Cbenf - moletghg(8); moletghg(4) + 5.345e7*moletghg(8) - 3.1e9;
Qgto + moletghg(5) - 171.4*moletghg(6) - 5.9e6];
end
```

B.2 The PE Model Solving Code

```
clear all;
Qm0607 = 10.7e6;
Qfemdt = 1906e6;
Qfem = Qfemdt + 267.1e6;
Jmfe = 204;
Jmsbe = 214;
Chg = 1050;
```

```
Jgbe = 350;  
Cbenf = 9;  
Qgto = 7.4e6;  
moletghg0 = [10.7e6; 1.309e6; 9.346e6; 2e9; 0; 8634.72; 2477.9; 20.58];  
options=optimset('Display','iter','MaxFunEvals', 10000,'MaxIter',2000);  
fn = @(moletghg)pemodv2(moletghg,Qm0607,Qfem,Jmfe,Jmsbe,Chg,Jgbe,Cbenf,Qgto);  
[moletghg, fval] = fsolve(fn,moletghg0,options)
```