Alternative Energy Science and Policy: Biofuels as a Case Study

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ABSTRACT

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This dissertation studies the science and policy-making of alternative energy using biofuels as a case study, primarily examining the instruments that can be used to alleviate the impacts of climate change and their relative efficacy. Three case studies of policy-making on biofuels in the European Union, United States of America and Brazil are presented and discussed. It is found that these policies have had large unintended negative consequences and that they relied on Lifecycle Analysis studies that had concluded that increased biofuels production can help meet economic, energy and environmental goals. A close examination of these Lifecycle Analysis studies reveals that their results are not conclusive. Instead of continuing to attempt to find answers from Lifecycle Analyses, this study suggests an alternative approach: formulating policy based on recognition of the ignorance of real fuel costs and pollution. Policies to combat climate change are classified into two distinct approaches: policies that place controls on the fuels responsible for emissions and policies that target the pollutants themselves. A mathematical model is constructed to compare these two approaches and address the central question of this study: In light of an ignorance of the cost and pollution impacts of different fuels, are policies targeting the pollutants themselves preferable to policies targeting the fuels? It is concluded that in situations where the cost and pollution functions of a fuel are unknown, subsidies, mandates and caps on the fuel might result in increased or decreased greenhouse gas emissions; on the other hand, a tax or cap on carbon dioxide results in the largest decrease possible of greenhouse gas emissions. Further, controls on greenhouse gases are shown to provide incentives for the development and advancement of cleaner alternative energy options, whereas controls on the fuels are shown to provide equal incentives to the development of cleaner and dirtier alternative fuels. This asymmetry in outcomes—regardless of actual cost functions—is the reason why controls on greenhouse gases are deemed favorable to direct fuel subsidies and mandates.

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I dedicate this work to my parents and to my grandparents.

Everything I do in life is an attempt to thank you for all you have given me.

Chapter I: Introduction and Overview

This dissertation deals with the subject of climate change—the measured increase in global temperatures as a result of an increase in human emissions of greenhouse gases. There are four big questions that shape the discussion of climate change and what to do about it[1]; this dissertation will deal primarily with the question of the instruments that can be used to alleviate the impacts of climate change and the question of the trade-offs between different instruments and tools. The other two questions concerning the impact of emissions on climate, and the impact of changing climate on human society are beyond the scope of this paper.[2]

In dealing with the aforementioned two questions, this study analyzes one of the most prominent alternative energy sources that has been touted as a tool to fight climate change—biofuels. This dissertation studies the science and policy-making of alternative energy, by using biofuels as a case study. The past decade has witnessed an unprecedented and historical rise in the production and consumption of biofuels in the United States of America, Brazil and the European Union. This rise was combined with expectations that biofuels would play a leading role in reducing greenhouse gas emissions, reducing dependence on foreign imports of energy, alleviating the problems of a perceived declining stockpile of fossil fuels, helping rural

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1 I thank Professor David Nissen for this framing of the questions

2 The reader is referred to the analysis of the IPCC Fourth Assessment Report (2006) and the Stern Report (2006)

development and providing a chance at export-led growth for developing countries. Over the years, reality does not seem to have materialized in that way.

A backlash has developed over the production of these biofuels, and there has been a lot of criticism of their production as being responsible for increasing greenhouse gas emissions, increasing fossil fuel consumption, increasing food prices during the 2007-08 food crisis, playing a major role in deforestation in Brazil, Indonesia and Malaysia, leading to large losses in biodiversity, causing damage to water aquifers and the Gulf of Mexico, generating a large investment bubble that collapsed, and consuming enormous amounts of government subsidies (See Chapter 3.d.).

This study contends that the reason for these negative consequences is in the policies enacted to support biofuels, which were based on evidence of their suitability that was not convincing. These policies aimed at reducing greenhouse gas emissions by mandating and subsidizing increased biofuels consumption and production. But this was done in light of an ignorance of the actual costs and pollution functions of biofuels, and resulted in disastrous negative consequences. A superficial accounting of costs and pollution from these fuels showed that their utilization would be favorable, but a more thorough study of their knock-on effects, particularly when including land-use change effects, reveals reasons for concern that they might cause more harm than good.

An alternative approach to understanding policy-making is suggested, whereby policies to combat climate change are classified into two distinct approaches: policies that place controls on the fuels responsible for emissions (through taxes, subsidies and mandates), and policies that target the pollutants themselves (through taxes or quantity mandates).

The research question this dissertation addresses is: In light of an ignorance of the cost and pollution impacts of different fuels, are policies targeting the pollutants themselves preferable to policies targeting the fuels?

The two policy tools are compared in light of the ignorance of cost and pollution functions of the fuels, with realistic assumptions about the shapes of these functions. It is concluded that in situations where the cost and pollution functions of a fuel are unknown, subsidizing, mandating or capping its consumption might result in increased greenhouse gas emissions, whereas a tax on carbon cannot increase greenhouse gas emissions. This asymmetry in outcomes—regardless of actual cost functions—is the reason why controls on greenhouse gases is deemed favorable to direct fuel subsidies and mandates. Further, controls on greenhouses gases are shown to provide incentives for the development and advancement of cleaner alternative energy options, whereas controls on the fuels are shown to provide equal incentives to the development of cleaner and dirtier alternative fuels.

Chapter II provides general background and context to the study of biofuels and climate change. Biofuels are defined, and are situated in the historical context of energy resource development, and the global realities of biofuels are discussed. The basics of climate change are explicated and its relationship with biofuels, agriculture, land use change are outlined.

Chapter III provides a basic overview of the development of policies on biofuels in the three main players in the biofuels stage globally: the United States of America, the European Union and Brazil. This is followed by a discussion of the consequences of the increases in biofuels production. Policies in the US and EU were aimed at reducing GHG emissions through increased biofuels use. The actual consequences of these policies are ambiguous in that regard, and there is considerable literature suggesting that increased biofuels consumption had a net negative impact on emissions and a host of other environmental problems. The policies were based on the assumption that increased biofuels use would correspond to reduced GHG emissions, but this, it turns out, cannot be taken for granted, and in order to know whether it is true, we need to analyze the scientific literature on whether increased biofuels use does in fact correspond to reduced GHG emissions.

Chapter IV takes a look at the literature that examines the question of biofuels efficiency, and analyzes it for Brazilian ethanol, American corn ethanol, biodiesel and cellulosic ethanol. The evidence is not conclusive in any of these cases, and there are widely disparate results in the literature, with results supporting any conclusion possible. Chapter V critically examines this literature to understand the disparities in results. It is found that there are serious methodological problems with Lifecycle Analysis studies that explain this disparity in results and make any claims about the shape of the cost and pollution functions to be ambiguous—particularly when the knock-on effects of land use change are included. Since these studies have serious limitations, and their results are ambiguous, it is suggested that the current EU and US model of making policies to target increases in alternative fuels might be a flawed approach.

Chapter VI analyzes the literature on pollutant controls, outlining the main landmarks in this literature—the Coase Theorem, Pigouvian taxes, the debates on price vs. quantity controls and the uncertainty over the right amount of price and quantity restrictions. In light of the ignorance of the actual cost and pollution functions of biofuels, and ignorance of whether they cause an increase in GHG emissions, a new framework is suggested for assessing policy tools. This framework aims to analyze the effects of different policy regimes given the fact that the actual cost and pollution functions are unknown. This is based on Nassim N. Taleb's approach of thinking about how to deal with and domesticate the unknown.

Chapter VII offers an analytical modeling exercise motivated by the analysis of the previous chapters. The starting point of the model is that the cost functions of different fuels are unknown, but that their shapes, or qualitative behavior, can be known based on the literature review of the previous chapter. To be specific, fossil fuels are assumed to have a marginal private cost increasing at a constant rate, with a marginal social pollution cost that is also increasing at a constant rate, but that is double the private cost. This is consistent with the literature that suggests the consumption of fossil fuels has negative externalities that exceed its private costs borne by the consumer. The alternative fuels are modeled after biofuels, and are assumed to have a strictly convex marginal cost function that starts off very cheap but rises quickly as the amount of biofuels utilized increases. This assumption is derived from the analysis of the Lifecycle Analysis which is almost unanimous in finding that at small concentrations, biofuels have low social and private costs, but that this increases drastically as production is increased and moved to less efficient lands, where land use change effects make the fuels very costly privately and socially. Two other forms of biofuels alternative energy are included later in the model, both having fixed costs that prevent their utilization in the no policy state, but one being cleaner and the other being dirtier than the normal biofuels. These two forms of biofuels are inspired by the biofuels literature on cellulosic ethanol and Indonesian palm oil.

The model compares the results of imposing a tax on carbon dioxide emissions to imposing a mandate that increases biofuels consumption. The result is that mandating increased biofuels use could lead to an increase or a decrease in emissions and costs, depending on the parameters that define the cost and pollution functions and the level of the mandate. The tax, however, can only lead to a reduction in the level of emissions—whatever the parameters that define the cost and pollution functions and the level of the tax.

Furthermore, mandating increased biofuels consumption will incentivize the development and adoption of both the cleaner and dirtier forms of energy, whereas taxing the carbon dioxide emissions will incentivize the development and adoption of the cleaner energy sources.

The key result here is inextricably linked to the unknowability of the cost function, which introduces the asymmetry in the outcomes of the mandate and tax policies. Whatever the actual cost function, any level of taxation will lead to a reduction in emissions; but the mandate will only lead to a reduction in emissions depending on the particular values of the cost function and the level of mandates.

The final chapter concludes and overviews the dissertation and its results, provides some qualifications and potential drawbacks of the tax mechanism, and suggests policy implications.

Chapter II: Background and Context

This chapter provides a general background as an introduction to the analysis of biofuels, in order to situate the rest of the discussion of this paper. The context of energy being ultimately derived from the sun is explicated, followed by an illustration of the quantities of energy consumed compared to resources underground. The technical aspects of biofuels production are discussed. Some background on the use and production of biofuels is provided. The chapter then discusses the basics of climate change and the role that biofuels could play in mitigating carbon emissions, explaining their role in the transportation, agriculture and land use change sources of emissions.

a. Bioenergy in Context

The sun is the ultimate source of all energy on planet earth[3]. All of the energy utilized today is solar energy transformed. Biomass energy is obtained from recent biomass that has grown through absorbing sunlight. Fossil fuels are fossils that have been underground for a very long time, concentrating the solar energy that had been embodied in the living material through millions of years.

3 Except nuclear, geothermal and tidal energy, which are not from the sun.

Throughout pre-modern history, biomass was the major source of energy for humans. Biomass constituted around 90% of human energy consumption until the beginning of the 19th Century. It was the invention of the steam engine around the end of the 18th century that spurred forward the utilization of coal as a significant energy source, and signaled the beginning of the industrial, urban, modern era with its reliance on fossil fuels to meet the stratospherically rising energy needs of the modern human. The invention of the Internal Combustion Engine around the turn of the twentieth century was, in turn, what saw the move towards oil as the major source of energy.

Turning towards fossil fuels marked a qualitative and significant change in human utilization of energy. Utilizing biomass and solar energy--as most humanity did until fossil fuels came about--meant that the energy consumed has always been a fraction of the recent solar energy absorbed by the earth. Human consumption of energy always remained at a tiny fraction of the earth's primary photosynthetic productivity (the amount of solar energy absorbed on earth to produce biomass). This also meant that earth was accumulating energy over time as sunlight falling on earth far exceeded human consumption, and that energy was being stored in biomass and fossils.

But tapping into fossil fuels changes this. Jeffrey Dukes' *Burning Buried Sunshine* provides a useful calculation that can help conceptualize the magnitudes dealt with when discussing different sources of energy. According to Dukes, human consumption of energy exceeded earth's primary photosynthetic productivity in the year 1888. We are now drawing down on the energy that has accumulated over billions of years under the surface of the earth. Dukes estimates that "[a]pproximately 44 Eg (44×10^{18} g; limits: 0.5 Eg and 15×10^{3} Eg) of photosynthetic product-carbon were necessary to generate the fossil fuels burned in 1997. This is equivalent to 422 times the net amount of carbon that is fixed globally each year, or 73 times the global standing stock of carbon in vegetation."[4] This means that in 1997 humans consumed the amount of energy that is absorbed by the earth from the sun in 422 years. This amount absorbed, it is worth remembering, is not all transformed to fossil fuels in the long term, and so this number is an underestimate of the time it took to accumulate these fossil fuels.5

As human population increases, along with incomes and living standards, we are increasingly drawing on a reserve of fossil fuels that have accumulated over billions of years. This means that these resources are not "renewable" since replacing them will take a very long time—orders of magnitude larger than the time it takes to consume then. It is from this context that we need to start understanding the issue of biofuels. Biofuels offer humanity the prospect of weaning ourselves off of fossil fuels, and moving back towards biomass as a source of energy--meaning the utilization of recent solar energy.

Yet even as we moved into fossil fuel use, utilizing energy from biomass continues to constitute a major share of the energy consumption of humanity, according to the International Energy Agency[6], in 2004, 11.1% of the Total Primary Energy Supply of the world came from 'Combustible Renewables and Waste', amounting to some 46 ExaJoules per year. -6 EJ is utilized in developed countries, and 38EJ in developing countries. Almost one half of all biomass energy is used in developing country cookstoves, which is usually an inefficient and unhealthy application. Throughout history, as societies have developed economically and become richer, they have moved away from biomass as an energy source, resorting to fossil fuel consumption, hydropower, nuclear energy or other technologically advanced sources.

4 Dukes, 2003. P.37
5 I thank Professor Klaus Lackner for clarifying this point.
6 IEA, 2004

However, today, we are witnessing an increase in the utilization of biomass in rich and middle-income economies as an alternative fuel. This is not being utilized in the traditional methods of small-scale burning in cookstoves, but rather in two main systems: transportation biofuels; and production of heat and power from biomass. This paper will only deal with the use of transportation biofuels.

Another way to frame the context of biofuels as an energy source is to look at the size of fossil fuel reserves as compared to the current consumption. H.H. Rogner (1997) provides an optimistic conclusion based on this calculation. Rogner distinguishes energy sources into three categories: Reserves, Resources and Additional Occurrences. Reserves are "occurrences that are identified, measured, and at the same time known to be technically and economically recoverable. Thus, reserve estimates inherently depend on the state-of-the-art of present exploration and production technologies as well as on the prevailing and anticipated market prices."[7]

Rogner defines resources as "occurrences with less-certain geological assurance and/or with doubtful economic feasibility." Additional occurrences are quantities "with unknown degrees of assurance and/or with unknown or without economic significance." Total reserves are 1,669 Gtoe (Gigaton oil equivalent), while extended resources are 3,415 Gtoe while additional occurrences tally up to 23,815 Gtoe. Total global energy consumption, on the other hand, in 1994 was 7.40 Gtoe.[8] The total amount of carbon-based energy consumed from 1860 to 1994 is around 291 Gtoe. If global fossil fuel consumption were to remain at its 1994 rate, it would take 225 years to consume the reserves, 459 years to consume the extended resources. If global fossil

7 Rogner, 1997.
8 Rogner, 1997.

fuel consumption were to triple from its 1994 level, we would still need 75 years to go through only the reserves, while we'd need 153 years to consume the extended resources. This estimate suggests that the problem of running out of fossil fuel energy is not very pressing at this point in time. The environmental imperative for biofuels use, however, is more powerful and will be discussed after the introduction of biofuels.

b. What Are Biofuels?

According to Robert C. Brown:

> "Biorenewable Resources, sometimes referred to as biomass, are organic materials of recent biological origin. This definition is deliberately broad with the intent of distinguishing fossil fuel resources from the wide variety of organic materials that arise from the biotic environment. Biorenewable resources are generally qualified as either *wastes* or *dedicated energy crops.*"[9]

Though they may be grown as crops, the vast majority of the world's biorenewable resources are forests, prairies, marches, and fisheries. Bioenergy is the conversion of the chemical energy of a biorenewable resource into heat and stationary power. Biofuels, in particular, is a term that refers to any solid, liquid or gas transportation fuel that is derived from biomass.

For the purposes of this paper, we will not be concerned with wastes as an energy source, but will concentrate on dedicated energy crops, which Brown defines as "plants grown specifically

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9 Brown, 2003, p.59

for production of biobased products; that is, for purposes other than food or feed"[10]—particularly those grown for transportation fuels, and not for stationary heat.

For a crop to be a suitable source of energy it would contain one or more of the main energy-rich components: oils, sugar, starches and lignocellulose.[11] Lignocellulose has a higher energy content than the three other energy-rich components, and is available in larger quantities, which is why they are widely touted as the sustainable and useful future of biofuels, especially in America. Table 1 offers a classification of biofuels according to the energy-rich component, the source plants, and the fuel that emerges from it.

Table 1: Classification of Biofuels

Energy-rich component	**Source**	**Fuel**
Oil	Palm oil, rapeseed	Biodiesel
Sugars	Sugarcane, soghrum	Ethanol
Starches	Corn	Ethanol
Lingocellulose	Switchgrass, wood	Ethanol

These dedicated energy crops can be used for several purposes and to produce several products: food, edible oils, chemicals, stationary energy production (heat and/or power), transportation fuels, and fibers. For this paper we will only consider their importance as

10 Brown, 2003, p.59
11 Brown, 2003, p.60

producers of transportation energy, though the impact that biofuels have had on food prices will be explored.

Transportation fuels are defined as "chemicals with sufficient energy densities (enthalpies of reactions per unit volume) and combustion characteristics to make them suitable for transportation applications."[12] Biofuels can be both gaseous (hydrogen and biogas) or liquid (ethanol, biodiesel).

The three main biofuels that can be used for transportation purposes today are methanol, ethanol and biodiesel. There are three main types of transportation fuels in general (non-biobased): gasoline, diesel and jet fuel.

Ethanol and Methanol can be used as substitutes for gasoline. Though ethanol contains 66% of the heating value of gasoline, which is a considerable obstacle for the development of ethanol as a substitute for gasoline. If a car maintains the same fuel tank size, then its range will be reduced 33% percent if it substitutes ethanol for gasoline; otherwise, if the car employs a larger fuel tank to increase its range, that would result in increased inefficiency through increased size and weight for the car. Often when comparisons are made in the popular press about the price of ethanol and gasoline[13], the comparison is made on a gallon or liter basis. This comparison is misleading; a correct comparison would be made on the basis of the energy delivered per monetary unit rather than volume per monetary unit. Biodiesel however, chemically, is methyl or ethyl ester, and as its name implies, is a useful substitute for diesel fuels, since it has a high cetane number.

12 Brown, 2003, p.60
13 See, as an example, Zakaria, 2005

So far, there seems to be no viable biofuel that can be used to substitute or enhance jet fuel; however, the US Department of Energy National Renewable Energy Laboratory is currently experimenting with producing fuel for jets from Microalgal Lipids.[14] Virgin Airlines and Air New Zealand[15] have flown two trial flights with biofuels blended in the fuel mix.

Table 2: Conventional transport fuel and their biofuel replacements

Conventional Transportation Fuel	**Biofuel replacement**
Gasoline	Ethanol, methanol
Diesel	Biodiesel/vegetable oil
Jet Fuel	synthetic jet fuel from vegetable oil

c. Global Context

Recently, two global phenomena have sparked a rise in interest in biofuels. The first is the rise of oil prices. Due to several reasons—large increases in demand from China and India, political instability in several oil producers and various other factors—oil prices have risen almost continuously from early 2002 to 2008 (See Figure 1). In July 2008, oil prices peaked at $144 per barrel, their highest value ever in real and nominal terms.[16] Prices have since moderated somewhat and in August 2010 they are at around the $70 mark, still above historical inflation-adjusted averages.

14 National Renewable Energy Laboratory. 1998
15 Biello, David. 2008.
16 The Economist, Sept 28, 2006, "The Heat Is Off"

Figure 1 shows the large rise in real oil prices over the last decade, expressed in 2010 US Dollars.[17]

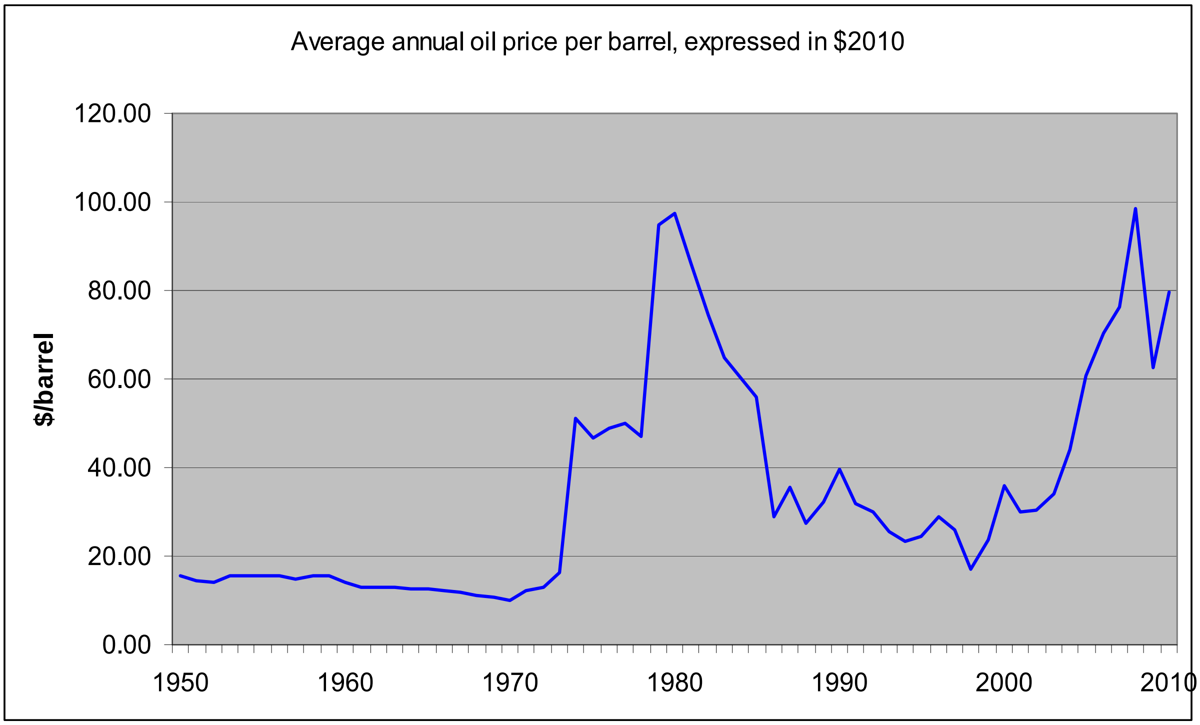

Figure 1: Global Oil Prices, in $2010

The other important driver of interest in biofuels is the rise of interest in—and awareness of—climate change. There is now an almost unanimous scientific consensus that human-induced global climate change is a real danger facing humanity.[18] Many governments have begun taking action towards reducing emissions, and there is a growing global movement towards reducing these emissions.

17 BP Statistical Review of World Energy, which can be accessed on: http://www.bp.com/statisticalreview
18 Stern Report, 2006

As these two concerns have grown recently, attention has turned towards finding alternative forms of energy to traditional fossil fuels. Finding cheap and clean energy would reduce the amount of pollutants and Greenhouse Gases (GHG) and reduce the pressure on global economies from rising oil prices. According to the United Nations Environmental Program, investment in 'clean energy' has risen from $33.2 billion in 2004 to $58.5 billion in 2005 to $92.6 billion in 2006, and a remarkable $148 billion in 2007.[19]

At the forefront of this push to find clean energy are biofuels. Though certainly not a new fuel, biofuels have been attracting great attention recently and production has increased dramatically in several countries, most notably Brazil and the United States of America. Brazilian ethanol comes from the sugar-rich sugarcane crops which are abundant in Brazil, whereas American ethanol comes from the starch-rich corn crops ubiquitous in America. This increased interest raises various questions about the usefulness and sustainability of biofuels, and whether pursuing them is a viable energy strategy in the long-term. To address these questions, research is being done on various issues related to biofuels: their efficiency, cost of production, applicability, potential production capability, social impacts, environmental impacts and more.

There is a large array of different biofuels produced all over the world, from different feedstocks and with different procedures. This paper will focus its analysis on the four most prominent types of biofuels. These are: Brazilian sugar-cane-based ethanol, American corn-based ethanol, biodiesel and cellulosic ethanol.

Brazil has long been the leader in utilizing biofuels. As early as 1920, ethanol was utilized as a fuel in Brazilian cars, and in 1931 the government passed the first laws decreeing a 5% blending

19 UNEP, 2008

of ethanol in fuels. In 1975 Brazil initiated the Proalcool Program aimed at increasing the production of biofuels and cars began to substantially blend ethanol with gasoline. Today all gasoline sold in Brazil continues to have between 20-26% ethanol by volume.[20] Brazil was the global leader in ethanol production until 2004, with 3,989 million gallons produced, and was only overtaken by the United States in 2005, when ethanol production in Brazil totaled 4,227 million gallons.[21]

Ethanol production in the United States of America is not as old or established as it is in Brazil. American ethanol production is almost entirely derived from corn feedstocks. The efficiency of this ethanol is widely debated among academics, journalists, politicians and the public.[22] It has historically lagged behind Brazil and still constitutes a far smaller share of total energy consumption. However, with extensive subsidies, government support and import tariffs on foreign ethanol, the American industry has picked up production in the recent years, finally overtaking Brazil in 2005 when production totaled 4,264 million gallons.[23] American ethanol production continued to increase rapidly in the following years, more than doubling from 2005 to 2008 to reach 9000 million gallons, constituting more than 50% of global ethanol production.

Together, Brazil and the USA produce around 80% of world ethanol production (See Table 3 and Figure 2), and studying them is important from an economic and environmental perspective, as they will largely be the two players that will determine the most the global status of biofuels. Further, since the USA is the richest country in the world and the biggest consumer of energy, the future of biofuels consumption there will have important global

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20 Sellers, Rick. 2004
21 F.O. Licht. 2006 "World Ethanol Outlook to 2015"
22 Wall Street Journal. June, 9, 2006. "Digging Into The Ethanol Debate."
23 Wall Street Journal. June, 9, 2006. "Digging Into The Ethanol Debate."

implications. Also, since ethanol production involves the use of large lands in agriculture, and Brazil contains the world's largest rainforest, the Amazon, the environmental impacts of increased ethanol production is an extremely important issue.

Table 3: World Ethanol Production, 2008[24]		
Country	Millions of Gallons	Percentage
USA	9000	51.9174858
Brazil	6472.2	37.3355946
European Union	733.6	4.23185195
China	501.9	2.89526513
Canada	237.7	1.37119849
Other	128.4	0.74068946
Thailand	89.8	0.51802114
Colombia	79.29	0.45739305
India	66	0.38072823
Australia	26.4	0.15229129
Total	**17,335.20**	100

24 Source: Renewable Fuels Association website: http://www.ethanolrfa.org/pages/statistics/. Last accessed August 2010.

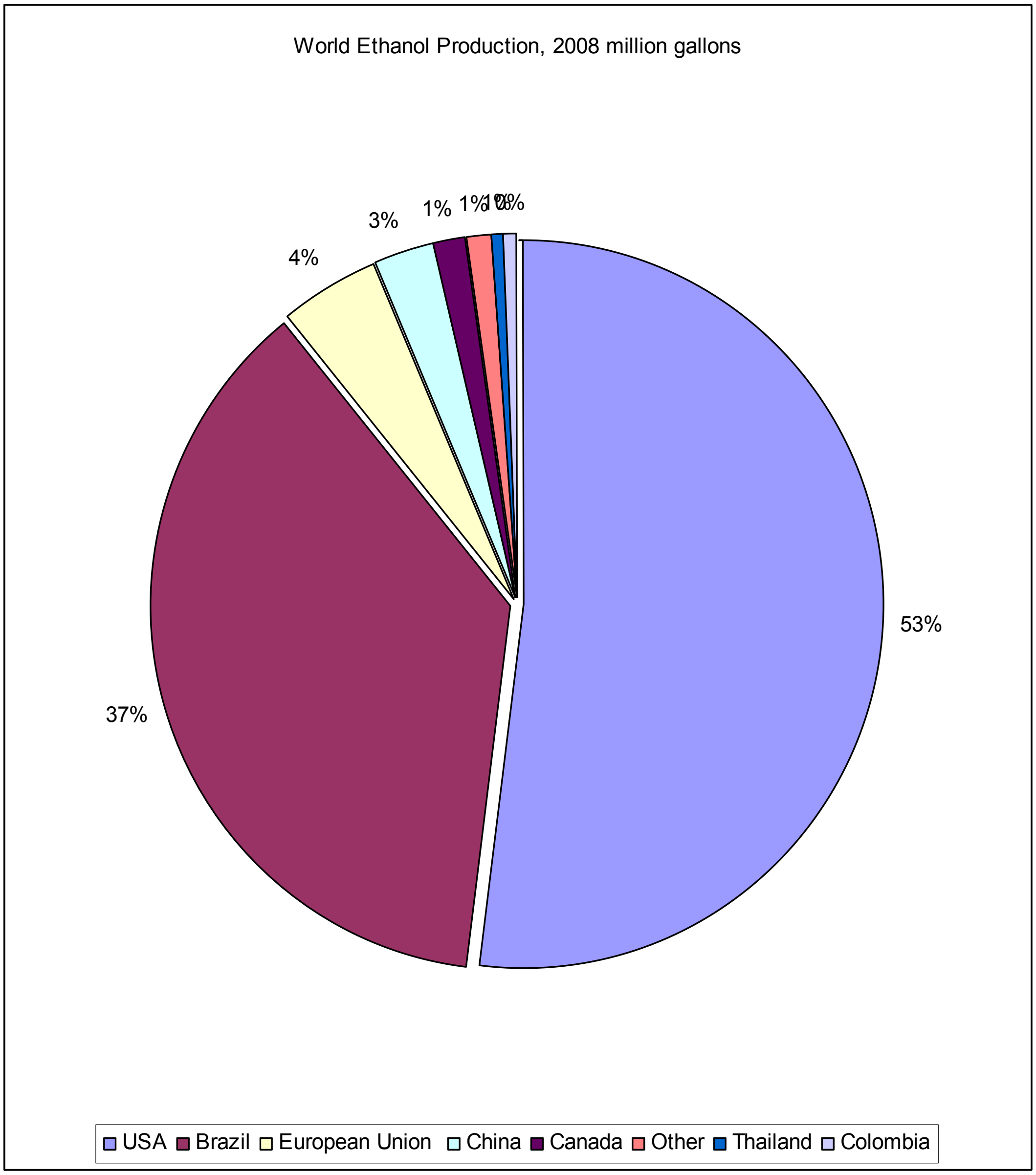

Figure 2: World Ethanol Production, 2008

Europe, however, is the world leader in production and consumption of biodiesel. Germany is the world's largest producer, with 1,920 million liters, followed by France with 511, the United States with 290 and Italy with 227. [25]

The production of biodiesel has also grown rapidly in recent years, rising from less than 1 billion liters to almost 11 billion liters in 2007.[26] The fourth type of biofuels, cellulosic ethanol, has not yet been produced on commercial scales, and there are significant impediments to its introduction into markets, as will be discussed in the next chapter.

d. Global Warming and Biofuels

Global Warming is a term used to describe the observed increase in the Earth's average surface temperature in the recent decades. According to the Intergovernmental Panel on Climate Change Third Assessment Report[27], the average temperature of the earth has risen by 0.6 degrees Celsius over the twentieth century (with a 0.2 degree margin of error).

There is now a virtual consensus among the scientific community that climate change has been happening and that it is caused by human activity. The IPCC Third and Fourth Assessment Reports, released in 2001 and 2007, respectively, and the Stern Review on the Economics of Climate Change, released in 2006 are viewed as the most conclusive and comprehensive reviews of the science and economics of climate change. Not only do these reports confirm that global climate change is human-induced, but also that the costs and effects of it are likely to be catastrophic for humanity unless serious action is taken.

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25 Source: Licht 2006
26 UNEP, 2009
27 IPCC, 2001

The cause of anthropogenic climate change is the increase in the concentration of Greenhouse Gas Emissions, particularly Carbon Dioxide. The World Resource Institute quantifies the sources of GHG emissions as being 24% Power Generation, 18% Land Use Change, 14% Agriculture, 14% Transport, 14% Industry, 8% Buildings, 3% Waste and 5% other energy related emissions. On its own, transportation is responsible for 5,743 $MtCO_2e$.[28]

From here it is tempting to conclude that action towards reducing emissions must tackle emissions from transportation. There have been several ideas put forward towards achieving this end, but one of the most prominent of these ideas has been the utilization of biofuels to replace fossil fuels in transportation. To this end, the development of ethanol, methanol, biodiesel has been gathering pace over the last years. There is also talk of using biogas, or hydrogen as a biofuel for some transport applications.[29]

It is instructive here to compare the magnitudes of the energy and environmental problems for this analysis. As discussed above, the amount of recoverable reserves of coal, oil and gas are very large compared to current consumption patterns, which means that running out of energy sources is not that pressing an issue in the short and medium terms. The climate change problem, however, is likely far more urgent.

The current concentration of carbon dioxide in the earth atmosphere is around 390 parts per million (ppm), and it is rising at an approximate rate of 1.9ppm per year, coming from 7 Gigatons of Carbon per year (GtC/year). This compares to a pre-industrial concentration of 280ppm. If humanity were to continue producing at the current rate for another 50 years,

28 Total emissions are measured in Giga-Tons of Carbon Dioxide Equivalent—a measure which weighs other gases according to the equivalent weight of CO_2 that produces their impacts.
29 See Worldwatch Institute, 2006

carbon concentrations would rise to around 500ppm. This is the level at which the 4th IPCC report aims to stabilize emissions in the long-run. But the rate of emissions is currently growing, and is projected to double by 2054 by Pacala and Socolow if emissions were to continue in a 'Business As Usual' scenario[30]. If this does happen, emissions will rise dangerously far above 500ppm by 2050, and cause large disastrous impacts on the planet.

If we compare these projections with the projections of fossil fuel consumption we can get an idea of the different magnitudes of the threats of depleting supplies and climate change. If consumption and emissions were to grow at similar rates to recent trend growth, it would be centuries before we run out of even the extended resources, while many additional resources can still potentially be uncovered, while we would be facing significant environmental risk by 2050 from increased CO_2 emissions.

The conclusion drawn from this is, as David Nissen put it: "We will run out of environment much sooner than we ever run out of energy."[31] Humanity will likely run into trouble from its fuel consumption much sooner than it has to worry about depleting its fuels. Thus, for the remainder of this study, the issue of biofuels will be primarily dealt with in terms of its impact on climate change.

In order for stabilization of emissions to happen, we would need to maintain emissions at their current level for the coming decades. Pacala and Socolow have produced an important study that discusses how such a target can be achieved. They argue that the goal of reducing carbon emissions is possible if we deploy seven "wedges" that can reduce the amount of emissions at a

30 Pacala and Sokolow. 2004
31 Nissen, David, 2008 guest lecture in Challenges to Sustainable Development class.

rate increasing up to 1GtC/year in the next 50 year (totaling to a cumulative reduction of 25GtC). They identify 15 potential wedges, one of which is the use of biofuels.[32]

For biofuels to be one of the seven successful wedges, however, the amount of biofuels produced needs to go up 50-fold from the level of production in 2003. Such a quantity of production would require around one-sixth of the world's cropland to be dedicated to growing energy crops[33]. The authors do not consider in depth the cost and pollution implications of such a drastic increase in biofuels production.

The Pacala and Socolow paper provides a good starting-point for the analysis of biofuels in this study. The fundamental point about their analysis is that it assumes that the way to tackle climate change is through ramping up one of the energy sources that supposedly lessens emissions. This study will attempt to compare the approach to the problem of climate change through advancing and promoting particular solutions (like Pacala and Socolow's "wedges") to an approach that remains neutral to specific solutions while targeting the problem of pollutants itself (such as a carbon tax).

e. Biofuels, Agriculture and Emissions

However, an important consideration that is often ignored when discussing biofuels is the impact that the increased agricultural activity for producing biofuels will have on GHG emissions in particular, and the environment in general. As discussed above, 14% of global GHG emissions come from agriculture—a share equivalent to transport. According to the

32 Pacala and Sokolow, 2004
33 Pacala and Sokolow, 2004

World Resource Institute (2006), 46% of these emissions are N_2O, 40% are CH_4, and the remaining 9% are CO_2. The CO_2 emissions from agriculture come mainly from the energy used in producing agricultural products (electricity and fossil fuels.)

Soils management (fertilizer use, tillage and cropping practices) accounts for about 40% of the total emissions[34], and livestock methane emissions account for 27%[35]. Wetlands rice cultivation and manure management are other main sources.[36]

While wetlands rice cultivation, manure management and livestock emissions are unlikely to be affected by increased biofuel production[37], the other factors would certainly be affected. Biofuels will increase the amount of energy that goes into agriculture, as well as fertilizer use and several other agricultural practices that will increase CO_2 emissions.

Another effect on agriculture will be that increased demand on certain crops that are edible will raise their price. In a world where 2 billion people live in poverty, a billion of whom live in extreme poverty, this is an important moral issue, particularly as a majority of biofuel production takes place in developing countries. However, it is not the scope of this paper to discuss this issue.

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34 WRI, 2006
35 WRI, 2006
36 WRI, 2006
37 One possible effect biofuels may have on these agricultural practices is that they would compete with corn and other food crops for land area, thereby driving up these crops' prices and leading to a substitution effect whereby farmers produce more and more of rice and other crops to substitute for corn and other displaced crops. As far as my review of the literature shows, there has not been an investigation of whether such a link exists, and even though it is slightly tenuous, the link remains possible.

f. Biofuels, Land Use Change and Emissions

Another important consideration is that impact of emissions from Land Use Change and Forestry (LUCF), which as discussed above, account for 18% of global emissions—a share larger than either agriculture or transport. LUCF also contributes 24% of CO_2 emissions. During the 1990s, 16.1 million hectares of the world's forests, mainly in the tropics, were converted to other land uses, resulting in about 1.6 GtC released per year.[38] According to WRI these estimates reflect "the CO_2 flux (emissions and sink absorptions) from the following activities: land clearing for permanent croplands (cultivation) or pastures (no cultivation), abandonment of croplands and pastures (with subsequent regrowth), shifting cultivation, and wood harvest (industrial and fuelwood). The largest source is deforestation driven by the conversion of forest to agricultural lands, primarily in developing countries."[39]

Houghton suggests that the two countries most responsible for these emissions are Indonesia (at 24%) and Brazil (at 18%).[40] The largest potential for biofuel production exists in developing countries in the tropics with significant forests. Mass utilization of biofuels may well lead to a reduction in the use of fossil fuels, but this will likely come at an increased rate of deforestation and intensive agriculture, which will reduce natural carbon storage in forests, but increase emissions.

The significance of this issue cannot be left out of the study of biofuels. Should biofuels production continue to increase, it will cause large amounts of Land Use Change that will

38 FAO, 2001
39 World Resource Institute, 2006
40 Houghton, 2003. It is worth noting that there is uncertainty over these figures, and the UNFCC data, taken from national communications, sometimes varies considerable with the estimates of Houghton (2003).

increase GHG emissions. Fossil fuel burning releases Carbon that has been locked up underground for millions of years, whereas burning of biofuels will release carbon that was captured by the plants from which the biofuels were made as they were growing. Technically, re-releasing this carbon into the atmosphere has a zero net effect: the plants absorbed the carbon when they grew, and burning them has returned them to the atmosphere. However, the reality is slightly more complex. Had these bioenergy crops been planted in areas that were previously forested, then a large release of CO_2 will occur when the dense forestation cover was removed and replaced with the small biofuels that will only absorb a fraction of the carbon that the forest previously absorbed. Further, the planting, processing, transport and delivery of biofuels are all activities that could release large amounts of carbon to the atmosphere.[41] This will be discussed in more detail in the following chapters.

This issue is beginning to receive more attention now, particularly as Indonesia and Malaysia are increasing their production of palm oil to produce biodiesel. And whereas the majority of Brazilian biofuels have been produced in the south and center of the country, away from the Amazon, the recent increase in biofuel production is leading to deforestation and making this issue more pertinent. Environmental scientist George Monbiot has even argued that "Biodiesel enthusiasts have accidentally invented the most carbon-intensive fuel on earth."[42]

41 See Delucchi 2005
42 Monbiot, 2005

g. Biofuels' Other Environmental Impacts

Finally, besides GHG emissions, there are other environmental impacts of biofuels production that are important to understand. Friends of the Earth[43] have released a report on the mass extinctions of orangutan apes in Indonesia and Malaysia being caused by the increased production of palm oil. Numerous concerns have been raised about the likely impacts that deforestation in Brazil will have on biodiversity, soil quality, water quality and availability, and other services that the rainforest provides. And American expansion of corn production has also raised several alarm bells among environmentalists because of its intensive use of fertilizers and the likely soil degradation it will cause. These will be discussed in more details in the following chapters.

This chapter has provided a background to the discussion of biofuels. While the increased recent attention to biofuels is caused by concerns over energy depletion and climate change, this chapter finds that the second is the more pressing of these concerns, as it is likely to create serious consequences for humans well before the first. The treatment of the topic of biofuels in this study will thus focus on the impact of biofuels on climate change. Further, this chapter has clarified that the impact of biofuels on emissions cannot be considered without careful consideration of the land use change impacts of biofuels production and growth. The following chapters will outline biofuels policies in the EU, Brazil, and the United States and how the biofuels industries have developed there over the years.

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43 Friends of the Earth, 2005

Chapter III: Biofuels Policies in the US, EU and Brazil

The previous chapter discussed biofuels production worldwide and showed that the main producers of ethanol are the USA and Brazil, while the main producer of biodiesel is the European Union. As will be shown, the recent large increases in the production of these fuels have been driven by strong interventionist policies by the US government and the European Union to promote biofuels. This chapter will provide an overview of these policies and discuss how they have evolved over time. The Brazilian experience with biofuels, however, has relied far less on subsidies and direct government support.

These policies in the US and EU were meant to promote biofuels as a means towards achieving larger environmental, economic, political and developmental goals. The conclusion drawn from this overview is that the policies have focused on the promotion of biofuels as if it were the end in itself, in the process seeming to ignore that biofuels were only a means towards the achievement of the larger goals.

The final section of this chapter outlines the impact that these policies have had. Even as it became likely that these policies were having negative unintended consequences, policy-makers persisted with the promotion of biofuels as a goal in itself.

The discussion leads us to the following two chapters which discuss the efficiency of biofuels and the problems with assessing them. Based on this difficulty, and on the mixed track-record of biofuels-promoting policies, the following chapters present an alternative approach which focuses on targeting the environmental goals sought from biofuels policies themselves.

a. The EU Biofuels Policies

Biofuels support in the EU is pervasive through the entire chain of production and consumption of biofuels, as it is in America. This section will outline the major laws and directives which have supported biofuels. For the purposes of this paper, we will divide the policies into three main parts: policies aimed at bioenergy in general, policies aimed at farming feedstock, and policies aimed specifically at biofuels for transportation.

i. Biofuels Policies

The birth of the EU policies on biofuels can be traced back to the European Commission's White Paper for a Community Strategy and Action Plan[44] which sought to draw up a framework for increasing the share of renewable energy in the member states' energy mix to 12% by the year 2010. It also included targets for increasing biofuels' share of the transport fuel market to 5.75% by 2010. In 2002, the EU issued a non-binding directive calling for all member states to achieve a level of 2% blending of biofuels in transport fuels by 2005, and 5.75% by 2010.

In 2005, the Commission of the European Communities issued communication COM(2005) 628 entitled "Biomass Action Plan", in which it called for doubling the current level of biomass

44 European Commission's White Paper for a Community Strategy and Action Plan (Com(97)599)

energy use (4%) to 8% by 2010. The plan claimed it would reduce EU fossil fuels from 80% to 75% of the total energy mix. And It "would at reducing oil imports 8%, prevent greenhouse gas emissions worth 209 million tons CO2-equivalent per year and create up to 300,000 new jobs in the agricultural and forestry sector."[45]

The plan contained 31 measures to promote bioenergy in heating, cooling, electricity and transportation. It contained a call on setting national targets for biofuels, and making the blending of biofuels mandatory for suppliers. The plan also called for investment into research into second generation (cellulosic) ethanol.

The 2006 Strategy for Biofuels[46] sought to provide a comprehensive strategy for the achievement of these three goals:

1- The promotion of biofuels within the EU and developing countries in an environmentally positive manner
2- Improving the cost competitiveness of biofuels through advances in cultivation, research, and market penetration
3- Supporting the development of biofuels feedstocks and biofuels production in developing countries, particularly those that stand to be harmed by the reform of the EU sugar policy

45 Commission of the European Communities. Communication from the Commissions. *Biomass Action Plan*. COM (2005) 628
46 Commission of the European Communities *An EU Strategy for Biofuels*. Communication from the Commission. (SEC(2006) 142)

Also in 2006, the Presidency Conclusions of the 2006 Brussels European Council (7775/1/06) recommended: "considering raising, by 2015, the share of renewable energies, considering a target of 15%, and the proportion of biofuels, considering a target of 8%"[47]

In January 2007, the European Commission released a comprehensive "climate change and energy package" which contained the following specific targets:

1- Making renewable energy 20% of the EU's total energy consumption by 2020.
2- Making biofuels responsible for 10% of transport fuels by 2020
3- Reducing greenhouse gas emissions by 20% (from 1990 levels) by 2020.

The March 2007 EU Summit endorsed the aforementioned package, while agreeing to work on a two-year action plan aimed at formulating a common European energy policy. In September 2008, the Industry Committee in the European Parliament voted "almost unanimously" in favor of adopting the climate change and energy package. The EU summit of 11-12 December 2008 agreed the final version of the climate change and energy package, and the European Parliament endorsed it on the 17th of the same month.

ii. Agricultural Policy

Biofuel policies are not the only avenue of support for biofuels in Europe; Europe's agricultural policy has also played a role in promoting biofuels. Though the European Union expects to be a net importer of biofuels if it is to meet the requirements of the policies, it still aims to establish as much independence as possible in the production of feedstock.

47 The Presidency Conclusions of the Brussels European Council 23/24 March 2006 (7775/1/06)

About 44% of the EU's budget goes on Europe's Common Agricultural Policy (CAP).[48] CAP has allowed for the cultivation of energy crops on areas on which prediction of food crops is not allowed.[49] The 2003 reform of CAP severed the link between payments to farmers and production, instituting a single payment to farmers regardless of their produce[50]. On top of this, this reform proposal introduced a special aid of 45 €/ha for the growing of energy crops on land that is not set-aside for food production. Further, this proposal extended the energy scheme to 8 new Eastern European members states of the EU. These are: the Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungary, Poland, and Slovakia. [51]

The new EU rural development policy also includes several regional and local measures that support the production of renewable energy crops such as grants and capital costs of setting up plants.[52]

Germany is the leading global producer of biodiesel and has established a technology exchange with Brazil. The goal of EU research is to develop cost effective means of producing second generation biofuels, like lingo-cellulosic ethanol, which create fuel from waste products rather than food sources. While the technology has been developed, it is still prohibitively expensive.

iii. Transport Policies

There are two directives aimed specifically at supporting biofuels for transportation.

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48 GBEP, 2007. P.242
49 Pelkmans et al, 2007,p3
50 Pelkmans et al, 2007,p3; GBEP, 2007. P.242
51 Press Release, "Commission proposes to extend energy crop aid scheme to all Member States," Europa, 22 Sept. 2006
52 GBEP, 2007. P.242

Directive 2003/30/EC set as a "reference target" the consumption of biofuels to make up 2% of transportation fuels from biofuels by 2005 and 5.75% of transport fuels by the end of 2010. While not specifying the strategy to achieve this goal, it obliges member states to set national targets based on these "reference targets". Directive 2003/96/EC mandates favorable tax deductions for biofuels, but left the levels of these deductions to member states to decide.

Further, the EU is in the process of revising its Fuel Quality Directive (98/70/EC) which, back in 1998, set specifications for petrol, diesel and gas-oil. The proposed revisions would alter the standards in order to take into account[53]:

1. Reflect developments in fuel and engine technology
2. Help combat climate change by promoting the development of lower carbon fuels, including biofuels
3. Meet air-quality objectives set out in a 2005 Clean Air Strategy, inter alia, by reducing emissions of sulphur and PAHs (Poly Aromatic Hydrocarbons) from diesel

A further provision is to include monitoring and reporting of lifecycle analyses of the emissions from these fuels in order to ensure these fuels provide a reduction in the greenhouse gas emissions.

iv. Current Status

The European Union is the world leader in the consumption and production of biodiesel. It is responsible for about 86% of world biodiesel production in 2005, the latest year for which comprehensive and consistent global statistics were available for this study.

53 EurActiv.com: The review of the EU's Fuel Quality Directive.

The majority of cars in Europe are diesel cars, and since biodiesel can almost seamlessly replace diesel, the EU has been a fertile ground for the growth in adoption of biodiesel. The real reason for the growth of the consumption of biodiesel is the massive amount of support biofuels receive from the EU and its member state governments. Locally produced biodiesel is still more expensive to produce than imported biodiesel, but it continues to be produced thanks to the aforementioned generous subsidies and different forms of support.[54]

Yet in spite of the growing consumption of biofuels, the EU region did not meet the target of making biofuels reach 2% of total fuel consumption by 2005. Germany, however, reached a remarkable level of 3.75%, which was larger than its 2% national indicative target. Of the other countries, only Malta exceeded its (very low) target of 0.3% by registering a 0.52% share. Sweden did come close to meeting its 3% target, however, and achieved a 2.33% blend.

In conclusion, Pelkmans et al provide a useful overview of what type of policies have supported which processes (both national policies and EU policies). They divide the biofuels production chain into Feedstock, Production, Distribution and Market and analyze their support.

Supporting biofuels feedstock, the EU has placed the aforementioned extensive agricultural support in the form of direct crop subsidy as well as the setting aside of land for feedstock planting. Supporting biofuels production the EU has extensive RD&D funding, loans and subsidies for production facilities, producer tax incentives and authorized quota system for producers and tax reductions. Supporting the distribution of biofuels, there are standards for blending, differential tax reductions for biofuels, mandates for biofuel distributors and loans and subsidies for filling stations. Finally, supporting the market for biofuels, the EU offers

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54 GBEP, 2007. P.246

funding of demonstrations, procurement requirements and incentives for consumers such as tax breaks on biofuels vehicles, and exemption from road taxes.[55]

An overview of the literature concludes that the main drivers behind the EU policies for promoting biofuels are:

1- Reducing dependency on foreign oil
2- Reducing greenhouse gas emissions
3- Rural development and farm support
4- Promoting development in the third world[56]

b. USA policies on biofuels

This section will provide an overview of the main and most important legislations, laws and directives that have influenced the biofuels industry in the USA, with a focus on ethanol. It is not a widely-known fact, but the Ford Model T which revolutionized the world of auto-making in 1908 was designed to run on ethanol, with Ford chairman Henry Ford calling ethanol "the fuel of the future."[57] Ethanol continued to be a popular fuel in America until the 1920's and 1930's, but then it lost its market share to cheaper and more powerful gasoline.

55 Pelkmans et al, 2007
56 See De Santi, 2007. See also: Berndes and Hansson, 2007
57 E85, 2005

It was only in the 1970s, after the "energy crisis" and growing environmental concern, that ethanol made a comeback into the fuel mix of the American automobile. Since then, a large number of government subsidies, legislations, and mandates have helped catapult ethanol from having no share in the fuel supply to its current state where it forms almost 2.56% of total transportation fuel consumption in 2007,[58] increasing ethanol production from dozens of millions of gallons to the current level of 9 billion gallons in 2008.[59]

American production of biodiesel has also grown significantly, though it remains trivial compared to ethanol. While America only produced two million gallons of biodiesel in 1999, this increased to 700 million gallons in 2008[60]. Biodiesel, however, remains very small compared to ethanol production, and it is not the main focus of American subsidies and support of biofuels. This paper will focus only on the American ethanol experience.

From the following overview of the types of support received by biofuels in the United States, one can conclude that the history of the development of the ethanol industry is the history of legislation supporting the development of the ethanol industry. At every point in the history of the development of this industry, it was always a government intervention that brought about a growth in the industry.

This section will attempt to highlight some of the main features of the most important policies enacted to support biofuels over the years. A more comprehensive and detailed outline of these policies can be found in the Institute for Sustainable Development's report *Biofuels At What Cost?*

58 EIA, 2008
59 Renewable Fuels Association website. www.ethanolrfa.org/
60 National Biodiesel Board website www.biodiesel.org/

US policies on biofuels came mainly in two main time periods: the early 1980's and the early 2000's. These periods both witnessed rising oil prices, growing concerns over oil scarcity, and growing environmental concerns. These periods witnessed the largest rates of growth in the ethanol industry. The first period launched the ethanol industry into the American fuel mix, while the second witnessed a massive increase in the production of ethanol that sees ethanol reaching previously unimaginable levels.

The following will be a run-down of some of the major policies enacted since the late 1970's to promote biofuels. Although a comprehensive listing of such policies is beyond the scope of this paper, the aforementioned IISD report will be used to provide the most comprehensive accounting of the totality of the monetary cost of all these subsidies and programs.

The beginning of the modern era of ethanol production can be traced back to the Energy Tax Act of 1978.[61] Under this law, E10 (90% gasoline and 10% ethanol) had its federal fuel excise tax reduced by 4 cents per gallon. This translates to a subsidy of 40 cents/gallon of ethanol. Only two years later, Congress's Crude Oil Windfall Profit Tax Act and the Energy Security Act legislated further subsidies for the ethanol industry; the first extended 1978's tax exemption while also implementing a higher tax credit for higher blended levels of ethanol, while the second provided loan guarantees for ethanol producers. Also in 1980, the Omnibus Reconciliation Act saw the imposition of a 50 cent import tariff on foreign-produced ethanol, which was increased to 60cents/gallon in 1984.

61 IISD, 2006. P.11

The US Federal government set up the Bioenergy Feedstock Development Program at Oak Ridge National Laboratory in 1978[62]. This program has been attempting to find economic ways of producing biomass since then.

These policies were to be increased in 1982 with the Surface Transportation Assistance Act raising the exemption from the excise tax from 4 to 5 cents per gallon. This was further increased in 1984 to 6 cents per gallon. Four years later, the Alternative Motor Fuels Act provided funding for RD&D programs and fuel economy credit for manufacturers. The tax exemption was decreased in 1990 to 5.4 cents/gallon, though it was extended until 2000.

On top of all these Federal programs, there have been several state-level programs to support the ethanol industry. According to IISD, a 1986 Congressional Research Service study concluded that there were ethanol incentives in 29 states, costing state treasuries over $450 million/year.

The Alternative Motor Fuel Act of 1988 saw the beginning of the addressing of the consumption side of the ethanol market, as it provided credits for meeting CAFE for car-makers who produced cars suitable for E85—not necessarily if these cars actually used it, just if the producers had made them capable of using them.

The 1990 Omnibus Budget Reconciliation Act of 1990 granted some producers of ethanol a 10 cent/gallon credit on their first 15 million gallons per year. The General Accounting Office has estimated that the revenue loss from the excise tax reduction over the 1980–2000 period was between $8.6 billion and $12.9 billion. Gielcki et al[63] estimate that Federal spending on biofuels

62 Schnepf, 2006
63 Gielke et al, 2001

from 1978 to 1998 ranged between $50-$100million per year. IISD cites the General Accounting Office estimating that the excise tax exemptions over the period from 1980 to 2000 has cost the US Government between $8.6 and $12.9 billion (in 2006 US Dollars).

The 1990 Clean Air Act was meant to address two main emissions from cars: ozone-producing hydrocarbons and Carbon monoxide emissions by mandating the blending of oxygenates. The most common oxygenate that emerged was Methyl tertiary-butyl ether (MTBE), but it also gave a boost to ethanol, since it can also be used as an oxygenate. But growing concerns over MTBE causing groundwater contamination have led to 22 states banning its use entirely by 2006. The slack in the market was taken up largely by ethanol, generating great demand for it. But in 2006 mandates on oxygenated fuel were removed. But banning MTBE means that ethanol remains as the leading oxygenate and leading agent for increasing octane in cars.

The 1992 Energy Policy Act officially designated E85 as an alternative fuel, with the Department of Energy later adding B100 to that designation. In 2000, USDA initiated the Commodity Credit Corporation (CCC) Bioenergy Program to stimulate demand and alleviate crop surpluses, which were contributing to low crop prices and farm income, and to encourage new production of biofuels. Since ethanol dominates the renewable fuels market in the United States, most of the funds went to ethanol plants. However, the few biodiesel plants that were in operation in 2000 took advantage of the CCC payments and the Program spurred new investment in biodiesel facilities.

In 2000, the Agricultural Risk Protection Act put in place mechanisms for supporting research and development to facilitate the commercial production and applications of bioproducts.

The 2002 Farm Bill contained several programs aimed specifically at promoting corn ethanol as an energy source, including procurement requirements for federal agencies.

Finally, and in what is perhaps the most significant law for the utilization of ethanol, Congress passed the Energy Policy Act of 2005. The act was meant to increase domestic energy production and increase the diversity of America's fuel mix.[64] For the first time, this act set minimums of consumption of ethanol within the American fuel mix under the Renewable Fuels Standards. By 2006, America was to consume 4 billion gallons of ethanol, rising to 7.5 billion gallons by 2012. Under this mandate, a gallon of cellulosic ethanol counts as 2.5 gallons of non-cellulosic ethanol. The act also mandated that after 2012, ethanol consumption must grow in proportion to the growth in gasoline consumption. And starting 2013, at least 250 million gallons of the ethanol consumed must come from cellulosic ethanol.[65]

The 2005 Energy Policy Act also contained a large number of other programs that provide subsidies, technical assistance, tax cuts and other incentives to the development of the biofuels industry. The Department of Energy has set goals to replace 30% of the liquid petroleum transportation fuel with biofuels and to replace 25% of industrial organic chemicals with biomass-derived chemicals by 2025.

Also under the 2005 Energy Policy Act, the government has dedicated $650 to the Department of Energy to fund research on cellulosic ethanol, as well as $550 to fund the creation of the Advanced Biofuels Technologies Program. The Act also established the Cellulosic Biomass Program, which provides $250 million for research on cellulosic ethanol.

64 Duffield and Collins, 2006
65 Duffield and Collins, 2006

The DOE recently started six biorefinery projects to study the potential for commercial production of cellulosic ethanol. The DOE intends to spend up to $385 million in these six projects over the next four years.

- Abengoa Bioenergy Biomass of Kansas, LLC of Chesterfield, Missouri, up to $76 million.
- ALICO, Inc. of LaBelle, Florida, up to $33 million.
- BlueFire Ethanol, Inc. of Irvine, California, up to $40 million.
- Broin Companies of Sioux Falls, South Dakota, up to $80 million.
- Iogen Biorefinery Partners, LLC, of Arlington, Virginia, up to $80 million.
- Range Fuels (formerly Kergy Inc.) of Broomfield, Colorado, up to $76 million.

In his 2006 state of the union address, US President George W Bush signified the new found lease of support for biofuels by specifically talking about them in his state of the union address, saying: "We'll also fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switchgrass. Our goal is to make this new kind of ethanol practical and competitive within six years."

From this complicated jumble of subsidies, the IISD report attempts a synthesis to quantify the total amount of subsidies spent on biofuels. The report lists more than 200 different subsidies for biofuels, and concludes that the levels of subsidies in 2006 was between $5.5billion and $7.3billion per year.

Current US President Barack Obama appointed former Iowa Governor Tom Vilsack as Secretary of Agriculture[66]. Being a well-known supporter of corn farmers, it is expected that Vilsack will continue the governmental largesse towards corn farmers and biofuels. Finally, the

66 Los Angeles Times. December 17, 2009. *"Obama taps Vilsack for Agriculture"*

overwhelming drive for more and more support for biofuels shows no signs of abating. At the time of the completion of this dissertation, the EPA is considering raising the allowance for gasoline blending of ethanol up to 15% from the current 10%.[67]

c. Brazilian Biofuels Policies

Brazil has had a long history of utilizing biofuels for transportation, dating back to the early Twentieth Century, when the first ethanol-powered cars ran on Brazil's streets. In 1931, the Brazilian government passed legislation mandating 5% blending of ethanol in transport gasoline, waiving taxes for ethanol production, and waiving tariffs on materials imported for ethanol producing mills.[68]

More recently, in 1975, Brazil began its ProAlcool Program in response to two seemingly unrelated problems in the 1970s. After the oil crisis, Brazil faced an increasingly large bill to pay for its large oil imports, a key cause of Brazil's crippling debt crisis. On the other hand, Brazil's farmers were suffering from the volatility and frequent drops of prices in agricultural products, most notably sugar. ProAlcool aimed at alleviating the negative impact of these two problems, by replacing expensive imported fossil fuels with locally grown ethanol produced by the country's large number of sugar farmers.[69]

ProAlcool stimulated the production of ethanol-only cars, culminating in more than 4,000,000 of these vehicles on the roads today, along with 680,000 flex-fuel vehicles (vehicles that can run on any combination of ethanol and gasoline).[70]

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67 Evans, Beth, 2010
68 Luis Carvalho, 2002
69 Bradley and Baumert, 2005
70 Coelho, 2005

Over the last 31 years, the ethanol industry in Brazil has gone through ups and downs. The production of ethanol to a large extent has grown constantly since the 1970s. The Brazilian government intervened extensively in the ethanol market in the 1970s and 1980s, helping bolster ethanol production, which continued to rise until the late 1980s, when it began to stabilize because of reduced government support and reduced oil prices.

The story of Brazilian ethanol-fueled cars is related though slightly diverging from that of ethanol. In 1979, Brazilian car producers started mass production of cars that ran on pure ethanol, which increased more or less steadily until 1989, when a shortage of ethanol dented consumer confidence in these cars, and led to a sharp reduction in production.

By the late 1990's, as the price of oil dropped and government subsidies for ethanol production ended in 1998, there was a short drop in ethanol production, which nonetheless picked up after 2001 as oil prices started rising and ethanol became competitive again, though without government subsidies. The sales of ethanol fueled cars also rose. However, customers have recently preferred to buy flex-fuel cars, which can accommodate both ethanol and gasoline instead of buying ethanol on its own, mindful of a possible shortage in ethanol. Throughout these years, the share of ethanol in gasoline has continued to rise, except for a sharp drop in the late 1980's with the shortage of ethanol fuels. Today, ethanol constitutes around 25% of Brazilian 'gasohol.'

A key virtue of Brazilian ethanol production is that producers have been able to shift relatively easily between sugar production and ethanol, depending on market demand. The Brazilian government's large investments in infrastructure have given many advantages to Brazilian sugar producers, that today they can produce without subsidies or intervention, and the infrastructure exists to allow easy transformation and substitution between sugar and ethanol.

Furthermore, in 2005, Brazil started a program aimed at increasing the production and consumption of biodiesel in the transportation sector.

The Brazilian ethanol program has been motivated by two larger goals: the reduction in foreign exchange payments for energy and reliance on foreign oil, and the socioeconomic goal of providing jobs and increasing the income of farmers[71]. Arguably, this program has succeeded in both these goals. According to Bradley and Baumert (2005), Brazil has saved around $100 billion in foreign exchange, when taking into account reduced import costs and debt servicing. According to Moreira, the gross turnover of the Sugar/Ethanol sector in Brazil is around US$12 billion, or 3.5% of GNP. Total employment in this sector is around 3.6 million jobs when including direct, indirect and some of the induced jobs.[72]

Goldemberg estimates that using ethanol for power production is a more labour intensive process, generating much more employment than other forms of energy. For every 1 job generated in the oil sector per unit energy, Goldemberg estimates that coal production generates 4 jobs, 3 jobs in the hydroelectric sector, and 152 jobs in the production of ethanol.[73] Further to all of this, Sellers (2005) argues that the program has had several beneficial impacts in terms of reducing pollution, causing significant reduction in the amount of lead, sulfur and particulate ma tter in the fuel mix and air.[74]

In view of all these issues, it is important to recognize that the Brazilian ethanol industry is more than just a commercial enterprise for the government or sugar producers. It is also a large social development mechanism for the government with large benefits pertaining to social,

71 Moreira (2004) and Bradley and Baumert (2005)
72 Moreira, 2004
73 Goldemberg, 2002
74 Sellers, 2006

rural and macroeconomic considerations. The goal of reducing carbon emissions, however, has only figured recently in the Brazilian ethanol program. As the concern over climate change has grown, so has the attention to this issue, and there is now considerable debate over whether the Brazilian biofuels industry helps reduce emissions or not.

d. Consequences of biofuels policies

The promotion of biofuels has had tangible and significant effects. The most obvious, of course, is that the consumption and production of biofuels have increased hugely, as outlined above. But beyond this one impact, there is an extensive literature that has sought to document what the impact of biofuels has been. This section will outline some of the main points outlined by this literature. More detailed analysis of the effects of biofuels on greenhouse gas emissions will be discussed in Chapter IV.

i. Impact on greenhouse gas emissions

For the purposes of this paper, the most important effect of biofuels is their impact on greenhouse gas emissions. On this, there is a large disagreement in the literature on what the real impact of biofuels has been. This issue will be tackled extensively in the next chapter. Briefly, however, the suggestion that utilizing biofuels produces more carbon emissions is largely motivated by the fact that biofuels production receives extensive subsidies.

A very large part of the inputs that go into biofuels production is energy, in different forms. Whether in planting the crops, harvesting them, manufacturing the fertilizers, processing the crops into fuels and transporting fuels—energy extensive processes are at the heart of every operation of biofuels manufacture. Energy costs are therefore a significant part of the costs of producing biofuels.

That biofuels production is not economically profitable as it stands, suggests these costs could exceed the benefits from it. This would suggest that more energy may go into making the biofuels than there comes out of the biofuel itself. As we saw above, about $1 of subsidy goes to support the production of each gallon of ethanol in the USA. This is a very high percentage of the final price of ethanol at the pump. This also means that without this subsidy, ethanol would not be cost competitive, and it would cost more to produce it than you could sell it for. And since energy consumption (in manufacturing of facilities, fertilizers, processing the plants, and transporting the fuels) is a significant part of ethanol production price[75], this suggests that ethanol production could be a waste of energy and that the wasted energy involves excessive greenhouse gas emissions. [76]

Looking at the scales involved in the EU's biofuels policies can be quite indicative of the magnitudes of emissions involved. EU consumption of biofuels has only reached 1.8% of transportation fuels by 2006. In spite of all the subsidies, mandates, incentives and R&D spending, EU consumption of biofuels has failed to grow to more than 1.8%. This gives a sense of how much emissions this biofuel project could have saved until today.

75 See Chapter IV for a discussion of estimates of energy balance of biofuels production.
76 A more thorough treatment of this question is presented in Chapter IV, this discussion is simply to suggest that the impact might be negative.

Total GHG emissions in the 27 member states of the European Union in 2006 were estimated at 5,142.8 Mt CO2-eq. Road transport is responsible for 19.3% of all emissions in the EU[77], meaning that total transportation emissions are 992.56 Mt CO2-eq.

Even if one were to make the unrealistic assumption that the biofuels replacing fossil fuels will have exactly zero associated emissions, the most emissions that can be produed are 1.8% of 992.56 Mt CO_2-eq, which is 17.87 Mt CO2-eq.

If the planting of biofuel crops and their growing, harvesting, processing into biofuels, production, distribution and consumption did not produce any emissions whatsoever, this would be the total amount of emissions reduced from European tailpipes. Of course, these processes do consume enormous amounts of carbon, and so the number will be much less. This is the maximum amount of carbon that could be reduced if biofuels production was immaculately clean.

In order to get a sense of how low this number is in the grand scheme of global emissions, and how little it is compared to emissions from deforestation, it can be compared the amount of emissions resulting from the peatlands drained and deforested to produce palm oil. Farigone et al estimate that converting peat lands to palm oil results in emissions of 3,452 tCO2/ha[78]. This means that one would only need to convert 5,175 hectares of peatlands into palm oil plantations in order to offset the theoretical maximum of emission savings possible from EU use of biodiesel. In other words, even if we assume that the production and transportation of biofuels involved no emissions whatsoever, then merely displacing 5,175 hectares of peatlands would

77 European Environment Agency. 2010.
78 Farigone et al (2008)

result in more emissions than all the gasoline that was displaced from the European fuel supply.

For some perspective, there are a total of 15,347,100 hectares of peat swamp forests in South East Asia. The years between 2000 and 2005 have witnessed an average deforestation of peatlands of 242,800 hectares per year. 27% of Indonesian peatlands are in palm oil and timber plantations, and a similar percentage is the case in Malaysia[79]. If one were to assume that only 10% of South East Asian forests were used for the production of palm oil (a very low estimate), then one can find that 24,280 hectares per year were being displaced. It would only take 5,175 hectares displaced to produce the maximum hypothetical amount of emissions that is offset by the substitution of gasoline.

For further perspective, note that in 2004 (before the major spike in demand for palm oil) Indonesia had oil plantations covering 5.3 million hectares. So, if EU regulations were responsible for an increase in Indonesian palm oil plantations by 1/1000, that would (all else being equal) lead to an increase of 5300 hectares of palm oil plantations. This, on its own, is enough to offset all the theoretical maximum reduction of emissions from EU biofuels policy.

The PEAT-CO2 project attempts to assess the amount of emissions released from deforestation in South East Asian peatlands. The report identifies European biofuel demand as a major culprit in the recent rise in deforestation in South East Asian peatlands. The report finds that the CO2 emissions each year from the decomposition drained peatlands ranges between 355 to 874 Mt/y, estimated at 632 Mt/y. The total maximum amount of emissions that could have been avoided by using biofuels in Europe, as shown above, was only 17.87 Mt CO2-eq.

79 Hooijer, A., Silvius, M., Wösten, H. and Page, S. 2006.

The report also estimates that in addition to that there was an average of 1400 Mt/y emitted from the burning of peatlands. This total of 2000 Mt/y, the report indicates, "equals almost 8% of global emissions from fossil fuel burning." To understand how remarkably high this number is, we must remember that these degraded peatlands comprise less than 0.1% of the world's surface area.[80] Because 90% of these emissions come from Indonesia, this places it as the third largest emitter of CO2 in the world, after the USA and China—countries that are far richer and far more populous (respectively) than Indonesia. The 2000 Mt/y produced from peatland deforestation are more than 100 times larger than the theoretical maximum of reductions possible from biofuels use in European cars.

Danielsen et al[81] attempt to estimate the difference in the amount of carbon saved from using biodiesel planted on deforested land and the carbon emitted from the same deforested land. They reach the staggering conclusion that it would take between 75 and 93 years for the former to compensate for the later—a result dependent on the type of emission. They also find that it would take more than 600 years of biodiesel production to make up for the emissions released from deforesting peat lands. They do however find that planting palm oil on degraded grassland could lead to the carbon being compensated in 10 years.

It is important to point out that the Danielsen et al study only looks at the carbon dioxide emissions. If one were to take into account the other pollutants, the results would be even more drastic. Crutzen et al look at the question of N2O emissions from the production of biofuels and find that they can be a very significant source of emissions. They conclude: "the production of commonly used biofuels, such as biodiesel from rapeseed and bioethanol from corn (maize), can

80 International Peat Society, 2007.
81 Danielsen et al, 2008

contribute as much or more to climate change by N2O emissions than cooling by fossil fuel savings."[82]

Righelato and Spracklen argue that maintaining forests is a better option for carbon mitigation than deforesting and producing biofuels.[83] In another, more detailed study, Page et al estimate that drained, degraded peatlands converted to palm oil plantations produce around 169 tons/ha of CO2 emissions per year for a 25 year life-cycle. Whereas an intact peatland acts as a carbon sink sequestering 2.6 tons/ha of CO2 per year.[84]

Florian Seigert has pointed out that 15% of all carbon dioxide emissions in the year 2006 were the result of peat and forest fires.[85] Seigert also notes that the emissions released from a hectare of land converted to palm oil are up to 30 times more than any emissions that could be saved by replacing fossil fuels.[86] Peatlands International, however, estimates that use of palm oil from peat results in "about 3 to over 10 times more CO2 emissions."[87]

In a study by the European Commission's Joint Research Centre, De Santi et al attempt an analysis of how much emissions EU biodiesel would produce. In a thoughtful paper that contemplates seriously the limitations of the data and calculations, the authors argue that if one were to ignore the "indirect" effects of EU biofuels consumption, they can generally reduce greenhouse gases. The problem, of course, is that we cannot ignore indirect effects, because it is the complete and comprehensive emissions that matter for the level of carbon in the atmosphere, not just the "direct" emissions. After discussing the limitations of the data, the

82 Crutzen et al (2008, p.389)
83 Righelato and Spracklen, 2007
84 Page et al (2007)
85 Ernsting, 2008
86 Quoted from the original German in Carbopeat press release (2007)
87 International Peat Society, 2007.

authors nonetheless arrive at the conclusions that that "[f]or 1st generation biofuels made in EU it is clear that the overall indirect emissions are potentially much higher than the direct ones whilst they are unlikely to be much lower."

Further, the authors make the following conclusion:

> ***Indirect land use change could potentially release enough greenhouse gas to negate the savings from conventional EU biofuels.*** However, we do not know even roughly the magnitude of these effects. It depends critically on the policy and effectiveness of control in the regions of the world where the extra demand for crops will result in expansion of farmed area. Certification schemes help, but cannot expect to prevent the problem on a global scale.[88] [emphasis in original]

The authors further emphasize the conclusion that "The uncertainties of the emissions due to indirect effects, much of which would occur outside the EU, mean that it is impossible to say with certainty that the net GHG effects of the biofuels programme would be positive."[89]

The magnitudes involved show us that there is clearly a cause for concern that biofuels use has been causing more emissions than it has been mitigating. All of this without taking into account any of the emissions that go into production, transportation, processing and use of biodiesel—only the land use change effects. This, however, is but a suggestive calculation, and cannot be taken as a definitive guide to the quantities of emissions increased or decreased by biofuels policies. For that, we'd need to look into the results of the LCA analyses on biofuels, discussed in Chapter IV.

88 De Santi et al (2008, p.11)
89 De Santi et al (2008, p.21)

ii. Increased fossil fuel consumption

The previous analysis and conclusions on emissions apply to energy as well: there is no evidence that biofuels have reduced energy use, although there is evidence to suggest that they did increase them. Conclusive evidence is not available. But on top of that, there is evidence to suggest that biofuels policies have actually *increased* fossil fuel consumption by consumers, not just the fossil fuels to produce biofuels. The reason for this is that combining a tax policy and a mandate on biofuels use effectively leads to a subsidy to oil consumption, as detailed by De Gorter and Just[90].

De Gorter and Just show that a tax credit would increase biofuels consumption, as would a mandate. But when the two are combined, the unintended effect is a subsidy to oil consumption. Their reasoning is that a tax credit allows the blenders of biofuels and gasoline to bid up the price of ethanol until it is higher than the gasoline price by the tax credit. Most of the benefits would accrue to ethanol producers because ethanol is a small fraction of total fuel consumption. A blending mandate, on the other hand, causes the price of the fuel to rise to the level where it is a weighted average of the price of the biofuel and ethanol. But when the mandate is combined with a tax credit, the net effect is a subsidy to gasoline. As De Gorter and Just put it:

> *"Because the ethanol price premium, due to the mandate, exceeds the tax credit, there is no incentive for blenders to bid up the price of ethanol as before. And market prices of ethanol cannot decline due to the mandate. Instead, blenders will offer a lower total fuel price -- ethanol plus*

90 de Gorter, Harry and Just, David R, 2008

> *gasoline -- to consumers to take advantage of the tax credit offered to them by the government. The lower price increases gasoline consumption and thus increases the market price of gasoline and oil."*[91]

Grafton et al use numerical simulations to arrive at a similar conclusion. They argue that "under a wide range of parameter values, biofuel subsidies will increase the rate of extraction of fossil fuels in the short and medium term, and possibly bring climate-change damages closer to the present."[92]

iii. Increased food prices

The subject of ethanol's impact on food prices remains a controversial one. There are various works that have claimed either a small, large or no impact of ethanol production on food prices. The rise in food prices that happened over the past few years can be easily demonstrated by a cursory look at the data. The IMF maintains an index of internationally traded commodities prices which records nominal dollar index of food commodity prices using global export value weights. This index rose by 130% from January 2002 to June 2008. Between only January 2007 and June 2008 this index rose by 56%.[93]

A study by the IMF estimated that biofuels accounted for 40% of the increase in soybean prices and 70% of the increase in maize prices. The Council of Economic Advisors to the President of the United States is another that has produced very low estimates of this impact, arguing that

91 de Gorter, Harry and Just, David R, 2008
92 Grafton, Kompas and Van Long, 2010.
93 Mitchell, 2008. P.3

"the increase in U.S. corn-based ethanol production accounts for approximately 7.5 percentage points of the 37% increase in corn prices" over the 12 months preceding May 2008. Further, increase in corn-ethanol production in other countries of the world accounts for an extra 5.5 percentage point of the 37%. This adds up to corn-ethanol contributing to one-third of the price rise in corn. When taken over all of the IMF's Global Food Index, this leads the CEA to conclude that corn ethanol lead to a 3% increase in global food prices, only.[94]

In a recent study, the Congressional Budget Office "estimates that from April 2007 to April 2008, the rise in the price of corn resulting from expanded production of ethanol contributed between 0.5 and 0.8 percentage points of the 5.1 percent increase in food prices measured by the consumer price index (CPI). Over the same period, certain other factors—for example, higher energy costs—had a greater effect on food prices than did the use of ethanol as a motor fuel."[95] A study by a World Bank economist Don Mitchell, however, was far more unequivocal in its conclusions, attributing as much as 75% of the recent rise of food prices to biofuels.[96]

iv. Deforestation

The impact of biofuels on deforestation is far more clear-cut than on emissions and energy. Whether it is American or European biofuels program—both have been implicated in causing large losses of forests in the Amazon, South East Asia and all over the world. The above

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94 Testimony of Edward Lazaer Before the Senate Foreign Relations Committee Hearing on "Responding to the Global Food Crisis" Wednesday, May 14, 2008 Accessed on: http://georgewbush-whitehouse.archives.gov/cea/lazear20080514.html
95 CBO, 2009
96 Mitchell, Donald, 2008

discussion of GHG emissions increase in Indonesia has already illustrated the impact that biofuels have had on deforestation in South East Asia. Scharlemann and Laurance have showed how increasing subsidies for corn have raised demand for soybeans, leading to an increase in deforestation in the Amazon as soybean infringes more and more on the Amazon.[97]

The Global Forest Coalition has provided evidence that biofuels are the cause of major deforestation in Indonesia, Malaysia and Brazil.[98] Further, the increased production of biofuels has been implicated in encroachment of farming into indigenous land in the Amazon, causing conflicts with the indigenous population.[99]

v. Species loss

Biofuels, by causing deforestation and habitat destruction, have lead to the extinction and near-extinction of many species. Among the most visible of these species is the Orangutan. In September 2005, Friends of the Earth, the Ape Alliance, the Borneo Orangutan Survival Foundation, the Orangutan Foundation and the Sumatran Orangutan Society published a report entitled *The Oil for Ape Scandal: How palm oil is threatening orangutan survival*.[100] This report detailed the extent of the threat posed to orangutans by the increasing destruction of their natural habitat in South East Asia through deforestation for palm oil plantations.

97 Jorn P.W. Scharlemann and William F. Laurance, 2008
98 Global Forest Coalition, 2007
99 Survival International, 2009
100 Friends of the Earth, 2005

vi. Hypoxia

Hypoxia is a term that refers to a low level of oxygen. It is a condition that exists in certain water bodies, when these bodies have been exposed to large amounts of pollution. The US Geological Survey defines the threshold for hypoxia in water bodies as being less than 2 parts of oxygen per million. Biofuels have been associated with the emergence of hypoxia in the Gulf of Mexico. The main cause of the hypoxia in the Gulf of Mexico is thought to be excess nitrogen from the Mississippi River, in combination with seasonal stratification of Gulf waters. The United States Geological Survey explains how hypoxia develops thus:

> "Hypoxia is caused primarily by excess nitrogen delivered from the Mississippi River in combination with seasonal stratification of Gulf waters. Nitrogen promotes algal and attendant zooplankton growth. The associated organic matter sinks to the bottom where it decomposes, consuming available oxygen. Stratification of fresh and saline waters prevents oxygen replenishment by mixing of oxygen-rich surface water with oxygen-depleted bottom water. Nitrogen promotes algal and attendant zooplankton growth. This lack of mixing limits the replenishment by oxygen and sustains the hypoxic zone."[101]

Corn, particularly as grown in industrial agricultural farms in America, uses fertilizers extensively. The run-off from corn fertilizer in the Midwest usually ends up in the Mississippi River, where it then goes to the Gulf of Mexico. [102] While this problem is not caused exclusively by agriculture for biofuels, since all fertilized agriculture contributes to it, biofuels nonetheless contribute a significant amount of pollution to it.

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101 US Department of the Interior, US Geological Survey website

102 Committee on Water Implications of Biofuels Production in the United States, Nation Research Council. 2007

Further, as the clamor for biofuels grows, and as energy and food prices rise, there is growing withdrawal of land from the Conservation Reserve Program[103] into corn farming, which is likely to increase biofuels crops growing, and lead to more fertilizer run-off and hypoxia.

vii. Aquifers

Biofuels production consumes a lot of water for growing the crops. This has had a detrimental effect on the water supply in several locations in America. Particularly, the Ogallala (High Plains) aquifer, which extends from west Texas to South Dakota, has suffered from a lot of depletion as a result of biofuel crops growing[104].

viii. Losing enterprises

In spite of all the subsidies handed to biofuels, the biofuels industry remains mired in financial trouble. Over the past few years, severe losses have befallen biofuel producers, and the outlook does not look encouraging.

Biofuels Digest publishes the *Biofuels Digest Index*, an index of a basket of public biofuels stocks. This index acts as a perfect thermometer for measuring the health of the biofuels industry. In

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103 Run by the US Department of Agriculture, the Conservation Reserve Program pays farmers to convert highly erodible cropland to vegetative cover, in order to reduce soil erosion, enhance and protect water supplies, and protect wildlife. More information can be accessed on the program's website: http://www.nrcs.usda.gov/programs/crp/

104 Committee on Water Implications of Biofuels Production in the United States, Nation Research Council, 2007

October 2008, the BDI was at a level of 105.24. Since then, the index has been in steady decline, and on May 1st 2009, it was at a value of 49.[105]

These losses have happened at a time when subsidies have been unprecedented, and oil prices rose very high. Oil is supposed to be the competitor to ethanol, and yet, even as its price rose to the levels of July 2008, it was still not enough to make ethanol plants profitable. A lot of capital, resources and labor have been wasted on these losing enterprises. This capital, resources and labor could have been put to better and more productive uses had it not been for the subsidies.

In conclusion, biofuels have had several negative consequences on the environment. Biofuels have also quite probably led to an increase in fossil fuel energy consumption. But even if they didn't, it is highly unlikely that they lead to significant reductions in fossil fuel consumption. Further, biofuels policies have contributed to making the food crisis worse for the world's poor. Economically, biofuels have represented a massive waste of resources that went to subsidies and meeting mandates. Politically, biofuels policies have distracted a lot from the goal of pursuing good environmental and energy policies. Pursuing biofuels subsidies has sidetracked governments from doing what are important and necessary policies for the environment, and instead wasted their efforts, time and resources on these wasteful subsidies to biofuels production.

105 Data for the index can be found on www.biofueldigest.com

e. Conclusion

From the preceding overview of policies enacted in Europe, USA, and Brazil, we can conclude that biofuels policies were promoted as a way to achieve several goals. The goal that is most relevant for the purposes of this paper, however, is the goal of reducing greenhouse gas emissions to fight climate change. This has arguably become the major motivation of biofuels promotion in the US and EU from the 1990's onwards, while being a more recent motivation for Brazilian biofuels policy.

The policies enacted, however, always aim at greenhouse gas emissions reductions through promoting the increased use of biofuels. Their only method of reducing greenhouse gas emissions was through increasing biofuel usage. But the preceding discussion of the impacts of biofuels raises an important question: how can we know that the impact of more biofuels consumption will lead to a reduction in greenhouse gas emissions? Given all of the aforementioned literature suggesting negative impacts, could it not be the case that increased biofuel consumption will lead to increased greenhouse gas emissions?

To answer this question, one needs to examine the literature on lifecycle analysis of biofuels. Lifecycle analysis is meant to assess the efficiency and environmental friendliness of biofuels. If these studies suggest that biofuels are environmentally friendly and can reduce greenhouse gas emissions, then the policies that promote biofuels discussed in this chapter can be judged to be a success in reducing emissions. If, on the other hand, these studies show that biofuels are not environmentally friendly and are net carbon negative, then the policies discussed in this chapter can be judged to have had more negative impacts on the environment. This is the subject of the next chapter.

Chapter IV: Can Biofuels Reduce Greenhouse Gas Emissions?

While chapter 2 looked at the general attributes of biofuels, this chapter will move to the more practical and important question of biofuels' suitability as a fuel. This suitability is usually assessed over two main criteria, which reflect the goals intended from the use of biofuels: energy efficiency and emissions reductions.

The energy and environmental efficiency of biofuels is important because it determines whether increasing biofuels use can help achieve environmental goals. As discussed in Chapter III, the policies enacted to support biofuels have done so in order to meet these goals; but they can only meet them if the fuels are efficient.

Those are the two main criteria by which biofuels should be assessed in order to realize whether biofuels' utilization would lead to a reduction of energy consumption and carbon emissions. Should biofuels be energy inefficient as many argue, then they do not make sense as an energy saving strategy, nor as an energy security strategy, since inefficiency means large amounts of fuel consumed to produce the biofuels—in other words, more energy would be spent producing the fuels than the fuels they displace. On the other hand, if biofuels produce high emissions, then they are not suitable as a strategy for fighting climate change.

There are, nonetheless, many studies that assess other criteria related to biofuels. These include the impact that biofuels can have on employment and job generation; the impact they can have on trade and international relation; their interaction with geopolitical issues and other energy sources. These are not issues that will be the focus of this chapter.

This chapter will first present some outlines of the public debate on the use of biofuels in the USA and EU, before moving on to discuss the academic and technical literature treating this topic.

The public debate:

This overview begins by outlining samples of opinions of media outlets, public figures and politicians on this issue, to situate the debate on the issue within its global context.

In an assessment widely echoed across American media, David Tillman and Jason Hill write in The Washington Post[106]:

> "*Biofuels, if used properly, can help us balance our need for food, energy and a habitable and sustainable environment. To help this happen, though, we need a national biofuels policy that favors our best options. We must determine the carbon impacts of each method of making these fuels, then mandate fuel blending that achieves a prescribed greenhouse gas reduction. We have the knowledge and technology to start solving these problems.*"

The New York Times, on November 18, 2008 echoed this same point. The editorial details how the US Congress' legislation on biofuels had "stipulated that ethanol be cleaner than gasoline and handed the job of measuring the emissions to the Environmental Protection Agency."[107] After discussing how different studies had revealed conflicting results on biofuels' efficiency,

106 David Tilman and Jason Hill, 2007
107 New York Times, 2008

emissions and impact on food prices, the NY Times argues that "it is the EPA's duty under the law to give the most unbiased, accurate accounting it can."[108]

In the International Conference on Biofuels held in Brussels in July 2007, which hosted European Commission President Jose Manuel Barroso and Brazilian President Luiz Inacio as well as many other important international figures, the consensus of the assembled leaders, panelists, speakers and participants, according to the Conference's final report was summarized as follows:

> *It seems there is a growing consensus that, sustainably managed, biofuels have important potential in three areas:*
>
> 1. *Biofuel use in the transport sector can contribute to global efforts to combat climate change. This contribution is crucial, given the limited number of alternative solutions in this field available today.*
> 2. *The use of Biofuels can contribute to enhancing security of energy supply, since they are currently the only option for significant diversification of fuel sources in the transport sector.*
> 3. *Biofuels also offer important opportunities for development in the fields of industry, agriculture and research. Biofuels production can benefit farmers in both in Europe and the developing world, strengthening and diversifying rural economies.*[109]

During this conference, European Commission President José Manuel Barroso remarked that:

> "*Properly managed, biofuels have the potential to offer important benefits: they can help to reinforce energy security and reduce greenhouse gas emissions. They also provide an important*

108 ibid
109 International Conference on Biofuels, 5-6 July, 2007, Final Report

> *opportunity for industrial development, innovation and employment promotion. We need to develop an EU biofuels policy which will meet our objectives of enhancing security of supply and tackling climate change, while ensuring sustainable development."* [110]

In the USA, the Union of Concerned Scientists—"an alliance of more than 250,000 citizens and scientists"[111] that "is the leading science-based nonprofit working for a healthy environment and a safer world"[112]—offers a similar appraisal. In its report entitled *Biofuels: An Important Part of a Low-Carbon Diet* (2007) the UCS argues a comprehensive accounting system for carbon emissions from biofuels "one that measures climate change emissions over a transportation fuel's entire life cycle." Using this accurate accounting, the report then urges policies that are "performance-based policies that will reward low-carbon transportation fuels for their performance and help them compete against highly polluting fuels such as liquid coal." [113] The global grassroots advocacy organization, Avaaz.org, also repeated the same point in a global letter-writing campaign to the leaders of the G8 summit in Glenneagles in March 2008, arguing for the need for implementing global biofuel standards that "ensure that biofuels do not undermine food security or cause more carbon emissions than they prevent. Some biofuels are good, others are a disaster--and our policies must tell the difference between the two."

The question that has vexed policymakers, pundits, academics more than any other on the issue of biofuels is the question of biofuels' efficiency. The most pressing desire is for these questions to be settled in order to inform policy on biofuels.

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110 International Conference on Biofuels, 5-6 July, 2007, Final Report
111 Union of Concerned Scientists, 2007.
112 ibid
113 Union of Concerned Scientists, 2007. P.1

On specific biofuels, the conventional wisdom and the majority opinion amongst the experts, public, and policy-makers can be broadly characterized as follows:

Sugarcane ethanol is far more efficient than corn ethanol. It produces far more energy than the energy invested in it. Its production has been an enormous help to the Brazilian economy, saving on fuel imports, foreign exchange, creating employment and generating rural development.

Corn ethanol is not a very desirable fuel on which we cannot rely in order to replace substantial amounts of fossil fuels. There is disagreement within this view whether corn ethanol is harmful to the environment, not helpful to the environment, or currently helpful but unlikely to be helpful if its production is stepped up. But there is large agreement, even among corn interest groups, that corn ethanol is unlikely to be the solution to the energy problems facing America.

Cellulosic ethanol is viewed as the promised fuel that will be the sustainable fuel of the future. Even the most skeptical of corn ethanol critics maintain that cellulosic ethanol will be far more efficient than corn ethanol, and will help in the achievement of many economic, political, social and environmental goals. Accordingly, even many critics of corn ethanol argue for subsidizing it as a way to set the scene for when cellulosic ethanol's production commences.

Finally, biodiesel continues to be a marginal topic in America (and as a share of biofuel production). It is, however, viewed as the most relevant fuel for Europe to reduce its consumption of fossil fuels and its emissions.

The general supposition of this debate is that scientists should determine which are the ‘good’ fuels to meet various environmental, economic, energy and social goals, and based on this, the government should support, subsidize and promote these fuels.

The academic and technical literature:

The method most-widely utilized in the academic literature for the assessment of the efficiency of biofuels is Lifecycle Analysis. Kammen et al define LCAs as a "technique used to evaluate the energy and climate change impacts of biofuels" adding that it is "both a method and a framework to evaluate biofuels". [114]

The basic intuition of an LCA is that it looks at the entirety of the lifecycle of a fuel, and estimates the amount of energy and emissions that go into and out of this cycle, arriving at the conclusion of whether this fuel's utilization relative to another fuel saves or increases energy; and whether it produces more or less emissions. Kammen et al define the life cycle as comprising "all of the physical and economic processes involved directly or indirectly in the life of the product, from the recovery of raw materials used to make pieces of the product to recycling of the product at the end of its life." [115]

Delucchi traces back current transportation LCA's to the "net energy" studies which began in the late 1970's, inspired by the oil crisis. Delucchi labels these studies "relatively straightforward, generic, partial "engineering" analyses of the amount of energy required to produce and distribute energy feedstocks and finished fuels." These studies faded in importance after prices of oil dropped, but returned to prominence in the late 1980's, motivated

114 Kammen et al, 2008
115 Kammen et al, 2008

by concern over the impact of fuels over the global climate. These newer studies, Delucchi argues, were similar to the earlier "net energy" generation, but they added estimates for net CO2 emissions.[116]

The techniques for carrying out LCA's have changed a lot over the years, and the questions have grown in complexity and significance. Of the more recent and more complex studies, the two most common issues that LCA's allow us to compare, according to Kammen et al, are:

> "*1) What is the net change in the world energy supply from increasing biofuel use by a given date*
>
> *2) How much of the GHG emissions in the world should we attribute to a unit of biofuel produced.*" [117]

There is a large body of literature attempting to assess different aspects of different biofuels' efficiency, energy intensity, environmental effects, and other factors such as social, political, employment, and international implications. As will become apparent from this overview, these studies employ drastically differing methodologies, arrive at widely disparate results, and do not appear to progressively build on each other's result in a constructive way. The result is that we see the number of studies continue to increase with time, while the results of the studies appear to not become any more precise or accurate. This chapter will concentrate on a few of the studies that are viewed as the most important and influential for each biofuel, and discuss their methodologies and shortcomings. Finally, building on the work of Mark Delucchi and others, I will attempt to arrive at what the construction of the right LCA model would entail, and what the best methodology for doing this would be. In reviewing studies of biofuels

116 Delucchi, 2004
117 Kammen et al, 2008

efficiency, I will focus on four main categories of biofuels: Brazilian sugar cane ethanol, European and East Asian biodiesel, American corn ethanol, and cellulosic ethanol.

a. Brazilian ethanol

The two most significant studies to report full-cycle analysis of Brazilian ethanol are by Kheshgi et al and Macedo et al. Kheshgi et al, building on work by Moreira and Goldemberg[118] provide an average production rate for sugarcane stems in 1996/1997 of 65 ton/hectare (t/ha) and that cane stem typically makes up about 53% of the dry-above ground biomass.[119] By taking the average value of sunlight energy falling on Brazil of 220 W/m^2 they find that the efficiency of cane stem production from sunlight is 0.49%. By taking the typical ethanol yield of Brazilian sugarcane, Kheshgi et al claim that Brazilian ethanol yields 114 GJ/ha/year. [120]

For calculating net emissions reduced, Kheshgi et al state that ethanol captures 33% of the energy in harvested sugar cane. They include the measures of energy used to produce sugarcane through all its stages, and subtract the emissions reduced when ethanol substitutes for fossil fuels, and find that avoided emissions would be 29% of the harvested cane primary energy. It is important to remember that this result is only achieved after omitting emissions from non-CO_2 gases from the calculation.

118 Moreira and Goldemberg, 1999
119 Kheshgi et al, 2000
120 Kheshgi et al, 2000

Further, this result does not include changes in carbon stock from land use change and deforestation. This is a very important consideration as these carbon emissions are likely to be very significant, as will be discussed below.

The Kheshgi study uses data from 1996/1997, so is slightly outdated, particularly as the Brazilian ethanol industry has witnessed remarkable improvements through the last 10 years, particularly since its latest major expansion phase that began in 2001/2002. Furthermore, the data used to estimate byproducts, inputs and outputs is not as reliable as the Macedo et al study, which is now viewed as the definitive source on Brazilian ethanol production.[121]

The Macedo paper observes three levels of energy balance: the first looking at only the direct consumption of external energy sources in the production of biofuels, the second also includes the energy required for the production of the chemicals and materials used in all the industrial and agricultural processes; and the third level even includes the energy necessary for the "fabrication, construction and maintenance of equipment and buildings".[122] This is much more comprehensive than the analysis carried out by Kheshgi et al, and any other on Brazilian ethanol.

The Macedo study also carries out the analysis in two scenarios. The first scenario is based on average values of consumption of energy and materials. For the first scenario, the energy consumed in producing one ton of cane is 48,208 kcal in the agricultural sector, and 11,800 kcal. Giving a total energy consumption of 60,008 kcal. While the total energy production for this scenario is 499,400 kcal. This gives a ratio of output(renewable) energy to input (fossil) energy

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121 In a comprehensive review of LCA studies, Larson (2005) finds that the Macedo study is the best study carried out on developing world biofuels and calls it "an excellent model that other biofuel LCA studies might emulate."
122 Macedo et al (2004), p.12

of 8.3. The second scenario is based on the "best values" being practiced in the ethanol industry. In this scenario, the agricultural energy consumption is 45,861 kcal and the 9,510 for the industrial energy consumption. The energy output is 565,700 kcal. This gives a ratio of output(renewable) energy to input (fossil) energy of 10.2.

The study then moves on to calculate the GHG emissions balance of sugarcane production. The emissions are divided into two groups: "emissions derived from the use of non-renewable energy (diesel and fuel oil) and emissions from other sources (cane trash burning, fertilizer decomposition)."[123]

For the first scenario, the first group of emissions were estimated at 19.2 kg CO_2eq./TC while the second group were estimated at 12.2 kg CO_2eq./TC. The emissions avoided because of sugarcane are calculated as the emissions avoided due to substitution of ethanol for gasoline and to the substitution of surplus bagasse for fuel oil. After deducting avoided emissions from the incurred emissions, the net avoided emissions for the first scenario are 2.6 tCO_2eq/m^3 for anhydrous ethanol, and 1.7 tCO_2eq/m^3 for hydrous ethanol.

In the second "best case" scenario, the first group of emissions were estimated at 17.7 kg CO_2eq./TC while the second group were estimated at 12.2 kg CO_2eq./TC. After deducting from the avoided emissions the incurred emissions, the net avoided emissions for the second scenario are 2.7 tCO_2eq/m^3 for anhydrous ethanol, and 1.9 tCO_2eq/m^3 for hydrous ethanol.

These results are the most comprehensive and systematic study of Brazilian biofuels, and have been quoted extensively. In his review of LCA studies, Eric Larson[124] calls Macedo 2004 "an

123 Macedo, 2004, p.17
124 Larson, Eric 2005

excellent model that other biofuel LCA studies might emulate". There is, however, one very important point which is omitted from this analysis: the effect of land use change. While deforestation is a serious problem in Brazil, the major drivers for it so far have been cattle ranching and small-scale subsistence agriculture. Though biofuels have not played a major part yet in the deforestation in the Amazon, they have been a part of the deforestation happening in the center and south of Brazil.[125] It is important to realize that sugarcane doesn't have to replace forests itself to cause deforestation, but it could indirectly cause it, by displacing other crops and cattle into forest areas. This is of course a very complex process and accounting for it will not be simple.

Land use change is an issue, as we will see later, that is not only pertinent to deforestation in the Amazon. Any change of the use of a land plot from one use to the other will entail a change in the carbon content of the land and its emissions to the atmosphere. A change in the use of the land will certainly entail a change in the amount of biomass on the land, which will necessarily involve a change in the emissions. This would be true if the farm used to be a forest, marginal land, or another type of farm. Further, the knock-on effect of changing land-use is not something that can be ignored. A change in the use of one plot of land will cause different knock-on changes to other plots of land. The defense presented by advocates of Brazilian ethanol which claims that land use change is insignificant in Brazil is simply untenable. The profile of Carbon emissions will inevitably be adjusted when the use of the land is changed.

Palm et al[126] suggest that as much as 500 tons of Carbon are released to the atmosphere whenever one hectare of forest is burnt up and ploughed. Based on these calculations, and

125 Coelho, 2005
126Palm et al (1999)

comparing them to Macedo's results, Righelato[127] claims that it is twice as efficient as a strategy of reducing carbon emissions to work on regenerating rainforests instead of investing in biofuels.

There are several problems with this calculation. First, the results taken from Palm et al[128] refer to forests with high carbon content, which does not reflect all the land on which sugarcane is being planted. In fact, the majority of sugarcane planting in Brazil takes place in the south and center of the country. Secondly, the data on carbon savings are taken from an old study by Macedo[129] reflecting old yields of sugarcane and lower savings of carbon.

In order to be able to fully assess the impact of biofuels on carbon, it is essential for more reliable data to exist on the linkage between energy crops' growth and deforestation, and for the full impact of this deforestation to be assessed in terms of GHG emissions. Studies on this topic must aim to distinguish the correct amount of deforestation being caused, directly and indirectly, by crops used for biofuels. The Macedo et al (2004) paper can provide an excellent assessment of the carbon emissions savings without land use change, but a more comprehensive study of the effect of land use change must be conducted if results are to be realistic. [130]

Finally, using the GREET model (discussed below) Wang et al[131] find that Brazilian sugarcane ethanol used for light-duty vehicles in the United States and find that it can result in a 78% reduction in GHG emissions and fossil energy use by 97%. They find that five sources are

127 Righelato (2005)
128 Palm et al (1999)
129 Macedo, 1997
130 Macedo et al, 2004
131 Wang et al (2008)

responsible for the emissions from sugarcane ethanol to be: open-field burning of sugarcane tops and leaves, N20 emissions from sugarcane fields, fertilizer production, sugarcane mill operation and sugarcane farming.

b. American Corn Ethanol

The vast majority of LCA's have been conducted to assess American corn ethanol. The results are inconclusive and vary widely, as are the different types of methodologies used. The question of the efficiency of American ethanol has received a lot of attention and regularly became a subject of public debate, with two sharply opposed views. On the one side, many critics continue to say that corn ethanol is inefficient and an energy loser and that it will not contribute positively to any emissions reduction because it consumes more energy from fossil fuels than goes into producing it than the energy that it produces.

However, many on the other side of this debate have different viewpoints arguing that the production of ethanol from corn is efficient and can have significant beneficial environmental consequences.

The two most prominent researchers who have continuously argued against ethanol are David Pimentel from Cornell University and Tad Paztek from the University of California, Berkeley. Pimentel and Patzek have published a series of papers discussing ethanol production from corn and other materials.[132] Their conclusions have continuously been negative and they have outlined a plethora of economic, energy-related and environmental factors against the production of ethanol. This paper will not provide an overview of these papers, but will

132 See Pimentel (2003), Patzek (2004), Pimentel and Patzek (2005, 2005a), Pimentel, Patzek and Cicel (2007)

concentrate on their last paper which used the most comprehensive Life-Cycle Analysis with the most recent and reliable data. It is also one of the most widely cited papers in academic circles in the mainstream media.

In a paper published in 2005, Pimentel and Patzek found that ethanol production using corn grain required 29% more fossil energy than that contained in the ethanol fuel produced. With switchgrass, the figure was 50% and with wood biomass the figure was 57%.[133] However, many criticisms exist of these studies. As an LCA, this study included several factors that are usually not included in LCA studies. For example, the authors accounted for the food and transportation costs consumed by workers in the biofuels sector, as well as things like police protection. Further, Farrell et al[134] criticized the paper for using old technology for producing ethanol that is outdated. As more money is being invested in producing ethanol, there are many more modern techniques coming on board for the production of ethanol that are more efficient. Farrell et al also critique Pimentel's allocation of energy from bi-products of ethanol which can have several useful applications like cattle feed.

Among the lead researchers on the "opposite side" of this debate are Michael Wang, Hossein Shappouri and Norman Brinkman. In a report[135] published in 2005, Brinkman et al published results that are contradictory to those of Pimentel and Patzek, in which they found that ethanol contained 1.35 times the energy that went into producing it, a very favorable ratio that they even claim is less than gasoline (which they claim contains 81% of the energy that goes into producing it.)

133 Patzek and Pimentel, 2005
134 Farrell et al (2006)
135 Brinkman et al (2005)

Hill et al[136] use a life-cycle analysis model to estimate that ethanol yields 25% more energy than the energy that goes into producing it. They also find that ethanol results in 12% less GHG emissions production than gasoline. Farrell et al find that ethanol from corn production is less petroleum intensive than gasoline, but that GHG emissions from corn ethanol production are similar to the use of gasoline. In other words, though ethanol may lessen dependence on foreign oil, a major American concern, it is unlikely to provide GHG emission reductions.

In another meta-analysis that normalized and standardized the analysis from 10 different papers, Hammerschlag[137]found that the energy return on investment in ethanol is positive. Hammerschlag defines the Energy return on investment in ethanol (r_E) as the total product energy divided by the nonrenewable energy input into its manufacture. With a value of r_E greater than 1 implying that ethanol production has captured at least some renewable and a value of r_E greater than 0.76 indicating that ethanol consumes less nonrenewable energy in its manufacture than gasoline. The results imply that corn ethanol has a $0.84 < r_E < 1.65$.

Hammerschlag and Farrell et al, among many others, show that the main barrier for corn ethanol is that as it expands, it will have to move to less productive land, where its problems will multiply. This again raises the question of land use change from emissions, and none of the aforementioned studies assesses this satisfactorily. In 2008, however, a new study by Searchinger et al used a worldwide agricultural model to estimate emissions from land-use change, and found that "corn-based ethanol, instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years." [138]

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136 Hill et al, 2006
137 Hammerschlag (2006)
138 Searchinger, 2008

Finally, we turn to analyze the results of the important and widely-used Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model. GREET was developed in 1995 by the Argonne National Laboratory with support from the US Department of Energy.[139] GREET is a very extensive and complex model, with "more than 85 transportation fuel patheways. Among them, four are fuel ethanol pathways (corn dry mill ethanol, corn wet mill ethanol, woody cellulosic ethanol, and herbaceous cellulosic ethanol).[140]

GREET's website states: "To fully evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels, the fuel cycle from wells to wheels and the vehicle cycle through material recovery and vehicle disposal need to be considered."[141]

Wang states that GREET's analysis "concludes that corn-based ethanol achieves energy and GHG emission reduction benefits, relative to gasoline. This is mainly because of 1) improved corn productivity in U.S. corn farms in the past 30 years; 2) reduced energy use in ethanol plants in the past 15 years; and 3) appropriately addressing of ethanol's co-products."[142] Previous GREET studies conducted by Wang have also reached similar results, though their methodology and specifications varied.[143]

Finally, Marko Delucchi's LEM (discussed below) finds that American corn ethanol emissions impact ranges between -25% to +20% compared to gasoline[144]. Delucchi interprets these findings as suggesting that corn ethanol does not offer real gains in emissions and efficiency.

139 Wang (2005)
140 Wang (2005)
141 Accessed on: http://www.transportation.anl.gov/modeling_simulation/GREET/index.html
142 Wang, 2005
143 See Wang et al. (1999a), Wang et al. (1999b) and Wang et al (2003)
144 Delucchi, 2006

c. Biodiesel

Fewer LCA studies have been conducted on biodiesel than on ethanol. The disparity in results and methodologies is even larger than that amongst corn ethanol studies, and it makes comparing the results sometimes seem meaningless. I will here provide an overview of the main and most cited results within this literature.

Hill et al use a life-cycle analysis model to estimate that biodiesel yields 93% more energy than the energy that goes into producing it. They also find that biodiesel results in 41% less GHG emissions production than diesel. The GREET model, however, finds that biodiesel from Soy results in reduction in GHG emissions of 40% to 80%. Finally, Marko Delucchi's LEM finds that biodiesel from soy emissions impact ranges between -20% to +50% compared to gasoline.[145]

An important issue with the production of biodiesel is the impact that is caused by the application of Nitrogen compounds, mainly from fertilizers. This is a more serious issue with biodiesel crops than with ethanol crops, as Delucchi illustrates[146]. Crutzen et al[147] account for the impact of N2O and find that this can more than account for any carbon savings biodiesel might have had.

Reijneders and Huijbregts find that South Asian palm oil used as a biofuel will result in large emissions of CO2-equivalent emissions. They estimate that the "losses of biogenic carbon associated with ecosystems, emission of CO2 due to the use of fossil fuels and the anaerobic conversion of palm oil mill effluent currently correspond in South Asia with an emission of about 2.8-19.7 kg CO2 equivalent per kg of palm oil. They attribute the large variability in their

145 Delucchi, 2006
146 Delucchi, 2006
147 Crutzen et al, 2007

results to the wide range of plausible assumptions that one can utilize in the estimates of the calculation. [148]

d. Cellulosic Ethanol

There currently is no commercial production of ethanol from cellulosic feedstocks. The technology for producing cellulosic ethanol is not yet commercially viable. This section will attempt an overview of the state of the art in research on cellulosic ethanol, and outline the expectation of cellulosic ethanol production.

According to the Department of Agriculture, "Cellulose-based ethanol is derived from the fibrous, generally inedible portions of plant matter (biomass) and offers a renewable, sustainable, and expandable resource to meet the growing demand for transportation fuel. It can be used in today's vehicles and distributed through the existing transportation-fuel infrastructure with only modest modifications. Additionally, the amount of carbon dioxide emitted to the atmosphere from producing and burning ethanol is far less than that released from gasoline."[149]

The crops from which cellulosic ethanol are produced require less fertilizers and are easier to grow and maintain than starch and sugar crops. Further, lignin, one of the side-products of cellulosic ethanol can be burned to produce power for the conversion facilities.

148 Reijneders and Huijbregts, 2008
149 Department of Agriculture, 2007. P1.

Cellulosic materials like willow and switchgrass are usually touted as the future of biofuels. The technology to utilize them may still be underdeveloped, but there is wide optimism on their use. The conversion process is more complex than that of ethanol from corn, since the cellulose must first be converted to fermentable sugar using enzymes, and the process is capital intensive.

The Department of Agriculture, for instance, in its press release touting the release of a "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda," expresses what is perhaps the prevailing conventional wisdom on this topic: "Although most of the ethanol produced today is derived from corn grain, dramatic increases in the availability of ethanol are expected through increases in quantity and decreases in cost of ethanol from biomass. Corn-based ethanol is helping the new cellulosic ethanol industry by providing technology improvements, infrastructure, and demand. Both corn and cellulosic-based ethanol are likely to assist each other's growth."

Converting cellulosic biomass to ethanol is not a new technology; it was first developed in 1930's Germany at a time when Germany had to deal with its shortage of oil for its war effort[150]. This process is still in use in Russia today. The processes has three main steps:

1. Thermochemical pretreatment of raw cellulosic biomass to make cellulosic biomass more accessible to enzymatic breakdown and to free up hemicellulosic sugars.
2. Production and application of special enzyme preparations for hydrolysis of plant cell-wall polysaccharides to produce simple sugars
3. Fermentation to convert sugars to ethanol, mediated by bacteria or yeast.

150 Department of Agriculture, 2007. P13

As we shall see below, each of these processes could be improved.

d.1 Possibilities

Former US Secretary of Energy Samuel Bodman has announced that it is the goal of the US government to displace 30% of gasoline consumption by 2030 with ethanol. Such a target would entail the production of 60 billion gallons of ethanol.

Writing in *Science*, Tilman et al[151] argue that low-input high-diversity grassland perennials "can provide more usable energy, greater greenhouse gas reductions, and less agrichemical pollution per hectare than can corn grain ethanol or soybean biodiesel." They further calculate that low-input high-diversity biomass could produce the equivalent of "13% of global petroleum consumption for transportation and 19% of global electricity consumption. Without accounting for ecosystem CO2 sequestration, this could eliminate 15% of current global CO2 emissions."

In a report for the Department of Energy and Department of Agriculture, Perlack et al attempt to analyze whether the United States could produce enough biomass to meet the 30% target called for by Congress. The authors suggest that meeting this goal would require 1 billion tons of dry biomass feedstock each year. They answer with an emphatic yes, arguing that 1.3 billion tons of dry biomass could be sustainably produced in the United States each year only from forestland and agricultural land. They insist that this is not a higher ceiling, but a scenario based on reasonable assumptions.[152]

Nonhebel argues that under a scenario of high yields of crops, there is a possibility for America to meet its demand for food and crops as well as for transportation fuels. In a scenario in which

151 Tilman et al, 2006
152 Perlack, 2005

the yield of the land is poor, however, this is not possible.[153] In a detailed report on the subject, the World Resource Institute expects commercial production to enter the market by 2012.

d.2 Challenges

a. Biomass Recalcitrance

There are several technical barriers to the commercial utilization of cellulosic ethanol. Himmel et al (2007) view the main obstacle to be biomass recalcitrance, defined as "the natural resistance of plant cell walls to microbial and enzymatic deconstruction". This recalcitrance, Himmel et al argue, evolved as a way for plants to protect their sugars from microbes and animals.

Himmel et al see that developing this technology will be the key to making transportation fuels from cellulosic ethanol, and "predict that the advances in scientific understanding necessary to achieve this goal appear realizable." They argue that there are three improvements that need to occur in order for cellulosic ethanol to gain commercial viability. These are:

1- Improvement in the kinetics of breaking down cellulose to sugar
2- Low yields of sugars from other plant polysaccharides
3- Removal of lignin

The authors cite two main areas where research is being done to overcome biomass recalcitrance:

153 Nonhebel, 2005

i. Designing plants for deconstruction:

Here, there are many possibilities in changing the structure of the plant, cell walls and plant tissue. By altering molecular interactions between hemicelluloses, lignin, and cellulose microfibrils, plant cell walls could be engineered to reduce the needed cost of enzymes.

Another more significant possibility, however, is the production of "wounded" cellulose, which is more amenable to deconstruction. The authors do not posit this as a prediction, but wonder about the possibility of it happening, and even question whether such a plant could survive. At the level of plant tissue, the authors discuss the possibility of the "genetic engineering of the organization of vascular bundles and cell-wall pit density." The authors again reiterate their concern on whether these plants could survive.

ii. Engineering catalysts and bioconversion systems:

A main handicap to the production of cellulosic ethanol is the slow action of cellulose enzymes, which increases costs significantly. Himmel et all suggest that two possible solutions for this could be mining diversity to find new enzymes and knowledge-based protein engineering. The authors conclude their analysis stating: "Although developing the technology for cost-effective motor fuel production by 2030 is challenging, the advances in scientific understanding necessary to achieve this goal appear realizable." [154]

Ragauskas et al also attempt an analysis of the path forward for cellulosic biofuels. They argue that these crops can address several societal needs, and that with advances in science leading to the development of what they call the biorefinery, a concept whose essence they describe as

154 Himmel et al, 2006

follows: “An abundant raw material consisting primarily of renewable polysaccharides and lignin enters the biorefinery and, through an array of processes, is fractionated and converted into a mixture of products including transportation fuels, co-products, and direct energy.”[155] This biorefinery will integrate the use of “innovative plant resources, synthesis of biomaterials and generation of biofuels and biopower”[156]

For Rasgauskas et al the real challenge facing the production of cellulosic ethanol is related to that of Himmel at al: developing crops whose physical and chemical traits are amenable to processing, while increasing the yield of the biomass. (p.486). They city six possible improvements[157]:

1. Improved sunlight capture through photosynthesis
2. Manipulation of genes involved in N-metabolism
3. Genetic engineered defense systems’ transfer
4. Preventing or delaying flowering
5. Shortening or delaying winter dormancy
6. Genetic manipulation to reduce lignin and increase cellulose; or alter structure of lignin

The authors posit that the whole process of the biorefinery will be carbon-neutral, since it will recycle its waste. “It leverages our knowledge in plant genetics, biochemistry, biotechnology, biomass chemistry, separation, and process engineering to have a positive impact on the economic, technical, and environmental well-being of society.” The authors nonetheless acknowledge that “advances in plant science will certainly be influenced by societal policies,

155 Ragauskas, 2006, p.486
156 Ragauskas et al, 2006, p.484
157 Ragauskas et al, 2006, p.485

land use practices, accelerated plant domestication programs, and research funding to develop this vision."[158]

The Department of Energy, in its Biomass to Biofuel (B2B) report, also agrees with Himmel et al that cellulosic-biomass recalcitrance to processing is the main barrier to the development of cellulosic ethanol. The DOE echoes Ragauskas in saying that the new technologies will create a new paradigm of the biorefinery. The DOE B2B report outlines a roadmap of a technical strategy towards successfully integrating cellulosic biofuels into fuel production by 2030, according to Congress's proposals, divided over three phases:[159]

1- Reasearch phase: This phase will occur within 5 years of the report, and would entail "reducing cost, enhancing feedstock deconstruction, improving enzyme action and stability, and developing fermentation technologies to more efficiently use sugars resulting from cellulose breakdown"[160]

2- Technology Deployment Phase: This phase, which is to happen within 10 years, "will include creation of a generation of new energy crops with enhanced sustainability, yield, and composition, coupled with processes for simultaneous breakdown of biomass to sugars and cofermentation of sugars via new biological systems."[161]

3- Systems Integration Phase: This phase, expected within 15 years, "will incorporate concurrently engineered energy crops and biorefineries tailored for specific

158 Rasgauskas et al, 2006, p.488
159 Department of Energy, 2006
160 Department of Energy, 2006, p29
161 Department of Energy, 2006, p32

agroecosystems."[162] This phase will attempt to reach the "theoretical conversion limits" to cellulosic biofuels.

According to DOE, the biotechnology breakthroughs that will increase biomass supply are:

- Biomass crops will be bred to increase the quantity of biomass per acre, grow better on marginal lands, be more drought- and pest-tolerant, and be less costly to harvest
- Biotechnology may lead to the breeding of biomass crops with characteristics that make them more easily converted to ethanol, such as the substitution of cellulose, which is easy to convert, for lignin, which is difficult to break down.

d.3 The efficiency of cellulosic production

Girouard et al[163] carry out a study of short-rotation forestry willow and switchgrass. The study carries out simulations of planting, production and processing of these two crops under different scenarios and attempts to measure the environmental and energy balance of these production processes, as well.

The study finds that both crops can yield net sequestration of carbon in the conditions in which they test them; they also find that willow is more efficient in carbon sequestering than switchgrass, and that it can produce more energy per unit of fossil fuel input (30:1 ratio for willow; 20:1 for switchgrass). They did find, however, that switchgrass is cheaper to grow than

162 Department of Energy, 2006, p.34
163 Girouard et al, 1999

willow. It is important to emphasize here that this is not a universal study that can talk about the impact of willow or switchgrass in general, but rather, a study that focuses on these crops in a particular environment in Easter Canada, under given conditions.

Farrel et al[164], in the same study cited above, using the Energy Resource Group Biofuels Analysis Meta-Model, also attempt an analysis of cellulosic ethanol efficiency. They begin with the disclaimer that the case they present is a "preliminary estimate of a rapidly evolving technology and is designed to highlight the dramatic reductions in GHG emissions that could be achieved"[165]. They find that cellulosic ethanol is likely to generate significant reductions in GHG emissions, as well as large reductions in fossil fuel use. They find that every MJ of energy requires cellulosic uses 0.08 as much gasoline as would getting that same energy from gasoline. They also find that it produces around a tenth of the GHG emissions of gasoline.

Wang, using the GREET model discussed above and finds that cellulosic ethanol reduces GHG emissions by 85% relative to gasoline[166]. Using various estimates of switchgrass yields in 2025 and 2050 by Greene[167] along with the estimates from Wang et al[168] of GHG reductions, Larson[169] arrives at the conclusion that cellulosic would offer significant reductions in gasoline consumption as well as GHG emissions. Delucchi's LEM finds that cellulosic ethanol would cause reductions in greenhouse gas emissions by between 40% and 80%.

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164 Farrel et al, 2006
165 Farrel et al, 2006, p.507
166 Wang et al, 2005
167 Green, 2005
168 Wang et al, 2005
169 Larson, 2005

On the other hand, several studies find that cellulosic ethanol would not offer improved environmental performance. Searchinger et al[170], after accounting for land use change impacts, find that biofuels from switchgrass, if grown on U.S. corn lands, increase emissions by 50%. Pimentel and Patzek similarly find increased emissions from the utilization of cellulosic ethanol.[171]

e. Conclusion

The only solid conclusion from the current LCA literature is that there is no consensus on the answers to the questions of biofuel efficiency in sugarcane ethanol, corn ethanol, biodiesel or cellulosic ethanol. There is no conclusive evidence to suggest that these fuels, if utilized heavily, can reduce carbon emissions. For cellulosic, there is no solid evidence to even suggest that it might be produced commercially soon, if ever.

Chapter III argued that biofuels policies were designed to increase biofuels use in order to reduce greenhouse gas emissions. However, since there is no solid evidence to suggest that increased biofuels use will actually meet these goals, serious doubt is cast on the efficacy of these policies and on the entire premise of using biofuels-promotion policies as tools in the fight against climate change and finding new energy sources.

Further, this analysis raises serious questions about the solution-centric approach to the problem of climate change, which aims to reduce emissions by boosting particular solutions to the problem, as seen in the Pacala and Sokolow paper. The absence of consensus on the

170 Searchinger et al, 2008
171 Pimentel and Patzek, 2005

efficiency of biofuels currently questions the likelihood of success that aims at boosting by 50-fold the production of these fuels.

The following chapter will discuss the methodological limitations of LCA's in more detail and emphasize the nature of the ignorance of the efficiency of these fuels, and why any results on their efficiency cannot be taken as decisive.

Chapter V: Analyzing LCA's

In Chapter IV it was shown that there is a large variability of results in the Lifecycle Analysis literature which makes it hard to derive any solid conclusions about the efficiency of fuels.

Extensive debates surrounding the numerous variables, measurements, factors and technical specifications have been raised within the LCA literature discussed above and the wider literature. In order to illustrate the problems with these studies, I will select some of the most widely-cited review studies and mention their most significant explanations for the variations in the results. I conclude with the work of Delucchi (2004), regarded as the most comprehensive and systematic treatment of the topic, along with Kammen et al (2008), which was a roundtable including Delucchi, Kammen, Farrell and others, building largely on the work of Delucchi.

From this discussion this chapter then moves on to provide some theoretical background on these issues from economics and philosophy of science literature.

a. Co-products as an illustrative example of problems with LCA's

As a guide to understanding the problems of LCA's, it is useful to begin with illustrating the complexity of debate surrounding one particular sticking point: allocation of biofuel co-product credit. Co-products are all products that emerge from the process of biofuels production other than the biofuel itself. These can have various useful applications, including cow-feed (corn ethanol co-products) and stationary energy (bagasse—sugarcane ethanol's by-product). The treatment of co-products is by no means the biggest sticking point in LCA's, nor is it the most methodologically intractable. It is, however, a very good illustrative example of the sort of problems that LCA's run up against, and it is widely discussed in the literature and illustrates wider problems with LCA's.

Pimintel & Patzek (2005) did not include co-products in their LCA's and found that ethanol is inefficient, Wang et al (2005) included them and found that ethanol is efficient. Wang et al argued that since the co-products of ethanol production can be used as cow feed, one must then credit ethanol production with the carbon saved from the averted production of cowfeed. In turn, Pimentel & Patzek responded by pointing out that this is invalid since the quantities of cowfeed produced as a co-product exceed the quantities of cowfeed consumed in America, making it absurd to consider that they would "replace" any production processes.[172]

More recently, Farrell et al[173] analyzed "six representative analyses of fuel ethanol" and argued in a widely cited Science paper that the studies that found negative net energy for biofuels "incorrectly ignored coproducts and used some obsolete data."

172 Patzek et al (2005)
173 Farrell et al (2006)

Quirin et al[174] examine the issue and find that co-production credit ranges very widely within the literature. In particular, they examine how much of the co-production credit will be charged against the primary biofuel product. They find that the range of allocating co-production credit varies from 15% to 95% of emissions among the literature. This wide range is reflected in the wide range of the results of these studies, which range from concluding that ethanol offers no emissions advantages compared to fossil fuels, to finding that it offers as much as a fourfold advantage.

In surveying the literature, Larson (2005) finds that there are six methods for allocating co-production credits. He lists these as:

1- No allocation: Under this method, co-products are simply not counted as relevant in the LCA calculation, and their emissions and energy content is ignored. Larson cites Woods and Bauen as following this method.

2- The weight of co-products

3- The intrinsic energy content

4- How much of the total process energy their co-production is deemed to consume

5- The market value of co-products

6- The energy displaced when the co-products substitute for products that would have been made by conventional routes and would have been used had the bio-based co-products not displaced them. [175]

174 Quirin et al (2004)

175 Larson, 2005

Larson provides evidence of how the results of an LCA would be skewed by adopting one of these methods versus the other. This raises the question of which is the correct way of calculating co-product credit.

It cannot be (1) because these co-products can be made useful, can contain energy that can be used in the process and can be sold as cow-feed. If (1) is chosen, then we have not accounted accurately for the energy balance of the process, because a lot of the cow feed being produced will substitute for other production of cowfeed through other means, which would reduce emissions. Thus, an accurate measure of the energy or carbon balance of the process should take this into account. So a correct accounting for LCA's must include co-product credit. But it cannot be (2), (3) or (4) either, because these assume that all co-products will be utilized and all their energy and carbon content will be useful. But since that is not the case, this is also incorrect accounting. (5) offers a more realistic estimate, since it will take into account what actually happens to the co-product on the market, but it is also insufficient, because it ignores that the market is dynamic and what happens with these co-products will itself affect the prices that they can fetch on the market. Further, accounting for the price alone will affect the financial calculation of the lifecycle, but not the calculation of energy and emissions. A more accurate accounting must include the effects that this production will have on other markets, other production processes and other commodities, calculating the changes in emissions and energy achieved there. Therefore, (6) comes closest to being the accurate way of assessing energy and emissions changes.

What (6) effectively measures, however, is the dynamic impact on the market of the production of ethanol and its co-products. Though it would be far easier to treat all inputs and outputs as lump sums of materials with well-defined prices, the reality is different. Consumption and production of new materials will affect their availability on the market and their prices, and influence other people's choices of what to consume and use. These will all carry energy and emission implications.

In order to assess this accurately, we would need to integrate the LCA with a dynamic economic general equilibrium model that traces the impact of the production across the economy. This requires an accurate general equilibrium model of the economy, where all the co-products consumed are calculated, and all the displaced products they replace are accounted for, and the difference in emissions and carbon is calculated.

The rationale here is straightforward: if a correct accounting of the changes brought about by ethanol production is to be performed, this must account for all the changes that occur to energy consumption and all the changes to carbon emissions caused by this production. An LCA cannot just count the impact of the effects that are easily measured, it must include everything to be comprehensive. And in order to include everything, all impacts on all production and consumption of co-products must be accounted for. And for that, only a comprehensive economic model that measures the amount of co-products utilized, as well as what they are replacing, will suffice. No existing LCA study has been integrated with such an accurate and general economic model.

But the issue of co-products raises further questions about other aspects of the lifecycle analysis. What applies to co-products must apply similarly apply to all inputs and outputs to the production of ethanol. When an ethanol plant consumes corn, this is corn that was taken away from food consumption and into ethanol production. This will have a ripple effect on corn markets: prices would rise, and this in turn will lead to other effects on production and consumption, each with its own impacts on the economy. These are referred to in the literature as 'knock-on effects'. Some corn producers will increase their production, producers of other corn crops will shift to corn production, and marginal land will then be transformed to corn farms. All of these processes will consume energy and produce emissions. An accurate LCA must account for all of these effects. The same will hold true not just for all other inputs into the production process, from fertilizers to equipment to infrastructure. The implication here is clear: an LCA must be situated within a comprehensive general economic model in order to be able to assess emissions and energy resultant from any production process.

This conclusion is affirmed in almost every LCA paper written. Even as scholars publish studies with decisive answers on biofuels energy and emissions efficiency, they nonetheless acknowledge the conflicting facts that their model is not comprehensive, and that only a comprehensive model could answer these questions.

Farrell et al (2006) emphasize that in order for a study to be able to understand the effects of biofuel use "the entire lifecycle must be considered, including the manufacture of inputs (e.g. fertilizer), crop production, transportation of feedstock from farm to production facilities, and then biofuel production, distribution, and use."

Similarly, Wang (2008) also emphasizes the need to take account of all knock-on effects when modeling impacts, arguing: "Researchers must use general equilibrium models that take into account the supply and demand of agricultural commodities, land use patterns, and land availability (all at the global scale), among many other factors … At this time, it is not clear what land use changes could occur globally as a result of U.S. corn ethanol production."

b. Sources of variation within the LCA literature

In their comprehensive review of LCA studies, Quirin et al (2004) survey 800 studies, 63 of which they find to fit their criteria of detailed analyses, giving them 109 energy and CO2 balances of biofuels. They find widely varying results in their survey.

Quirin et al attribute the variance in the findings to four main differences in assumptions. (1) The difference in data basis, such as different studies using widely varying estimates of the use of fertilizer, and the energy that goes into making the fertilizers. (2) The difference in crop yields, which vary by study and are location dependent. (3) The differences in process technology. (4) The assessment of co-products. [176]

In his overview of LCA studies, Larson notes that one of the main "striking features" of these LCA studies is the wide range of results. Larson argues: "one may conclude that there can be a number “right” answers to the questions of how much GHGs and fossil energy can be saved through use of biofuels. It would appear to be difficult to draw unequivocal conclusions regarding the precise quantitative energy and environmental benefits (or costs) of any particular biofuels pathway without detailed case-specific information and analysis." He identifies four key factors for the uncertainties and differences in results between these studies: (1) The inclusion of climate-active species, (2) the analysis of N_2O emissions and other emissions, (3) allocation of co-product credits, and (4) soil carbon sequestration. [177]

But the most systematic and comprehensive overview comes from Delucchi (2004) and Kammen et al (2008), which built extensively on Delucchi's work. Delucchi argues that

176 Quirin et al, 2004
177 Larson, 2005

"[t]oday, most LCAs of transportation and global climate are not appreciably different in *general* method from the analyses done in the early 1990s. And although different analysts have made different assumptions and used slightly different specific estimation methods, and as a result have come up with different answers, few have questioned the validity of the general method that has been handed down to them."[178] Delucchi identifies the major areas of uncertainty, disagreement and incompleteness in the existing literature as:

- "*treatment of lifecycle analyses within a dynamic economic-equilibrium framework;*
- *major issues concerning energy use and emission factors; and*
- *incorporation of the lifecycle of infrastructure and materials.*
- *representation of changes in land use;*
- *treatment of market impacts of co-products;*
- *development of CO2 equivalency factors for all compounds;*
- *detailed representation of the nitrogen cycle and its impacts*"[179]

Delucchi is responsible for constructing the Lifecycle Emissions Model (LEM), which is arguably the most comprehensive and sophisticated of all the LCA models surveyed. The LEM is superior to other LCA's in several important respects, and it has a scope far greater than all of them. The LEM is a model that can be incorporated into analyzing many more countries than other models. LEM also spans much longer time periods in its analysis, can integrate many biofuels and production pathways. Further, the LEM raises an important new consideration that is not usually discussed in the rest of the literature: pollutants other than CO2. Since our concern is climate change, it is not sufficient to worry about Carbon Dioxide emissions

178 Delucchi, 2004
179 Delucchi, 2004

exclusively when other pollutants can also contribute to climate change. Hence, a process that reduces carbon dioxide but increases other pollutants might actually end up contributing to climate change. From this consideration, Delucchi develops the concept of CO2-Equivalency Factors. This is similar to the concept of Global Warming Potential (GWP) used by the IPCC. LEM also includes a full accounting of the Nitrogen cycle, as well as taking full Carbon Equivalence Factors for many other pollutants. Finally, LEM also includes the very important factor of Land Use Change.

But the work of Delucchi himself serves as a very good illustration of the short-comings of current LCA's and even his LEM. The LEM demonstrates the complexity of any attempt at modeling the lifecycle of biofuels. And Delucchi moves on to discuss the major differences among different LCA's, and what a better LCA would look like. Delucchi comprehensively sketches the outlines of how an ideal LCA model would look, compares it to our current lot, and finds the latter coming significantly short. Delucchi's ideal LCA model can be summarized in Figure 3.

Delucchi posits four main differences between the ideal model and the conventional LCA: prices; policies; the consumption of energy and materials and use of land; and the treatment of other emissions and the climate system. I will briefly discuss each of these issues, though the reader is referred to Delucchi's work for a more thorough treatment.

i) **Policy**

Robert Merton raises an important point about the impact of policies on the predictions on which they are built, which he terms the self-defeating prophecy. As a prediction is made by a policy-maker and acted upon, the conditions that the policy-makers had held for their policy will no longer hold, because of this policy. As Merton puts it: "Thus, to the extent that the predictions of social scientists are made public and action proceeds with full cognizance of these predictions, the "other-things-being-equal" condition tacitly assumed in all forecasting is not fulfilled. Other things will not be equal just because the scientist has introduced a new "other thing" - his prediction."[180]

Delucchi's analysis of modeling policies in LCA speaks to the same point, arguing that most LCA's do not look at policy decisions and analyze them, but instead seem to analyze two sets of activities defined as the "biofuels cycle" versus the "gasoline cycle" and evaluate their impacts. This, Delucchi argues, is flawed because it is impossible to imagine that these two sets of activities can be replaced in a straightforward way that has no impact on anything else--rather, there will be far-reaching effects on prices, consumption and production worldwide. These effects will in turn have significantly different energy and environmental impacts, which cannot be ignored. The method of looking at fuel cycles does not take this into account and is therefore not reliable.

Delucchi argues that LCA's should instead focus on analyzing the effect of specific policies pertaining to biofuels on emissions and costs. By framing the question that way, LCA studies can analyze specific policies, their impacts and their knock-on effects and compare them to alternative policy options and scenarios. This is a more relevant answer to real world concerns, where we do not face a choice between extreme stylized cases of two different energy cycles of different fuels, but rather, between changes at the margin of current patterns of consumption. Framing the question in this way allows the answer to be applicable to the situation at hand. It

180 Merton, Robert. 1996.

is also more useful for policy-makers, because they need to make practical choices between policy alternatives that can be directly assessed.

Since LCA's should be used for guiding and informing policy-making, the questions that the LCA addresses must be framed in a way that can inform that, rather than answer unclear questions with undefined terms.[181]

ii) **production and consumption of energy and materials, and use of land**

Delucchi argues that "there remain serious concerns and oversimplifications"[182] in the accounting of the energy use and material and infrastructure part of LCA models. Perhaps even more significantly, the important question of land use changes is either ignored or treated very simplistically. The change in the use of land results in changes in emissions in several regards: changing the living matter on the land leads to a direct change in the carbon content, releasing/absorbing carbon into/from the atmosphere. Further changes in land use result in changes in many "physical parameters, such as albedo (reflectivity), evapotranspiration, and fluxes of sensible and latent heat."[183]

iii) **Prices**

Any environmental, food or energy changes will invariably affect prices in significant ways that will carry with them significant repercussions on consumption and production decisions of others. A move from using one fuel to another will inevitably cause price changes in both fuels and in its substitutes and compliments. When one fuel is substituted for another, we cannot

181 Delucchi, 2006
182 Delucchi, 2006
183 Kammen et al, 2008

assume that the quantities of production will be altered in precisely the same numbers. A drop in the consumption in one fuel will result in a drop in its price, which will in turn lead to an increase in its consumption in other places, and vice-versa.

This is the point that was illustrated by the earlier discussion of co-products. One cannot assume that a co-product will be utilized entirely, nor that it can be ignored completely. The reality is that its fate will be determined by a complex price-mechanism that will determine what is utilized and what isn't. This is true for much more than just the co-products of the ethanol-making process.

The traditional LCA model, by failing to account for this, becomes woefully lacking. Delucchi thus concludes that in order to be able to estimate a useful LCA, one must integrate the physical and lifecycle aspects of it with a dynamic general equilibrium model. Kammen et al arrive at a similar conclusion on the effect of prices, concluding: "Ideally, one would use an economic model to determine the effect of coproducts on their markets and the extent to which co-products displace other production. No LCA has such an economic model built into it, although LEM does have a single parameter that is meant to account for these market-mediated impacts of co-products."

iv) **Other emissions and the climate systems**

Delucchi raises the important point (ignored in most LCA's) that the parameter that we care about is not so much the emissions of CO2, but the general effect on the climate system. This makes it important to look into GHG's other than CO2 and assess their impact on the atmosphere, as well as looking into other sources of GHG's. This also means that an LCA will need a comprehensive estimation of emission factors, which will quantify the impact of different gases on the atmosphere. A further complication is added when Delucchi states that an LCA would also need to assess the impact of different GHG's on each other; since the interaction of different pollutants will change the likely impacts they will have on the atmosphere.

After his extensive critique of old LCA's, and outlining of the traits of a better LCA, Delucchi concludes his call for new models saying:

> "...lifecycle models must be designed to address clear and realistic questions. In the case of lifecycle analysis comparing the energy and environmental impacts of different transportation fuels and vehicles, the questions must be of the sort: "what would happen to [some measure of energy use or emissions] if somebody did X instead of Y," where – *and here is the key* – X and Y are *specific and realistic alternative courses of actions.* These alternative courses of actions ("actions," for short) may be related to public policies, or to private-sector market decisions, or to both. Then, the lifecycle model must be able to properly trace out all of the differences – political, economic, technological -- between the world with X and the world with Y. Identifying and representing all of the differences between two worlds is far more complex than simply representing the replacement of one narrowly defined set of engineering activities with another." [184]

Delucchi summarizes the differences between his proposed better model and the traditional approach in this figure:

184 Delucchi, 2004

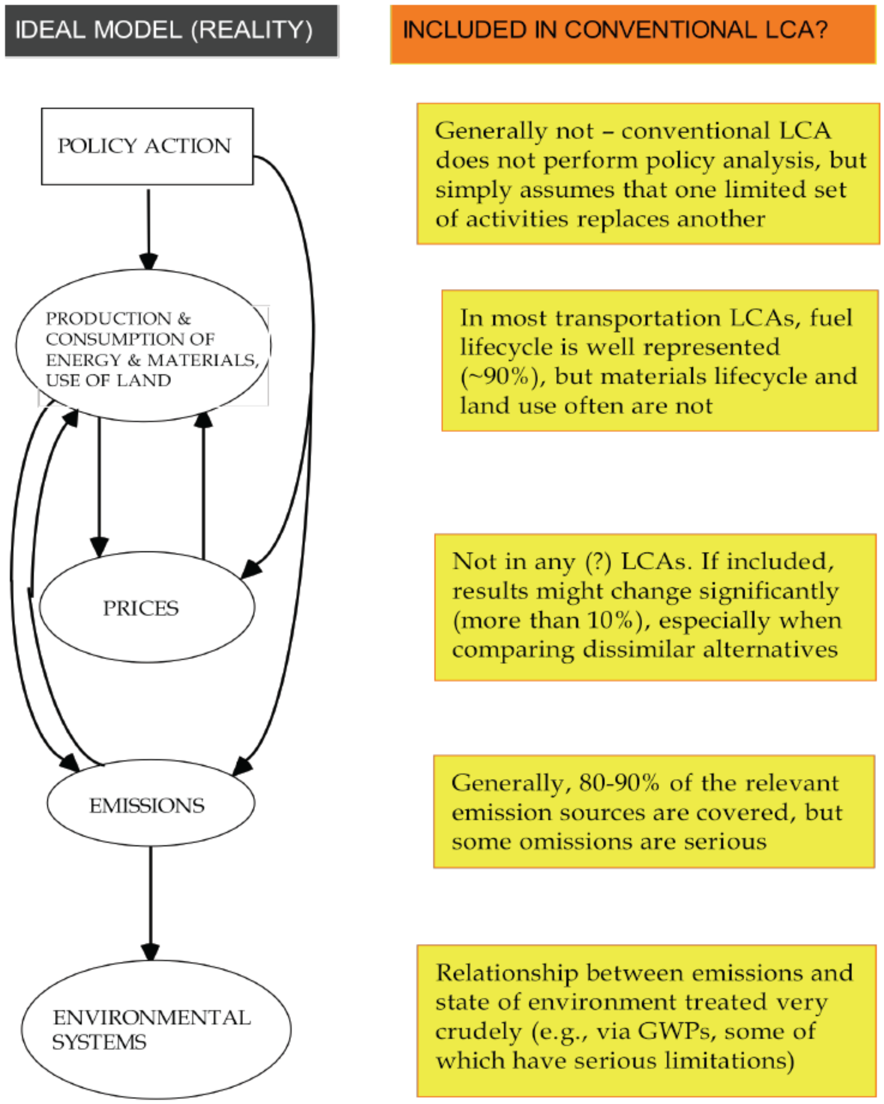

Figure 3: Ideal versus conventional LCA[185]

c. Conclusion: Problems with LCA Results

From reading the literature reviews on the problems with LCA results, and based on the problems cited by Quirin et al, Larson and Delucchi, we can classify the problems of LCAs into

185 Source Delucchi (2004)

five broad categories which illuminate why the results of this literature have been so inconsistent.

i. Complexity and Predictability:

The analysis of LCA's runs up against several problems of complexity which is hard to systemize and reduce for straightforward analysis, as well as factors whose prediction is very hard. Under this broad heading we can classify Quirin's points about the differing energy quantities that go into making fertilizers, the difference in crop yields, and the allocation of co-products as well as Larson's points about the inclusion of climate-active species, other emissions, co-products and soil-sequestration. And this also includes Deluchchi's points about the consumption and production of energy and materials, land use change and other emissions. The current theme running through all these arguments is that LCA's have a short-coming due to the fact that they analyze complex phenomena and do not account for them fully.

Warren Weaver (1961) in his discussion of the evolution of scientific understanding of complex phenomena begins by attempting to illustrate the meaning of complex phenomena, and how science treats them. Weaver argues that before the Twentieth Century, physical science's greatest advances and most momentous contributions to human welfare came from applying the scientific method to studying questions that involved only two (or only a few) variables[186]. Relatively straightforward theories and experiments were sufficient to establish scientific rules which then became very important for human knowledge and society. Enormous gains from science and technology ensued from applying the scientific method to these laws and rules.

186 Weaver, 1961, p.57

Weaver then explains that the twentieth century presented an attempt to apply the methods of science studying a few variables to studying many more variables—studying complexity. Weaver draws the distinction here between two types of complexity: disorganized complexity and organized complexity. He defines disorganized complexity as:

> "a problem in which the number of variables is very large, and one in which each of the many variables has a behavior which is individually erratic, and may be totally unknown. But in spite of this helter-skelter or unknown behavior of all the individual variables, the system as a whole possesses certain orderly and analyzable average properties."[187]

As examples of this type of complexity he cites a telephone exchange predicting the average frequency of calls, or an insurance company attempting to assess death rates. The key feature of disorganized complexity can be seen to be the lack of complex interrelations between the multiplicity of variables. Weaver argues that disorganized complexity is amenable to investigation by statistical and mathematical techniques. Because there are no complex interrelations between the variables, the totality of the variables can be assessed using statistical and mathematical techniques.

Organized complexity, on the other hand, is not amenable to easy analysis with mathematical and analytical techniques. The distinction, Weaver insists, is not in the number of factors or variables, but rather in the existence of complex interrelations between the multiple factors. "They are all problems which involve dealing simultaneously with a sizable number of factors

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187 Weaver (1961), 58

which are interrelated into an organic whole."[188] These complex interrelations make trying to study the complex systems difficult because one cannot reduce the complexity away.

This distinction between "organized" and "disorganized" complexity is similar to the distinction between the concepts of *Extremistan* and *Mediocristan* identified by Nassim Taleb[189]. Taleb's analysis of fat-tails as defined in the Central Limit Theorem allows him to distinguish between these two phenomena, where he defines *Mediocristan* problems as being scalable problems, where a large sample cannot be altered significantly by the introduction of a single observation, no matter how large or small it is relative to the others. These scalable problems are ones where the range of variation of the values of the variables is not wide enough for one observation to skew the total results.[190] Examples of distributions that are from *Mediocristan* include height, weight, calorie consumption, car accidents, mortality rates.[191]

Extremistan, on the other hand refers to situations where one extreme observation can disproportionately impact the aggregate or mean.[192] In these distributions, the value of one observation can be so high or low compared to the rest that it could completely alter the final result. Taleb provides the example of the wealth of a group that includes Bill Gates. The mere introduction of Gates, even to a very large group of a thousand people, would completely change the metrics for the group, since Gates would account for 99.9% of the wealth of the

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188 Weaver, 1961, p.59
189 Taleb, N. N, 2007a. See also Taleb, Nassim, 2009 and Taleb, N. N. 2007b
190 Taleb, 2007, p.32
191 Taleb, 2007, p.35
192 Taleb, 2007, p.35

entire group. Further examples include: book sales, number of references on Google, populations of cities, financial markets, and inflation rates. [193]

FAO Hayek illustrates this point by demonstrating the difference between physics and other fields of inquiry.

> "More particularly, what we regard as the field of physics may well be the totality of phenomena where the number of significantly connected variables of different kinds is sufficiently small to enable us to study them as if they formed a closed system for which we can observe and control all the determining factors; and we may have been led to treat certain phenomena as lying outside physics precisely because this is not the case. If this were true it would certainly be paradoxical to try to force methods made possible by these special conditions on disciplines regarded as distinct because in their field these conditions do not prevail."

For Hayek, it is the simplicity of the questions that physics tackles that makes these questions suitable for the methods of physics. Questions which do not exhibit this simplicity are, according to Hayek, unsuitable to be examined using the tools of physics.

In agreement with, and elaboration on, Weaver, Hayek defines the complexity of systems to be dependent on "the minimum number of elements of which an instance of the pattern must consist in order to exhibit all the characteristic attributes of the class of pattern in question." [194]

As we move from simple physical inanimate systems that are amenable to investigation by physics' methods, we progressively witness increasing degrees of organized complexity, and

193 Taleb, 2007, p. 35
194 Hayek, 1967, p25

increasing numbers of irreducible relationships that cannot be abstracted away in any attempt to study or manage the system.

Here, it is useful to turn to the more recent literature on Complexity Studies, which provides a useful insight into the issue of reductionism. Tamas Viscek argues:

> "Although it might sometimes not matter that details such as the motions of the billions of atoms dancing inside the sphere's material are ignored, in other cases reductionism may lead to incorrect conclusions. In complex systems, we accept that processes that occur simultaneously on different scales or levels are important, and the intricate behaviour of the whole system depends on its units in a nontrivial way. Here, the description of the entire system's behaviour requires a qualitatively new theory, because the laws that describe its behaviour are qualitatively different from those that govern its individual units."[195]

As these interrelations increase, the investigation of the systems then must be able to account for all of them in order to accurately study the system. One will need all the data that is relevant to the question to be included in the analysis. As we move towards investigating complex social and economic systems, we are faced with two main problems that make such studies difficult.

The first problem is the lack of data. A lot of the important relations in complex systems do not have adequate data measuring them—though this could in some instances be remedied with better data collection, the real problem remains when one remembers that a lot of the data needed is simply unquantifiable and immeasurable.

195 Vicsek, 2002

The second problem is the proliferation and unknowability of the real relations governing such complex phenomena. With many interrelated factors and variables, it can be hard to determine what the actual relations between different variables are, and how they influence each other. Modeling these relations accurately is not possible unless one can know them exactly.

This understanding of complexity problems illuminates the disagreements in the LCA literature and why the results in them are so varied. In the quest to finding the environmental effect of biofuels utilization, studies run across the problems of the inability to define all the factors that matter for biofuels production, or all the interrelations that tie these factors together. Further the measurement of these factors and their interrelations continues to be dogged by uncertainty. The reason different studies have arrived at starkly different results is because they have defined different factors as being of importance, have defined their interrelations differently, and have measured them differently.

ii. Agent-based vs. Aggregate modeling

Delucchi's argument on the need to structure LCA's as policy-specific questions introduces a methodological issue of immense importance in the structuring of the analysis of biofuels. Delucchi argues against the models of abstract physical processes or fuels compared to one another because these abstract processes or fuels are not real life issues with which humans have to contend. The comparison between gallons of gasoline and ethanol in the abstract is a meaningless comparison as it tells us nothing useful to the real world. There will be gasoline and ethanol produced from countless sources and locations, each with differing impacts and costs, comparing an average of both is not very useful for informing policy-makers, whose policies need to be informed by real-life implications. Whatever the result of the comparison and the policies, there will still be gasoline and ethanol produced, and the abstract results matter little given the wide variety of production processes. These aggregates from LCA's do not exist in real-life and do not carry real implications beyond a theoretical thought-exercise.

The actual relations in the real world happen on a micro level as a result of direct interaction between countless agents. Aggregates modeling ignores this for the sake of constructing theoretical relationships between aggregates while ignoring the real-life relationships that exist between different factors.

A better way of framing the question is to address it as a specific policy-assessment question, which assesses the impacts and knock-on effects of real-life processes. Delucchi is effectively saying that aggregates-based modeling is inadequate because it does not provide us with the answers we need, nor is it built on analyzing the correct constituting relations between different factors.[196] The driving forces of these models are constructed by theoreticians, and do not exist in the real world. The way they are constructed will therefore shape the result. This in turn helps explain the widely divergent results between different LCAs.

Delucchi's urging to use policy-specific basis for the models is a micro-based analysis that attempts to find the relevant and necessary outcomes as consequences of specific actions.

196 Deluchi, 2004

iii. Need for a dynamic analysis of the economy

As discussed above, Deluchi's point about the need to take account of the effect of prices necessitates a comprehensive analysis of the dynamic economic impacts of different policies. Static and partial-equilibrium analysis will not suffice in a large complex system which includes significant knock-on effects to actions.

As Delucchi, Farrel, Wang and other LCA authors agree, there is a need for LCA's to calculate the impacts of economic actions across the economy. An understanding of the dynamics of an economy is instructive to understanding this type of problem. To do so, we turn to an analysis of the coordinating mechanism of a market economy: the price mechanism.

The price mechanism is the naturally emergent way of coordinating exchange. The scarcity and abundance of different goods is reflected in their relative prices to one another. The price emerges to coordinate the production and consumption of all goods relative to one another.

Hayek adds in *The Use of Knowledge in Society*:

> The economic problem of society is thus not merely a problem of how to allocate "given" resources—if "given" is taken to mean given to a single mind which deliberately solves the problem set by these "data." It is rather a problem of how to secure the best use of resources known to any of the members of society, for ends whose relative importance only these individuals know. Or, to put it briefly, it is a problem of the utilization of knowledge which is not given to anyone in its totality.[197]

197 Hayek, 1945

Prices are the way that signals and information about products and markets are communicated from an individual to another, and in the process, decentralized decision-making is coordinated among all the dispersed individuals and their dispersed knowledge.

Beyond the complexity of the market or social order, another problem is that the knowledge of each small pocket within the complex social order is dispersed, and situated with the actor in their respective locations within the complex structure. Every individual in the market possesses a small fragment of knowledge: that which is related to them. This is what is known as Hayek's knowledge problem.

A dynamic analysis of the economic impacts of an action, then, will need to internalize the different knowledge that different actors in a market have, and aggregate it into one large model of the market interaction. The dispersal of this knowledge and the difficulty of aggregating it is what makes dynamic modeling very difficult. This is the problem that the more complex and sophisticated LCA studies encounter when attempting to quantify biofuels' impacts in a lifecycle analysis. Different studies will have different pieces of knowledge and information incorporated and will therefore yield different results from the dynamic analysis.[198]

iv. Technologies implemented

The final major problem with LCA studies is the modeling of technological processes and technological advance. Quirin and Delucchi allude to the importance of correctly specifying in the model the technologies used in production processes. Without an accurate specification of

198 This discussion of LCA's is parallel to the discussion of Dynamic Stochastic General Equilibrium models in macroeconomic analysis. For a treatment of this, see Leijonhufvud, 2008.

the model, then the results will likely be skewed. Different LCA studies have different methods of specifying production process. Some will assess the most efficient processes and as a result find favorable results, while others will use less efficient production processes and arrive at unfavorable results.

This problem is further complicated when the analysis is oriented towards technologies which have not been developed commercially. This problem is particularly important for the analysis of cellulosic ethanol, a fuel whose technology for commercial production has not been implemented yet. In many Lifecycle analyses, large assumptions are made about the future course of technological advance in the production of a fuel.[199] Predictions are made about the likely course of efficiency increases in the manufacturing processes of biofuels. This matter is an issue of dispute between different authors. The problem with such estimates is that they are built on the assumption that technological and technical advances are easily predictable and can be estimated. But being projections about future technologies means that they are beset by uncertainty, since these discoveries have not yet been discovered and it is hard to estimate how the production processes will look like once the innovations take place. The projections these studies use about future rates of advance in production cannot be easily considered robust and reliable projections—they are likely to result in errors in estimates.

Nowhere is this more pronounced than in the many analyses of the efficiency of cellulosic ethanol production. Once one considers the nature of the uncertainty of future scientific advance, one realizes the problems inherent in attempting to assess the environmental friendliness of production techniques that have not been invented yet, and whose very inception in not certain.

199 For examples of this, see Wang et al (2005), Delucchi (2004), Pimentel and Patzek (2005)

As discussed in Chapter IV, although there is great potential for the development of cellulosic ethanol in the future, there are significant technical barriers standing in the way. One of the most important ones are biomass recalcitrance, which might be overcome by successfully designing plants for easy deconstruction for processing, or by engineering catalysts and bioconversion systems. While for Rasgauskas et al[200] the opportunities lie in improved sunlight capture through photosynthesis, manipulation of genes involved in N-metabolism, genetic engineer defense system transfer, preventing or delaying flowering, shortening or delaying winter dormancy, and genetic manipulation to reduce ligning and increase cellulose.[201]

When cellulosic ethanol production arrives no one knows which of these avenues (or any others still unknown ones) will be the ones responsible for the breakthrough. And this will have significant impact on the type of production process utilized and the way it is structured. This, in turn, will reflect in any Lifecycle Analysis of the fuels.

In fact, a historical review of the history of development of cellulosic ethanol would show why such analyses are misplaced by their very nature. As far back as 1980 one can find this statement in the USDA Yearbook of Agriculture:

> "In 3 to 5 years, technology advances should occur that will allow the conversion of cellulosic materials, tree trimmings, old newspapers, crop residues, etc., to alcohol on an economic basis."[202]

One of the co-authors of these lines, Otto Doering, also co-authored this about cellulosic ethanol in 2008:

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200 Rasgauskas et al. 2006.
201 Rasgauskas et al. 2006.
202 O.C. Doering III and R.M. Peart, 1980

> "Currently, ethanol derived from corn kernels is the main biofuel in the United States, with ethanol from "cellulosic" plant sources (such as corn stalks and wheat straw, native grasses, and forest trimmings) expected to begin commercially within the next decade."[203]

Since the 'energy crisis' of the 1970's, biofuels researchers have touted cellulosic ethanol as the technology that will make biofuels a viable significant contributor to the energy mix. There are still countless technical, technological and industrial challenges to the introduction of cellulosic ethanol, as discussed in Chapter IV. The predictions of advancements that will overcome these challenges are all built on a largely arbitrary speculation about the shape of the production process. This further helps explain the disparity of the results of different studies. When the scientific processes that are being modeled do not yet exist, it is to be expected that serious discrepancy would exist between different studies depending on their projections.

The conclusion of this chapter is that there are good reasons for the failure of LCA's to provide reliable and consistent results on the efficiency of biofuels. The problems of constructing LCA's are deep-rooted, and can help explain why these studies have arrived at such disparate and different results.

Chapter III had shown how biofuels policies were designed to increase biofuels use, based on the premise that increased biofuels will result in favorable environmental and energy cost goals.

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203 Schnoor et al, 2008

But this is built on the premise that the impact of biofuels will indeed be to reduce emissions and costs. Chapter IV showed that that cannot be definitely ruled to be the case, since the studies that attempt to ascertain this do not seem to be conclusive. Chapter V elucidated the problems of these LCA studies and why their results are so divergent.

In light of the inconclusive results of these studies, this paper will compare a different approach to biofuels policy than the one currently utilized: a policy based on targeting the pollutants rather than the fuels.

Chapter VI will overview the literature about policies targeting pollution externalities. And Chapter VII will then present a model that will compare two policy approaches to environmental policies:

1- Placing quantity or price controls on the fuels
2- Placing quantity or price controls on the pollutants

Building on the work of Delucchi, instead of carrying out Lifecycle Assessments of the efficiency of fuels, a better approach is to carry-out agent-based modeling of the impacts of different policies on emissions, while remaining agnostic as to the particular cost and efficiency profile of the fuels involved. The model of Chapter VII, therefore, will begin from the starting point of an unknown cost and pollution function for fuels, and will aim to assess the economic and environmental impacts of different policy regimes *regardless of the actual cost and pollution profile of the energy sources*.

Chapter VI: From Fuel to Pollutant Control

The previous chapters looked at the Lifecycle Analysis literature, which analyzes the efficiency of biofuels and alternative energy sources. These studies can help inform policies that aim to subsidize or promote these biofuels as part of a strategy to reduce emissions. This approach of targeting the technologies that produce the emissions is the one that Pacala and Socolow outline, and is also the one that has underpinned most policies aimed at fighting climate change. The problem with applying this approach to biofuels policy, however, is that before doing so, the policy-maker must be sure that the impact of increased biofuels use will in fact translate to reduced greenhouse gas emissions. The studies that attempt to show that are inconclusive, as was shown in Chapter IV. Chapter V identified underlying problems with this literature that makes these studies very difficult to implement and explain why they are currently inconclusive.

Instead of continuing to try to ascertain from LCA's the impacts of increased biofuels use, this study will suggest an alternative approach. Based on the fact that the impacts are unknown, it is suggested that policies target the pollutants, rather than the fuel. This chapter will provide an overview of the literature on pollution avoidance and abatement and policies to tackle them.

The aim of the next chapter is to model the impact of different government policies aimed at reducing emissions and costs of energy sources, in light of unknown cost functions.

a. The Coase Theorem

The simplest and most elegant solution to externality and pollution problems is that formalized by Ronald Coase in his eponymous theory.[204] Coase argued that if property rights are assigned, and there are no transaction costs, affected parties will trade until they arrive at an efficient outcome. This result does not depend on the initial allocation of property rights. There is no need for government intervention in this scheme for parties to reach an agreement; affected parties have an incentive to trade in ways that maximize their utility and could arrive at a bargain that improves both their situation—provided transaction costs are not too prohibitive.

The Coase theorem, however, is not useful when dealing with externalities or pollution problems where property rights are not defined, and externalities are widespread. The case of carbon emissions represents such a case. While the benefits of carbon emission are private, accruing to the person who consumes the fuels, the costs are universal and affect everyone on the planet. No one owns the atmosphere, and the damages from increased carbon emissions are universal. As such, the Coase theorem is not useful when dealing with carbon emissions without the explicit assigning of property rights to the atmosphere or to the emission of the pollutant.

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204 Coase, Ronald, 1937

b. Pigouvian Tax

When dealing with public property or environmental damage that has spillovers outside clearly defined property rights, the consensus is that government intervention is the solution. The standard solution to the problems of negative environmental externalities is to impose a tax on this externality in order to discourage its production. The rationale is that the cost of the externality is not internalized in the market cost of the activity that produces this externality, which will lead to the market activity being carried out too much, and the externality cost being too high on those who bear it. This idea was first introduced by Alfred Pigou[205], and is named after him. It has inspired a long tradition of environmental policy regulation. Today, several prominent economists have formed the Pigou Club in order to advocate that the government place Pigouvian taxes on gasoline in order to reduce its consumption and reduce emissions. It is worth noting that they suggest that the tax be placed on gasoline, and not the pollutant itself, Carbon Dioxide. The literature on Pigouvian taxes sometimes fails to make the distinction between taxing the pollutant itself and taxing the source of the pollutant. This is an important distinction that lies at the heart of this study.

When taxes or subsidies are placed on the fuel, technology or production process that results in the pollution, this raises questions about whether such policies will lead to the intended outcome or not. In order to be able to assess that, a comprehensive lifecycle analysis of impacts would need to be formed. There is, as was shown in Chapter V, significant uncertainty over how the entire knock-on effects on the fuel will translate to impacts on the pollutants.

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205 A. C. Pigou, 1932

c. Prices vs. Quantities

When the government wants to place controls on pollutants or fuels, it has two options: price or quantity controls. Under price controls, the government issues a price which polluters must pay to pollute, resulting in a reduced quantity of pollution. Under quantity regulations, the government decrees a set quantity of emissions that polluters cannot exceed, and punishes transgressions. The regulator can utilize different ways of allocating these pollution credits to emitters. In some versions, polluters can trade these rights to pollute among themselves, which results in a price on pollution.

Traditionally, the literature on regulation viewed the two instruments as equivalent, since both instruments can be deployed to lead to the same exact outcome. Setting the price at a certain level will lead to limiting the quantity to a certain level, while setting a quantity regulation at that level will lead to the emergence of the same aforementioned price.

This consensus view, however, was challenged by Weitzman's seminal 1974 piece *'Prices and Quantities'*. While Weitzman recognizes that there are no advantages of one method over the other "[f]rom a strictly theoretical point of view",[206] he argues that in more realistic cases, the two will be different. Depending on the marginal abatement costs there will be different costs and impacts to each policy and they can lead to different outcomes. This suggests there are scenarios where quantity regulations would be preferable to price regulations, and vice versa.

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206 Weitzman, M. 1974.

This paper has set the tone of research on instrument design since its publications. Recently, however, Weisbach has argued that with proper design the two instruments are equivalent, and that the differences between the two instruments are due to unjustified assumptions about design. Weisbach argues that while there may be some preferences for taxes as an instrument, "the benefits of taxes are swamped by the benefits of good design".[207]

The debate over this topic continues to take place in academic, policy and public circles. Economists generally tend to favor taxes[208], but the legislative attempts at establishing carbon controls have been cap & trade, which are viewed as being more politically feasible.

d. Comparing controls on pollutants to controls on fuels

When designing environmental policies aimed at reducing carbon emissions, it is useful to distinguish between two different kinds of policies:

1- Placing quantity or price controls on the fuels
2- Placing quantity or price controls on the pollutants

The first type of policies relies on knowing the environmental impacts of particular fuels, and then stipulating whether their consumption should be encouraged or discouraged by government policy. The use of LCA's to assess the efficiency of biofuels and the policies

207 Weisbach, David, 2009
208 See Stiglitz, Joseph E, 2006. See also: *Doffing the Cap*, 2007, *Economist*, vol. 383, no. 8533, pp. 86-88.

outlined in Chapter III to promote biofuels is necessary for this. Chapter IV and V showed that it is not clear, currently, what the environmental impacts of biofuels are, and that there are problems with the construction of LCA studies that attempt to assess these impacts.

This approach of targeting the technologies that produce the emissions is the one that Pacala and Socolow outline, and is also the one that has underpinned most policies aimed at fighting climate change. Pacala and Socolow's paper identifies 15 different activities that reduce greenhouse gases, and assumes that they can be intensified to cause a reduction of up to 1GtC/year by 2050.[209] But the problem with this approach is that policy-makers need to be sure that the increased utilization of these wedges will have the intended consequences, and that the unintended consequences of such activities will not do more harm than good.

The review of lifecycle analysis has shown the problems with being able to estimate the knock-on effects of these activities. And the underlying problems with such attempts at estimating impacts makes these studies very difficult to implement. This casts doubt on the usefulness of the first type of policies. So long as the impacts cannot be known for sure, there is always a risk that the policy's knock-on effects might make matters worse.

Rather than continue to attempt to measure the impacts of fuels in order to shape environmental policies, this paper suggests that policy-makers acknowledge this ignorance and think about how policies can be designed in light of this ignorance. This approach is motivated by Nassim Taleb's in thinking about the unknown expressed in his essay *The Fourth Quadrant: A Map of the Limits of Statistics* in which he writes:

209 Pacala, S., and R. Socolow, 2004

> *"my new project is about methods on how to domesticate the unknown, exploit randomness, figure out how to live in a world we don't understand very well. While most human thought (particularly since the enlightenment) has focused us on how to turn knowledge into decisions, my new mission is to build methods to turn lack of information, lack of understanding, and lack of "knowledge" into decisions…"*[210]

The second type of policies does not rely on knowing the environmental impact of a fuel, but instead focuses on limiting the emissions themselves leaving the freedom of choice for agents on what method to use to achieve the reductions necessary. A tax is placed on the pollutant itself, and not on the fuel source that emits. The tax must be placed at the pollutant at the point during the production cycle in which it leaves the earth and enters into the atmosphere. Such a method would ensure that the tax is carried through into the price of the fuel to the consumer, without anyone needing to know how much of the price is due to carbon emissions or how much carbon emissions were produced.

The discussions in the literature on instrument design are usually between quantity and price controls, but there is little distinction made between instruments targeting the pollutants and instruments targeting the fuels. This study sidesteps the discussion on quantity vs. price restrictions, and instead focuses on the fuel vs. pollutant distinction.

It is the starting point of this model that the true cost and environmental functions of different fuels are unknown. The question tackled is what can be done in light of this ignorance. In that vein, this paper will assess the difference between a price/quantity control on the pollutant on the one hand, and a subsidy/mandate on the fuels emitting the pollutants on the other hand, given the ignorance of the costs and environmental impacts of different fuels. There will be no

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210 Taleb, Nassim, 2009

distinction made between price and quantity controls on emissions. The model will not attempt to compare prices to quantity controls, nor will it treat them as being in any meaningful way different. The model will assume the original assumption in the control literature, as outlined (but qualified) by Weitzman, and reanimated by Weisbach, that the two methods are equivalent. The mathematical model of this paper will, for simplicity, talk about a tax on carbon, when that could also be used to mean a cap on carbon emissions resulting in a price on emissions. The questions of proper mechanism design of this price/quantity restriction are outside the scope of this paper.

This is not to say that the important differences between tax and cap-and-trade are immaterial or inconsequential, or that the design and magnitude problems are trivial. Rather, what this model does is assume that any price/quantity restriction is placed on carbon, and carry out the comparison with a mandate on the consumption of biofuels. The results of this comparison are immaterial to the specifics of the design mechanism or the quantity/price magnitude. As will become clear in Chapter VII, the results hold regardless of the magnitude of the tax or mandate.

Similarly, policies supporting biofuels have taken two main forms: direct subsidies and mandates for blending requirements. As discussed in Chapter III, both the USA and EU have utilized both these policy tools extensively. The net effect of either these policies is to increase the consumption of biofuels. For the purposes of this model we will be looking only at a blending mandate that stipulates a particular increase in the percentage of alternative fuels in the fuel supply. The same effect can be achieved through a production or consumption subsidy, but in less certain and more difficult to model methods. The practical consequences are the same, though, and this model will for the sake of simplicity only look at blending mandates as the policies on the fuels.

In conclusion, this paper aims at assessing two different measures of combating climate change: the first targets the emissions of carbon dioxide, while the second targets the fuels themselves. This is a comparison between the wedges approach of Pacala and Socolow and a Pigouvian approach that tackles the externality itself—and not its causes. While there are several criteria on which to compare the merit of the two strategies, the criteria considered here primarily is how to reduce greenhouse gas emissions in light of an ignorance of the effects of increased fuel utilization in complex systems.

e. Challenges to enforcing carbon controls

The most important issues in this debate, as Weisbach emphasizes, is the design issue, and the technical, political and practical problems that will confront any attempt at implementation. There are two main difficulties confronting and carbon tax or cap-n-trade scheme.

a. Measurement of carbon

The first difficulty is tallying carbon effectively from the multitude of its sources. For a tax/cap system to succeed it must tax uniformly all sources of carbon worldwide; it would otherwise lead to large distortions. If, for example, a tax is placed on fossil fuel sources of carbon while no tax is placed on agricultural sources of carbon dioxide, this would, at the margin, lead to a reduction in fossil fuel consumption without necessarily leading to a reduction of carbon emissions, as polluters move from consuming fossil fuels to consuming biofuels whose planting emits high concentrations of carbon dioxide. This would defeat the purpose of the tax, which was to reduce carbon emissions. Further, if the tax is imposed on one country while not another, then highly polluting activities could be moved from the taxed country to the untaxed country, and there would be little, if any, reduction in carbon emissions.

Taxing (or capping) carbon dioxide from fossil fuels is relatively straight-forward, since the carbon content of these fuels is easily determined, and a tax could be placed on them at the source. This is not the case with carbon emissions coming from agriculture and land use change, however, where much more creative institutional and technical solutions need to be devised to manage to cap or tax carbon emissions. There is an extensive treatment of this topic in the academic literature as well as in the publications of international organizations.

The United Nations Intergovernmental Panel on Climate Change (IPCC) has issued a Special Report on Land Use, Land-Use Change, and Forestry[211] with details on afforestation, reforestation, deforestation, and other human-induced activities, as well as detailed definitions and accounting rules for measuring these effects on the carbon cycle. Further, the IPCC has developed, as a response to the request by the United Nations Framework Convention on Climate Change (UNFCCC), a detailed report entitled *Good Practice Guidance for Land Use, Land-Use Change and Forestry*.[212] This report provides the methods and guidance for estimating, measuring, monitoring and reporting on carbon stock changes and greenhouse gas emissions from land use, land-use change and forestry.[213]

211 IPCC, 2000
212 IPCC, 2003
213 IPCC, 2003

Guo and Gifford have overviewed data from 74 publications to estimate the carbon impact of land use change. [214] They estimate that changing land from pasture to plantation causes carbon stocks to decline by 10%, while changing it from native forest to plantation causes it to decrease by 13%, going from native forest to crop causes a 42% decline, and changing land from pasture to crop causes a 59% decline. On the other hand, when land changes from native forest to pasture, carbon stocks increase by 8%, when it changes from crop to pasture, it increases by 19%, changes from crop to plantation increases carbon by 18%, and changing from crop to secondary forest increases carbon by 53%.

Studies like those by the IPCC and Guo and Gifford are essential to the implementation of successful quantity/price controls on carbon. It is important here to stress the difference between the measurement of carbon changes from land use change on the one hand, and the measurement of carbon changes from biofuels production in LCA studies on the other. The first presents a tractable and clearly defined objective accounting problem that can be settled with accurate measurement over a specific plot of land. The techniques for estimating the carbon content of different types of land cover exist, and can be applied. The second measurement, on the other hand, represents a problem with a different nature of complexity and uncertainty. As discussed in Chapter V, measuring the effects of an increase in biofuel use involves being able to identify all the knock-on effects of the increased use of the fuel, and being able to ascertain the magnitude of these changes. The problem does not lie in being able to measure the effect of one specific change in the use of one particular plot of land, it is a more complex problem that involves being able to identify which changes in land use were the result of the increase in biofuel use, as well as all the other knock-on effects on agriculture and energy consumption.

214 Guo and Gifford, 2002

The first challenge is simply one of accurate measurement; the second is one of accurate identification of what should be measured, on top of the measurement challenge.

b. Magnitude of price/quantity restriction

The second contentious point in the imposition of price/quantity controls on carbon emissions concerns the right quantity or price restriction that needs to be imposed initially. Whereas there is agreement that theoretically both policy tools are equivalent and would produce the same outcome, there is no agreement on what this outcome is. Advocates of cap-n-trade differ on what the initial cap on emissions should be, whereas supporters of a tax differ on what the tax rate should be. There is large uncertainty associated with any prediction of the effect of either policy on prices and emissions. This uncertainty, it is worth noting, is symmetric: setting the price of carbon produces an uncertain reduction in emissions, while setting a cap on emissions will produce an uncertain price of carbon.

There is, however, no uncertainty over the direction of the change. A properly enforced tax will necessarily lead to a reduction in emissions, and a properly enforced emissions cap will lead to a positive price on carbon. This result is derived from the simple economic law that demand curves slope downwards. The shape of the demand curves, however, can remain unknown while we know the sign of its slope. In the modeling exercise of the next chapter the magnitude of the tax is not relevant to the results. The modeling exercise is intended to show that the tax will either reduce emissions or keep them constant, but not increase them, and this result is independent of the magnitude of the tax.

Chapter VII: A Model of Alternative Energy Policies and Emissions, Costs and Technological Adoption

Abstract:

This paper constructs an individual and societal utility maximization exercise to assess the relative merits of three different policy regimes in relation to alternative energy. The first is the no policy regime, the second is the placing of a mandate to increase the consumption of an alternative energy fuel, and the third is a tax on the emissions of carbon. The starting point is that the cost and pollution functions of different fuels are unknown, but that the general shape of the functions is known. The analysis shows that in light of an ignorance of the costs, a tax regime provides the maximum reduction in costs and pollution, whereas a mandate regime could lead to a reduction or an increase in costs and pollution. The model also assesses the three policy regimes' effect on technological innovation and adoption and concludes that a tax is more likely to lead to the innovation and adoption of cleaner energy technologies, whereas a mandate is more likely to lead to the adoption of dirtier alternative energies.

a. Introduction

Chapter III showed how biofuels policies were designed to increase biofuels use, based on the premise that increased biofuels will result in favorable environmental and energy cost goals. But this is built on the premise that the impact of biofuels will indeed be to reduce emissions and costs. Chapter IV showed that that cannot be definitely ruled to be the case, since the studies that attempt to ascertain this do not seem to be conclusive. Chapter V elucidated the problems of these LCA studies and explained why their results are so divergent. Chapter VI gave an overview of the literature on pollution avoidance and abatement and policies to achieve them. With that background in mind, and in light of the inconclusive results of LCA studies, this chapter will compare a different approach to biofuels policy than the one currently utilized: Instead of continuing to try to ascertain from LCA's the impacts of increased biofuels use, it is suggested that policies target the pollutants, rather than the fuel.

This chapter will present a model that will compare two different policy approaches to environmental externalities:

1- Placing quantity or price controls on the fuels
2- Placing quantity or price controls on the pollutants

This is a comparison between the "wedges" approach of Pacala and Socolow, which focuses on forwarding specific solutions, and a Pigouvian approach that tackles the externality itself—*and* *not its particular fuel sources*. While there are several criteria on which to compare the merit of the two strategies, the criteria considered here primarily is: ***how to reduce greenhouse gas emissions in light of an ignorance of the effects of increased fuel utilization in complex systems***.

To begin with, there is an important distinction to be made between two types of costs associated with the use of a fuel: the private costs incurred by the individual to purchase the fuel for their own use, and the public cost incurred by society from the use of this fuel, in the form of pollution and other externalities. These two costs can be considered related but do not have to be. A fuel that is inexpensive for the consumer can have significant negative costs on society, whereas a fuel that is expensive for the consumer can have a trivial economic impact on society. Define C(x) to be the total private cost of the use of fuel x, and P(x) to be the total public, social or pollution cost to the use of fuel x. C(x) is the integral of the marginal cost c(x), integrated over the quantity of fuel consumed (o to x). Similarly, P(x) is the integral of the marginal pollution cost p(x), integrated over the quantity of the fuel consumed.

The motivation for creating the distinction between private and public costs comes from the study *Hidden Costs of Energy* by the Committee on Health, Environmental Costs and Benefits of Energy Production and Consumption[215]. The report emphasizes the need to take into consideration the hidden costs for the utilization of energy. Whereas the consumer will only pay the price at the pump, there are external costs that affect society, and costs from climate change are a pertinent example of these costs.

Further, a second distinction is made between two types of choices to use a fuel. On the one hand, there is the decision of the consumer at the gas pump to buy a fuel, and on the other

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215 Committee on Health, Environmental Costs and Benefits of Energy Production and Consumption, 2010.

hand, there is the decision of the regulator to subsidize, tax or mandate the use of a fuel. The main difference between these two choices is that the regulator makes the choice based on the private and social costs of the fuel, whereas the consumer, we assume, only makes the choice based on the private costs she incurs at the gas pump.

Consumer minimizes the private cost function: Min C (x)

Regulator minimizes the private and public cost function: Min (C(x)+P(x))

The minimization of the cost of the fuel happens by choosing the percentages of fuel that minimize the cost. In a straight-forward choice between two fuels with similar cost functions, the cheapest combination of the two fuels would be chosen. If the fuels that existed did not have public costs, but only private costs, and if the regulator and the consumer knew these costs, then the choices of the regulator and the consumer would be identical. The following examples illustrate this point.

We define f as the ratio of fuel f to the total fuel supply. In the presence of several fuels f1, f2… fn, it necessarily follows:

f1+f2+…+fn = 1

We assume there is a set amount of energy that society needs to consume, and we set the utility derived from this energy consumption (U*) to be equal to unity:

$U^* == 1$

Consumers seek to maximize utility by meeting their set need of energy consumption while minimizing the cost of their fuel mix. The assumption that the quantity of energy needed is constant irrespective of the mix of the energy sources is equivalent to stating that the utility curve from the consumption of energy declines at a very steep rate. The initial amount of energy consumed carries a very high utility, but after the amount of energy that is currently consumed, utility drops off very rapidly. This suggests a low elasticity of demand for fossil fuels. Therefore, under changes in prices or taxes, we expect the quantity of energy consumed to remain largely similar. For simplicity, we assume the quantity of energy consumed remains constant regardless of changes in prices and quantities, because the aspect we are interested in examining in this model is the composition of the fuel supply and not the changes in the quantities of fuel consumed.[216]

As a base case, we look at the cost profile of fossil fuels. The cheapest and most readily available fossil fuels are extracted from the ground first, followed by the more expensive fuels. This means that the cost of extraction increases, and that the marginal cost of extraction also increases. The more fossil fuel has been extracted, the more expensive will be the extraction of the next unit of fossil fuel. We can thus formulate the marginal cost of fossil fuel extraction as being a positive function of the quantity of fossil fuel that has been already extracted. Seeing as such, the marginal cost of fossil fuel extraction is positive, and its first derivative is also positive. For simplicity, we assume the second derivative is zero.

Thus, we define the marginal cost of fossil fuel extraction to be

$c(f) > 0$

The first derivative is:

$c'(f)>0$

While the second derivative is:

216 I thank Professors Klaus Lackner and David Nissen for illuminating this point for me.

$c''(f)=0$

Similarly, the social (pollution) cost can be assumed to have a similar shape to the private cost function. One possible objection here is that the damage could reach a level of saturation. However, in the context of carbon dioxide emissions and climate change, it is safe to say that we are not near a saturation point, since the scientific consensus clearly predicts that further carbon dioxide emissions will have further warming effects. Thus we can define:

$p(f) \geq 0$

$p'(f) \geq 0$

$p''(f) = 0$

For simplicity, we assume the second derivative vanishes to zero.

For a base example, if society has two fossil fuels (f1 and f2) available, both fuels would have similar cost function shapes, but with different parameters defining these functions. The decision over which fuels to consume (or the respective values of f1 and f2) would be determined by the minimization exercise carried out by the consumer or regulator.

In the case where there is no regulation and the consumer makes the choice freely, their choice is to minimize the total private cost while meeting their energy needs from both f1 and f2.

$\text{Min } C(f1) + C(f2) = {}_0\int^{f1} c(f1) + {}_0\int^{f2} c(f2)$

subject to $f1+f2 = 1$

The regulator, however, would also take into account the social cost from the use of this fuel, reflected in the pollution and associated negative externalities involved with the consumption of these fuels, and expressed with the function P(f1) and P(f2). The regulator's optimization function is thus:

$$\text{Min } C(f1) + C(f2) + P(f1) + P(f2) = \int c(f1) + \int c(f2) + \int p(f1) + \int p(f2)$$

$$\text{s.t. } f1+f2 = 1$$

In this case, cost and pollution functions have a similar shape, but different parameters. The allocation of fuel between f1 and f2 will be determined by the parameters used in this equation. When the consumer makes the choice, the allocation is determined by the difference in parameters between the two private cost functions c(f1) and c(f2). When the regulator makes the choice, it will also be affected by the social cost functions p(f1) and p(f2).

For our base example, we look at two fuels that have known private cost functions that are equal, as well as social cost functions that are identical. Hence, the cost functions are:

$$c(f1) = k\ f1$$

$$p(f1) = k\ f1$$

$$c(f2) = k\ f2$$

$$p(f2) = k\ f2$$

where k is a constant.

The representative consumer chooses the fuel mix based on the private cost only, and his optimization equation is:

Min C(f1) + C(f2) = $_0\int^{f1}$ c(f1) + $_0\int^{f2}$ c(f2)

s.t. f1+f2 = 1

The result is that f1 = 0.5 and f2 = 0.5

The regulator chooses based on the private costs and the social costs.

Min C(f1) + C(f2) + P(f1) + P(f2) = ∫ c(f1) + ∫ c(f2) + ∫ p(f1) + ∫ p(f2)

s.t. f1+f2 = 1

The result is that f1 = 0.5 and f2 = 0.5

The results are identical in both scenarios.

The total cost to society from utilizing these fuels, in both cases, is:

TCS: C(f1) + C(f2) + P(f1) + P(f2) = ∫ c(f1) + ∫ c(f2) + ∫ p(f1) + ∫ p(f2)

= 0.5 k

When there are no external costs, then the choice of the private consumers and the central planner are identical. But the results would be different if we had different pollution costs. This can be illustrated in an example of two fossil fuels that have identical private cost functions but different pollution profiles.

c(f1) = k f1

p(f1) = kf1

c(f2) = kf2

$p(f2) = 2kf2$

Where k is a constant.

The private cost of both fuels is identical, but the social pollution cost for fuel f2 is twice that of f1.

In the case where there is no regulation, consumers will optimize based on the private cost c. Their optimization function is:

$\text{Min } C(f1) + C(f2) = \int c(f1) + \int c(f2)$

s.t. $f1+f2 = 1$

The result is that $f1 = 0.5$ and $f2 = 0.5$

Since both fuels have identical costs, consumers minimize their costs by getting half their energy needs from each source (this is cheaper than getting it from one source, because as noted above, the cost of each sources increases the more of it is used.) The total private cost from this allocation is:

The total cost to society is: $C(f1) + C(f2) + P(f1) + P(f2) = \int c(f1) + \int c(f2) + \int p(f1) + \int p(f2)$

$TCS = 0.625\ k$

If a regulator attempts to influence this outcome, he will not only take into account the private cost, but will also optimize for the social cost as well. The regulator's minimization function is therefore:

$\text{Min } C(f1) + C(f2) + P(f1) + P(f2) = \int c(f1) + \int c(f2) + \int p(f1) + \int p(f2)$

s.t. $f1+f2 = 1$

The result is $f1=0.6$ and $f2 =0.4$.

When the regulator takes into account the dirtier pollution profile of f2, the result is increased consumption of f1 and decreased consumption of f2. The regulator imposes this fuel mix on society and consumers comply. Calculating the total cost to society, we find it is:

$TCS = 0.6k$

This is smaller than the cost in the case of free consumer choice. This stylized example lays out the case for public regulation: The introduction of pollution regulation and the mandating of fuel percentage consumption had a welfare increasing impact on society. Since the regulator was able to optimize for the total (social and private) cost to society, he reduced it. When consumers make their own choices, they only optimize to reduce their own profit. In cases where the public cost is different for different fuels, this leads to a suboptimal outcome. The same outcome could be achieved by placing a tax on the consumption of f2 in order to reduce it to the optimal level. This reflects the equivalence of quantity and price regulations discussed in the previous chapter.

For this stylized example to hold in reality, however, a big assumption is needed: that the regulator knows ex ante the social pollution cost of the fuels. With this knowledge, he can calculate the mix of fuels that reduces pollution, but without it, his calculations do not produce the optimal mix. The key concept of this paper, however, was about the problems with calculating and realizing the costs of biofuels. As the previous chapters made amply clear, the actual costs of biofuels are the subject of intense debate and have not been ascertained decisively. Since we cannot discern what the costs of the biofuels will be, it becomes impractical and problematic to follow the aforementioned regulatory approach. Without a correct ex ante estimation of costs, the regulator cannot know what mix of fuels will reduce emissions, and cannot thus impose these controls confident of their outcome. Further, a mistaken estimate of the costs of the biofuels will probably result in the regulations leading to a sub-optimal and inefficient allocation.

To conclude, if the social pollution costs are known ex ante to the regulator, then regulation can reduce emissions and costs. ***The model this paper introduces differs from the usual models presented in this literature in that it starts from the assumption that the cost function of a fuel is unknown, and asks what can be done about that***. The rest of this chapter presents more detailed stylized examples, further illustrates the case with biofuels, and introduces the topic of technological innovation.

Unknown cost functions

While the motivating assumption of this model is that the true cost function of the biofuels is not known, the shape of this function can be known from the overview of LCA results in Chapter IV. This is because whereas the literature may differ widely on the costs and pollution associated with biofuels, there is nonetheless a consensus on one fact: at low levels of usage biofuels can be cheap and clean, whereas at high levels of usage they can be very expensive and polluting.

The literature on the energy efficiency of biofuels suggests that its cost is likely cheaper than fossil fuels at low levels of utilization, when the most efficient and convenient biofuels are utilized. At larger concentrations of biofuels, however, the price rises. The same is true for the environmental impact of biofuels use. This assumption finds its motivation in the LCA literature. Hammerschlag (2006) and Farrell et al (2006), among others, show that the main barrier for corn ethanol is that as it expands, it will have to move to less productive land, where its problems will multiply. Searchinger et al (2008), however, find that when the impact of increased ethanol production on forests is included in lifecycle analysis, the result is that ethanol is harmful to the environment.

In a study for the World Bank, Timilsina and Shrestha find that though there is a consensus on the fact that biofuels can cause reductions in greenhouse gas emissions, these positive findings disappear once studies take account of impacts on land use change. [217] This enforces the distinction in our model between direct polluter costs (C) and indirect social pollution costs (P). The distinction also clarifies the rationale for the shape of the pollution function of biofuels.

At low levels of utilization, biofuels could be produced from marginal crops grown on non-agricultural land near biofuel production facilities, or can be produced from waste material. Such production has very low marginal costs and low marginal environmental damage or pollution cost. At large levels of utilization, however, biofuels production leads to deforestation, mass conversion of farm land, and extensive production processes that involve high pollution costs. As the level of production increases, the costs and pollution can be viewed to increase at an increasing rate. The production of fossil fuels, however, does not have this property, and its marginal cost can be viewed as increasing linearly.

As the utilization of biofuels increases, the move towards less efficient production processes increases the private and the pollution marginal costs at an increasing rate. This suggests a

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217 Timilsina, G. and Shresta, 2010

strictly convex marginal cost function and marginal pollution function for biofuels, with positive first and second derivatives.

Fossil Fuel	Alternative Fuel
c(f) > 0	c(a1) > 0
c′(f) > 0	c'(a1) > 0
c′′(f) = 0	c''(a1) > 0
p(f) > 0	p(a1) > 0
p′(f) > 0	p'(a1) > 0
p′′(f) = 0	p''(a1) > 0

Table 4: Fossil fuel and alternative fuel cost and pollution functions' signs

The shape of these functions is plotted below, where the x-axis plots the fraction of the total fuel consumption that is used in a fuel, whereas the y-axis represents the cost of the utilization of the fuel:

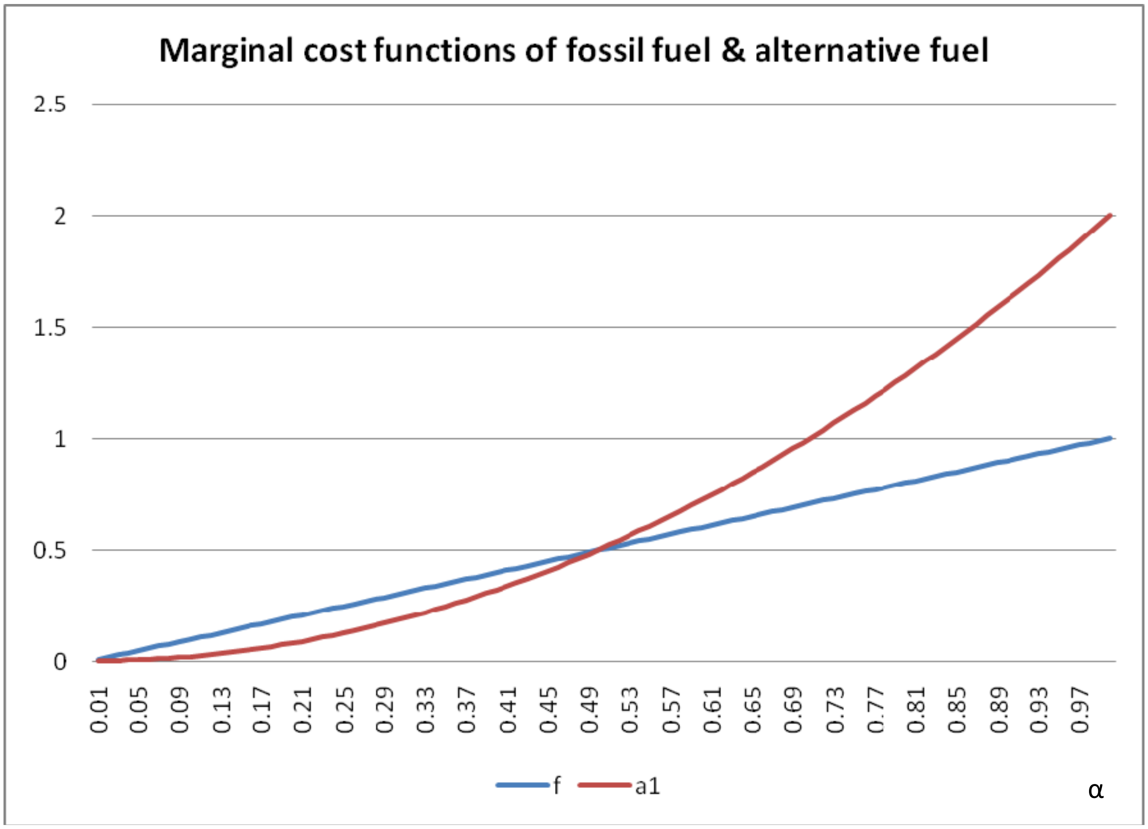

Figure 4: Marginal cost functions of fossil fuel and alternative fuel as a function of alpha

As the figure shows, at low levels of utilization the marginal cost of a unit of alternative fuel is lower than that of a fossil fuel. But at high levels of utilization, the marginal cost is higher. Should the alternative fuel be very dirty, we can imagine the function looking more along these lines:

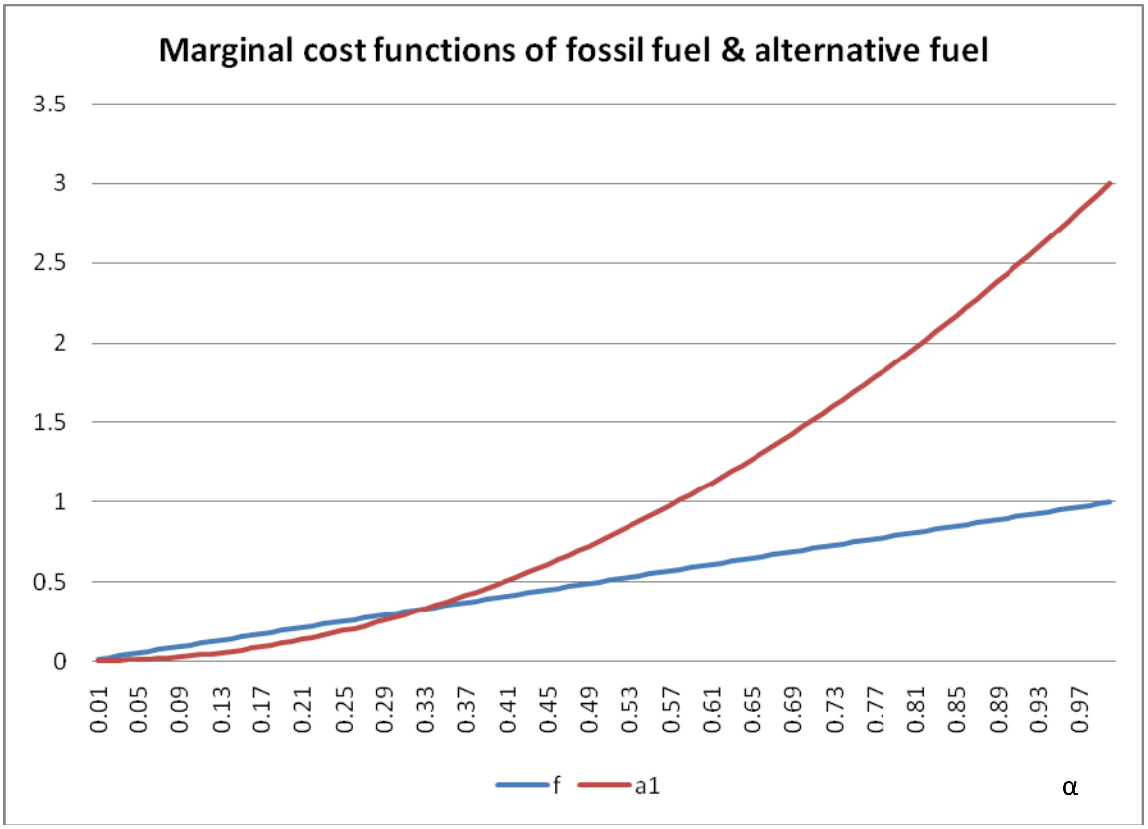

Figure 5: Marginal cost functions of fuel as function of alpha

Only at very low levels does this fuel's utilization make sense, beyond that the costs become too high and it becomes more economic to use fossil fuels. On the other hand, for a particularly clean alternative fuel, the marginal cost curve would look like this:

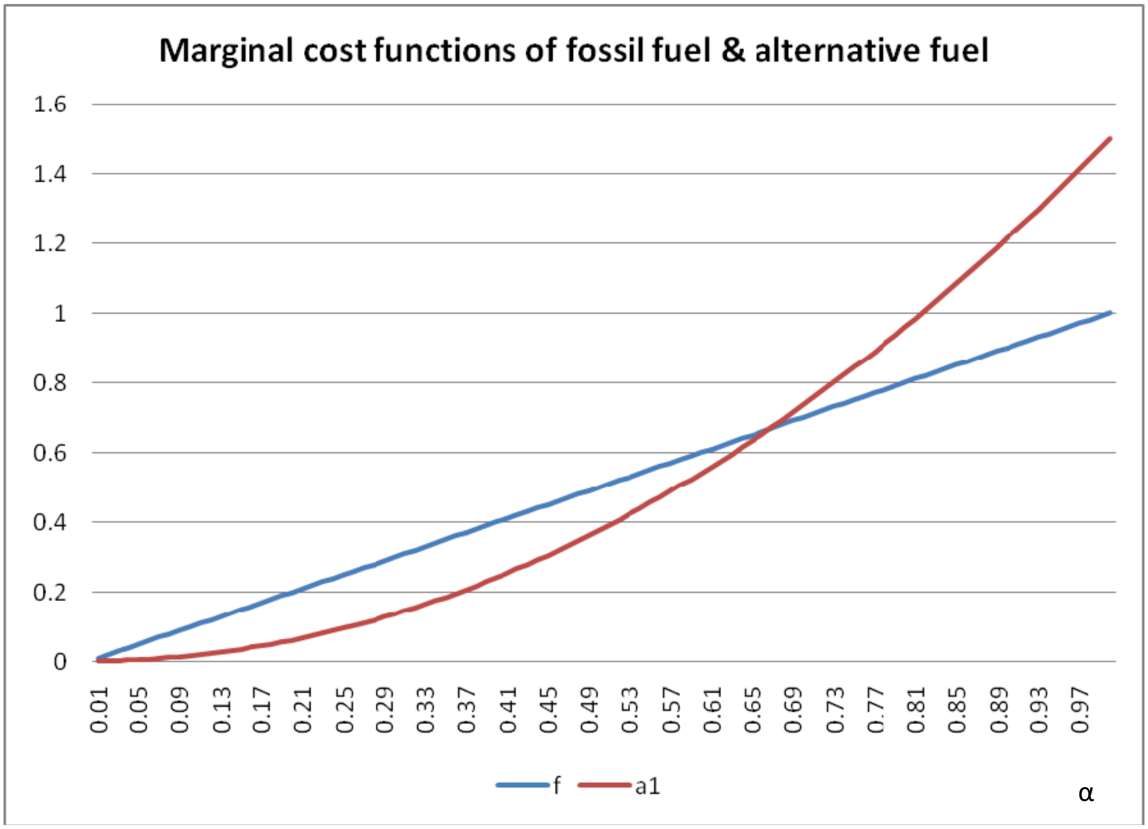

Figure 6: Marginal cost functions as a function of alpha

In this case, the alternative fuel has low marginal costs even when utilized extensively. If such a fuel existed, it would likely displace a large amount of fossil fuel from the fuel supply.

This is a largely accurate description of the shapes of the fossil and alternative fuel marginal cost and pollution function, as can be ascertained from the literature on their costs. The actual costs are unknown, and estimating them can clarify for a particular fuel which of the three graphs above is a more accurate representation.

An approximation of the previous cost functions can be of the form: $Ca1 = \alpha x^2$, where x is the percentage of biofuels utilized by society, whereas α is a constant. The magnitude of α determines the specific cost of a biofuel at different utilization levels. For high values of α, the marginal cost and pollution functions will look more like the second figure: utilizing the alternative fuel involves high costs at a relatively low level, meaning the fuel would not be utilized a lot. For low values of α, however, the marginal cost and pollution functions will look more like the third figure above.

The LCA literature discussed in the previous chapters can be seen as an attempt to assess the particular values of α for specific biofuels. In this exercise, we attempt to study the results of particular policies regardless of the value of α. The fundamental question here is what should regulators do when they do not know the alternative fuel's cost functions.

The specifications of the model

This chapter uses a utility-maximization model to assess the impact of three different policies on biofuels on emissions and costs. The model assumes no knowledge of the exact pollution functions. It only assumes the general shape of the function. The results of the model are not dependent on the exact values of the cost function, but on its shape.

There are four different energy sources available for consumers, a fossil fuel and three alternative energy sources: A1, A2, A3. The ratio of the fossil fuel to the total fuel supply is w, while the three alternative energy sources' ratios are x, y and z respectively.

By definition,

$$w + x + y + z = 1$$

There is a set amount of energy that society needs to consume, and we set the utility derived from this energy consumption (U*) to be equal to unity:

$U^{*}==1$

Consumers seek to maximize utility by meeting their set need of energy consumption while minimizing the cost of their fuel mix. The quantity of energy needed is assumed to be constant irrespective of the mix of the energy sources. It is assumed that the utility curve from the consumption of energy declines at a very steep rate. The initial amount of energy consumed carries a very high utility for it, but after the amount of energy that is currently consumed, utility drops off rapidly. This suggests a low elasticity of demand for fossil fuels. Therefore, under changes in prices or taxes, we expect the quantity of energy consumed to remain largely similar. For simplicity, we assume the quantity of energy consumed remains constant regardless of changes in prices and quantities, because the aspect we are interested in examining in this model is the composition of the fuel supply and not the changes in the quantities of fuel consumed.[218]

We take fossil fuels' cost as a baseline cost with which to compare the other fuel costs. For simplicity, we assume fossil fuels to have a marginal cost that increases at a constant rate. Their total cost is directly proportional to the quantity of fuel utilized. The excavation of fossil fuels is a uniform process, where the cheapest fuels are extracted first, and the extractors move from cheap to more expensive, giving a uniformly rising cost.

We take fossil fuels' marginal cost function to be C_f =w, where w is the percentage of fossil fuels utilized by society. We take the social cost (pollution cost) of fossil fuels to be larger than the direct cost of the fossil fuels, and so we assume a marginal pollution function P_f = 2w. This assumes that the market value of the social costs associated with fossil fuel use is larger than the

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218 I thank Professors Klaus Lackner and David Nissen for illuminating this point for me.

costs at the pump to the consumers. This is a finding consistent with estimates of the damage of fossil fuels found in studies such as *Hidden Costs of Energy.*[219]

Based on the discussion of biofuels cost function in the preceding section, alternative energy sources are given a strictly convex marginal cost function for biofuels of the form: $Ca1 = \alpha x^2$, where x is the percentage of biofuels utilized by society, whereas α is a constant. The magnitude of α determines the specific cost of a biofuel at different utilization levels. The LCA literature discussed in the previous chapters can be seen as an attempt to assess the particular values of α for specific biofuels. In this exercise, we attempt to study the results of particular policies regardless of the value of α.

In order to study the impact of these policies on technological adoption, we construct the other two alternative energies A2 and A3 as energy sources that would not be utilized in normal conditions because of a set fixed cost that makes F and A1 always preferable. They have the same cost function as A1, with a fixed cost parameter β, which is high enough that A2 and A3 are not utilized under normal conditions without policy interventions.

Whereas both A2 and A3 have the same cost function, the difference between them lies in their pollution function. A2's marginal pollution cost is double that of A1, whereas A3's marginal pollution cost function is half that of A1. We can think of A2 and A3 as being two alternative forms of biofuels. They have a higher cost than traditional biofuels, but one is a dirtier, more polluting way of producing biofuels, whereas the other is a cleaner, less polluting way of producing biofuels. We can think of A2 as being Indonesian palm oil biofuels—it involves a fixed cost compared to other biofuels because of the large transportation costs, but it also

219 Committee on Health, Environmental Costs and Benefits of Energy Production and Consumption, 2010.

involves more environmental destruction because it is produced from palm oil plantations built through massive deforestation. We can think of A3 as analogous to cleaner cellulosic biofuels. They involve fixed costs of research, development and adoption, but they are much cleaner than regular biofuels.

This model assesses how different policies would affect the adoption of A2 and A3 by consumers. We examine what the impact of a tax and a mandate would be on the adoption of either energy sources.

In summation, Table 5 shows the marginal pollution and cost functions for the four energy sources:

	Private marginal cost to polluter (c)	Social externality marginal pollution cost (p)
Fossil Fuel (F)	$c_f = w$	$p_f = 2w$
Alternative Energy (A1)	$c_{a1} = \alpha.x^2$	$p_{a1} = \alpha.x^2$
Dirtier Alternative Energy (A2)	$c_{a2} = \beta + \alpha.y^2$	$p_{a2} = 2.\alpha.y^2$
Cleaner Alternative Energy (A3)	$c_{a3} = \beta + \alpha.z^2$	$p_{a3} = \frac{(\alpha.z^2)}{2}$

Table 5: Marginal cost and pollution cost functions for four energy sources

b. Two technologies

This model will assess the impact of three different policy regimes on pollution and cost. These regimes are: no policy, a blending mandate specifying a set percentage of biofuels utilization, and a tax on carbon emissions. We first assess these three scenarios in a case where only F and A1 are available for consumers. We then assess this in the case where F, A1, A2 and A3 are available. We assess the utility maximization function of the representative consumer, and find their most efficient allocation of energy. We then compute the total cost and the total pollution cost. We then compare the different scenarios.

Case 0: Only F available

We first begin by outlining the basic case where there are no options for consumers except the fossil fuel.

Consumers can only use F, and so: w = 1

$$C_f = \int w \cdot dw = \frac{w^2}{2} \Big]_0^1 = \quad = 0.5$$

$$P_{fm} = \int 2w \cdot dw = w^2 \Big]_0^1 = 1$$

The total cost to society is

$$P_f + C_f = 1.5$$

*Net utility = U * - Total Cost to Society = 1 – 1.5 = - 0.5*

Under this scenario, the aggregate utility that consumers derive from consuming the fossil fuel is 1. The cost of the fossil fuel is 0.5. The consumers' surplus is 0.5. The pollution cost, which is not born by the consumers, is 1. The net result is that the damage done to the environment and the cost of the fossil fuel add up to 1.5, which is 50% more than the utility derived from the fuel.

This can be viewed as a realistic description of the use of fossil fuels, and the negative externality problems they pose. We see that fossil fuels are beneficial for the individuals who use them because their private benefits exceed their private costs, while their use is detrimental to society as a whole since their total societal costs exceed their total societal benefits.

Case 1: F and A1 as options

When we introduce the alternative energy source A1 into the market, consumers internalize it into their consumption function and attempt to find the cheapest combination of F and A1 that meets their energy needs.

Find *w (= 1-x)* to minimize cost.

The representative consumer's utility function is:

$$U = U^* - TC$$

$$U = U^* - C_f - C_{a1}$$

$$U = U^* - \int w \cdot dw - \int \alpha.x^2 \cdot dx$$

$$U = 1 - \frac{w^2}{2} - \frac{(\alpha.x^3)}{3}$$

The consumers find the allocation of w and x that minimizes this. We find this allocation by taking the derivative of U and setting it to zero, and substituting x = 1-w

$$\frac{dU}{dx} = \alpha . x^2 + x - 1 = 0$$

Solving, we get:

$$x = \frac{\sqrt{1+4\alpha} - 1}{2\alpha}$$

$$w = 1 - x = 1 - \frac{\sqrt{1+4\alpha} - 1}{2\alpha} = \frac{2\alpha - \sqrt{1+4\alpha} + 1}{2\alpha}$$

Figure 7 shows the values of *x* and *w* for as a function of alpha:

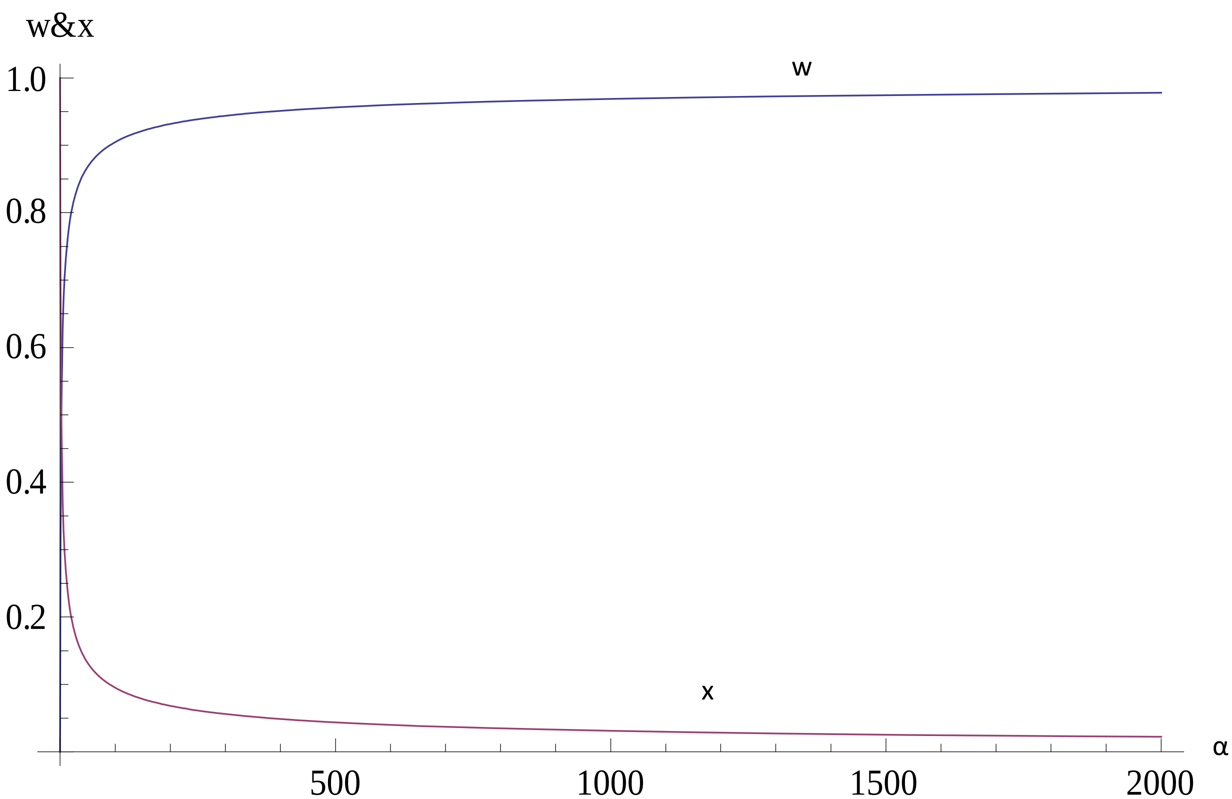


Figure 7: Fuel ratios for different values of alpha in Case 1

Figure 8 magnifies the plot for values of alpha between 1 and 20.

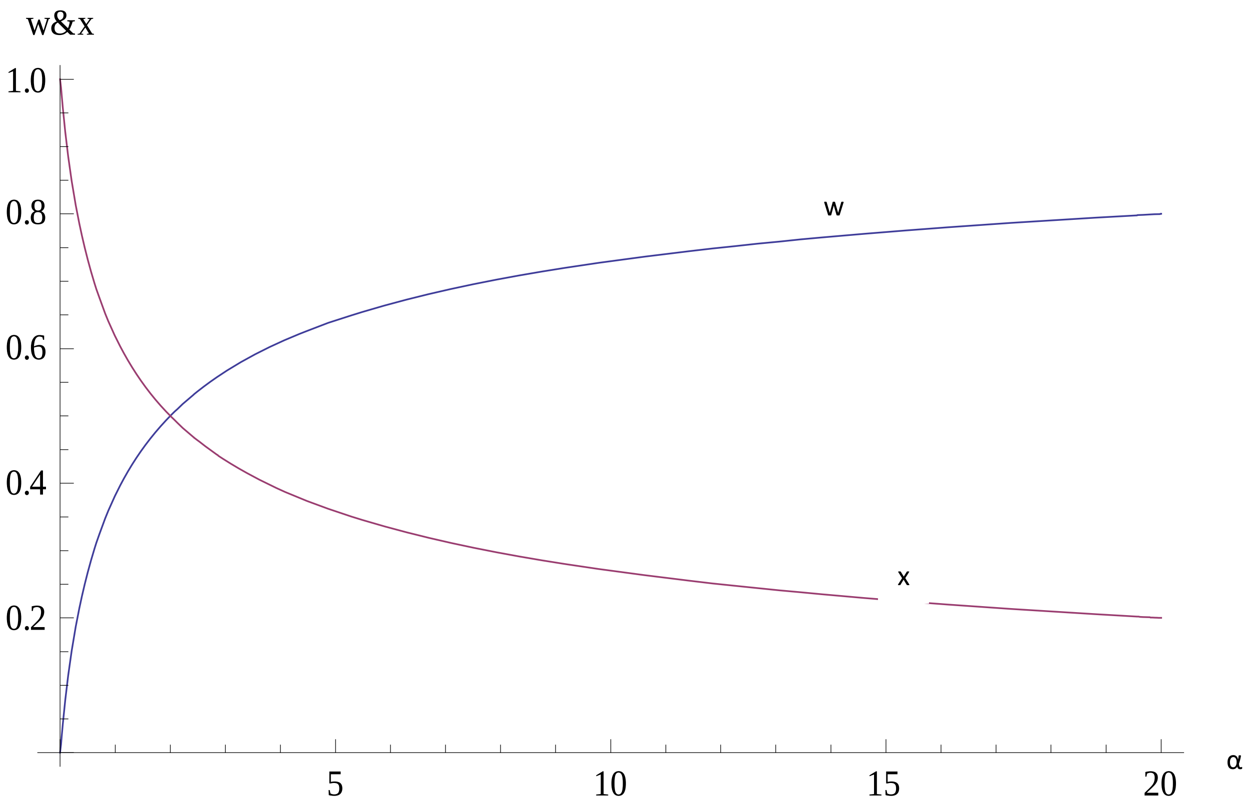


Figure 8: Fuel ratios for different values of alpha in Case 1

This graph clarifies the rationale behind the cost functions. At a very low alpha, the alternative fuel is very cheap, and so in a market with no policy interventions, consumers obtain a large percentage of their energy needs from this alternative fuel.

But as alpha's value increases, the fuel is more expensive, and its share in the fuel supply decreases. As alpha approaches infinity, the share of A1 approaches 0% and the share of F approaches 100%. As alpha approaches 0, the share of A1 approaches 100%, while F approaches 0%. We now attempt to find the cost of the use of these fuels. Substituting in the cost functions, we get

$$C_f = \int w \cdot dw = \frac{w^2}{2} = \frac{2\alpha^2 - 2\alpha\sqrt{1+4\alpha} + 4\alpha + 1 - \sqrt{1+4\alpha}}{4\alpha^2}$$

$$C_{a1} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} = \frac{\sqrt{1+4\alpha} - 1 + \alpha\sqrt{1+4\alpha} - 3\alpha}{6\alpha^2}$$

$$\textit{Total cost} = C_t = C_f + C_{a1} = \frac{(-4\alpha - 1)(\sqrt{1+4\alpha}) + 6\alpha^2 + 6\alpha + 1}{12\alpha^2}$$

Figure 9 shows the values of C_f while Figure 4 shows the values of C_t , C_f *and* C_a for values of alpha from 1 to 300.

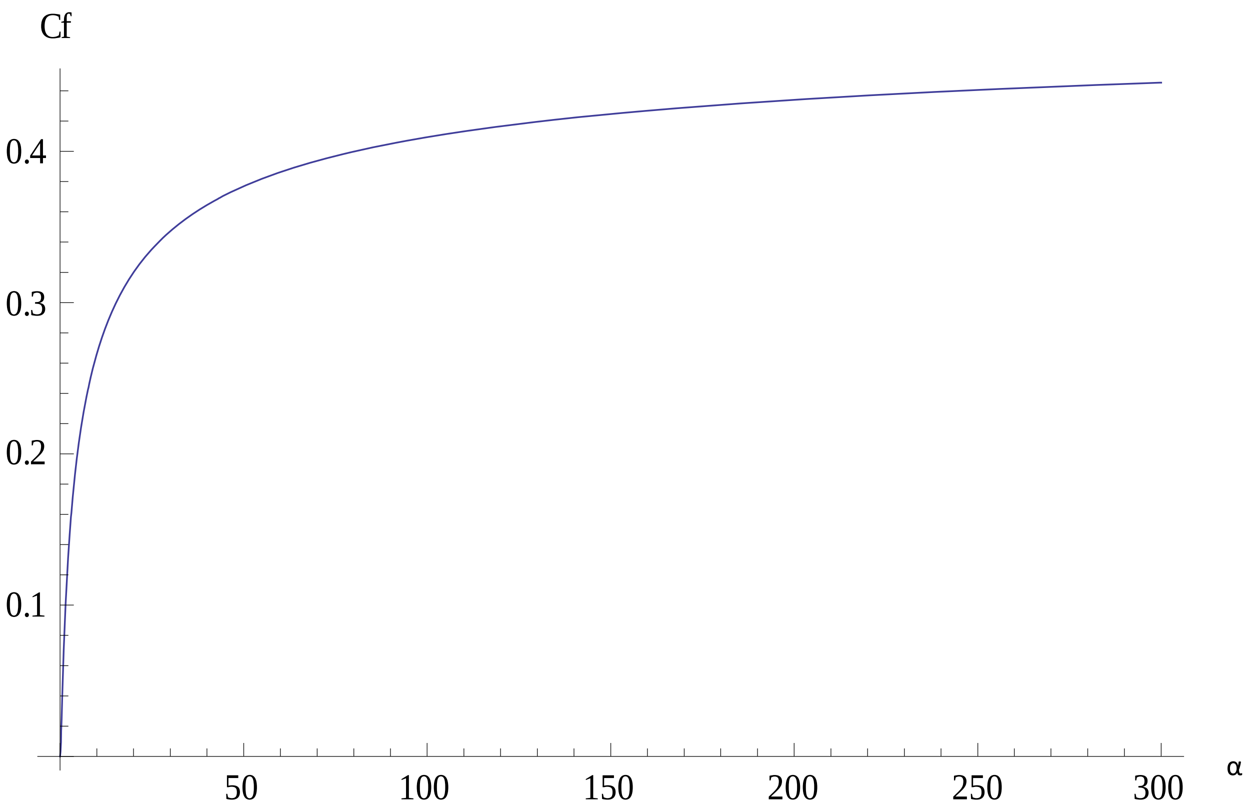


Figure 9: Cost of fossil fuels in Case 1

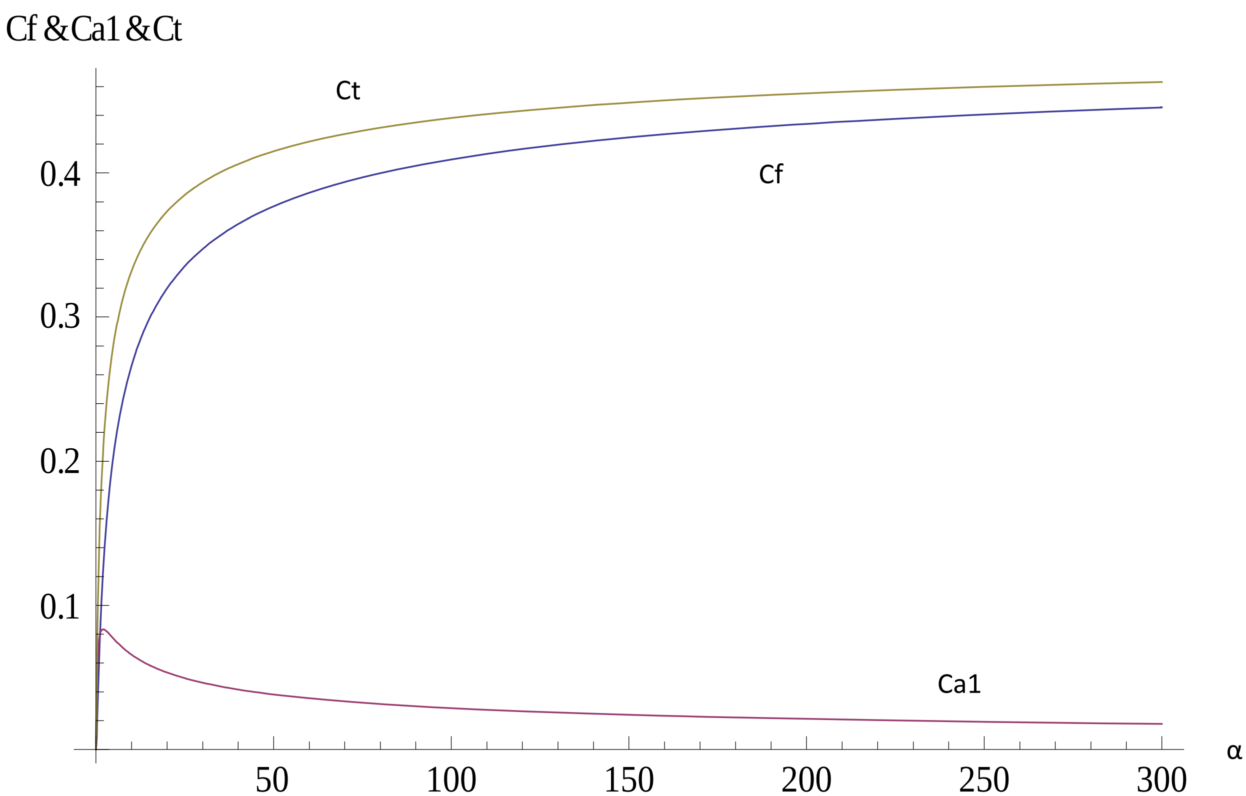


Figure 10: Cost of alternative fuel, fossil fuel, and total cost in Case 1

We can see that as the value of alpha approaches infinity, the total cost approaches 0.5, which was the total cost of the scenario where only F is used. As alpha approaches zero however, the cost approaches zero. Since the smaller alpha, the cheaper it is, and the more likely it is to be utilized.

Substituting in the pollution functions, we get

$$P_f = \int 2.\omega.d\omega = \omega^2 = \frac{2\alpha^2 - 2\alpha\sqrt{1+4\alpha} + 4\alpha + 1 - \sqrt{1+4\alpha}}{2\alpha^2}$$

$$P_{a1} = \int \alpha.x^2.dx = \frac{\alpha..x^3}{3} == \frac{\sqrt{1+4\alpha} - 1 + \alpha\sqrt{1+4\alpha} - 3\alpha}{6\alpha^2}$$

Total pollution cost = $P_t = P_f + P_{a1} = \frac{(-5\alpha - 2)\sqrt{1+4\alpha} + 6\alpha^2 + 9\alpha + 2}{6\alpha^2}$

These functions are plotted in figure 11.

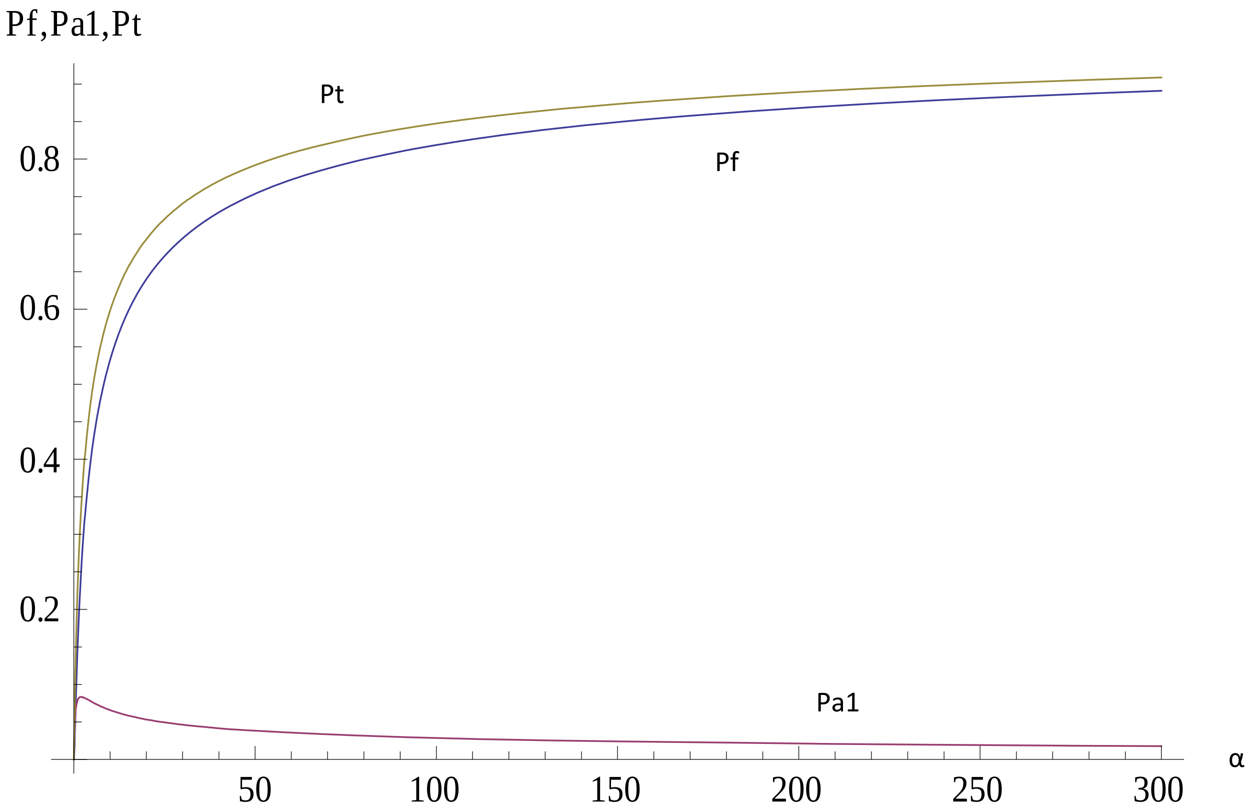


Figure 11: Pollution costs in Case 1

Total cost to society is = *TCS* = *Ct* + *Pt*

$$= \frac{(-14\alpha - 5)\sqrt{1 + 4\alpha} + 18\alpha^2 + 24\alpha + 5}{12\alpha^2}$$

Figure 12 plots TCS

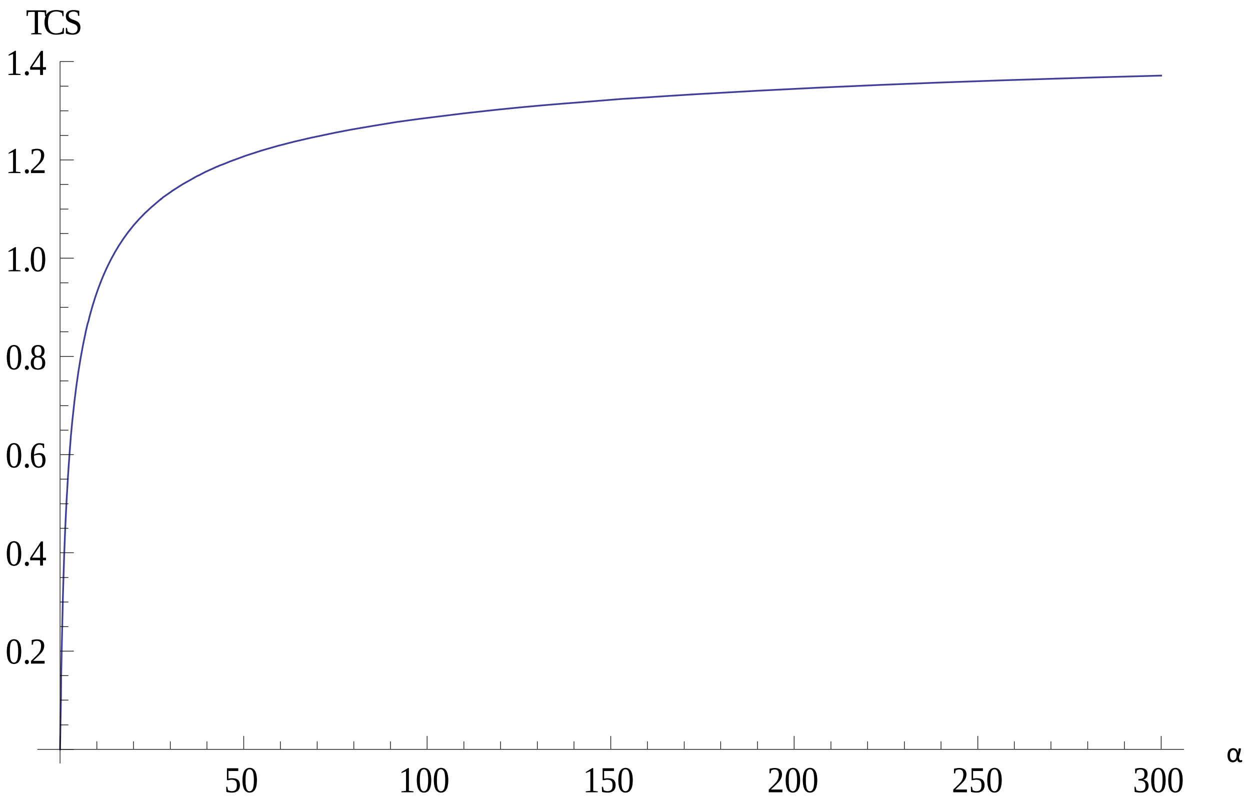


Figure 12: Total cost to society in Case 1

Therefore, total utility is $U_{case\ 1} = 1 - TCS$

$$= \frac{(-14\alpha - 5)\sqrt{1 + 4\alpha} - 6\alpha^2 + 24\alpha + 5}{12\alpha^2}$$

Figure 13 plots society's total utility as a function of alpha:

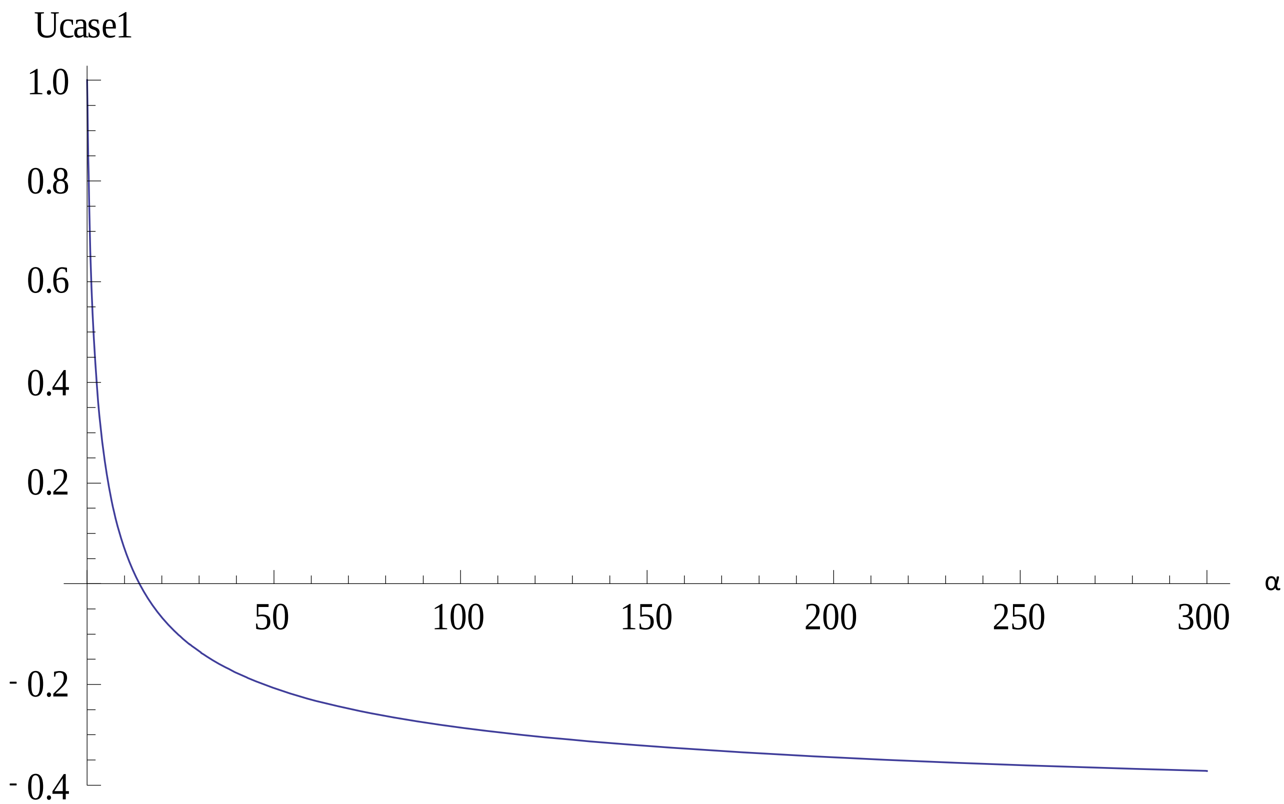


Figure 13: Total utility for Case 1

Here this should be compared with Case 0, where only fossil fuel F is available. In that case, total cost to society was always -0.5, since the societal negative externality exceeded the private benefits from the fuel consumption. We see that with the introduction of an alternative fuel, the utility can be increased. As alpha approaches infinity (meaning A1 is very expensive), the total utility is equal to that of the fossil fuel case (-0.5), meaning that no alternative fuel is utilized.

But as soon as any alternative fuel is utilized, it is cheaper, and the societal cost declines. For values of alpha <15 (A1 very cheap), the value of the net utility is positive.

Case 2: Mandate on the use of A1

The starting point of policy legislation will generally be a low level of biofuels, as is the case in the US and EU. At such low levels, the costs of production and pollution associated with biofuels are low. Only the most efficient crops, production techniques and lands are utilized. At low levels of utilization, one can think of waste vegetable oil being used to produce small amounts of biodiesel that can be added to cars' fuel mix. Such small techniques carry small environmental damages and marginal costs.

LCA studies will generally show favorable results for the utilization of these fuels, as we saw with the Wang and Shappouri early studies.[220] This creates a clamor for legislating a doubling mandate, under the supposition that the increase in utilization will result in a reduction in cost and pollution.

A mandate dictates the increase of the value of x to a certain threshold x_m, where x_m = 2* x_m. We define this as a doubling mandate. This would double the % of biofuels, whatever it was. This could not apply in the cases where x is > 0.5 to start with. In this case,

$$x_m = 2x$$

$$x_m = \frac{\sqrt{1+4\alpha} - 1}{\alpha}$$

220 Wang and Shappouri, 1995, 1998

$$w_m = 1 - x_m = 1 - \frac{\sqrt{1+4\alpha} - 1}{\alpha} = \frac{\alpha - \sqrt{1+4\alpha} + 1}{\alpha}$$

Figure 7 shows the values of w and x at different values of alpha. The same relationship between alpha and w and x is maintained from Case1.

Substituting in the cost functions to find the cost, we get:

$$C_{fm} = \int w \cdot dw = \frac{w^2}{2} = \frac{3\alpha^2 + 6\alpha + 3 - 6\sqrt{1+4\alpha} - 6\alpha\sqrt{1+4\alpha}}{6\alpha^2}$$

$$C_{a1m} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} = \frac{8\alpha\sqrt{1+4\alpha} + 8\sqrt{1+4\alpha} - 24\alpha - 8}{6\alpha^2}$$

Total cost to consumers = C_{tm} = C_{fm} + $C_{a1m} = \frac{(2\alpha+2)(\sqrt{1+4\alpha}) + 3\alpha^2 - 18\alpha - 5}{6\alpha^2}$

Figure 14 shows the values of C_{tm} , C_{fm} *and* C_{a1m} for values of alpha from 1 to 200

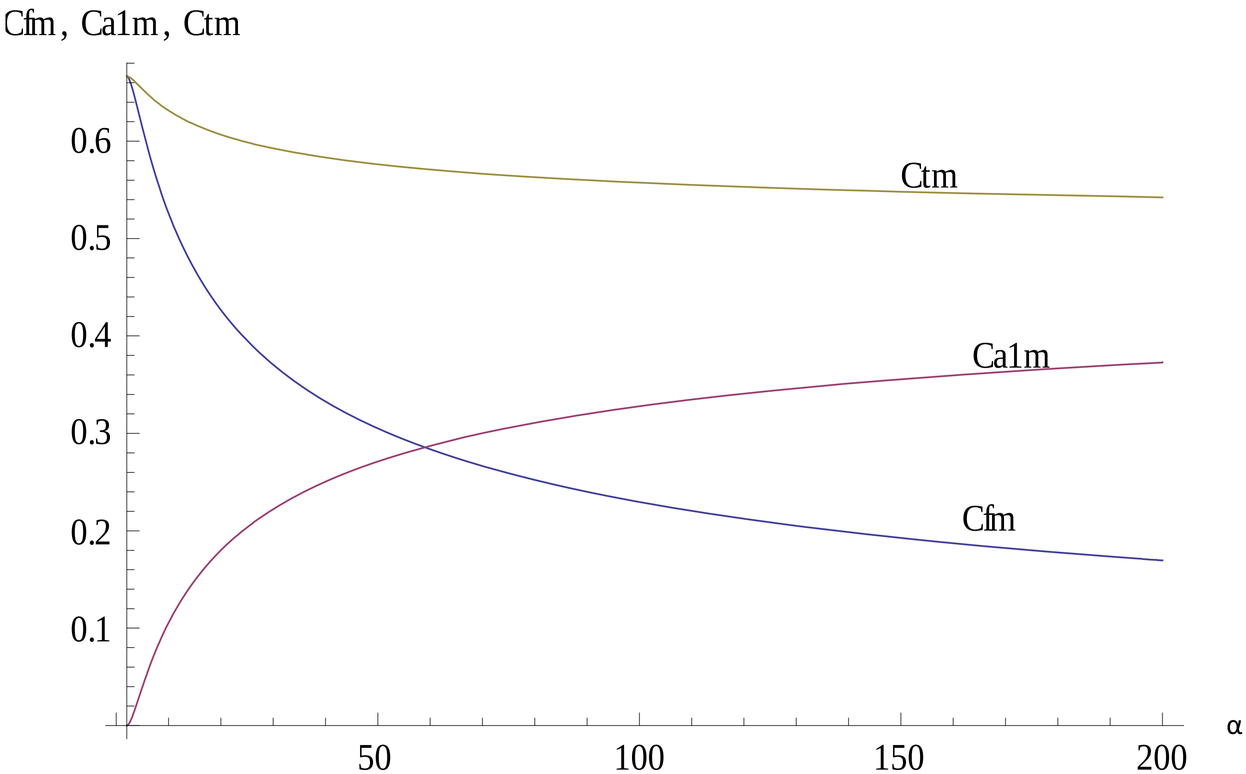


Figure 14: Costs as a function of alpha in Case 2

Substituting in the pollution functions, we get

$$P_{fm} = \int 2\omega \cdot d\omega = w^2 = \frac{6\alpha^2 + 12\alpha + 6 - 12\sqrt{1+4\alpha} - 12\alpha\sqrt{1+4\alpha}}{6\alpha^2}$$

$$P_{a1m} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} = \frac{8\alpha\sqrt{1+4\alpha} + 8\sqrt{1+4\alpha} - 24\alpha - 8}{6\alpha^2}$$

Total pollution cost = $P_{tm} = P_{fm} + P_{a1m} = \frac{(-4\alpha - 4)\sqrt{1+4\alpha} + 6\alpha^2 - 12\alpha - 2}{6\alpha^2}$

Figure 15 shows pollution costs from the doubling mandate as a function of alpha

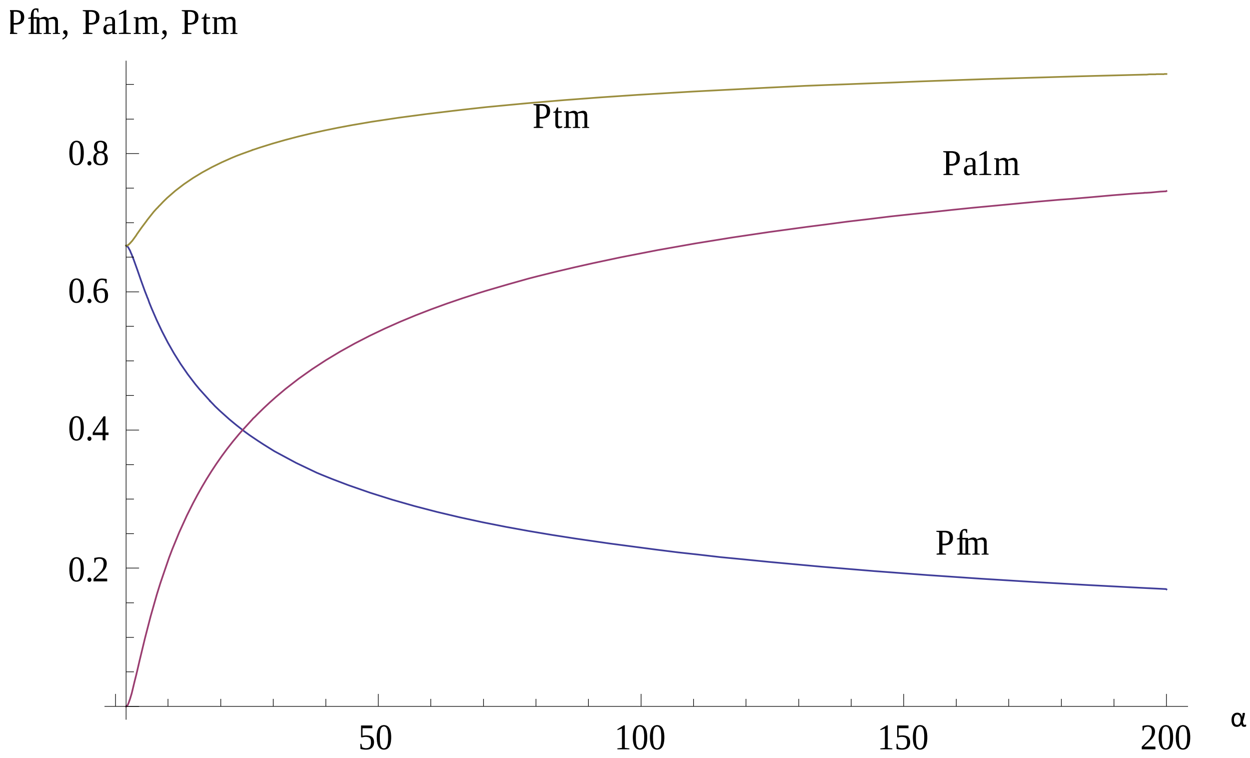


Figure 15: Total pollution costs as a function of alpha in Case 2

Total cost to society = $P_t + C_t \; = \dfrac{(-2\alpha - 2)\sqrt{1+4\alpha} + 9\alpha^2 - 30\alpha - 7}{6\alpha^2}$

Total Utility = 1- *TCS* $= \dfrac{(-2\alpha - 2)\sqrt{1+4\alpha} + 3\alpha^2 - 30\alpha - 7}{6\alpha^2}$

Figure 16 shows the total pollution, total costs and total societal costs.

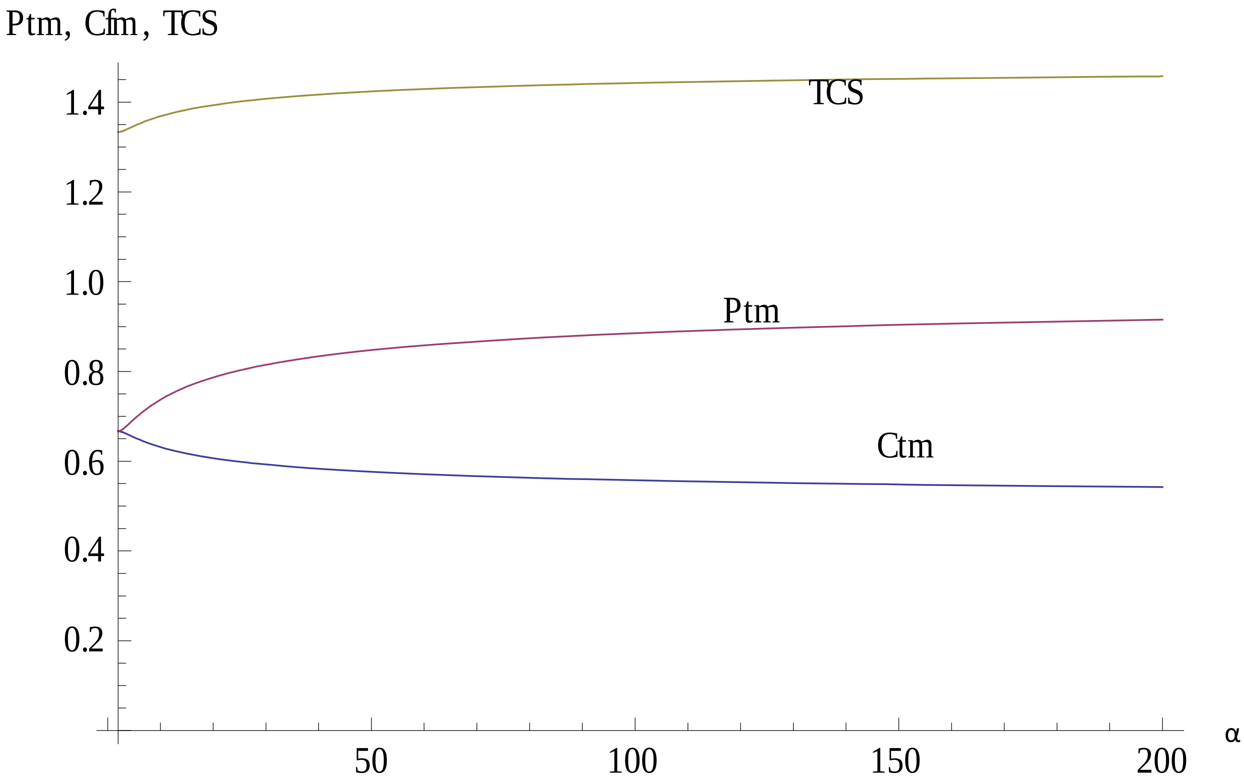


Figure 16: Cost, pollution cost and total cost for Case 2

We find that for doubling, at all values of α, the total cost to society increases as opposed to the baseline no policy scenario.

Figure 17 shows society's total utility with a mandate in place

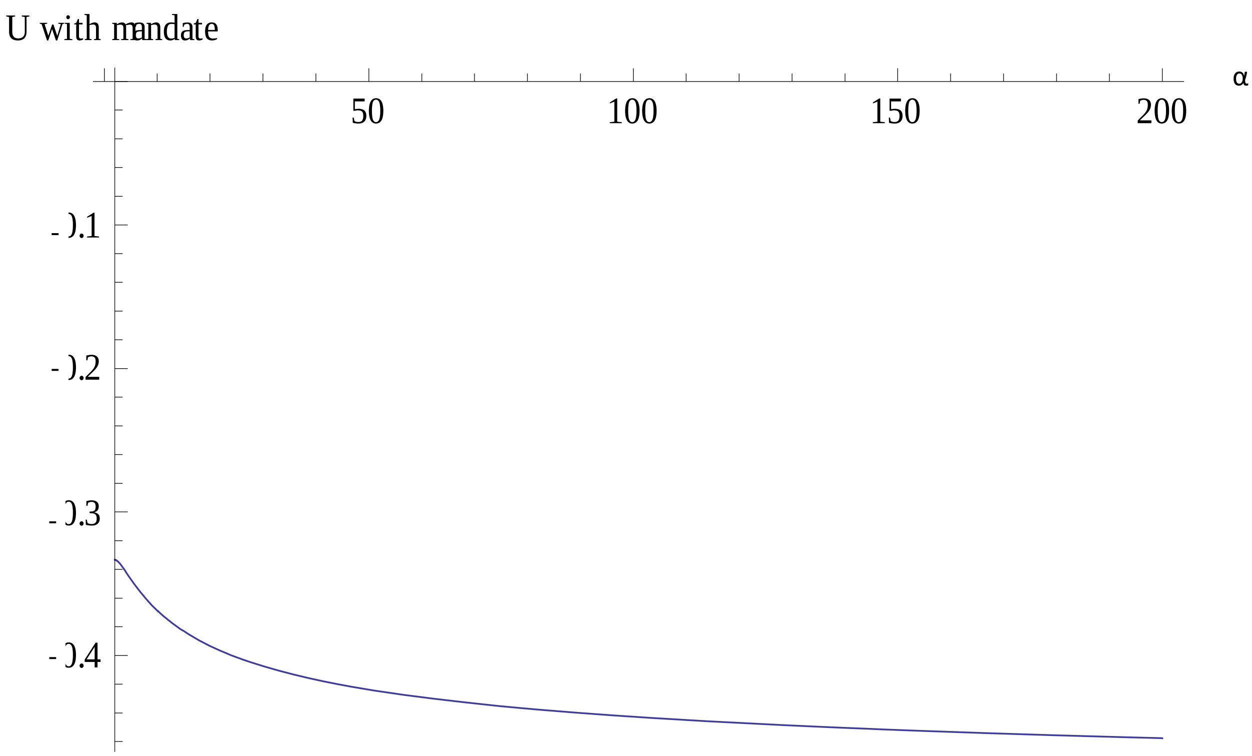


Figure 17: Society's total utility in Case 2

In this example, one can think of the impact of doubling the consumption mandate causing the production of biofuels to go from the clean, cheap local production techniques to mass industrialized techniques that involve large externalities. In this particular example, we can find that this level of mandates has caused an increase in the costs at all levels—only when alpha is infinitely high do we approach the level of U with no policy.

Case 3: Tax on pollution regardless of source

We now consider the case of taxation on the pollutant. In this case, the tax is *not* imposed on the cost to the consumer; it is not a tax placed on C or P, as that would be a tax on the fuel and would be effectively no different than the mandated increase in biofuels. As discussed in Chapter VI, a tax/subsidy on the fuel in this model would be equivalent to a blending mandate limiting/increasing fuel consumption. Based on the analysis of chapter VI, the tax we are discussing here is one that is placed directly on the *pollutant*—CO_2 in our case. While calling it a tax for simplicity, it is vital to remember that the same results, in theory, could be achieved by placing a cap on carbon emissions and having a market to trade these emissions.

It is vital to note that the tax is on the pollutant itself, and not the fuel, as it is inextricably linked to the analyses of Chapters IV and V. The problem of calculating the emissions from biofuels production means that attempting to place a tax on carbon by adding it on the fuel necessitates knowing the carbon that went into making the fuel. But the previous analysis showed us that the problem is simply that we cannot know the carbon content of the fuels we have. Therefore, for the tax to be placed directly on the pollutant, it must be placed at the pollutant itself, wherever it may be found, at the moment it enters the atmosphere.

This means that for fossil fuels, the carbon tax is placed at the quantity of carbon as it is being extracted from the earth. The producers will then pass the cost on to the consumers. All the processes that produce carbon emissions need to be taxed when the carbon leaves the earth and enters the atmosphere. Implementing it this way is the way to get around the knowledge problem embodied in the calculation of emissions content. By placing the tax at the source, the cost is then passed on to the consumers of the fuels or products responsible for the emissions. This is also true for emissions from agriculture and land use change. When the tax is placed at the source of the land use change the public hidden cost will be internalized into the calculation of the producers of the crops, and they will be in turn passed on to the consumers.

The key insight from chapters IV and V is that it is very hard to reverse-calculate all the carbon inputs that went into a production process because of the complexity of the system, the difficulty of modeling dynamic market processes, the difficulty of modeling technology accurately, and the problems of aggregate-based modeling. By placing the tax at the source of carbon, there is no need for anyone to make this calculation and build a comprehensive system of understanding the market production process. The price is internalized and carried through in the process until it reaches the consumer.

This brings us back to the motivating assumption of this modeling exercise, which is that the values of the cost function are unknown. To know the cost function, one needs to know alpha, and to know that, one needs to be able to compute the entirety of carbon produced throughout the production process. But by placing the tax at the source of carbon emissions, no such calculation or knowledge is needed—the price of carbon will be passed on from producer to consumer and the decisions of the consumer to optimize their benefits and costs will in turn be responsible for deciding what gets produced and what doesn't.

For the purposes of this model, the cost of the pollution is carried through to the consumer. This cost is P, but it cannot be observed or calculated by anyone, neither can alpha be observed or calculated by anyone, because this cost is dispersed to pay for countless processes across the world that went into producing the fuel for the end-consumer—everything from growing crops, producing fertilizers, producing the fuels, transporting the fuels and producing the distribution facilities. But, as can be learned from the insights on market processes from Chapter V, these costs are carried through to the consumer. For this model, then P is added to C and the consumer optimizes the combination of the two that reduces their total costs.

The magnitude of the tax, for the purposes of this model, is assumed to accurately reflect the social damage from pollution in the production of the fuels. What is needed for this is an estimate of the damage that carbon dioxide emissions cause and for the price to be placed on the carbon emissions. The results of this modeling exercise, however, are independent of this assumption as will be shown shortly. The key result from this analysis is that the carbon tax leads to a reduction in emissions, and this would be true whatever the magnitude of the tax.

The consumer's utility function is:

$$U = 1 - \frac{w^2}{2} + \frac{\alpha x^3}{3} + \omega^3 + \frac{\alpha x^3}{3}$$

$$\frac{dU}{dt} = 2\alpha x^2 - 3x + 3$$

Solving for x we get:

$$x = \frac{\sqrt{9 + 24\alpha} - 3}{4\alpha}$$

$$w = 1 - x = \frac{4\alpha - \sqrt{9 + 24\alpha} + 3}{4\alpha}$$

Figure 18 shows the x and w for different values of alpha.

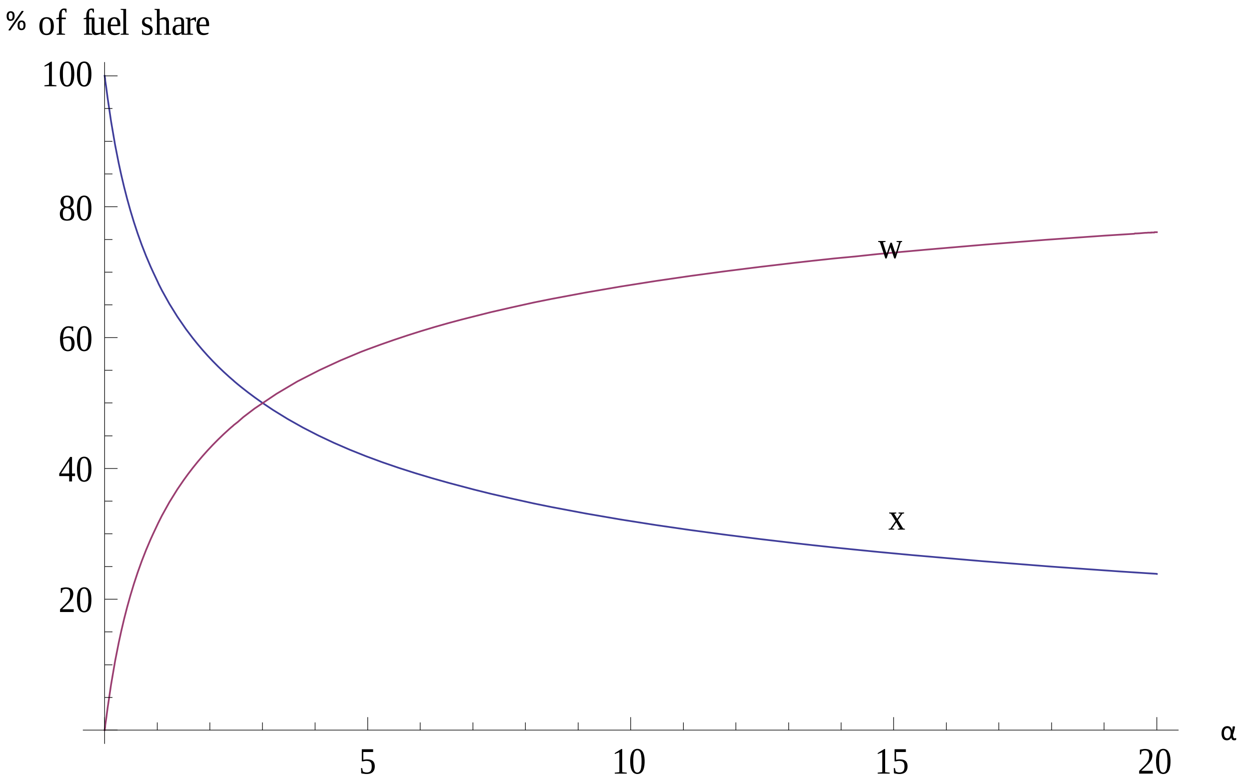


Figure 18: Fuel ratios for Case 3

Substituting in the cost functions to find the cost, we get:

$$C_{ft} = \int w \cdot dw = \frac{w^2}{2} = \frac{16\alpha^2 + 18 + 6\sqrt{9+24\alpha} - 8\alpha\sqrt{9+24\alpha}}{32\alpha^2}$$

$$C_{a1t} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} = \frac{4\alpha\sqrt{9+24\alpha} + 6\sqrt{9+24\alpha} - 36\alpha - 18}{32\alpha^2}$$

Total cost to consumers = $C_{tt} = C_{ft} + C_{a1t} = \dfrac{-4\alpha\sqrt{9+24\alpha} + 12\sqrt{9+24\alpha} + 16\alpha^2 - 36\alpha}{32\alpha^2}$

Figure 19 shows the values of C_{tt} , C_{ft} *and* C_{a1t} for values of alpha

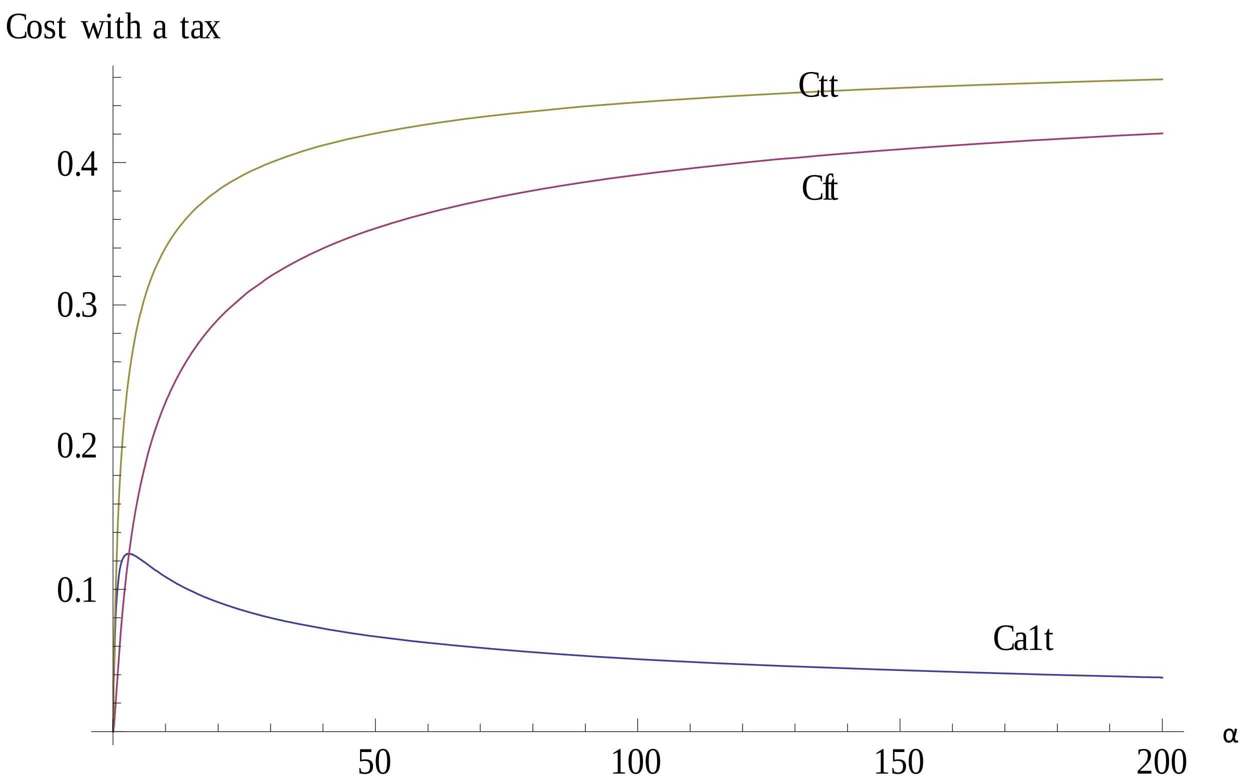


Figure 19: Costs as a function of alpha for Case 3

Substituting in the pollution functions, we get

$$P_{ft} = \int 2w \cdot dw = w^2 = \frac{32\alpha^2 + 36 + 12\sqrt{9+24\alpha} - 16\alpha\sqrt{9+24\alpha}}{32\alpha^2}$$

$$P_{a1t} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} = \frac{4\alpha\sqrt{9+24\alpha} + 6\sqrt{9+24\alpha} - 36\alpha - 18}{32\alpha^2}$$

$$\textit{Total pollution cost} = P_{tt} = P_{ft} + P_{a1t} = \frac{-12\alpha\sqrt{9+24\alpha} + 18\sqrt{9+24\alpha} + 32\alpha^2 - 36\alpha + 18}{32\alpha^2}$$

Total cost to society =P_{tt} + C_{tt} = $\dfrac{-16\alpha\sqrt{9+24\alpha}+30\sqrt{9+24\alpha}+48\alpha^2-72\alpha+18}{32\alpha^2}$

Figure 20 plots costs, pollution and total social cost

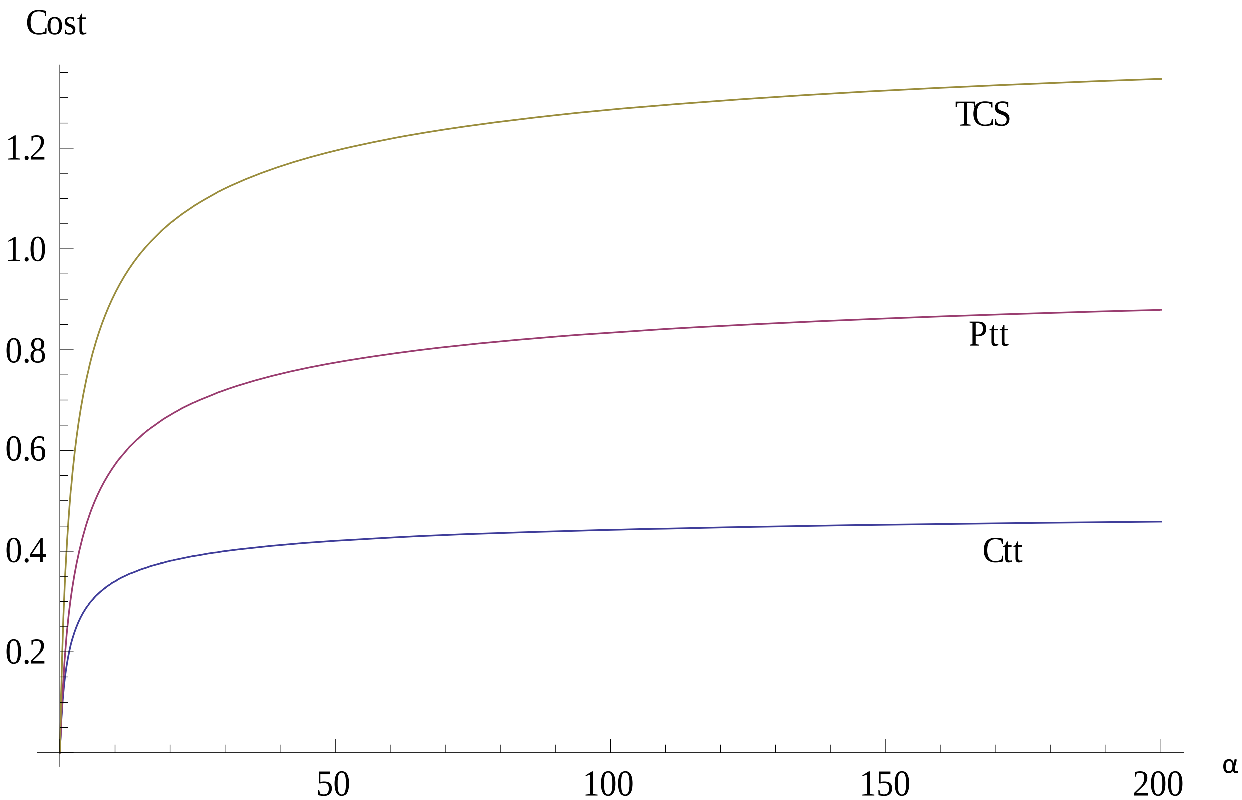


Figure 20: Costs in Case 3

Total Utility = 1- *TCS* $\dfrac{-16\alpha\sqrt{9+24\alpha}+30\sqrt{9+24\alpha}-16\alpha^2-72\alpha+18}{32\alpha^2}$

Figure 21 plots Total Utility with a tax.

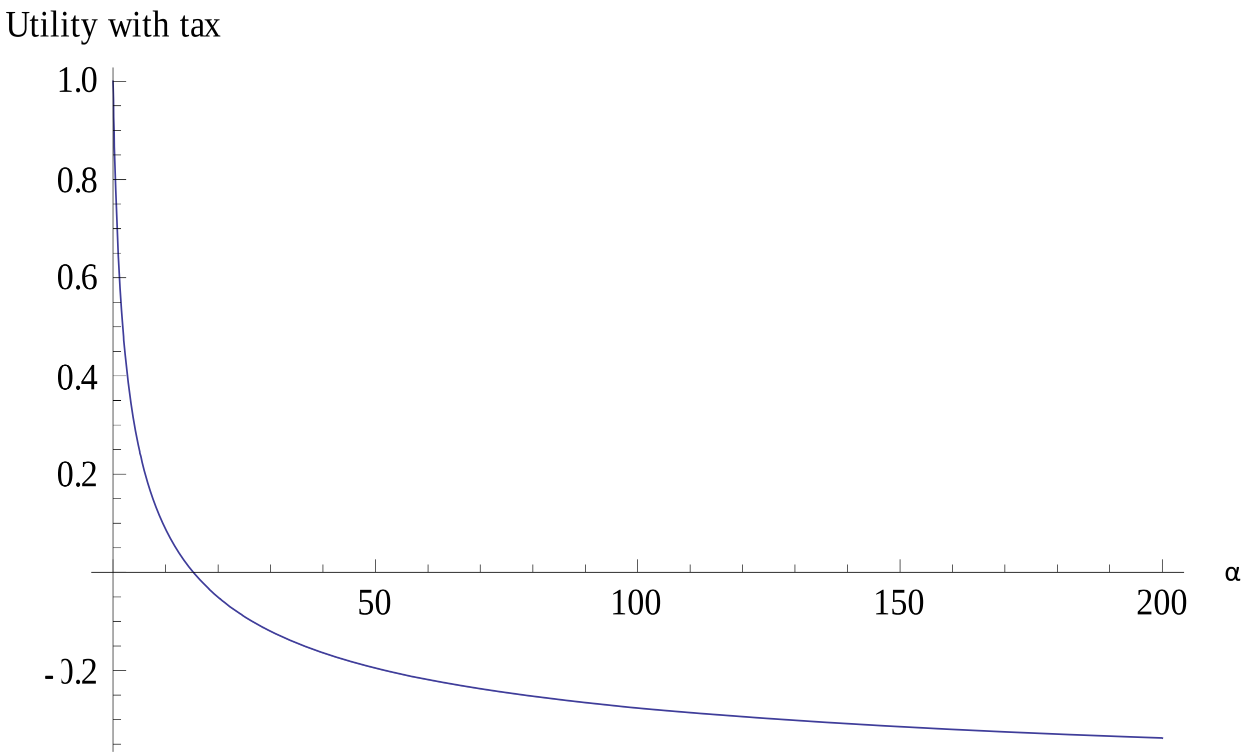


Figure 21: Society's total utility in Case 3

If the government imposes a tax on the pollutants we will obtain a reduction at the lowest possible total cost to society. This shows us the lowest possible value for TC regardless of the value of α. Consumers have taken the choices that have reduced the pollution without having to know the costs of each process. No one, not even the regulator needs to know this information—the internalizing of the cost of carbon from the beginning of the process into the price has carried it through to the consumer, whose choice reduced the pollution and the costs.

Figure 17 shows a plot of the different costs of the different policy regimes as a function of alpha.

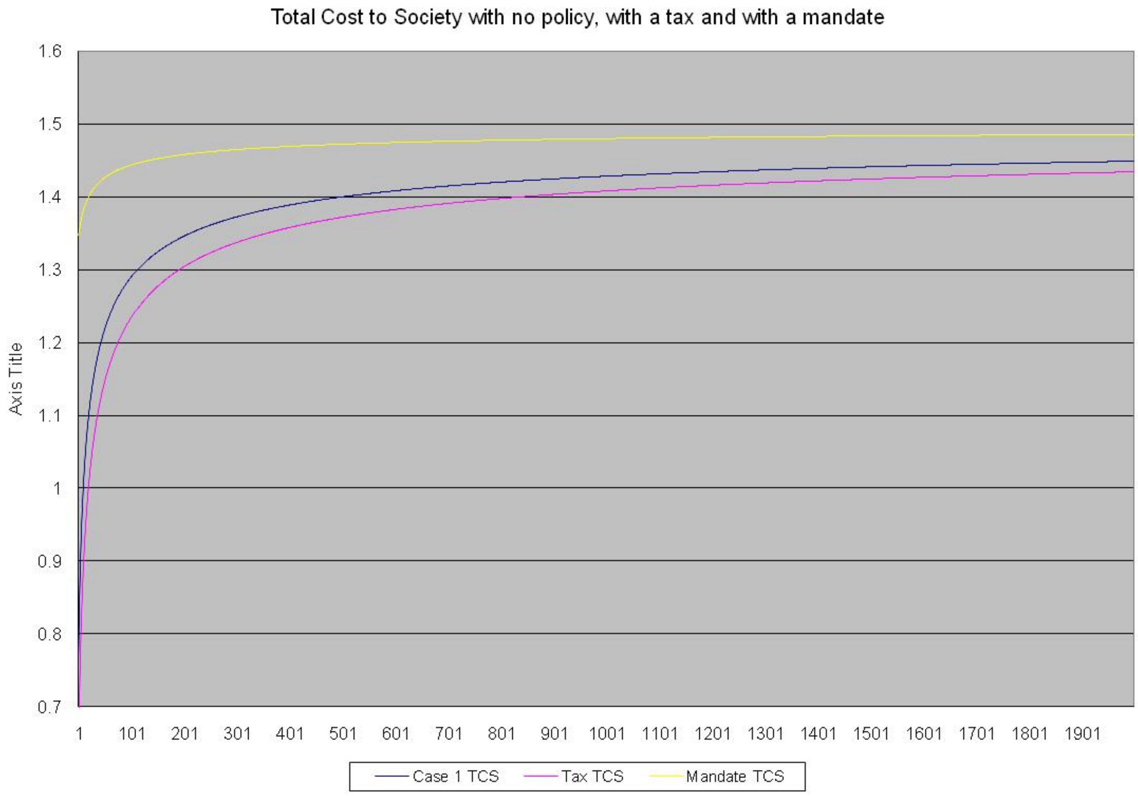


Figure 22: Total cost to society in Cases 1, 2 and 3

As we can be seen in Figure 21, and as explicated in the equations, the pollutant-tax regime always represents the lowest total cost to society followed by the no policy regime, with the mandate the highest. The conclusion drawn here is that a mandate to increase the percentage of fuel may result in an increase in emissions and costs, while a tax results in a reduction of costs and emissions. This has implications for the EU and USA policies on biofuels to be discussed in the following chapters.

This result is important in light of the preceding discussion of the problems with knowing the true value of alpha. The LCA literature makes it clear that an accurate measure of the cost functions of fuels is not currently available. In light of this ignorance, we compare the effect of different policies on the cost and pollution of different fuels and find that placing a tax on the negative externality is always superior to mandating an increase in the use of a fuel.

While the tax will always produce the best outcome, this result is subject to two small caveats:

In case the mandate happens to lead to an increase in the consumption of A1 that is equal to the rate produced by the tax, then the total cost of the mandate would be equal to the total cost of the tax regime. However, since we posit alpha as unknown, we cannot know the right mandate level in advance.

The optimum mandate would be the value that is found from the tax. But that value depends on α. Since we do not know alpha, we cannot know the right mandate. The tax just finds it spontaneously. The chances of hitting at the right mandate are very slim, because we do not know alpha.

Finally, Figure 21 shows the total cost to society for five different policy regimes, at lower levels of alpha. On top of the three previous regimes we discussed above, we add two new mandate regimes: a mandated increase of 25% and a mandated increase of 50%.

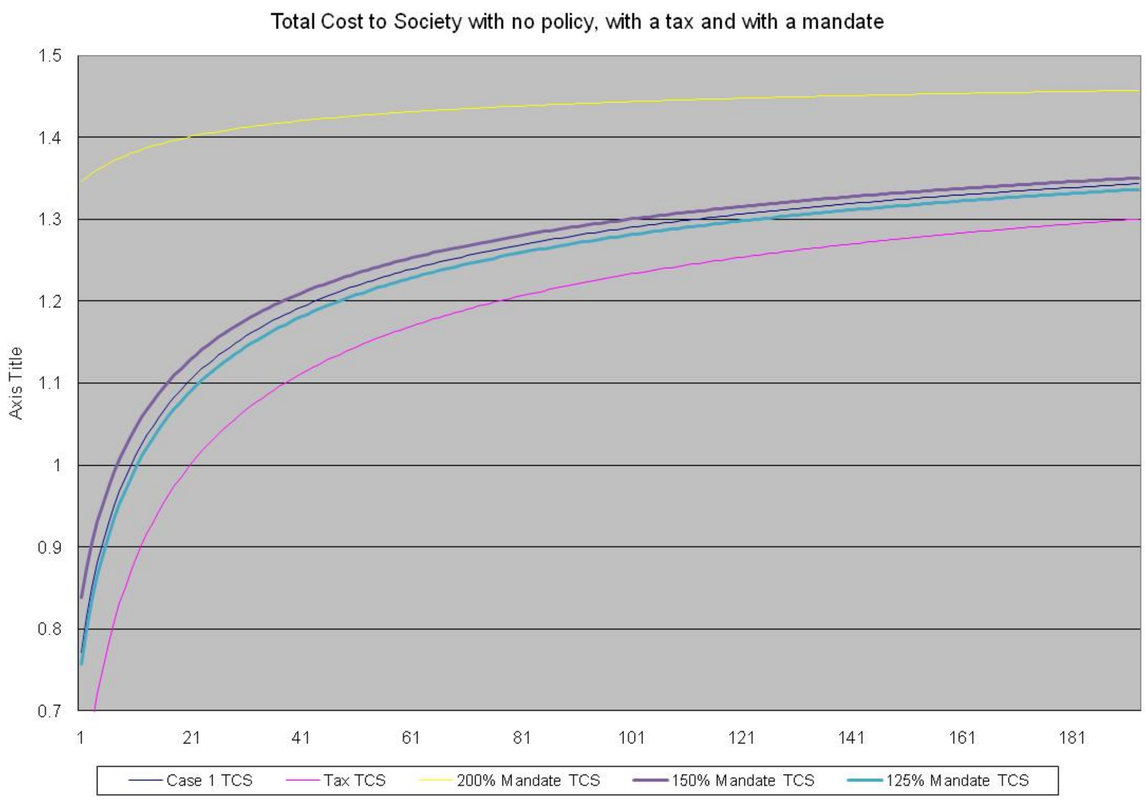


Figure 23: Total costs to society in 5 cases

The 125% mandate provides a decrease in costs, while the 150% mandate provides an increase in costs over the no-policy scenario. The 200% (doubling) mandate provides the highest cost. The conclusion drawn from this is that under certain combinations of values of alpha and the mandate percentage, the mandate could produce a reduction in total costs. But since the value of alpha is unknown there is no way of knowing whether any specific mandate would lead to a reduction or not ex ante. The tax, on the other hand, at every given tax level, produces the optimum reduction in total costs without anyone having to know the value of alpha.

c. With Four technologies available

We now introduce the two alternative energy fuels, A2 and A3. Both these fuels have high fixed costs that prevent their utilization under a no policy scenario. The point of this exercise is to examine what happens when the two policies are introduced in terms of the adoption of the two technologies. Fuels A2 and A3 both have the same higher fixed cost β that makes their initial adoption expensive. They have the same cost function, but A2 produces twice as much pollution as A1, while A3 produces half as much pollution as A1.

Case 4: No policy scenario

In this scenario, the consumers have a choice between the four fuels. Consumers seek to minimize their own cost, and do not take into account the social cost of the fuels.

Their utility function is:

$U = U^* - C_t$

$U = U^* - C_f - C_{a1} - C_{a2} - C_{a3}$

$$C_t = \frac{w^2}{2} + \frac{\alpha..x^3}{3} + \beta.y + \frac{\alpha.y^3}{3} + \beta.z + \frac{\alpha.z^3}{3}$$

Consumers seek to minimize this function, subject to the constraint:

$w+x+y+z = 1$

and a and β are positive constants

For this problem we use the lagrangian multiplier:

$$\Lambda = \frac{\omega^2}{2} + \frac{\alpha..x^3}{3} + \beta.y + \frac{\alpha.y^3}{3} + \beta.z + \frac{\alpha.z^3}{3} - \lambda(w + x + y + z - 1)$$

We notice that *y* and *z* behave identically in this equation, and so we can replace *z* with *y*.

$$\Lambda = \frac{\omega^2}{2} + \frac{\alpha..x^3}{3} + 2\beta y + \frac{2\alpha.y^3}{3} - \lambda(w + x + 2y - 1)$$

To find the solution, we take derivatives and set them to zero

$$\frac{d\Lambda}{dw} = 0 = w - \lambda$$
$$\frac{d\Lambda}{dx} = 0 = \alpha x^2 - \lambda$$
$$\frac{d\Lambda}{dy} = 0 = 2\beta + 2\alpha y^2 - 2\lambda$$
$$\frac{d\Lambda}{d\lambda} = 0 = w + x + 2y - 1$$

Solving these equations, we find the following percentages of each fuel for different values of alpha and beta:

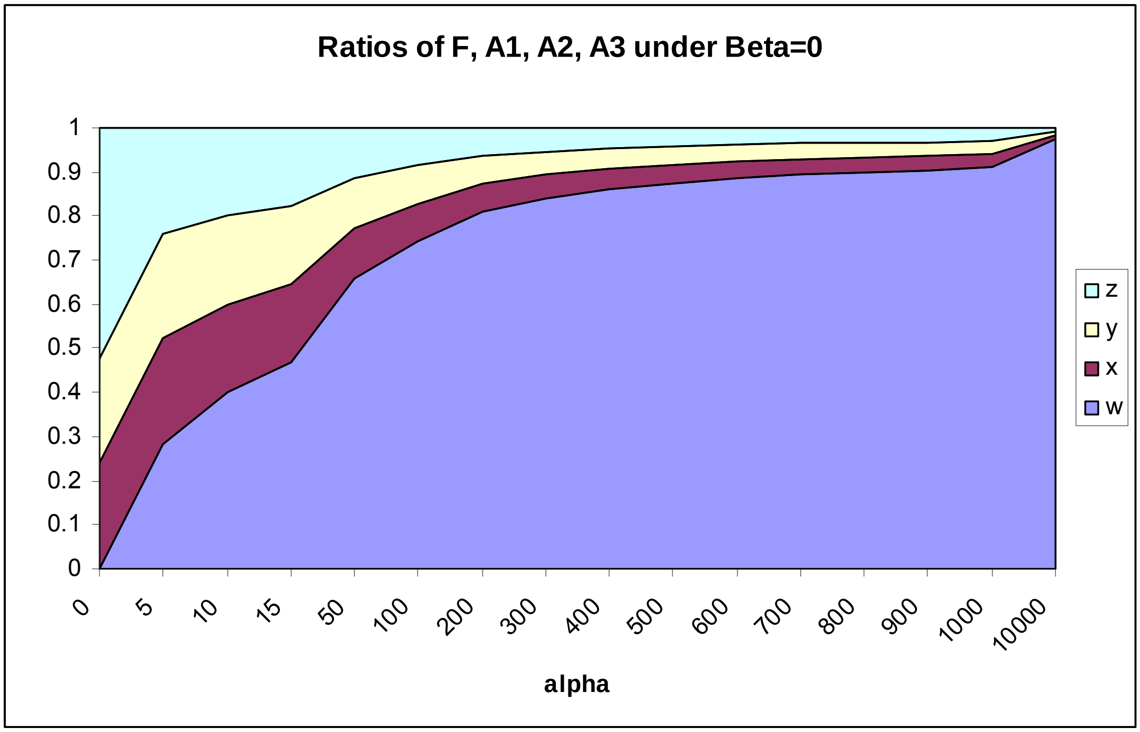


Figure 24: Fuel ratios under Beta = 0

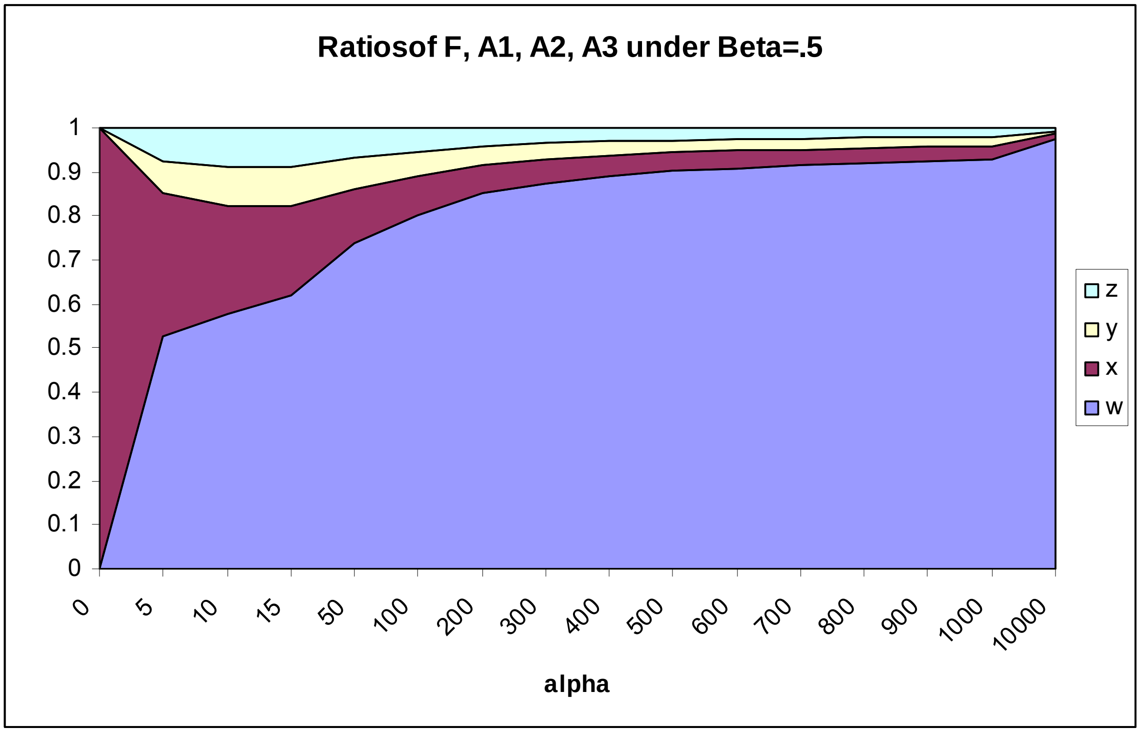


Figure 25: Fuel ratios under Beta = 0.5

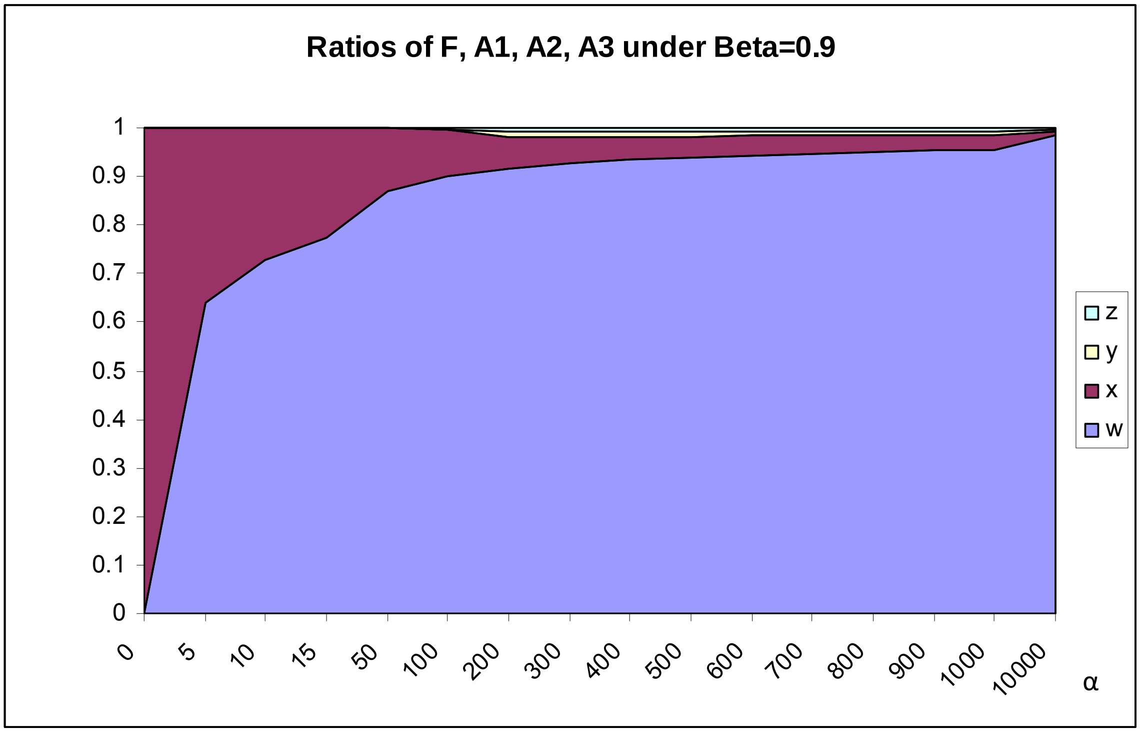


Figure 26: Fuel ratios under Beta = 0.9

We find that as β increases, the adoption of the fuels A2 and A3 decreases. This result is intuitive, since as the fixed cost increases, the cost of adopting the fuels increases, making their adoption less likely.

We substitute the values of w, x, y and z into their respective cost functions to find the total cost:

$$C_f = \int \omega \cdot d\omega = \frac{\omega^2}{2} =$$

$$C_{a1} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} =$$

$$C_{a2} = \int \beta + \alpha y^2 \cdot dy = \beta y + \frac{\alpha . y^3}{3}$$

$$C_{a3} = \int \beta + \alpha z^2 \cdot dz = \beta z + \frac{\alpha . z^3}{3}$$

We substitute the values of w, x, y and z into their respective pollution functions to find the total pollution cost to society:

$$P_f = \int 2.\omega.d\omega = \omega^2 =$$

$$P_{a1} = \int \alpha . x^2 .dx = \frac{\alpha .. x^3}{3} =$$

$$P_{a2} = \int \beta + \alpha y^2 .dy = \beta y + \frac{\alpha y^3}{3} =$$

$$P_{a3} = \int \beta + \alpha z^2 .dz = \beta z + \frac{\alpha z^3}{3} =$$

The total cost to society is then found by adding the total pollution cost to the total cost.

The total cost with no policy can be plotted as a function of alpha and beta:

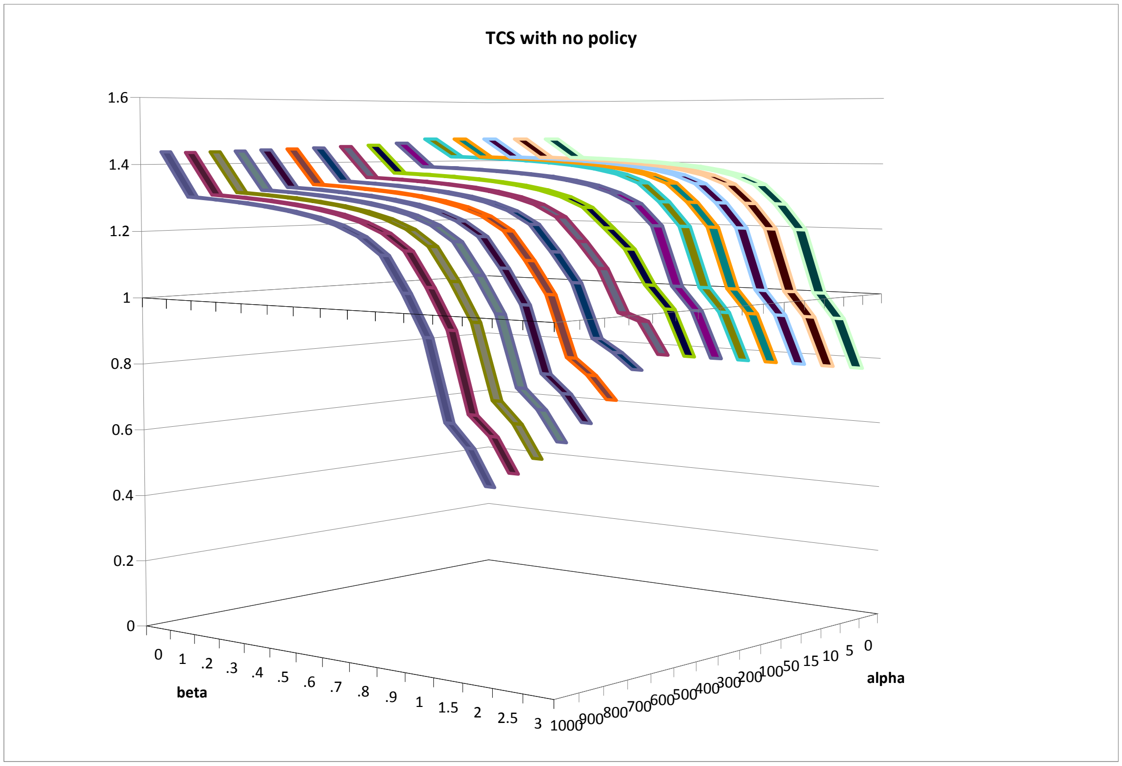


Figure 27: Total cost to society as a function of alpha and beta

As we can see here, the total cost to society varies from a high approaching 1.5 (when beta > 3 and alpha approaches infinity) to a low approaching 0 as alpha and beta approach zero. The lower the fixed costs of A2 and A3 and the lower the unknown coefficient alpha in the energy function, the lower the total cost to society. We will now see how this result compares to other policy scenarios.

Case 5: Doubling Mandate Scenario

In this case, the regulatory authority mandates a doubling of the amount of alternative energy to be used. This means that the sum of A1, A2 and A3 should add up to double the original level of all three fuels. In some cases, when beta is too high, there would have been no A2 and A3 fuel utilization before the mandate, but their utilization was spurred by the mandate. Since the costs of these two fuels are identical, they behave identically in the cost function and their percentages are identical.

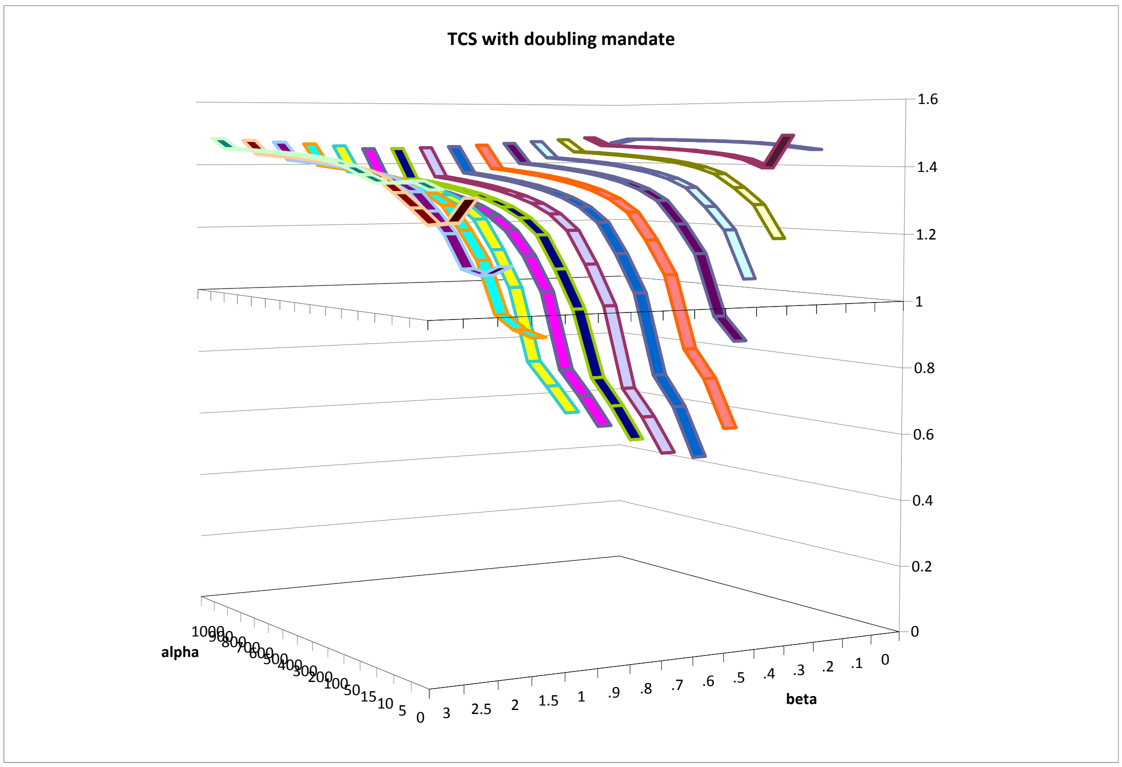


Figure 28: Total cost to society with a doubling mandate as a function of alpha and beta

In this case we find the costs under the mandate scenario. As with the no policy scenario, we find that the cost varies from a high approaching 1.5 (when beta > 3 and alpha approaches infinity) to a low approaching 0 as alpha and beta approach zero. The lower the fixed costs of

A2 and A3 and the lower the unknown coefficient alpha in the energy function, the lower the total cost to society.

Case 6: Tax scenario

In this case, as in Case 3, the regulatory authority places a tax on the carbon pollutant at its source wherever it is found. The price is internalized into the cost of the fuel without anyone having to calculate how much emissions are coming out of the fuel, because each producer of an emission is charged for it, and they will pass it on to their consumers.

Consumers' utility function is:

$U = U^* - C_t - P_t$

$U = U^* - C_f - C_{a1} - C_{a2} - C_{a3} - P_f - P_{a1} - P_{a2} - P_{a3}$

$$C_t + P_t = \frac{3\omega^2}{2} + \frac{2\alpha x^3}{3} + \beta y + \alpha y^3 + \beta z + \frac{\alpha z^3}{2}$$

Consumers seek to minimize this function, subject to the constraint:

$w+x+y+z = 1$

and a and β are positive constants

For this problem we use the lagrangian multiplier:

$$\Lambda = \frac{3\omega^2}{2} + \frac{2\alpha . x^3}{3} + \beta y + \alpha y^3 + \beta z + \frac{\alpha z^3}{2} - \lambda(w + x + y + z - 1)$$

To find the solution, we take derivatives and set them to zero

$$\frac{d\Lambda}{dw} = 0 = 3w - \lambda$$
$$\frac{d\Lambda}{dx} = 0 = 2\alpha x^2 - \lambda$$
$$\frac{d\Lambda}{dy} = 0 = \beta + 3\alpha y^2 - \lambda$$
$$\frac{d\Lambda}{dz} = 0 = \beta + \frac{3\alpha z^2}{2} - \lambda$$
$$\frac{d\Lambda}{d\lambda} = 0 = w + x + y + z - 1$$

We substitute the values of w, x, y and z into their respective cost functions to find the total cost:

$$C_f = \int \omega \cdot d\omega = \frac{\omega^2}{2} =$$

$$C_{a1} = \int \alpha x^2 \cdot dx = \frac{\alpha . x^3}{3} =$$

$$C_{a2} = \int \beta + \alpha y^2 \cdot dy = \beta y + \frac{\alpha . y^3}{3}$$

$$C_{a3} = \int \beta + \alpha z^2 \cdot dz = \beta z + \frac{\alpha . z^3}{3}$$

We substitute the values of w, x, y and z into their respective pollution functions to find the total pollution cost to society:

$$P_f = \int 2.\omega . d\omega = \omega^2 =$$

$$P_{a1} = \int \alpha . x^2 . dx = \frac{\alpha .. x^3}{3} =$$

$$P_{a2} = \int \beta + \alpha y^2 .dy = \beta y + \frac{\alpha y^3}{3} =$$

$$P_{a3} = \int \beta + \alpha z^2 .dz = \beta z + \frac{\alpha z^3}{3} =$$

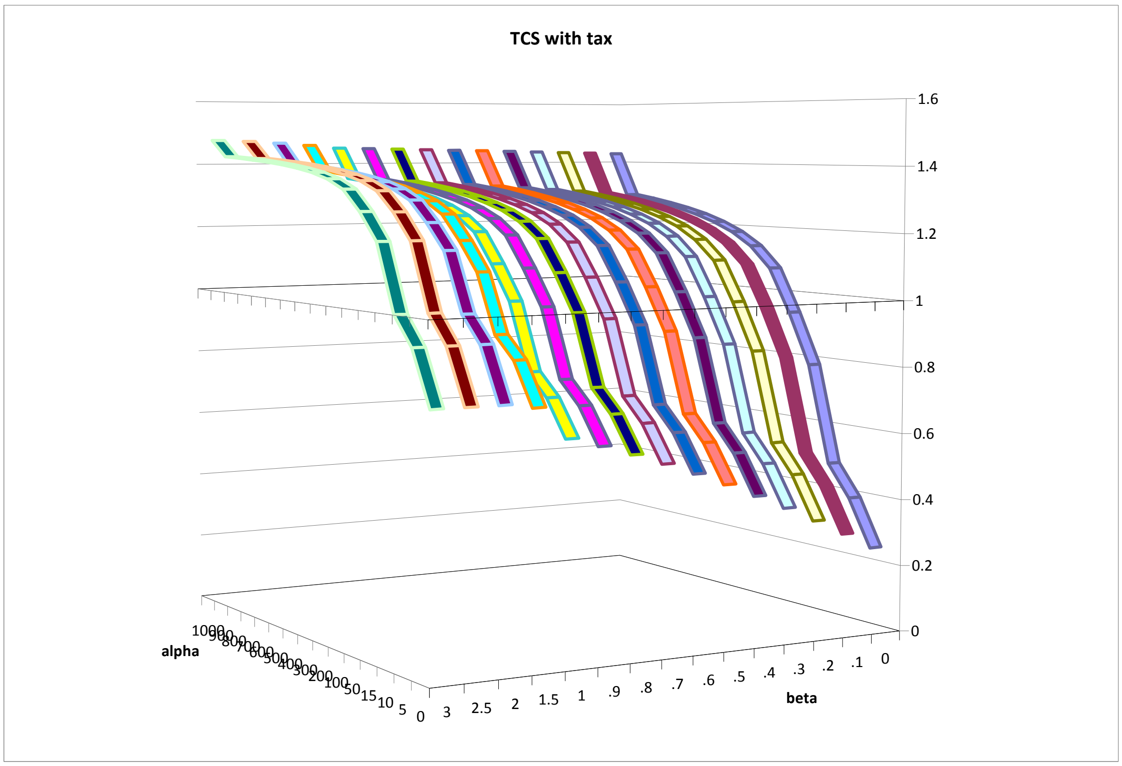


Figure 29: Total cost to society with a tax as a function of alpha and beta

As with the previous two cases, we also find that the cost varies from a high approaching 1.5 (when beta > 3 and alpha approaches infinity) to a low approaching 0 as alpha and beta approach zero. The lower the fixed costs of A2 and A3 and the lower the unknown coefficient alpha in the energy function, the lower the total cost to society.

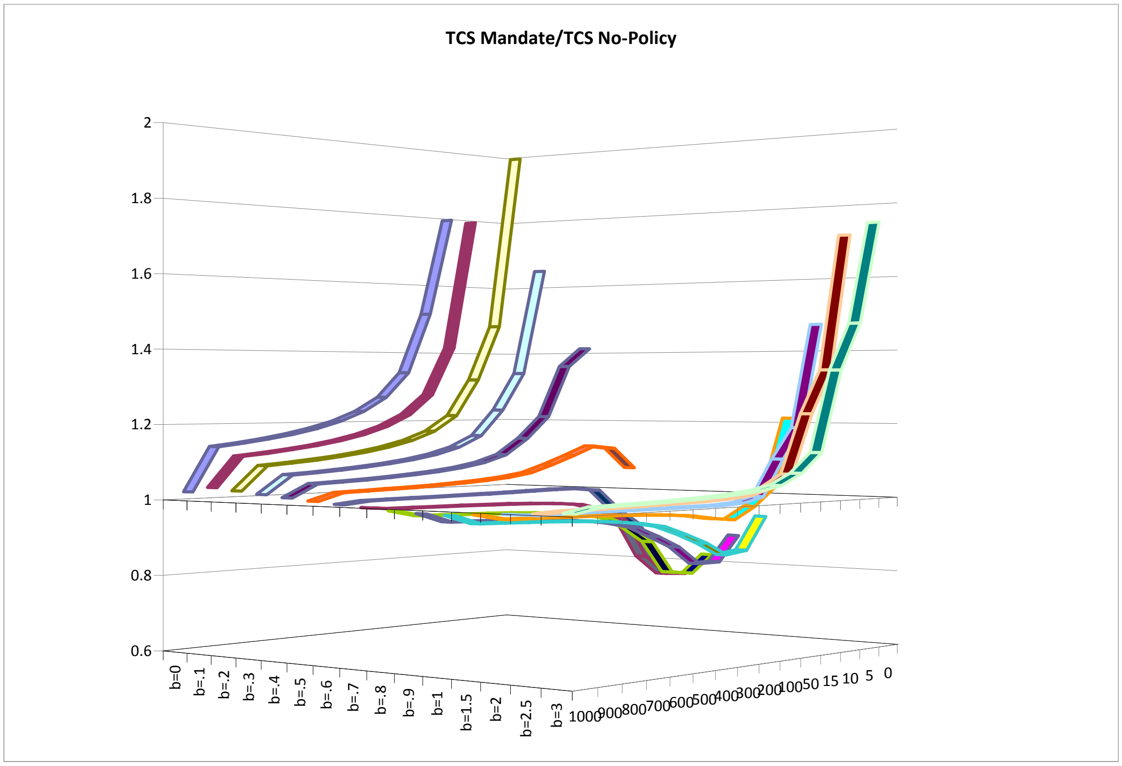
These results on their own are not very instructive. The result of the analysis will only become apparent when we compare the costs to each other. We now have the different cost profiles of the different policy options at various combinations of alpha and beta. The values of alpha and beta we have chosen are sufficient to illustrate the general relationship.

Comparing costs under different policy regimes

We now compare the costs of the different policy scenarios to each other.

1. Mandate vs No-Policy

We start by comparing the no-policy scenario to the mandate scenario, by finding the ratio of the costs under a no-policy scenario to the costs under a mandate scenario.



<u>*Figure 30: Ratio of total cost to society under a doubling mandate over total cost with no policy*</u>

When the ratio in this plot is equal to 1, that means that the doubling mandate's total costs to society are equal to those of the no policy option. When the value is above 1, they are higher; and they are lower for values less than one. Values under 1 indicate that the policy succeeds in lowering costs, while values over 1 indicate it failed.

We can see that for low values of alpha and beta the doubling mandate would result in an increase in costs. At medium values of beta (~0.5 to 1) and low values of alpha (~0-200) there is a reduction in total costs achieved by implementing a doubling mandate.

This plot shows that the values in this case can be greater than 1, equal to 1 or less than 1. This means that the doubling mandate could increase, decrease or keep the same the costs to society, depending on the values of alpha and beta. In other words, the mandate's impact on pollution and costs is unknown because the specific values of the cost functions are unknown.

If alpha and beta were known ex ante, then the actual costs to society could be estimated, and a mandate that decreases costs could be devised.

2. *Taxes vs No-Policy*

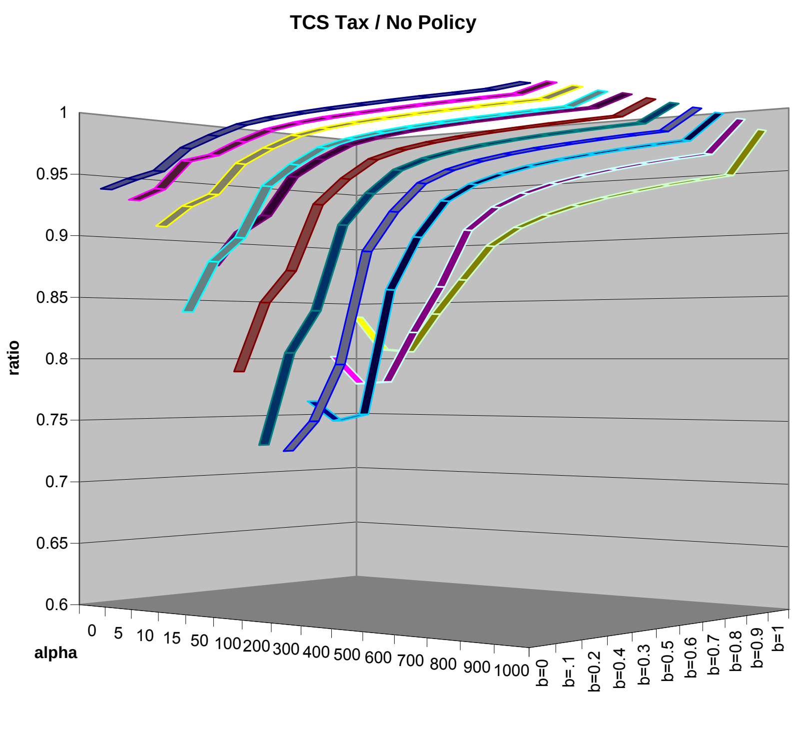


Figure 31: Ratio of total cost to society under a tax over total cost to society with no policy

When comparing the total costs to society under a tax system to a no-policy scenario, we find that the tax scenario always produces a cost lower than, or equal to, no policy. The ratio of costs is always less than or equal to one. The tax, we find, will always lead to a reduction in costs, or keep costs at their current level, but cannot increase costs.

3. *Tax vs Mandate*

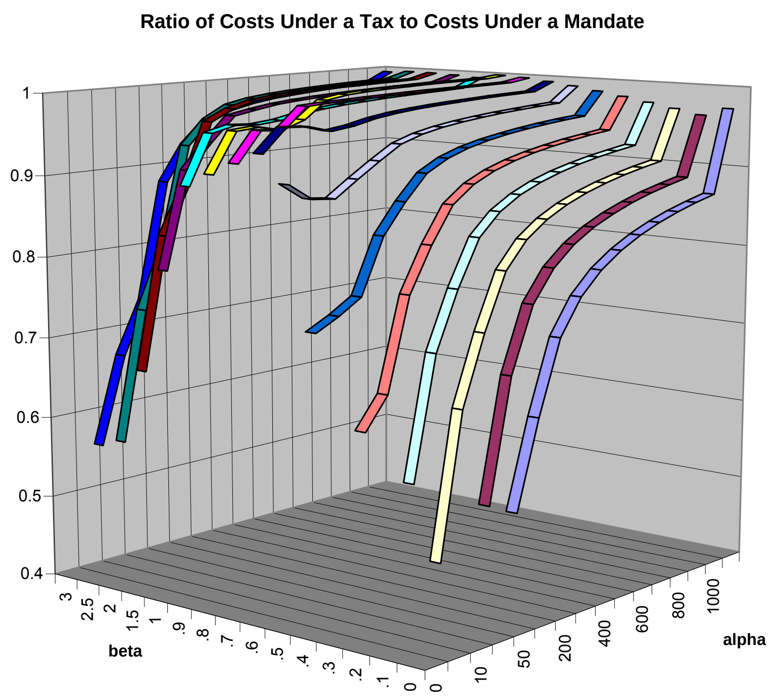


Figure 32: Ratio of total cost to society under a tax over total cost under a doubling mandate

We finally compare the costs under a tax regime to costs under a doubling mandate. We find that the ratio of tax to mandate costs is always less than, or equal to one. This means that a tax will always result in total costs that are less than those of a mandate, or at least, equal to them. The disparity between the two is largest for low values of alpha and beta, as well as low values of alpha and high values of beta.

From these three comparisons we can discern that the tax is either significantly better than a mandate, or, at best, equal to the mandate.

d. Technology Adoption Rates

This section draws on the discussion of technological innovation from chapter 5. There is uncertainty over which technological processes will be adopted. There are scientists and entrepreneurs attempting to discover new sources of energy and technologies all the time. When their ideas are profitable, they can be mass produced and adopted. When they are not, they are not. As a technology becomes economically profitable, it presents an opportunity for entrepreneurs to innovate it and improve it in order to market it and make a profit. In this case, we see the introduction of the new technologies as being conditioned on their profitability on the market. The higher the demand for the fuel under its current cost function, the more it is utilized and the more learning-by-doing takes place to improve this technology.

Since a technology introduced is likely to improve in performance over time, it is important that policies bring about the desirable and cleaner technologies rather than dirtier undesirable technologies.

Examining the outcomes of the mandate and tax scenario, we can see the different impacts that these policies have on the adoption of alternative energy technologies. For comparability, we assumed that both A2 and A3, the dirtier and cleaner energy alternatives, have the same fixed costs and the same cost functions. The only difference is that A2 produces more pollution for society than A1, whereas A3 produces less pollution than A1.

By examining the outcomes of the optimization of the consumer functions, we find that the doubling mandate will lead to the adoption of the two technologies at equal rates. For whatever value of alpha and beta, we will find that the percentages of A2 and A3 utilized are equal.

In the tax scenario, however, we find that there is a higher rate of adoption of the cleaner technology A3 and less adoption of the dirtier technology A2. Whatever the values of alpha and beta, we find that there is a constant ratio between the amount of A2 and A3 utilized.

Under a tax:

$$\frac{A2}{A3} = \frac{1}{\sqrt{2}} = 0.7071$$

Under a doubling mandate:

$A3 = A2$

In order to illustrate this relationship, we can look at the different rates of adoption of the A2 and A3 fuels under different values of alpha and beta, under the three different policy scenarios. The x-axis shows the values of alpha, while the y-axis shows the percentage of the fuel supply that each fuel makes up.

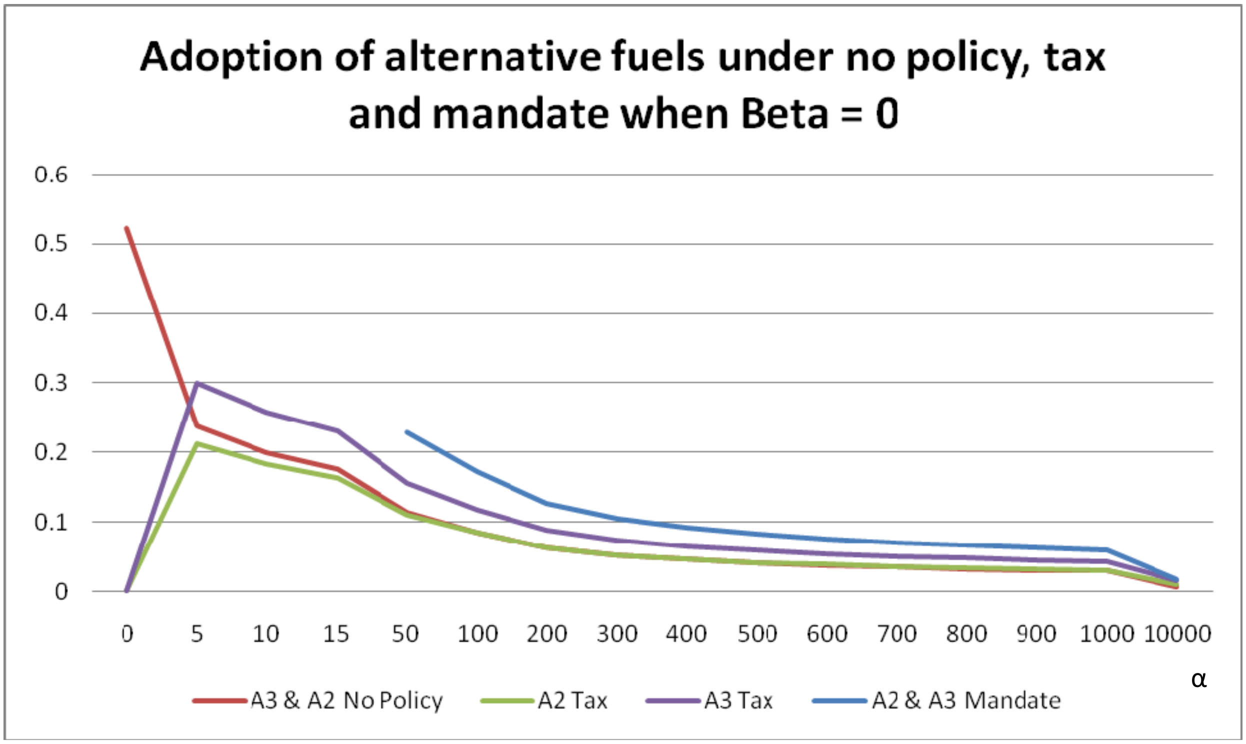
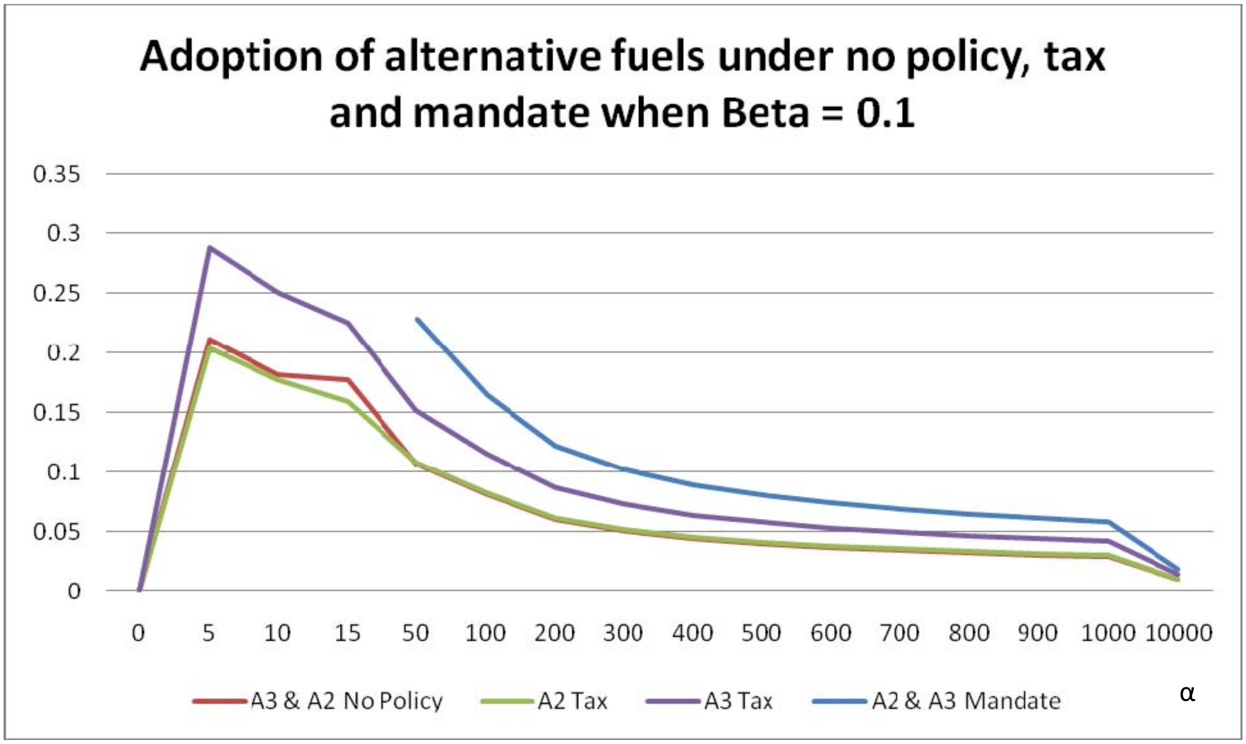


Figure 33: Adoption of alternative fuels under no policy, tax, and mandate, for beta = 0

The red line shows the values for the adoption of A2 and A3 under no policy. Since we assumed the two fuels have identical cost functions, they will be adopted at the same rate. Under a doubling mandate, they will also be adopted at the same rate (blue line) and there will be an increase in their adoption. Under a tax regime, however, we can see how A3 (purple) is adopted more than A2 (green). This result holds for all values of alpha.

This result is replicated when examining various other values of beta.



<u>*Figure 34: Adoption of alternative fuels under no policy, tax, and mandate, for beta = 0.1*</u>

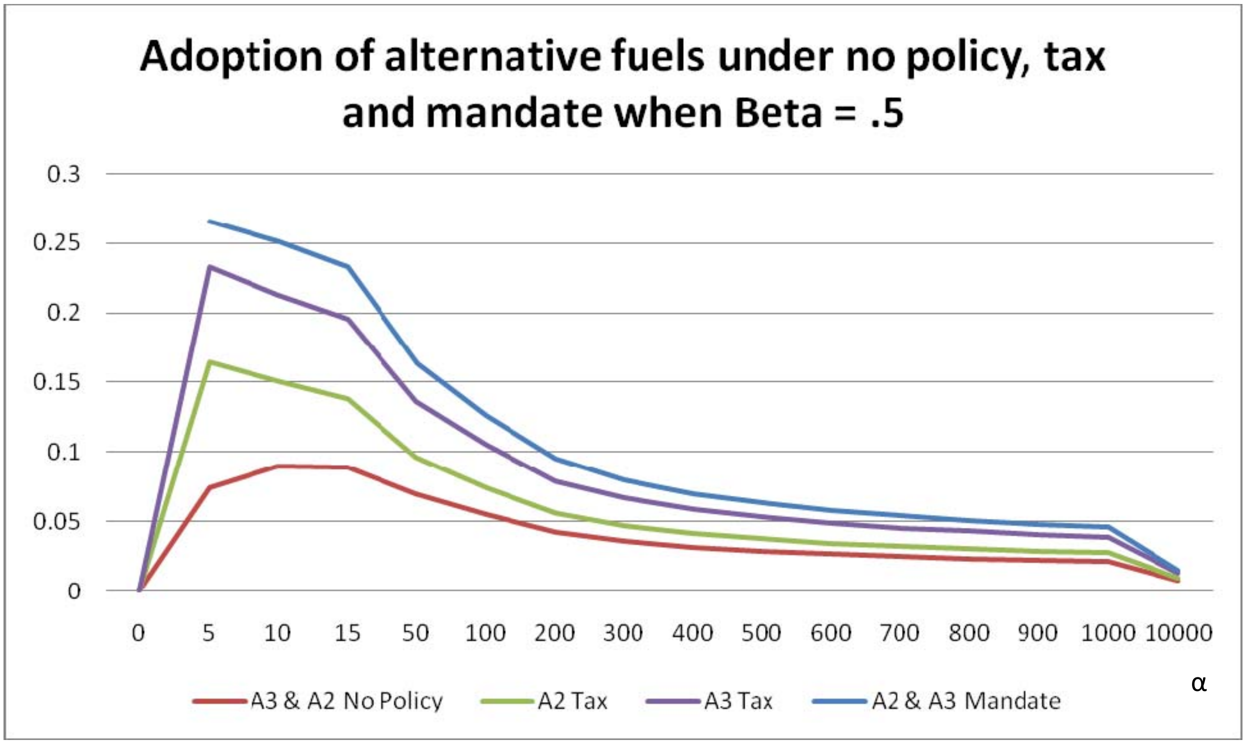


Figure 35: Adoption of alternative fuels under no policy, tax, and mandate, for beta = 0.5

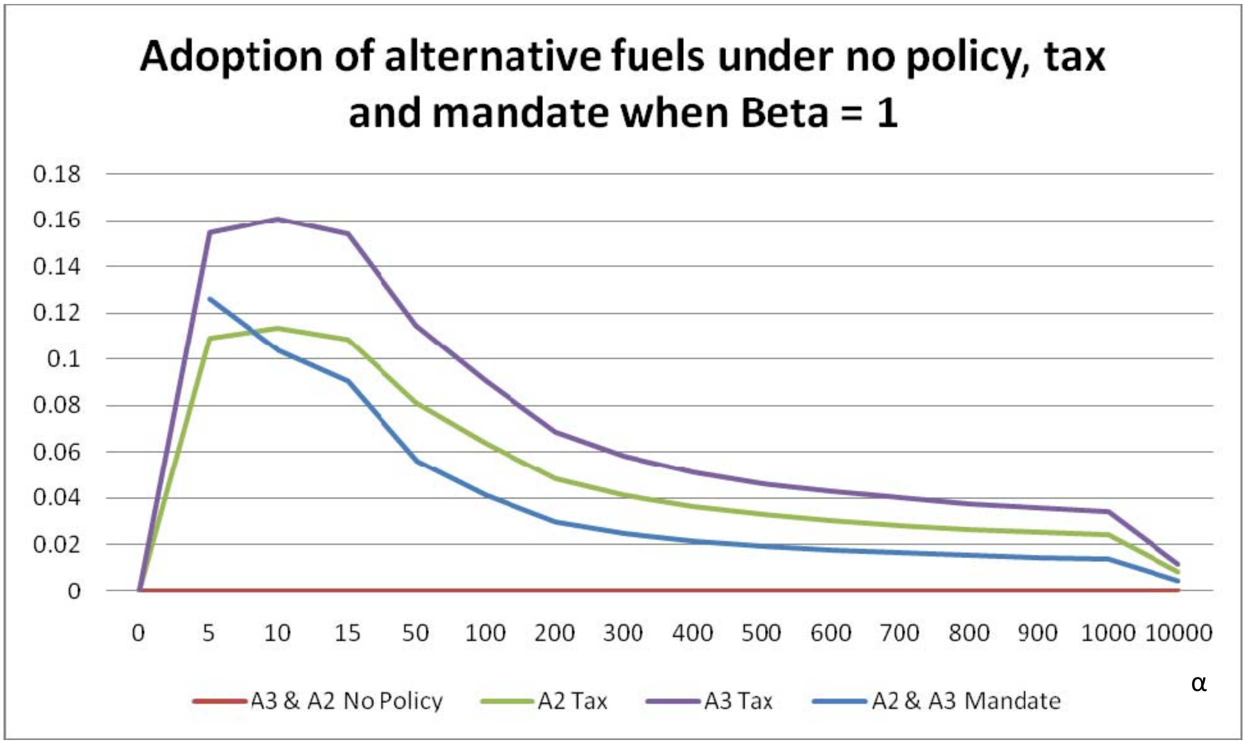


Figure 36: Adoption of alternative fuels under no policy, tax, and mandate, for beta = 1

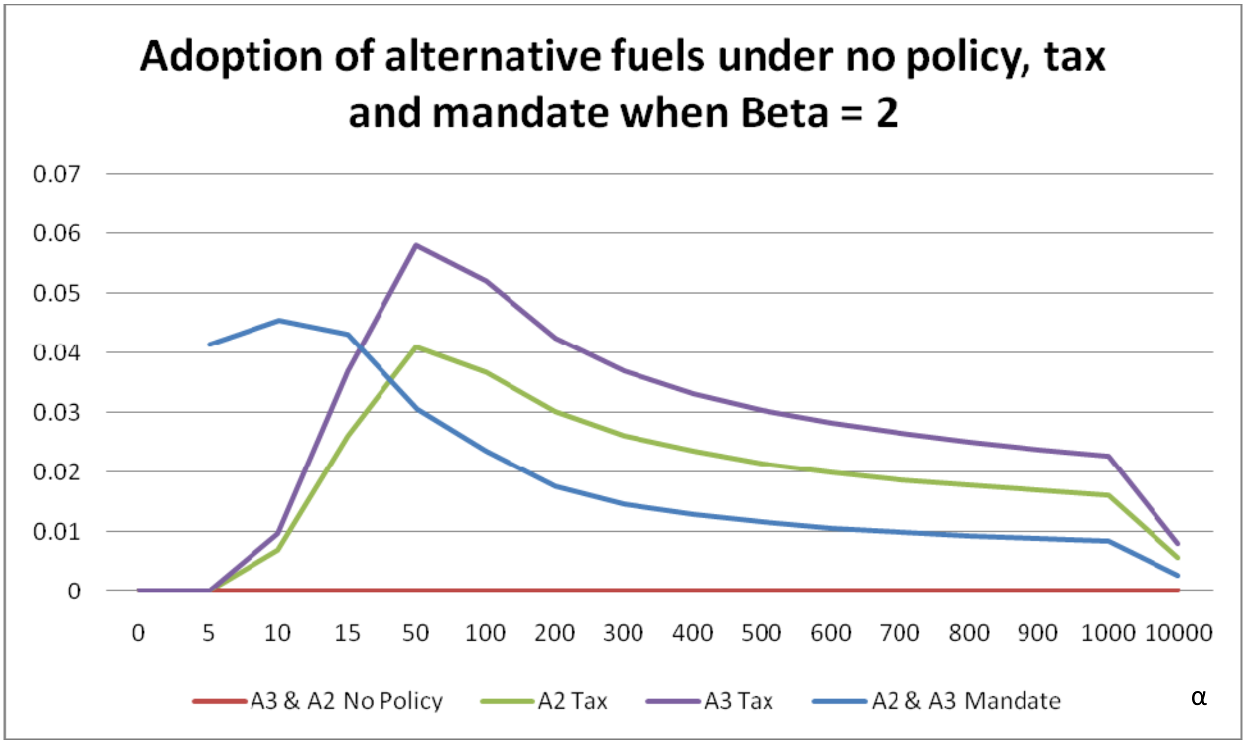
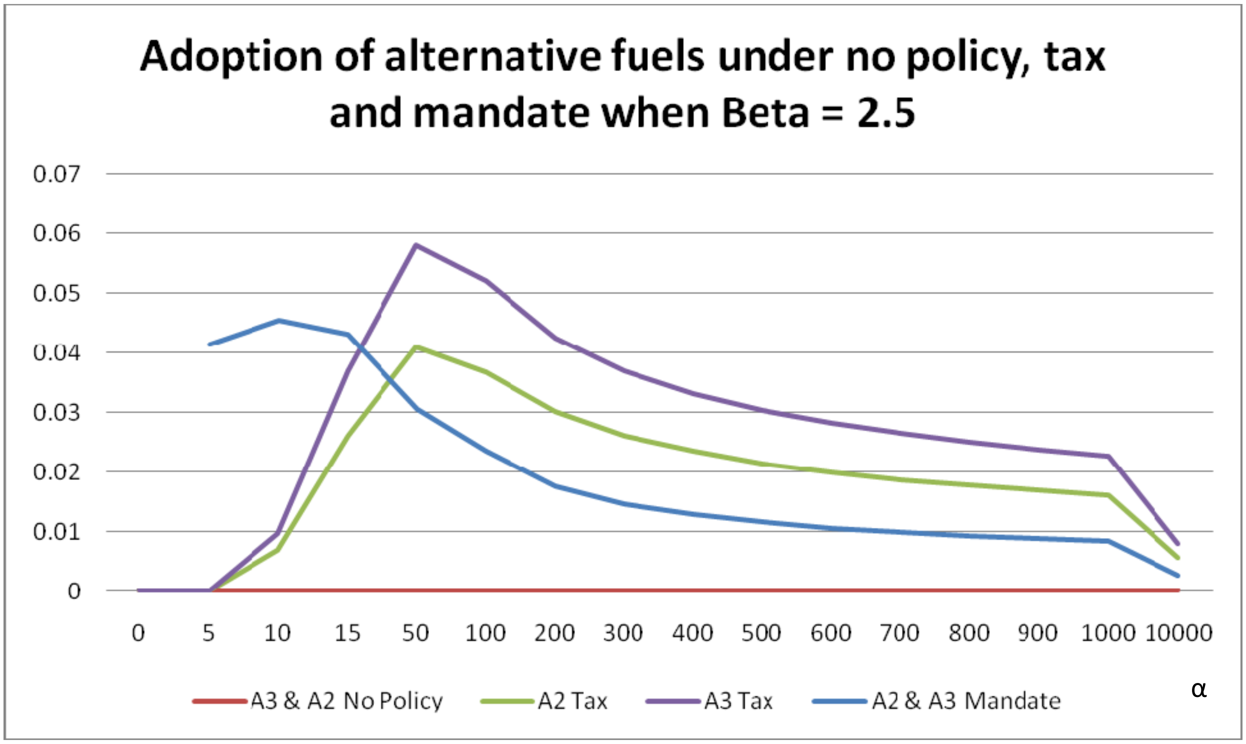


Figure 37: Adoption of alternative fuels under no policy, tax, and mandate, for beta = 2



<u>*Figure 38: Adoption of alternative fuels under no policy, tax, and mandate, for beta = 2.5*</u>

We can thus conclude that a tax is more preferable for the adoption of the cleaner technology than a mandate. When the tax internalizes the price of the pollutant into the complex market process that produces it, this pollutant becomes less profitable economically. Consumers' choices will naturally be skewed away from it, and away from all production processes that produce it. This, in effect, will favor the discovery of cleaner energy technologies over dirtier energy technologies. With a mandate on fuel use, on the other hand, any production process that produces this fuel will be incentivized and promoted. Thus, what can emerge are outcomes such as the Indonesian and Malaysian deforestation disasters which deforested large swathes of rainforests and peatlands in order to increase the quantity of biodiesel.

The best thing about the pollutant tax policy, then, is that it protects us from such a negative disaster. In light of the unknown likely costs of different technologies and production processes, a mandate for increased energy use might end up promoting the production of dirty energy sources from inefficient sources. But with a tax, only energy sources that are cleaner will be promoted, because the other technologies will be taxed unfavorably and disencouraged.

Further, with nascent technologies, a major issue is economies of scale. A new fuel technology will benefit from increased utilization as mass production stimulates more research and development and motivates more benefits from scale. Thus, the increased rate of adoption of the cleaner A3 in the tax scenario could be a spur for more gains in productivity, further improvements in efficiency and less pollution.

e. Conclusion:

Simple and plausible assumptions about the shape of the cost functions of different sources of energy were made and different policy scenarios' impact were analyzed based on the costs and pollution produced from them, in light of an ignorance of the actual cost functions. Based on the limitations of lifecycle analyses discussed in Chapters IV and V, no knowledge of the actual costs of different fuels was assumed, but their shapes were assumed in a realistic way—marginal cost increasing at a constant rate for fossil fuels, but strictly convex marginal costs for alternative fuels—an assumption that reflects the move from low-volumes sustainable biofuels to mass-produced biofuels replacing high-carbon-content forestland.

When analyzing only two energy sources it is found that the imposition of a tax on the pollutant leads to a reduction of costs and pollution, or to them remaining the same. A doubling mandate on the fuel, on the other hand, could lead to an increase or decrease in costs and pollution, or could keep them the same. Comparing a tax to a mandate shows that the tax always produces lower costs and pollution than a doubling mandate, or in exceptional cases, it could remain equal to it. This result is independent of the tax rate or the mandate rate assumed. Any tax rate will cause a reduction in emissions, while any mandate will carry the risk of increasing the emissions and costs.

When we introduce two new alternative energy sources (with fixed costs, one cleaner and one dirtier than the default alternative energy) we find that the results are largely unchanged: A tax will either reduce cost and pollution or at least keep them the same, while a mandate could increase or decrease cost and pollution. A tax is always a preferable strategy to a mandate, or at least equal to it.

Further, it is found that the tax scenario is more likely to lead to the adoption of the cleaner A3 technology, whereas the mandate regime is equally likely to lead to the adoption of the cleaner A3 and the dirtier A2 technologies.

Had the unknown values of alpha and beta been available, then it would have been possible for a social planner to optimize the costs and the pollution by dictating the amount of each fuel to be utilized. But since these values are unknown, any mandate on the levels of fuel utilization will be unlikely to optimize for cost and pollution. Depending on the magnitudes of these factors, the move towards increased alternative energy use could result in an increase or a decrease in emissions.

The tax system, on the other hand, relies on placing a price for carbon *at the source of its emission-*—regardless of where that happens along the production chain. For this to work, the tax needs to be global and comprehensive, as was discussed in Chapter VI. By placing this tax at the source, the price of all the inputs into the production of the fuels will internalize the carbon emissions involved in them. This sidesteps our ignorance of the actual cost functions. No one needs to know what the real pollution cost of the fuel is, since the cost will be internalized into the cost to the consumer who will make their cost minimizing choice and, as a result, minimize the emissions of carbon. Therefore, in light of the ignorance of the actual costs and emissions of different energy systems (ignorance of the values of beta and alpha) we find that imposing a tax is a strategy superior to imposing a fuel mandate.

This result is important in two important respects which are often ignored in the literature: First, it is an analysis of action based on the unknown, rather the known. Secondly, it is an analysis that is conservative in the sense of aiming to protect from negative consequences. The most significant fact of this analysis is not the quantities by which pollutant taxes or fuel mandates reduce emissions, for after all, these are a function of how the model was constructed; rather, it is the fact that one strategy (mandate) can involve significant downside risk, whereas the other (pollutant tax) does not.

The rationale for this result comes from an understanding of the way the price mechanism works. Demand curves slope downwards: an enforced increase in the price of carbon will lead to a reduction in the amount of carbon produced. The source of reduction cannot be known in advance. But as the price increases, the activities with the lowest marginal benefit from carbon will become unprofitable and will not be carried out. Substitute activities that produce less carbon emissions, were not profitable without a tax will become profitable. The tax mechanism on the pollutant works by side-stepping the knowledge problem in targeting the fuel. While we do not know the effect of the tax on particular technologies, we do know that the emissions will be reduced.

When targeting the fuel, on the other hand, the unknowability of the knock-on effects cuts the other way. Failing to predict the linkage between fuel utilization and pollutant emissions will mean that the pollutant-specific goals will be achieved while the goals related to the fuel might be improved or exacerbated.

f. Further considerations on Pollutant-based vs. Fuel-based policies

The magnitude of the tax, for the purposes of this model, is assumed to accurately reflect the social damage from pollution in the production of the fuels. What is needed for this is an estimate of the damage that carbon dioxide emissions cause and for the price to be placed on the carbon emissions. The results of this modeling exercise, however, are independent of this assumption. The key result from this analysis is that the carbon tax leads to a reduction in emissions, and this would be true whatever the magnitude of the tax. It is one added advantage of the carbon tax that its magnitude does not need to be assessed accurately for the result to go in the correct direction. The magnitude of the reduction of emissions from a tax will be uncertain because of the uncertainties of the production processes discussed in Chapter V, but the emissions will be reduced. This feature is another main advantage for taxes on pollutants: it allows for conservative piecemeal legislation that can start with low taxes and see what the impacts are, and can then increase them slowly until there is a sufficient reduction.

This feature becomes more important when one considers the dynamics of technological adoption. As small taxes are introduced on pollutants, this will, as the model above showed, incentivize the development of cleaner energy sources and technologies. Once tipping points of fixed costs are overcome, there can be large improvements in a technology based on learning-by-doing and economies of scale. The improvements can thus be larger and larger with time.

This furthers the asymmetry that makes pollutant-taxes preferable. Not only are they unlikely to lead to negative consequences, whereas fuel-based policies are, but pollutant-based policies are likely to stimulate advances in technology that can lead to unknown benefits for the future. This means that a very modest tax will be a good start for policies with increasing benefits as time goes on. Policy-makers can then assess the impacts of this small tax and see whether the reductions it has induced are sufficient or not; if they are, the tax is sufficient. If they didn't, the tax can be slowly and predictably increased.

Finally, it is imperative to note that this analysis cannot constitute an unequivocal endorsement of pollutant-based policies over fuel-based policies. There are still many other potential drawbacks to both policy tools that were not considered here. The role of policy-makers will be to assess which of these considerations are the most relevant.

As discussed in Chapter VI, these results are reliant on a couple of key assumptions about the implementation of the carbon tax: the tax is comprehensive to all sources of carbon dioxide and enforced globally. Without those two assumptions, a carbon tax would cause distortions to the patterns of production but might not cause a decrease in the amount of carbon emissions.

There is scope for further research on the feasibility of implementing such a tax scheme but targeting not just CO_2 emissions, but all types of Greenhouse gases and environmental damage.

This would likely make the measurement issues more complex, but would nonetheless make the impact on climate change more accurate. The ideal way to proceed with this would be by further developing the concept of Carbon Equivalence Factor discussed in Chapter V. With the calculation of emissions other than CO_2, their carbon equivalence factor can be used to assess their actual impact on the environment.

The implementation of a comprehensive and global carbon tax is a complex issue that is likely to face many technical, political and logistic hurdles. There would need to be methods for reliably estimating emissions from all their major sources. Fossil fuel emissions are arguably the easiest to estimate, but land use change from agriculture and deforestation will be harder, but might be tractable with advanced mapping techniques. What might prove most tricky; however, are agricultural emissions from small changes in the biomass content of lands.

The problems facing estimating these emissions, however, are of a different category than the problems of estimating these emissions for an LCA. The first problem is one that is physically tractable; the other is a complex mathematical problem reliant on estimates of emissions as they relate to a complex barely-understood production process.

The LCA needs to estimate the emissions that have been produced from a very complex production process which the modeler will have a lot of difficulty construing and measuring accurately. Measuring emissions from the sources avoids this, because there are no dynamic processes that need to be modeled and understood. It is a straight-forward measurement of a physical process as it happens, where it happens. How it is reflected onto the production processes of fuels is not relevant to the measurement, and all the complexity of the calculations of LCA's is avoided. The understanding of how some of the knowledge and uncertainty problems discussed in Chapter V reflect on the implementation and design of a carbon tax is an important question that can be an excellent avenue of further research.

A major hurdle facing the implementation of any policies to address climate change is the political economy problems of successfully passing these policies as legislation. In this regard, fuel-based approaches are more likely to succeed, since there are particular groups that would benefit from them and are likely to lobby for them. That is not the case for pollutant-based policies, which are likely to cause widespread gains to everyone in society. By offering concentrated and identifiable benefits to particular groups, fuel-based policies will always be more likely to pass.

Chapter VIII: Conclusion and Policy Implications

This dissertation has attempted a treatment of the problems of policy-making to combat climate change. The dissertation began by addressing the kind of policies that is the predominant form of legislation in the United States and Europe—policies that target the fuels and the technologies responsible for emissions. The rationale of these policies is that better environmental outcomes can be achieved by increasing or decreasing the consumption of particular fuels based on whether they produce, on net, an increase or decrease in the emissions of greenhouse gases.

An example of these policies can be found in any blending mandate on transportation fuels such as the minimum requirements of biofuels blending. The underlying assumption of these policies is that there is a clear and unambiguous relationship between these fuels and emissions. If it was known for sure that an increase in a particular fuel would necessary result in a decrease in emissions, then these policies would be failsafe.

The example of European blending mandates on biodiesel, however, provides reason to explore this rationale for policy-making more closely, and was in itself the motivating factor that inspired the writing of this dissertation. By increasing the percentage of biodiesel in the fuel supply of European cars, European policy-makers may have succeeded in achieving very small reductions in emissions from the tail-pipes of European cars. But the growth of the market for biodiesel motivated a massive increase in the burning down of forests and peatlands in South East Asia to produce biodiesel. In all likelihood, and according many reasonable estimates, the emissions produced by the land use change in South East Asia exceed by far any reductions in emissions from European tail-pipes.

What this example exposed is that the simple assumed relationships between specific fuels and emissions cannot be taken for granted, and that a full and accurate accounting of all knock-on effects is needed to establish the correct relationship between a fuel and greenhouse gas emissions. When such analyses are attempted, however, they leave much to be desired. The results of these lifecycle analyses are inconsistent and inconclusive. A careful analysis of this literature reveals that there are good reasons why these results are so inconsistent.

There is an enormous complexity to the production processes of the fuels which most studies come nowhere near addressing sufficiently. There is no adequate treatment of the fact that these production processes happen within the context of dynamic market processes that cannot be simplified away by sweeping assumptions about the effects on different products, substitutes and complements. The technological processes used are not adequately and accurately modeled and over-simplifying assumptions and erratic predictions are made about future prospects for improvements in these technologies. Further, these studies use aggregates-based analysis which neither gives the answers that are needed to correctly inform policy, nor does it succeed in studying the correct constituting relations between different factors.

Because of these reasons it is apparent that currently there are no reliable methods of estimating whether mandating an increase in any fuel will result in a decrease in greenhouse gas emissions. The array of unforeseen effects and unintended consequences from such actions can alter any model's results significantly. For the past twenty years, Lifecycle Analysis researchers have been attempting to refine their analyses to arrive at better, more consistent and more comprehensive results—to no avail. Based on Taleb's discussion of thinking about the unknown, this study proposes an alternative track to address these problems. Instead of trying to figure out which are the good fuels to mandate, policies should be directed at ensuring that no major negative consequences accrue. Instead of trying to think of what are the correct fuels—an increasingly frustrating and futile exercise—policy-makers should instead think of what are the policies that will produce the least undesirable consequences.

From this consideration, and after discussing the different tools of environmental policy and pollution mitigation, this study tries to compare two policy tools in terms of their impacts on greenhouse gas emissions and technological innovation. The first policy tool is policies directed at particular fuels or technologies, the second is the policies directed at the pollutants directly. The basic founding block of this comparison is the ignorance of the true cost functions of the two different fuels.

It is found that the imposition of a tax on the pollutant leads to a reduction of costs and pollution, or to them remaining the same. A doubling mandate on the fuel, on the other hand, could lead to an increase or decrease in costs and pollution, or could keep them the same. Comparing a tax to a mandate shows that the tax always produces lower costs and pollution than a doubling mandate, or in exceptional cases, it could remain equal to it. This result is independent of the tax rate or the mandate rate assumed. Any tax rate will cause a reduction in emissions regardless of the cost function, while any mandate will carry the risk of increasing the emissions and costs depending on the fuel cost function.

When we introduce two new alternative energy sources (with fixed costs, one cleaner and one dirtier than the default alternative energy) we find that the results are largely unchanged: A tax will either reduce cost and pollution or at least keep them the same, while a mandate could increase or decrease cost and pollution. A tax is always a preferable strategy to a mandate, or at least equal to it. Further, it is concluded that the tax scenario is more likely to lead to the adoption of the cleaner technology, whereas the mandate regime is equally likely to lead to the adoption of the cleaner and the dirtier technologies. These results are insensitive to the magnitudes of the tax or the mandate; the important point is that the tax leads us in the right direction, whereas the mandate can lead in the wrong direction—regardless of magnitudes.

a. Policy Implications:

1. In light of uncertainties about costs, policy-makers and researchers should think of how to act with a recognition of the limits of their knowledge rather than mistakenly assume knowledge that doesn't exist, as that could lead to disastrous unintended consequences
2. When there is uncertainty in the transmission mechanism from fuel to externality, the policy should not target the fuel, because this could make things worse. Whatever its limitations, a policy that targets the pollutant directly has the merit of protecting from a significant negative downside.
3. In order to reduce pollutants, it is preferable to target the undesired pollutants directly with a tax or quantity control (that is global and comprehensive) since this will either lead to a reduction of emissions or keep them the same—it cannot increase them.
4. A mandate on increased fuel use could lead to an increase in emissions as well as a decline in them because of uncertainty over the cost function.
5. A tax on pollutants is likely to incentivize more the adoption of cleaner technologies.

6. A mandate on fuel consumption will likely incentivize the adoption of cleaner and dirtier technologies equally.

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