LUND UNIVERSITY
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Master programme in Economic Growth, Innovation and Spatial Dynamics

The Replication of the Brazilian Ethanol Model in Developing Countries: A General Feasibility Assessment.

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Abstract: Brazil is the only country that has managed to successfully implement an economically viable large-scale biofuel program. In 2008, locally produced ethanol derived from sugarcane replaced more than half of the domestic gasoline market, without the aid of any government subsidies. Ethanol in Brazil represents an economically lucrative industry that also contributes to national energy and environmental security. This industry, however, is not a recent development. The Brazilian ethanol system has developed gradually over the past 35 years, and is the result of concerted efforts by the government and other relevant industries. The price of ethanol has declined markedly since the inception of the program due to constant technological innovations. In 2004, ethanol production costs had declined by more than 71 percent to a point where subsidy-free prices at the pump were competitive with gasoline for the first time. Recent research has demonstrated increased cost efficiencies in sugarcane production have been the main driver of ethanol's increased competitiveness, as it accounts for roughly 60 percent of final ethanol costs. Given (1.) the demonstrated benefits the system in Brazil, (2.) the reliance of this system on sugarcane and (3.) the cost efficiencies that have resulted from potentially transferable technology, this study aims to generally access the extent to which the Brazilian Ethanol Model can be replicated in other sugarcane-producing developing countries.

Key words: Brazil, ethanol, sugarcane, developing countries, technology transfer

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Final Evaluation and Grade

Author **Paper title** **(Supervisor code; Examiner code)**	Luke Leyow The Replication of the Brazilian Ethanol Model in Developing Countries: a general feasibility assessment. (LS; LOO)	**G R A D E**
Clarity: problem, aim and conclusion	Excellent introduction exhibiting a strong theoretical and factual understanding of the issue. Very good delineation of the study.	6/**6**
Theory and previous research	Concentrated and adequate theoretical approach. Innovative and up-dated. Lessons from previous studies are well used.	6/**6**
Analysis: data and methods	An uncomplicated but most relevant methodology is used. Constraints in data are presented. Use of simplifications is discussed in depth. Evaluation of the Brazilian model including critical factors in the development is very clarifying and good. The application test of the Brazilian model on other developing countries is informative and relevant. Good final discussion and conclusion.	6/**6**
Contribution to the field	The thesis' focus on general conditions required for wide-scale replication and not on single country contribution is adding new knowledge to the field.	6/**6**
Formal aspects: presentation, referencing, tables & graphs	Excellently structured. Illustrations and references very good. Hardly any flaws at all.	6/**6**
Final grade:	Adjustment considering thesis defense: 6.0 + 0.1 (6-4) = 6.2	**6.0** **A**

The Replication of the Brazilian Ethanol Model in Developing Countries: A General Feasibility Assessment.

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1 Introduction

In 2008 in Brazil locally produced bioethanol surpassed gasoline as the major transportation fuel source for light vehicles[1], and today constitutes 40 percent of domestic total transport fuels[2]. This bioethanol is derived from sugarcane which is one of the most efficient energy crops in commercial use today[3]. The ethanol industry in Brazil has been able to compete with gasoline successfully without government assistance since 2004 due to a sustained rise in oil prices and, more importantly, to significant gains in the efficiency of ethanol production[4].

This substitution towards bioethanol, a renewable energy source, has created several environmental, political and socioeconomic benefits to Brazil, as well as to the wider international community. These include the development of national agriculture and industry, increased employment, reduced national energy costs, indirect macroeconomic benefits, and increased international energy security. The program has not been without its disadvantages however. In its development there have been concerns raised about ethanol shortages and consequential price volatility, the labor conditions of cane workers, and the aggregate environmental effects of increased sugarcane production.

However, given the economic success of the Brazilian Ethanol Model in recent years, several academics and politicians[5] have made calls for its replication in other countries with a history of sugarcane production. Countries undertaking such a program have the significant advantage of being able to 'leapfrog.' That is, they could benefit from simply *adapting the technology and management systems* developed in Brazil, while *mitigating the negative environmental and economic, and social consequences* of the program. Through leapfrogging, countries stand to gain comparable benefits to those demonstrated in Brazil more cost-effectively and at faster rates.

1.1 Aim of the Study

Therefore, the main aim of this study is to investigate if the replication of the Brazilian Model is indeed feasible in other developing countries. In order to do this, firstly (1.) a detailed assessment of the performance of the Brazilian Model will be performed to establish if it is worth replicating. Secondly (2.), the Brazilian Model will be scrutinized to identify those factors that have been critical in its development, and that therefore would be critical in its replication. Finally (3.), the potential for the replication of the program will be analyzed in a number of small developing sugarcane-growing countries. These countries will be compared to establish the effect of Brazil's technology and management on its efficiency in *sugarcane production*, as this is the most critical cost factor in ethanol production[6]. Subsequently, a general feasibility analysis will be carried out for each country assuming cost reductions equivalent to the Brazilian case.

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[1] Versus heavy diesel powered vehicles. Agência Brasil (2008), Cornélio Noticias (2008)
[2] Or about 40 percent. Kojima and Johnson (2005) 1
[3] Goldemberg (2006) 3
[4] Goldemberg (2006) 4
[5] Kojima and Johnson (2005), Coelho (2006), IEA (2006), WWI (2006) 21-24, Boddiger (2007), Guardabassi (2007), Goldemberg (2007, 2009), Van Den Wall Bake (2009) 657, Foster (2010), Watson (2010), UNICA (2011)
[6] Estimated by the World Bank to account for 58 – 65 percent of the cost of ethanol production. Kojima and Johnson (2005) 3, Van Den Wall Bake (2009)

1.2 Outline of the Thesis

This study is divided into seven sections, each addressing a specific theme. Sections are indicated by number as well as by title in the top right corner of each page.

1. Introduction
2. Theoretical Foundations
3. Methodology
4. Performance of the Brazilian System
5. Critical Factors in the Performance of the Brazilian System
6. Applicability in Other Developing Countries
7. Discussion of Results and Conclusion

1.3 The Context of the Study

This study will focus specifically on the biofuel *ethanol*, its manufacture and use the *Brazilian* context, and the applicability of this system in *developing countries*. The justification for these three precise choices is explained in detail below. Please note that for the reader's convenience, some rudimentary facts about sugarcane and ethanol are expounded upon in section 9.1 of the appendix.

1.3.1 The Advantages of Sugarcane Ethanol

Currently the main biofuels[7] used in transport globally are bioethanol and biodiesel[8]. Ethanol can be used as an additive to gasoline, or in some cases as a complete substitute. Bioethanol accounts for more than 80 percent of the world liquid fuels market measured in energy content, while biodiesel accounts for the majority of the remainder. All biofuels taken together, however, account for 1ess than 1.8 percent of global transport demand[9].

Sugarcane is superior to other commercially used ethanol feedstocks for three reasons[10]. Firstly, (1.) sugarcane ethanol is currently the most cost-effective commercial biofuel[11]. The production cost of ethanol from sugarcane is 60 percent lower than that from corn and 75 percent lower than from sugarbeet. This is because tropical plants generally have higher energy ratios than those grown in temperate regions[12]. This is demonstrated in the case of sugarcane, which has the best energy balance[13] of all commercial ethanol feedstocks[14] (See Figure 1).

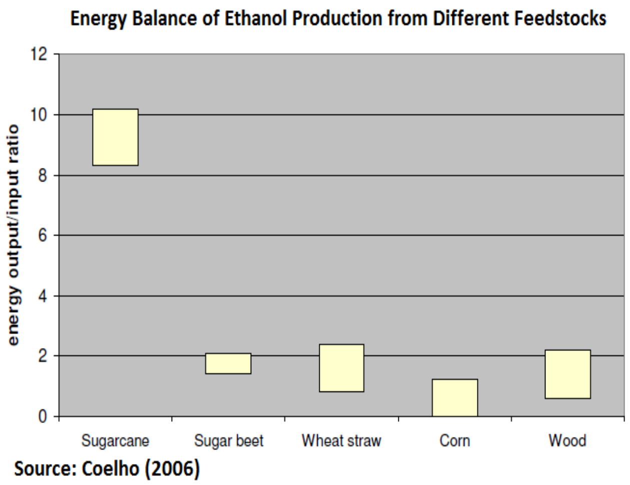

Figure 1.

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[7] Biofuels for the purpose of this study, refer to liquid or gaseous forms of energy derived from biological matter, as opposed to biomass, which is constituted by solid forms of energy.
[8] Followed by vegetable oil and biogas which are still mostly restricted to local and regional pilot cases are. Kojima and Johnson (2005) 1
[9] Bringezu (2009) 25-34
[10] Goldemberg (2009) 18
[11] Kojima and Johnson (2005) 2
[12] World Watch Institute (2006) 17-18

Secondly, (2.) the yield of ethanol produced per hectare of sugarcane is 6470 l/ha, which is considerably higher than that from corn, 4108 l/ha, or sugarbeet 5500 l/ha. This implies that sugarcane has a lower opportunity cost in food crops forgone in its production, which is one of the major arguments against the use of 1st generation biofuels[15].

Finally, (3.) on a life-cycle basis, sugarcane ethanol reduces green house emissions by 84 percent[16], compared to 30 percent from corn ethanol and 40 percent from sugarbeet[17]. This is significant because global warming mitigation policy has been one of the most important drivers of the development of biofuel technology.

1.3.2 Growing Energy Demand in the Developing World

This study is focused specifically on the development and utilization of bioenergy resources in developing countries. Arguably, for the past century it has been developed countries that have controlled the exploitation of major energy resources[18] and that have been the major consumers of these resources[19].

The most important of these resources has been oil, defined both in terms of the total volume of energy consumed and the highly inelastic nature of demand[20]. There are, however, significant complications that stem for using oil as a primary fuel source, firstly (1.)because of its high geographic concentration, which increases the risk of supply disruptions and thereby contributes to disruptive price instability. Secondly (2.), oil is a finite resource that in the eyes of many academics has already begun to show signs of peaking[21]. And finally (3.), the combustion of oil has several negative environmental side effects even when global warming is not considered[22].

The Brazilian Ethanol Model perhaps represents the beginning of a paradigm shift away from energy markets dominated by developed countries, where a clean and renewable energy resource can be more evenly distributed across world regions[23]. This would have significant implications on the political independence of developing countries, but also more importantly on their long-term *economic* development.

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[13] Much less energy needs to be put into the energy production process than is liberated by it.
[14] Goldemberg (2006) 3
[15] Those biofuesl that a derived from feedstocks that can be used as food,.
[16] The CO^2 from ethanol combustion is later sequestered in subsequent crops; however this figure takes into consideration the GHG emissions from non-renewable sources utilized in the production of ethanol.
[17] Goldemberg (2009) 18.
[18] Either through direct national ownership, for example in the case of oil and gas in the United States and Canada; exploitation through multinational energy corporations, for example the Royal Dutch Shell Group which operates in over 100 countries; or through international political agreements, such as between the United States and Saudi Arabia. Chomsky (2008, 1977), Smil (2004)
[19] IEA (2010)
[20] Due to a lack of economical substitutes. IEA (2010)
[21] Kerr (2011)
[22] Ramanathan (2009)
[23] Dauvergne and Neville (2009)

Since the 1970s energy consumption in developing countries has more than doubled[24] (See Figure 2) and it is estimated that by 2030 these countries will account for 60 percent of total energy demand (See Figure 3). Given oil's global importance and increasing scarcity, biofuels present significant economic opportunities to countries that can produce them efficiently. The Brazilian example is powerful because, firstly, it provides a new source of energy that will help to reduce national dependence on increasingly expensive imported oil, especially in rapidly growing developing countries. And, secondly, it also positions these countries to take advantage of potentially lucrative value-added export opportunities that have stated to emerge, such as the U.S., India, China, Sweden and the Netherlands.

Figure 2.

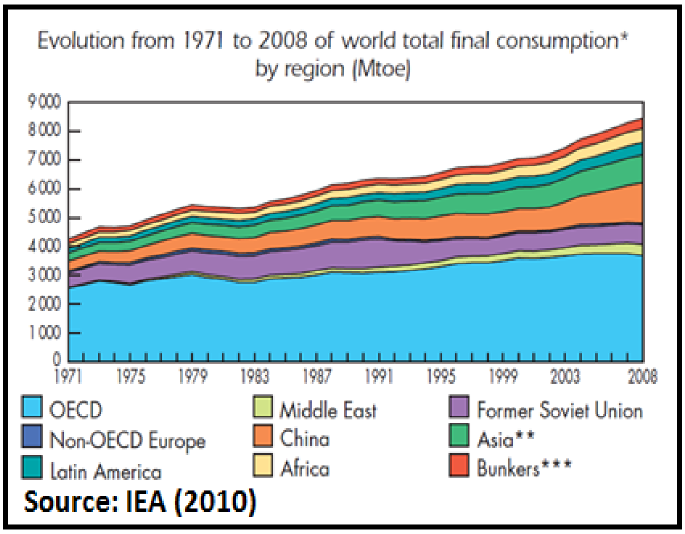
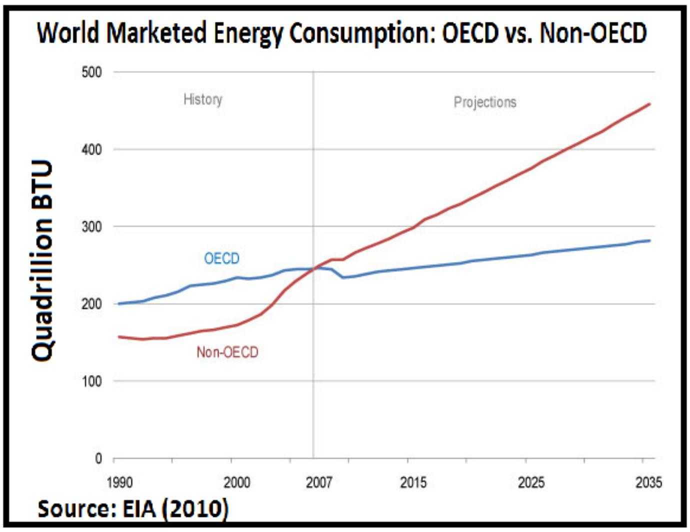


Figure 3.



1.3.3 Comparative Advantage of Developing Countries

The fact that sugarcane can only be effectively cultivated in warm climates has significant repercussions for the developing world. Land areas most suited to sugarcane cultivation area approximately located between 30 degrees north or south of the equator, where temperatures are higher (See Figure 4). These countries have a comparative advantage in the production of ethanol when compared to the rest of the world. Geography and the evolution of the sugarcane plant have in a way created for these warmer countries a natural monopoly, which Brazilian technology is now giving them a chance to exploit.

Further, most of the countries located in these regions of the world are considered to be developing nations, also known as non-OECD countries (See Figure 5). These countries represent those regions in the world where poverty and hunger are most intense (See Figure 6). An interesting opportunity, however, arises when the implications of these two facts are considered in tandem. Firstly, because most of these countries area still developing, large proportions of their economies are still dependent on agriculture. And secondly, as sadly contradictory as it may seem, most of the world's *undernourished* are rural *farmers*[25]. When these two situations are taken together, it becomes apparent that with Brazilian technology perhaps developing countries have an opportunity to increase global energy security while at the same time contributing to poverty reduction and hunger alleviation.

[24] IEA (2010)
[25] Alexandratos (1998)

Figure 4.

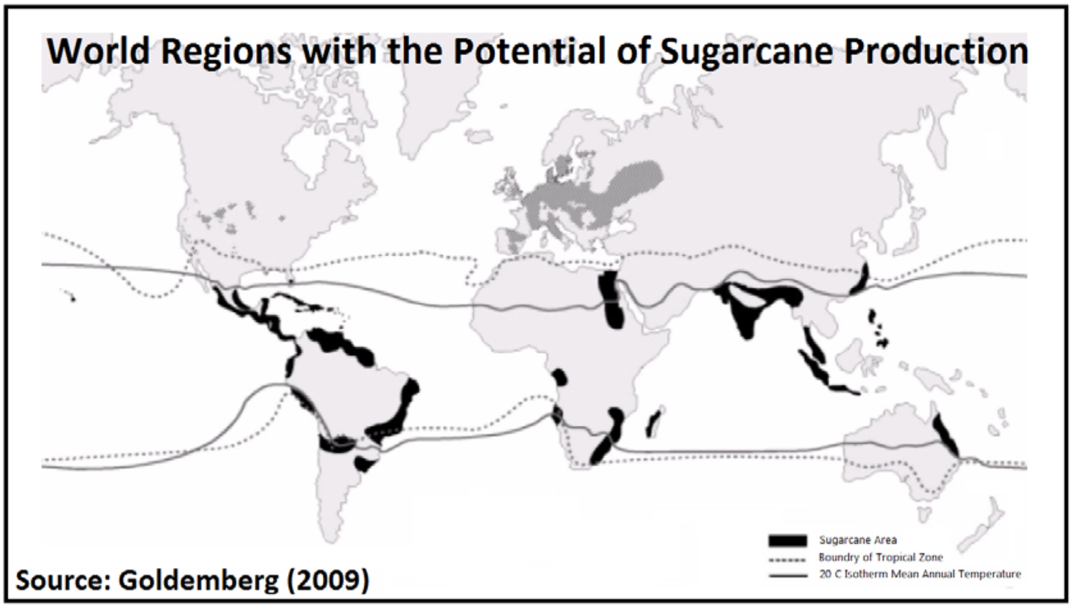


Figure 5.

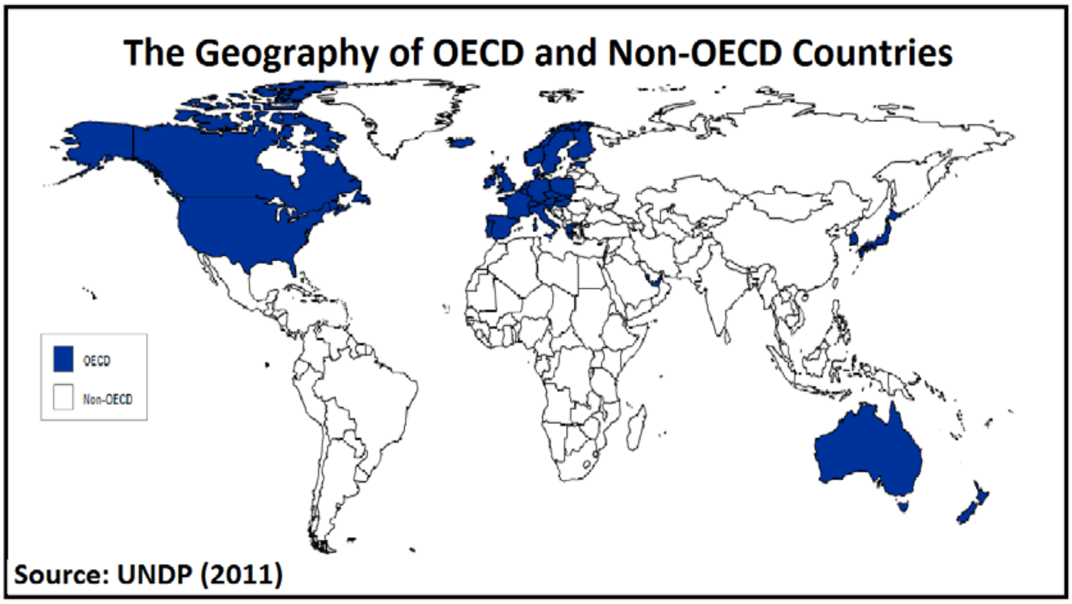
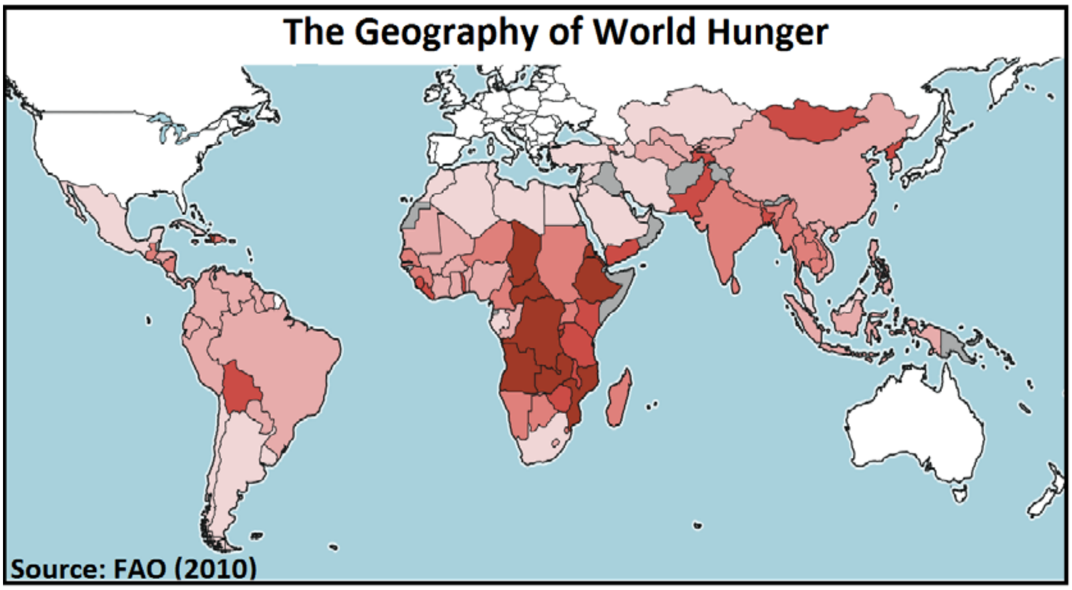


Figure 6.



One of the major debates surrounding biofuels currently is whether there is enough land to meet both growing energy and food demands. Two recent reviews[26] of a range of studies on this issue accessed he future potential of bioenergy, given increased food demand. Though the resulting range in estimates in theses reviews was large, virtually all studies found that there will be enough land available in the world to support both food and a substantial proportion of primary energy demand[27]. Interestingly, however, much of the land available for the expansion of both food agriculture and energy agriculture is located in the *developing world*. One recent study by Doornbosh and Steenblik[28] estimated the land required to meet the food and housing needs of the world population up to 2050. The study found that even with food and housing needs met, there would still be 430 million hectares of land still available for biofuel production. Almost all of this additional land, however, will be located in *Africa* and *Central and South America* (See Figure 7). Given the climate of these regions, these results have significant implications for the potential of sugarcane ethanol as a major fuel for the future. With rough calculations, it can be shown that using only 3.4 million hectares, Brazil is able to displace roughly 1 percent of global gasoline demand[29]. Given the availability of land predicted by the study and assuming that this land is suitable for sugarcane agriculture[30], even at *current* productivity and technological levels, it would be hypothetically possible to displace gasoline completely with ethanol[31].

Figure 7.

Available Land for Biofuels

Land (in Gha)	North America	South & Central America	Europe & Russia	Africa	Asia	Oceania	World
Total land surface	2.1	2.0	2.3	3.0	3.1	0.9	13.40
1. Apt for rain fed cultivation	0.4	0.9	0.5	0.9	0.5	0.1	3.30
2. Apt and under forest	0.1	0.3	0.1	0.1	0.0	0.0	0.80
3. Apt, already in use	0.2	0.1	0.2	0.2	0.6	0.1	1.50
4. Necessary for food, housing and infrastructure until 2030/50	0.0	0.1	0.0	0.1	0.1	0.0	0.30
5. Available (Gross) (5=1–2–3–4)	0.00	0.25	0.08	0.44	0.07	0.04	0.74
6 % for grassland	0%	0%	50%	60%	n/a	0%	
7 Additional land potentially available (7) = (5)x(1-% for grassland)	0.00	0.25	0.04	0.18	–0.07	0.04	0.44

Data Source: Doornbosch (2007)
Table Source: Goldemberg (2009)

[26]Rokityanskiy et al. (2006) and Dornburg et al. (2010)
[27] Murphy et al. (2011) 55
[28] Doornbosch et al. (2007), Goldemberg (2010) 22
[29] Presently ethanol replaces roughly 3% of global gasoline use. In 2008, Brazil produced 22.5 of a total 65.6 billion liters produced, based on figures in Goldemberg (2010). Thereby, Brazil currently accounts for roughly 35% of ethanol production or roughly 1% of global gasoline equivalent.
[30] Which if course all of it is not, but the assumption is use to make a point.
[31] The Brazilians used 3.4 million hectares to produce 1% of gasoline equivalent. Given the availability of 420 million hectares, ethanol production reach 420/3.4 = 123% of *current* gasoline demand, ceteris paribus.

Assuming therefore that biofuels will not displace food crops, then ethanol represents a potentially lucrative agricultural and industrial product for *poor rural communities*. This is because the cause of global hunger is not simply the unavailability of food or agricultural land to produce it. In recent decades food production in the world has increased relative to world population[32](evidence of this is given in the footnote); however insufficient national and household incomes have prevented the global poor from satisfying their basic nourishment needs[33]. According to the UN Food and Agriculture Organization (FAO)[34], "Poverty is a major cause of food insecurity, and sustainable progress in poverty eradication is critical to improve access to food." The growing of sugarcane and subsequent value-added production of ethanol, therefore can be used as an instrument to develop rural communities and alleviate hunger by reducing poverty. Additionally, another major factors affecting food scarcity is inefficient agricultural practices[35]. In this way the transfer of best practices from professionally managed sugarcane production may provide positive efficiency spillovers in the production of other food crops.

The demonstration that the production of bio-ethanol is feasible in a number of developing countries, therefore, would have dramatic consequences for their long-term economic viability, the development of their rural communities, and also for sustaining high standards of livings in the developed world that are based on imported energy.

1.4 Previous Research on Ethanol Potential in Developing Countries

In the dedicated research review sections of this study, Sections 4 and 5), the work of a number of authors and organizations on the Brazilian ethanol system will be compiled. Not least of these works will be those by Jose Goldenberg[36], a noted Brazilian academic physicist and former Secretary of State for Science and Technology in Brazil. Much of his work in this field has pointed to the positive overall results of the program. He has repeatedly argued for the *replication of the program* in countries with a history of sugarcane production; a sentiment that is echoed by several other politicians and academics[37]. This study is very much an extension of this proposition and is aimed at testing the extent to which it is valid.

An extensive literature search revealed a few articles aimed specifically at analyzing the feasibility of sugarcane-based ethanol programs in certain Latin-American, Asian and African countries: Cuba[38], Colombia[39], Mauritius[40], Mozambique[41], Nepal[42], Thailand[43] , Tanzania[44] ,

[32] According to data from FAO (2011). Between 2000 and 2009, total world population has increased from 6.11 to 6.83 billion, or by 11.6percent, while the total production of primary food crops has increased by 14.3 percent, from 8.9 to 10.2 billion tonnes.
[33] Escobar et al. (2009) 1284
[34] FAO (1996)
[35] Escobar et al. (2009) 1284
[36] Goldenberg (2004, 2006, 2007, 2008)
[37] See note 10 for full list of references.
[38] Alonso-Pippo et al. (2008)
[39] Quintero et al. (2008)
[40] Elahee, M. K. (2011)
[41] Schut et al. (2010)
[42] Silveira and Khatiwada (2010)
[43] Nguyen et al. (2007)
[44]Felix (2010)

Zimbabwe[45] and other southern African Countries[46]. These studies all point to the positive economic potential for sugarcane bioethanol in offsetting oil imports, given the constraint of oil exceeding a certain price per barrel. In a few cases the potential for production for export markets was evaluated, as well as the possibility of electricity cogeneration[47].

All of the studies reviewed made reference to specific aspects of the Brazilian ethanol system. However, with the exception of the Cuban study, none attempted to analyze the applicability of the majority of the system, i.e. from the growing of sugarcane, the production of ethanol, utilization of co-products, and use of flex-fuel cars that can run on either ethanol or gasoline. In this regard, the Cuban study stands out. It used the Brazilian experience as a benchmark to analyze the potential feasibility of the replication of the Brazilian ethanol model in Cuba. The studies about Nepal and Tanzania investigated the feasibility of adoption of very specific aspects of the Brazilian experience, for example the adoption of E20[48] gasoline standard, however just as the other studies, they failed to access the potential of adapting the system in its entirety.

Further, all of these studies are very specific in their geography, and aim at establishing the feasibility of ethanol production in only a *single* country, or within a very limited area. This is significantly different from identifying the *general conditions* required for the wide-scale replication of Brazilian system that will be analyzed by this study.

1.5 Contributions of This Study

This study furthers the current body of knowledge by investigating the *general* conditions necessary for the application of the Brazilian Ethanol system in other developing countries[49]. This will be accomplished by firstly identifying key factors that have led to the development of the Brazilian system, and secondly by showing that given the presence of these factors in other countries, the systems is replicable there. This study is novel in that rather than looking at the *specific* circumstances of individual countries to determine applicability of the Brazilian system, it focuses on evaluating the *general* factors necessary for the replication of the system, thereby establishing *external* rather than *internal validity*.

[45] Jingura and Matengaifa (2009)
[46] Johnson (2006)
[47] Cogeneration involves the burning sugarcane bagasse to produce heat, and in some cases electricity that can be used to power sugar mills, with excess being into commercial electricity grids.
[48] A 20 percent blend of ethanol with gasoline.
[49] Despite the extensive body of work that has been carried out on different aspects of the Brazilian Ethanol System, in his literature search the author was unable to find any academic articles that explored the general applicability of the Brazilian Ethanol Model.

1.6 Scope and Limitations

1.6.1 Ethanol from an Economic and Socioeconomic Perspective

Recently the issue of biofuels has become increasingly important and controversial on the world stage. Consequently, there is an already large and growing body of academic work addressing a myriad of environmental, economic, social and political issues related to biofuels. Not least of these are the competition between biofuels and food[50], the effect of indirect-land-use on green house gas emission[51], the distortionary effect of developed world policies on biofuel markets[52], and the potential of biofules for rural development[53].

Despite this range of issues, according to the World Bank[54], "The greatest barrier to the widespread development of the biofuel industry is *economics*." With this in mind, the following study will take a very narrow focus, and concentrate on: (1.) the aggregate *economic and socioeconomic* viability of the ethanol program in different countries, rather than focusing excessively on environmental or social concerns. And (2.) the *supply side aspects* of the market involving production cost and efficiencies, rather than external demand or the price of ethanol which are influenced by trade policies and the actions of large suppliers. Noticeably absent from this study will be a discussion about the environmental impacts of biofuels as well as the competition between biofuels and food. There is an exhaustive amount of literature already available on these topics, and to delve into them in this analysis would serve as a distraction from this study's main theme. This is of course not to say that these issues will be all together neglected. On the contrary, where relevant to the arguments laid out in this study, they will be duly noted and explained.

1.6.2 Ethanol in Small Developing Countries

In this study, a selection of four countries will be used to examine the potential for the general transferability of the Brazilian Ethanol system. These countries are *Belize, Jamaica, Fiji and Swaziland.* Additionally, a fifth country, Mauritius, will also be made reference to occasionally. The limited sample size used is due to restrictions on time and resources. However, countries in the sample have been selected so that all countries share the same basic similarities[55], but still have significant differences[56] relevant to this study. A detailed explanation as to why these countries in particular were selected is given in the methodology section.

The study will focus on smaller developing countries, as opposed to larger ones. This is because of the growing economic and technological abilities of larger countries may have already led to improvements in their sugar and ethanol production capabilities. This is the case in China, Colombia, India and Thailand, all of which have large land masses, are significant producers of sugarcane, and have recently implemented their own ethanol programs in

[50] Oxfam (2008)
[51] Liska (2009)
[52] Farinelli (2009)
[53] Escobar (2008)
[54] Kojima and Johnson (2005) 25
[55] They are all small island developing countries with a history of sugarcane production.
[56] The cost of sugar cane production in each of the countries is either defined as high-cost, medium-cost, or low cost.

various forms[57]. Additionally, the demonstration of feasibility in smaller countries with less potential for the attainment economies of scale, almost implicitly demonstrates feasibility in larger countries.

[57] Kojima and Johnson (2005)

2 Relevant Theories

The first important consideration in determining the applicability of the Brazilian model in other countries is the extent to which technology can be efficiently and effectively transferred. Therefore, a review of the theoretical factors that affect the rate of technological diffusion will be undertaken. The second important theoretical consideration is the level of technology should be transferred in order to maximize the potential benefits to the adopting country. In this regard, there is a recent theory that argues that technologies should be adapted in their *most advanced form*, rather than following all of the steps that have led to their development. This theory is known as 'technology leapfrogging.'

2.1 Technology Transfer

The concept of technology transfer is not a new one. Rather, society as we know it today has been shaped by the transfer of novel ideas developed in one geographical location, but later transferred and adopted in countless others. Prominent examples of such mass transfers that have shaped economic history are the industrial revolution, which started in Britain and then spread to the rest of Europe, and the post WWII economic expansion or the Golden Age of Capitalism, much of which was based on the adaption of American technology developed during the interwar period[58].

The first empirical investigation into factors affecting the diffusion of technology, coincidentally as it were, referred to agricultural issues similar to those addressed in this study. Performed in 1957 by Zvi Griliches[59], the study focused on the factors affecting the diffusion of hybrid corn seed in the United States. The conclusions of this study were that the rate of diffusion of this new seed technology was dependent on perceived profitability, which was in turn a function of the size of potential markets and the cost of adaptation of the product to local conditions. More importantly however, his study demonstrated that the phenomena involved in the diffusion of technology could be subjected to quantitative analysis.

From the time of this his initial investigation, a significant body of work on the economics of technology diffusion has emerged. These developments are aptly summarized by Bronwyn H. Hall in the Oxford hand Book of Innovation[60]. From this through review of theories related to the diffusion of innovation, some key insights about the nature of technology transfer and the main factors that influence it will he highlighted. Unless otherwise specifically stated, the subsequent discussion on technological diffusion is based on Hall's work.

2.1.1 The Nature of Technology Diffusion

There are certain stylized facts that typify the diffusion of new technologies that offer insights into how diffusion will progress under different circumstances. Firstly, the adoption of new technologies generally requires substantial initial investment cost that cannot be recovered, or 'sunk costs'. Because of these sunk costs, it is unusual for new technologies to be abandoned in favour of old technologies, and in some cases even for newer better technologies, as exemplified by technology lock-in and path dependence. Additionally, due to this high initial

[58]Rosenberg and Frischtak (1985), Findlay and O'Rourke (2009)
[59] Griliches (1957)
[60] Hall (2006)

investment cost, in situations where the benefits of technology are uncertain, there is more incentive to delay adoption.

Secondly, the adoption of new innovations will typically follow an S-shaped distribution where time is plotted against the number of adapters (See Figure 8). The inferences that can be made from this curve are that new technologies are adopted slowly at first, then accelerate quickly through potential adaptors, and then finally patter out based on market saturation or the introduction on new superior technology.

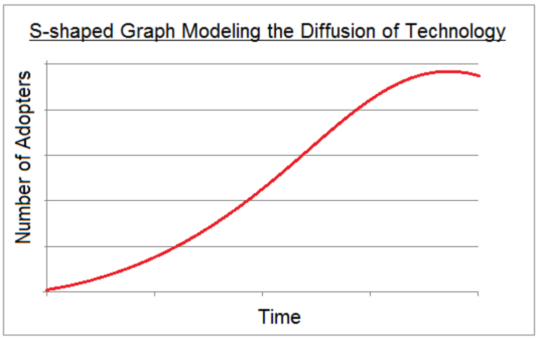


Figure 8.

Factors Affecting the Rate of Technology Diffusion

Over the past fifty years both the theoretical and empirical growth in innovation studies has led to the characterization of six factors that have a pronounced effect on the rate at which new technologies diffuse. These are subsequently addressed individually.

The Profitability or Benefit of the Technology

The amount of improvement that a new technology provides, whether this be in increased profitability or some other evaluation criteria, is considered the most important factor in the spread of technology. And this is, of course highly dependent on the extent to which technology alternatives exist and their relative availability.

Indeed, Rosenberg[61], one of the leading authors on technical change, notes that improvements in innovations after their first introduction is a major determinant in profitability and hence their diffusion. Therefore, an important consideration about the profitability of new innovations is that despite the ample availability of new general technology, versions of this technology that have been ideally adapted to maximize returns in specialized circumstances are scarce. This is due to the time required for the spread of awareness of the new knowledge and for subsequent technical understanding of the new technology to develop to a point where modification to local conditions can be engineered.

The Cost of Acquiring and Implementing New Technology

This factor on the surface may seem implicit, however it is important to consider the *total cost* of technology adaption, rather than simply the cost of physical machinery or methodological instructions. This is because technology seldom operates in a vacuum, and the actual implementation of technology often requires the training of personnel, further investments in complimentary technology, and in many cases dramatic changes to organizational structure[62]. By some estimates, the costs of adapting information technology systems can be up to ten times the cost of the hardware. These complementary requirements have the aggregate effect of slowing technology adaption, firstly because it increases the cost (and hence the risk of

[61] Rosenberg (1972) 10
[62] ibid. 21

investment due to higher possible losses), and because developing the requisite absorptive capacity, such as training and restructuring, takes time. In this regard, radical innovations will be more costly to implement, while innovations that are more incremental[63] in nature will be less expensive to adopt because they avoid the need for significant retraining or reorganization[64].

The Availability of Information and Uncertainty

Obviously, it is impossible to adopt technology which is unknown, and imprudent to adopt technology about which little is known. This is because, as mentioned before, the generally high initial investments and the incremental nature of returns involved in the adaption of new technology. Therefore, the asymmetry of information then retards the rate of technology transfer because it increases riskiness and therefore hinders financial investment. Long-term projections about the performance of technology are necessary to accesses the economic feasibility of adaption. However, large amounts of information are necessary to accurately formulate these projections.

In this respect physical geography as well as cultural distance, such as differences in language for example, play important roles in the distributions of information about new technologies. Indeed, research by Asheim[65] has shown that different forms information about new innovations, for example tacit versus codified knowledge, are more sensitive to geographical proximities. From this point of view, it is important for potential suppliers and consumers of new technologies to take steps necessary to overcome geographical constraints.

Network Effects

A very important consideration in the adaption of new technology is whether or not a market for services for this technology will emerge. Take for example the number of programs available to a MS Windows versus a Linux operating system. The emergence of services for a given technology is contingent on a large enough pool of users of this technology or the 'network' of users.

This is of course simple economics; as the number of users grows the fixed costs of service providers are spread over a larger number of transactions, thereby increasing their profitability and their business continuity. Conversely, the existence of these service firms creates avenues for further innovation and efficiency gains in the use of new technology. Therefore, with increasing size of network the costs of complimentary services will fall, while the variety of services available will increase. Network effects also make consumer learning and problem solving easier. As the network in a given geographic area grows it becomes easier for users to consult other user for advice or assistance.

Industry Environment and Market Structure

Interestingly, it has been demonstrated that market regulation can either retard adoption rates or accelerate them. In the former case, this can be due to a lack of government expertise

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[63] Building on old technology or congruent with it.
[64] Rosenberg (1972) 15
[65] Asheim (1999, 2005, 2008)

in the emerging technology, and the latter case is often related to the setting of specific technology standards.

Firm size and market share also affect the rates at which technology is adopted. History has shown that larger firms are usually, but not always, quicker to adopt new technologies. This could perhaps be due to larger capital buffers that allow for greater risk taking or their ability to employ more specialized staff. As we have seen before, the larger the market share of a given firm, the more it is possible to spread the cost of initial investments in technology over a wider customer base, thereby effectively reducing the financial risk of adoption.

Cultural and Social Conditions

Finally, varying attitudes and belief that are embedded in different cultures can also affect the spread of technology. One example of this is the extent to which the fermentation technology for alcohol may not have been diffused due to the prohibition of alcohol consumption by the religion of Islam.

2.2 Energy Technology Leapfrogging

From the above review, it becomes apparent that the rate of adoption of new technologies can be managed, given the manipulation of certain factors. However, recently an old debate has resurfaced as to whether technology transfer must necessarily follow a *linear* progression. That is, if all of the steps in the development of a given industry must be passed through in order to reach the cutting edge of technology. This argument can be traced back to the 1960s and the noted Economic Historian Alexander Gerschenkron[66]. He argued that given the coexistence of advanced and backward countries[67], the latter could adopt the advanced technology of the former, rather than following linear stages of development.

More recently, this concept has reemerged and become known as *technology leapfrogging*[68]. Essentially, this involves the adaption of newer more efficient technologies at the forefront of a given industry in place of the adaption of older less efficient technologies that fit an industry's historical development. In the case of *energy technology leapfrogging*, this concept involves the omission of inefficient and environmentally damaging technologies and instead utilizing newer cleaner and more efficient alternatives that have already been developed.

An example of this can be seen in the automobile industry in Less Developed Countries (LDCs). In these countries where the number of automobiles per capita is often low compared to developed countries, as incomes and consumer demands rise governing authorities are faced with two choices that have potentially radically different outcomes. The first and usual option involves following the trends set by the developed world by adopting the standard gasoline vehicles, along with the known negative externalities that go along with them, such as pollution and oil dependency. While the second and more unusual option involves facilitating the adoption of cleaner and more efficient technologies such as electric vehicles and omitting

[66] Gerschenkron (1962)
[67] A term used by Gerschenkron to denote what are today considered developing countries.
[68] Soete (1985)

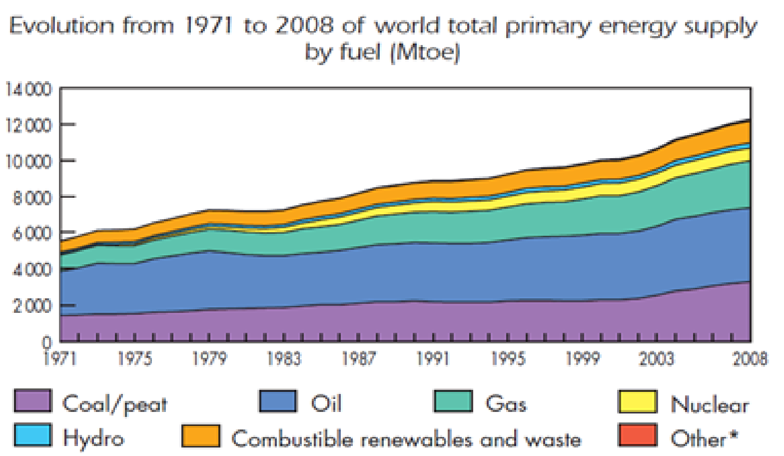
the intermediary technology all together. This is a situation that can arguably be seen unfolding with the rapid adoption of electric cars in China today[69].

2.2.1 The Relevance of Leapfrogging in Energy Technologies

One early proponents of energy technology leapfrogging is Jose Goldemberg[70], who argues that leapfrogging is not a luxury afforded to developing countries by virtue of their laggard technological position, but rather a necessity due to global resource constraints. The gravity of this claim becomes apparent when a few simple facts highlighted in his work are considered.

(1.) The vast majority of the world's population is located in developing countries. These countries constitute three-quarters of the global population, many of whom still live in absolute poverty or very close to it.
(2.) Many of these non-OECD countries, such as Indian and China, have very high growth rates. And as incomes rise, too will their citizens' aspirations of attaining living standards equivalent to the developed world's.
(3.) However, 70 percent of world commercial energy is consumed by the 25 percent of the global population that live in industrialized countries.
(4.) As of 2008, 76 percent of world primary energy supplies was still derived from non-renewable resources (See Figure 9). And oil which still accounts for one-third of global energy supplies is becoming an increasingly scarce resource[71].
(5.) Developing countries have generally been laggards in both technological development and adoption. Further, older manufacturing and consumer technologies typically diffuse to the developing world after newer technologies have begun to displace them in the developed world.

Figure 9.



Source: IEA (2010)

[69] Bradsher (2009)
[70] Goldemberg (1998)
[71] Kerr (2011)

When these facts are taken together, the environmental and political sustainability of our current energy paradigm becomes questionable. Thus, it becomes evident that if the developing world must find ways to adapt and adopt cleaner more efficient energy technologies at faster rates.

2.2.2 The Reality of Leapfrogging in Developing Countries

A recent review of energy leapfrogging literature and case studies was performed by Suater and Watson[72]. Their study demonstrates that both energy and environmental leapfrogging are possible, but that interestingly the factors that lead to the successful adaption of the new technology were different in each case studied. At the same time, there are also a number of examples from Africa[73], China[74] and developing countries as a whole[75] of a failure to leapfrog despite the presence of considerable potential. Both sets of studies, not surprisingly, point to the critical importance of the technology diffusion factors in determining the success of leapforgging. Throughout the literature reviewed, repeated emphasis was placed on the need for an appropriate level of absorptive capacity and government regulation.

[72] Sauter and Watson (2008)
[73] Murphy (2001)
[74] Gallagher (2006)
[75] Benthem (2010), Tukker (2005)

3 Methodology

The methodology for this study is separated into two distinct parts, as the subject matter of each section is most appropriately analyzed through different methods.

3.1 Methodology - Sections 4 and 5

The first major segment of this study involves a qualitative analysis and is dedicated to two themes. These are demonstrating the viability of the Brazilian system, with a focus on economic sustainability (Section 4), and identifying the major factors that have led to the development of the Brazilian situation (Section 5).

Data for this section comes mainly in the form of the most recent and relevant[76] academic sources. Care has been taken to include a large sample of authors, and also to include research in opposition to the socio-economic viability of the Brazilian Ethanol System, in order to provide balance to the study. In addition to this, sources published by Brazilian authorities have been given particular weighting due to their proximity to the topics under discussion, despite the skewed perspective that they may have. The situation is such that, they have an informal monopoly on many of the reporting aspects associated with sugarcane and ethanol production. Sources published by recognized international agencies such as the World Bank and the United Nations Food and Agriculture Organization have also been given particular weighting.

3.2 Methodology - Section 6

For this section of the thesis, quantitative methods will be used to evaluate the applicability of the Brazilian Model in other developing countries.

3.2.1 Concept

In order to simplify the analysis, the efficiency with which sugarcane can be produced has been used as the as the *sole criteria* for the evaluation of feasibility. This is however justified by the fact that feedstock costs account for up to 65 percent of the cost of ethanol production in Brazil[77]. Additionally, in accordance with assertions made by the World Bank[78], it is assumed that comparable levels of efficiencies can automatically be achieved in the industrial segment of production by simply transferring Brazilian plant and distillery models. This is because the technology is already developed and implemented in Brazil, with almost 100 percent of machinery used produced locally in Brazil[79]. Additionally, ethanol distilleries do not currently exist in any of the comparison countries in the study which eliminates any baseline for accurate comparison with the Brazilian Model. This is as there are a multitude of factors that contribute to industrial costs in Brazil, such as investment costs, taxes and administrative costs[80], which would be impossible to accurately predict.

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[76] Highly sighted in accordance with results from Google Scholar and the Social Sciences Citation Index, and of course, relevant to the topics at hand.
[77] Kojima and Johnson (2005), Van Den Wall Bake (2006, 2009)
[78] ibid. 4-5
[79] Macedo (2005), Kojima and Johnson (2005) 24
[80] Van Den Wall Bake (2006) 47

3.2.2 Data

The data is based on agricultural and labour statistics from the United Nations Food and Agricultural online database[81]. The major advantages of this data set are, firstly (1.) it has been compiled from a reputable and internationally recognized source, secondly (2.) it covers all the countries in the study[82], and finally (3.) it is wide enough to encompass a number of different parameters relevant to this study. The main parameters used in this study were: sugarcane yield per hectare, sugarcane area harvested, sugarcane production quantity, sugarcane producer price and the population of agricultural workers.

3.2.3 Characteristics and Limitations of the Data

Producer Prices

The producer price statistics are composed of annualized data for prices received by cane farmers collected at the initial point of sale (farm-gate prices). The prices have been adjusted for inflation at 1999-2001 International Dollar Prices. Prices expressed in USD were selected over local currency to facilitate comparison across countries. Data for this parameter was only available starting in 1991, but is not a limiting factor as it will only be used to establish the *current* potential of the application of the Brazilian system. Unfortunately, there was no data for this parameter available for Swaziland. However, because of the importance of this country as the only "low-cost producer" of sugarcane in the study, data was adopted from the neighboring country of Mozambique. This substitution is not egregious however, because the two countries are very similar in respect to climate, geography, human development and having economies with large agricultural bases.

Due to the unavailability of data on the costs that producers face, this price data will be used instead as a proxy for costs. This is based on the assumption of perfect competition where market price is equal to marginal costs. This kind of assumption is not uncommon, and has been utilized in previous studies on the feasibility of ethanol[83].

Agricultural Population

The agricultural population statistics were available for the majority of the period under investigation, starting from 1980. These statistics however, were unfortunately only available on an aggregate basis, and as such specific information on the population involved in sugarcane production *could not* be obtained. The aggregate data has nonetheless been used under the assumption that the *proportion* of sugarcane workers within the sample has remained more or less constant over the period of observation. Calculations involving this data have been presented in percentage form in order to highlight *changes* in productivity per worker over the period, rather than *actual* productivity per worker. This is so that the relative size of sugarcane production in relation to other segments of the economy is down played, and changes in the number of workers are emphasized. This is because using aggregate agricultural

[81] FAO (2011)
[82] With the exception of one instance where data for Swazi land was absent, however in this instance data for a neighboring country, Mozambique, with similar climatic, political and cost conditions was substituted.
[83] Goldemberg (2004) 302

population can be misleading in economies where sugarcane makes up only a small proportion of agricultural labour. For example, in the case of cane produced per worker (production quantity / agricultural population) would appear very small due the disproportionately large denominator representing total agricultural labour. This is the case however only in Brazil where the cane industry has historically occupied less than 10 percent of agricultural lands. While in other countries this percentage falls between 20 – 50 percent of agricultural lands[84]. Data for this parameter were available for the majority of the period, starting in 1980.

The author recognizes that the analysis involving the agricultural population statistics has several significant limitations. Nonetheless, it has been included in the study because the results, though not entirely accurate, still shed light on the role of technology and innovation in the development of all countries involved in the study.

3.3 Quantitative Methods

The development of productivity in the sugarcane industry in four comparison countries where sugarcane has been historically grown will be measured against developments in Brazil, using simple quantitative methods. This analysis will include the comparison of two measures of productivity, *yield of sugarcane per hectare* of land and *cane produced per worker* over the applicable times period. By examining the differentials in the relative productivity development between Brazil and the other developing countries where similar sugarcane/ethanol programs have not been pursued, the effects of productivity accruing to the Brazilian system will be highlighted.

3.4 The Sample Selection Process. Brazil, Belize, Fiji, Jamaica and Swaziland.

3.4.1 Brazil

The five countries involved in this study have been selected for specific reasons. Brazil has been chosen as it is the benchmark which the other countries will be compared to. The reason for this is that Brazil is world's leading producer of sugarcane, sugar and ethanol, both in terms of volume and efficiency. Much of the relative efficiency that Brazil is able to achieve in the production of ethanol is due to the high energy balances that result from using sugarcane as a feedstock. Therefore, the replication of the Brazilian system is assumed to only be plausible in countries with a *climate and agricultural conditions suitable for growing sugarcane.*

3.4.2 Criteria 1: A History of Sugarcane Production

There are a wide range of countries that could potentially match this description. This basically includes those countries 30 degrees north or south of the equator with access to adequate water and other climatic conditions. The suitability of land for sugarcane agriculture is a crucial factor for the replication of the Brazilian system. However, ideal conditions for the cultivation of cane are dependent on a large number of factors[85] which change depending on the variety of cane in question. Further, *reliable* information on the suitability of soil and climate conditions for sugarcane agriculture in various regions is not readily available, if it exists at all.

[84] Based on data from FAO (2011)
[85] Netafim (2011)

Therefore, in order to ensure that it was indeed possible to grow sugarcane on a commercial scale in these countries, the selection criterion was limited to those countries with a history[86] of *sugar production from sugarcane*.

3.4.3 Criteria 2: Small Size

Small developing countries have been chosen in this sample because it is these countries that will best highlight the potential of the adaption of the Brazilian Ethanol Model. This is because their limited agricultural lands and economic size present certain limiting factors that are of interest to the goals of this study.

Firstly (1.), it has been assumed that the small size of these economies has precluded large capital investments and R&D from government and other enterprises. This would not be the case in, for example, India[87] and China[88] which despite being classified as developing countries have research facilities and access to financial resources sufficient to independently develop their local industries. These small countries, therefore arguably represent more rudimentary forms sugarcane industry, and therefore will best highlight the full potential of the Brazilian model. Secondly (2.), it is assumed that the smaller size of these countries will prevent them from achieving dramatic economies of scale. The rational here is that if it can be demonstrated that the program can work in these countries despite their limitations to economies of scale, then it would certainly be applicable in larger countries that can benefit from increased production volumes. Additionally, (3.) it is assumed that smaller countries have a greater geographic homogeneity of factors of production, and (4.) that these factors of production are easier to quantify given the smaller scope of analysis.

The state of Sao Paulo in Brazil, where roughly 85 percent[89] of national ethanol is produced, has a land area of 248,000 km squared. However, production is highly centralized to the North East of the state, and some of the most productive districts such as Priacicaba and Ribeirao Preto are no larger than 1369 km squared. Therefore, for the purposes of this study, small countries were defined as those with a landmass less than half the size of Sao Paulo, roughly 125,000 km squared, with no restriction on the lower limit. This made the size range of countries considered for the study rather wide.

3.4.4 Criteria 3: Developing Countries

As elaborated on earlier, much of the land area where sugarcane currently grows and where sugarcane can potentially be grown is located in the developing regions of the world. Further, the Brazilian system has evolved in the developing world, and arguably in such a way that makes it more suited to developing world conditions, such as cheap and abundant labour. Also, given the potential for rural development, perhaps the most advantageous implementation of the Brazilian ethanol model would be in poor developing countries. Therefore, all countries that were defined as having "Very High Human Developed' by the United Nations Human Development Index were dropped from contention for this study. This

[86] Longer than 50 years.
[87] SBI (2011)
[88] Ching-long (1982)
[89] Kojima and Johnson (2005) 3

however only excluded two small countries with a history of sugarcane production, Barbados and Singapore (formerly part of British Malaya).

3.4.5 Criteria 4: High, Medium and Low-cost Producers of Sugarcane

From the list of small countries with a history of sugarcane production, countries were divided into three categories: high-cost, medium-cost and low-cost sugar producers. The reason for making this distinction is that the cost of sugar is the major determinant of the final cost of ethanol, and therefore one of the most significant factors in determining the viability of the ethanol system[90]. By including countries from each category, general inferences can perhaps be made about the relative importance of this factor in adoption of the Brazilian system.

The designation as low, medium and high-cost producers was taken from a recent World Bank report[91]. For the high-cost producer category, two countries Trinidad and Tobago and Jamaica met the above motioned criteria. However, Trinidad and Tobago was not selected due to fact that they are an oil producing country, and their access to cheap oil could potentially distort incentives for an ethanol program there. For medium-cost producers, Belize, Fiji and Mauritius all met the selection criteria. However Mauritius was not included in the main study because at the time of the study, they had already implemented an ethanol program of their own. There were two countries in the low-cost production category, Swaziland and Malawi, however Malawi was not included in the analysis because of its significantly larger landmass[92] when compared to other countries.

3.4.6 Variation within the Sample

The countries selected for this sample despite being chosen for their similarities, are also different in many respects. They are all developing countries and former sugar colonies. Further, all meet the criteria of being relatively small both in land mass and scale of cane production, certainly too small to affect the external market demand or international price of sugar or ethanol. The sample, however, represents four distinct geographic regions: Africa, the Caribbean, Central America and the Pacific. Half of the sample consists of island nations, while the other half consists of continental territories. Further, the four countries cover a range of development according to the UNDP Human Development Index[93] with Belize and Jamaica classified as having 'High Human Development', Fiji as 'Medium Human Development' and Swaziland as 'Low Human Development'. None of these variables are being directly investigated in this study; however, perhaps these varying conditions may help to explain certain results and allow for further generalization of the results obtained.

[90] Kajima and Johnson (2005), Van Den Wall Bake (2006, 2009)
[91] Mitchell (2005) 12
[92] 120, 00km squared compare to 18,274, 10,991 and 17,363km squared for Fiji, Jamaica and Swaziland respectively. While Belize is a more comparable 22,966km squared. EOE (2009)
[93] UNDP (2010)

3.4.7 Summary

In summary, all comparison countries in the study are small developing countries with a history of sugarcane production. Importantly, these countries range from high to low cost producers of sugar, a factor that is assumed to be critical in determining if the Brazilian system is generally applicable in sugarcane producing countries. Small countries have been used because of an assumed homogeneity of factors of production and because results are expected to be even more dramatic, due to a lack of previous technological development and the absence of economies of scale. Further, it is assumed that if applicability can be demonstrated in small countries, where economies of scale are absent and aggregate shared resources are smaller, then it will also be applicable in larger countries as well.

4 Evaluating the Brazilian Model

In this section, the economic and socioeconomic performance of the Brazilian Ethanol Model will be considered. This analysis will generally focus on those aspects of economic performance that are more or less quantitatively measurable.

4.1 The Opportunity Cost of Sugarcane Production

An important consideration in evaluating the economic performance of any industry is its opportunity cost. For this study, that is the profitability foregone by not employing the land, labour and capital used in the ethanol system in other productive capacities. Despite, the importance of this exercise in deriving an absolute measure of performance of the Brazilian system, such an undertaking would be both highly technical and highly speculative. And therefore any rigorous analysis is beyond the scope of this study.

Nonetheless, a simple analysis of data from the FAO[94] data suggests that the opportunity cost of producing sugarcane as opposed to other agricultural endeavors is not dramatic. This data is summarized in Figure 10, and demonstrates that sugarcane has the second highest gross production value[95] of any other crop, and is also the second most productive crop per hectare. However, production value is not necessarily a precise reflection of profitability. Still, the fact that sugarcane acreage has increased more than any other crop, would suggest that it is a comparatively profitable application of agricultural labour, land and capital.

Figure 10. The profitability of Sugarcane versus other major crops in Brazil (Ranked by Production Value)

	Gross Production Value of Agricultural Produce in Brazil (constant 1999-2001 million Brazilian Reals)			Area Harvested (Ha)			Prodcution Value of Crop/ Ha (constant 1999-2001 of Brazilian Reals)		
Agricultural Product	1975	2008	Percentage Change	1975	2008	Percentage Change	1975	2008	Percentage Change
Soybeans	2977	17831	499	5 824 490	21 246 300	265	511,1177	839,2520	64
Sugar cane	**1800**	**12691**	**605**	**1 969 230**	**8 140 090**	**313**	**914,0629**	**1559,0737**	**71**
Maize	2912	10509	261	10 854 700	14 444 600	33	268,2709	727,5383	171
Oranges	1369	4022	194	403 192	836 602	107	3395,4047	4807,5429	42
Rice, paddy	2147	3328	55	5 306 270	2 850 680	-46	404,6157	1167,4408	189
Coffee, green	1463	3218	120	2 216 920	2 222 220	0	659,9246	1448,1014	119
Beans, dry	1766	2678	52	4 145 920	3 781 910	-9	425,9609	708,1078	66
Seed cotton	1052	2399	128	3 876 390	1 063 820	-73	271,3865	2255,0807	731
Indi. Cattle Meat	5140	21646	321						
Cattle meat	5156	21573	318						

Data Source: FAO (2011)

4.2 Economic Performance of the Program

The performance of the Brazilian Ethanol Model can first and foremost be evaluated in real economic terms. Because of the multifaceted nature of the program, it has lead to the development of business, the stimulation of research into new technology, the creation of new home-grown equipment manufacturing industry, and significant foreign exchange savings by reducing imports of foreign oil.

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[94] FAO (2011)
[95] Units produced times farm gate prices.

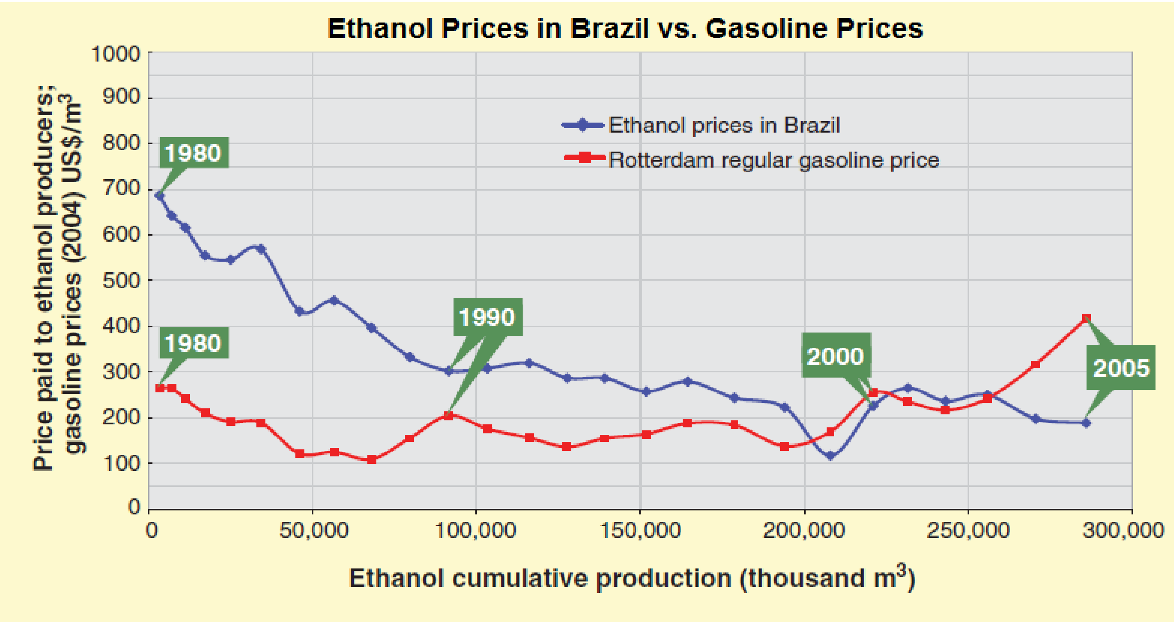
One striking example of the economic returns to the ethanol program is that an estimated USD 60.7 billion[96] in savings was generated through the substitution of ethanol for gasoline between the program's start in 1975 to 2004. When interest rates are considered, this figure becomes even more dramatic and stands at a significant USD 121.3 billion. When this is compared with the estimated USD 5 billion[97] invested in the program by the Brazilian government between 1975 and 1989[98], the economic returns to the program seem evident.

Despite this dramatic example, there are other ways in which the ethanol system affects the economic performance of the country.

4.3 Reduced Fuel Costs: Macroeconomic and Consumer Benefits

In Brazil in 2004, the price of ethanol at the pumps dropped bellowed the price of gasoline for the first time since the government subsidies were withdrawn in 1999[99]. In instances like this, when the sales price of ethanol is below that of gasoline, the difference in cost represents a cost savings to consumers. In 2005, for example, in the Sao Paulo region of Brazil average consumer price for hydrated ethanol was USD 23.9/GJ, or roughly 20 percent less than the price of gasoline at the time which was USD 30.4/G J100. This price differential was also throughout Brazil, as Figure 11 illustrates. This example however is not an isolated incident.

Figure 11.



Ethanol learning curve in volume, comparing the price paid to ethanol producers in Brazil with the price of gasoline in the international market of Rotterdam.

Source: Goldemberg (2007)

[96] At December 2004 exchange rates. Macedo (2007) 36

[97] Using 2001 as the base year. Goldemberg (2006) 3

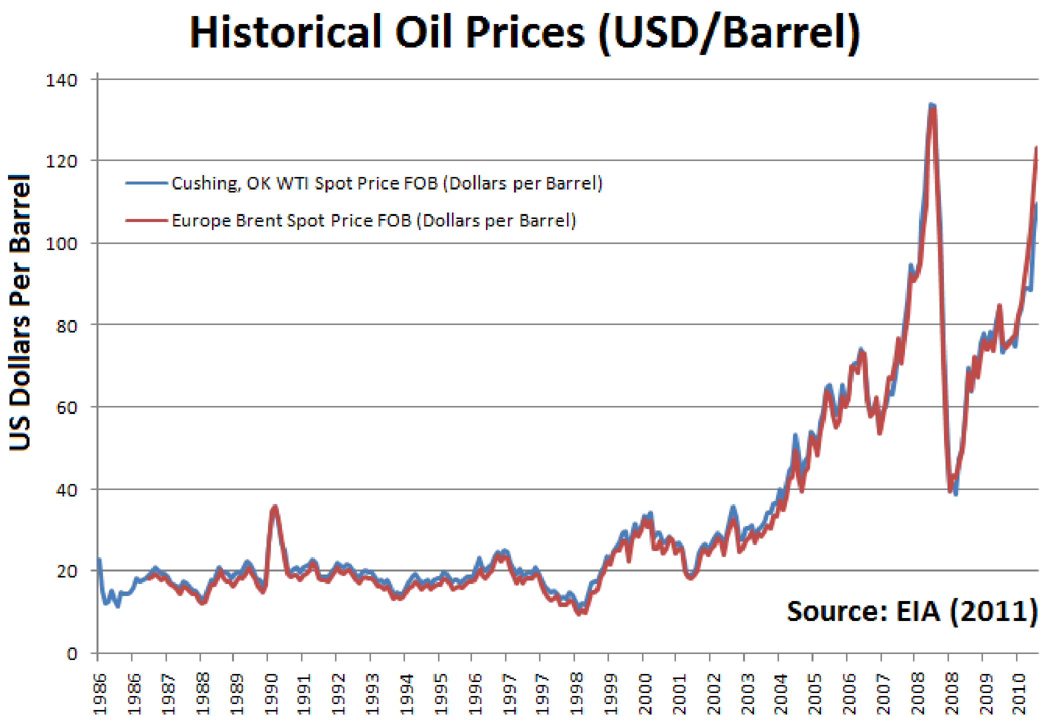
[98] This period covers the first phase of the PROALCOOL program when much of the governmental investments into the program were made. Subsequent to this, during the 1985 – 1995 period the program was devastated by low oil prices and much of the government support for the program dried up. During this period, much of the research and development funds to the program were cut and the government set price of ethanol to producers was set below production costs. Goldemberg (2004), Van Den Wall Bake (2006) 21

[99] Kojima and Johnson (2005) 92, Goldemberg (2006) 4

[100] Van Den Wall Bake (2009) 645

It is estimated that Brazilian ethanol is competitive with oil prices over USD 30 per barrel [101]and crude oil prices have not been below this level since 2004, as illustrated in Figure 12. In fact, since that time, the lowest oil prices have been is USD 39 barrel, with an average price of roughly USD 70 and a high of over USD 130 per barrel. Brazilian consumers benefit directly from the ethanol program, because due to these reduced fuel costs at the pumps. Since 2005, the differential in prices has directly saved Brazilian consumers BR 20 billion, or roughly USD 12.3 billion[102].

Figure 12.



This benefit of this price differential is not constrained only to the transportation sector, but rather has wider spillover effects on the economy at large. It is a well documented that increases in the price of oil has a marked inflationary effect on the wider economy[103], because of the importance of transport to industry and the relative inelasticity of oil demand. Indeed the Brazilian government subsidized ethanol prices in the 1980s to levels below that of gasoline in an attempt to curb the high inflation of the time[104]. Today as well, the with Brazil's relatively high growth rates, on average above 4 percent for the past six years[105], rising inflation is an issue of concern for the government[106]. In this instance, with ethanol prices undercutting that of gasoline since 2003, the production of ethanol continues to contribute to curbing inflation in Brazil. Unfortunately however, as the international market for ethanol

[101] Walter (2008)
[102] Jank (2011)
[103] Hamilton (2005) 10
[104] Goldemberg (2004)
[105] World Bank (2011)
[106] Bloomberg (2010)

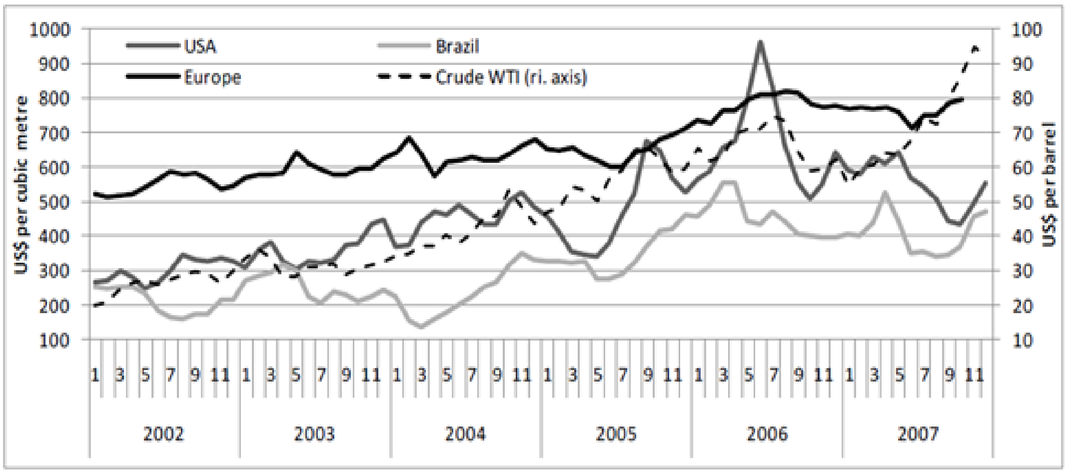
develops and it price becomes more closely tied with that of oil prices, this advantage will gradually dissipate[107].

4.4 Export Markets

Aside from reducing domestic fuel costs, growing international demand for clean alternatives to gasoline has created a lucrative export market for Brazilian ethanol. As of 2006 roughly 20 percent of ethanol produced in Brazil was destined for export markets[108]. The external demand for ethanol stems from the fact that many countries have made environmental commitments to reduce CO^2 emissions, of which gasoline constitutes a significant percentage[109]. The use of ethanol is important in meeting these commitments because when mixed with gasoline it reduces aggregate carbon emissions[110] and also enhances octane of gasoline, eliminating the need for highly polluting lead-based octane enhancers [111].

Brazil has a considerable competitive advantage in the production of ethanol. This is demonstrated in the fact that Brazil is able to produce commercial ethanol cheaper than any of its major competitors (See Figure 13). Indeed, despite being the world's second largest producer of ethanol, Brazil is still the world's largest exporter. Currently Brazil controls 50 percent of the market in ethanol exports, with their biggest customers being India and the United States in that order[112]. Brazil however also exports to a host of countries including Venezuela, Nigeria, China, South Korea and a number in Europe. Brazil is also currently negotiating with Japan, the world's third largest economy to begin exports there as well. Japan has approved the substitution of up to 3 % of its gasoline needs with ethanol in keeping with

Fuel Ethanol Prices in Brazil, USA and Europe



Source: OECD (2008)

Figure 13.

[107] Serra et al. (2010)
[108] Kamimura and Sauer (2008), OECD (2008) 19
[109] For example in the United States, transport fuels are the second highest human-related source of CO^2 Emissions. EPA (2011)
[110] Due to the fact that it is a renewable resource.
[111] Tetraethyl lead is added to gasoline to provide octane. The usual concentration is 0.6 g/l, which can be replaced by 20% blend ethanol in gasoline. Alonso-Pippo et al. (2008), Thomas and Kwong (2001)
[112] IEA (2006) 11

its Kyoto Treaty commitments[113]. This however is no small feat and would require 1.8 billion[114] liters of ethanol which is the total amount of ethanol that was exported in 2010[115].

There is still further room for profit growth in export markets for Brazil. Currently, Brazilian ethanol is subject to quota restrictions by the United States. In order to circumvent these quota restrictions, Brazil currently exports hydrous ethanol to a number of Central American and Caribbean countries to be further processed to into the gasoline additive anhydrous ethanol[116]. Though these countries enjoy special duty free access to the US market based on the Caribbean Basin Initiative (CBI) , most of the ethanol that they process is in fact imported from Brazil. One example of this is the agreement between, Coimex, Brazil's largest ethanol exporter and Jamaica's state-owned petroleum company, which despite having a local sugar industry still imports 100 percent of the hydros ethanol from Brazil, processes it and takes a profit on the spread between the Brazilian and American prices[117].

Currently, Brazil exports roughly 20 percent of ethanol produced, or 3.46 billion liters. However, by 2020 Petrobras, Brazil's state run liquid fuels company, estimates ethanol total production will more than double the current level of 15.76 to 46 billion liters. Of this total, exports are estimated to rise to 16.5billion liters, representing an increase of more than 370 percent[118]. Though no direct profitability figures are available for the export of ethanol, the fact that Brazil can afford to export through its CBI middlemen and the industry's substantial planned expansion program would seem to imply the lucrative nature of the business.

4.5 Improved Balance of Payments

The improvement of Brazil's balance of payments is an indirect economic benefit accruing to the substitution of local ethanol for imported gasoline. Again, due to the importance of oil and transportation, oil is the most important item in international trade[119], and constitutes a substantial proportion of most countries imports. Brazil in the 1970s was no exception to this; with oil imports representing the equivalent to 40 percent of the nation's exports[120].

Economically, there are inherent costs to accumulating a current account deficit, namely the financing costs involved with international capital and the exchange rate cost involved in currency devaluation. When a country runs a current account deficit, this deficit must be financed by inflows of foreign capital into the country. For developing countries such as Brazil, this can be particularly burdensome because of the high returns to international capital that are demanded of them compared to OECD countries[121]. Further, as national debt and hence risk of default increases, so does the cost of borrowing. This situation unfolded in Brazil in the

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[113] Orellana (2006)
[114] ibid.
[115] Riveras (2011)
[116] Yacobucci (2004)
[117] Myers (2008)
[118]Kamimura and Sauer (2008)
[119] Goldemberg (2006) 1
[120] Macedo (2007) 12
[121] For example, Canada 1%, England 0.5%, Japan 01.%, USA 0.25% and Brazil 12% (FXSTREET 2011)

1970s; in the face of soaring oil prices, the government was forced to finance oil imports through external debt which weighed heavily on the economy even into the 1980s[122].

Ethanol production therefore plays an important role in mitigating national debt service payments. In 1996 for example, it was estimated that due to government overpricing of gasoline relative to ethanol, Brazilian customers paid an additional USD 2 billion fuel costs. However, this increase is almost twice offset by the estimated USD 4.9 billion in savings derived from the program[123]. Similarly, Macedo estimates the amount of *interest payment* avoided by substituting ethanol for to be roughly USD 60.0 billion[124]. By contrast, ethanol which is produced locally avoids much of the external financing costs involved with imported oil.

Balance of payment deficits also put downward pressure on foreign exchange rates, depressing the international value of local currency due to oversupply. This has adverse effects in that it threatens to increase imported inflation and also put pressure on interest rates to increase, both of which have a negative effect on demand, output and employment.

4.6 Increased National Industry and Productivity

Another economic benefit of the program is reflected in the increased production that arises from growing fuel domestically, as opposed to importing it from abroad. The sugar and ethanol industries together account directly for 2 percent of GDP, with a value of about USD 8 billion in 2006[125]. Further, these figures do not capture the contribution to GDP made further along the industry value-chain including distribution, fuel stations, international trading operations, and equipment manufacturing. The latter industry in particular has performed remarkably well over the past thirty years, and has reached a level where all aspects of machinery for sugar, ethanol, and power generation are now almost 100 percent produced locally[126]

Information about the specific profitability of ethanol-related companies in the Brazil was not available. However an indirect assessment can be made about the industry's profitability by considering certain related factors. Firstly, the industry has operated completely free of government assistance since 1999, and since this time, ethanol production has doubled[127]. This growth in production and the continuity of underlying companies over the past ten years implies that these firms have been operating profitably. Unfortunately, given the lack of data it is impossible to say how profitably.

Another indirect indicator of the profitability of the industry is the extent to which new investments are being made. And by this indicator, it would seem that Brazilian companies are performing particularly well. International investors have been raising billions[128] to invest in further increasing Brazil's ethanol capacity. As of 2010 an estimated 77 new ethanol plants were expected to come online, representing an increase of roughly 20 percent increase from the existing 378 in operation. Of note is the increasing involvement of international oil

[122] Geller (1985) 114
[123] Papageorgio (2005) 24
[124] In 2004 dollars. Macedo (2007) 7
[125] Winfield (2008)
[126] Macedo(2007) 199
[127] Brown, (2010)
[128] In United States currency, Bloomberg (2007)

companies in the industry. The first and most substantial entrant into the market so far has been BP (formerly known as British Petroleum), in the form of its subsidiary company BP Biocombustives. As of 2009, this subsidiary had acquired ownership stakes in three ethanol production companies at a combined cost of more than USD 1.1 billion[129]. Even more recently, March 2011, BP also invested an additional USD 680 million to acquire a controlling stake of Companhia Nacional de Açúcar e Álcool (CNAA)[130], bringing its total ethanol capacity to 1.4 billion liters annually, compared to national production of about 27.5 billion[131].

4.7 Employment

Compared to other energy sectors, the production of ethanol from sugar is very labour intensive relative to other energy industries (See Figure 14), as well as in relation to other major crops in Brazil. Of the four major crops in Brazil[132], sugarcane is by far the most labour intensive[133]. In socioeconomic terms, the program has provided jobs and income creation for a large spectrum of both agricultural and industrial businesses. In the first five years of the program alone, 40,000 permanent jobs were created and an additional 82,000 seasonal jobs[134]. This growth has continued over the life of the program, and the combined total direct employment in the sugar and ethanol industries reached 700,000 in 1999[135], and increased further to approximately 1 million in 2005[136]. However, by some estimates, the total employment generated by the industry, including direct, indirect and induced employment is 3.6 million[137], or roughly 1.4 percent of the Brazilian population. These jobs are roughly evenly distributed between agriculture and industry and have a low incidence of strictly seasonal work.

Figure 14.

Direct jobs in energy production

Sector	Jobs (person-years) Terawatt-hour
Petroleum	260
Offshore oil	265
Natural gas	250
Coal	370
Nuclear	75
Wood energy	1000
Hydro	250
Minihydro	120
Wind	918
Photovoltaics	76,000
Ethanol (from sugarcane)	4,000

Source: Goldemberg (2002).

4.7.1 Quality of Remuneration [138]

In the 1990s Rank and file workers in the sugarcane industry had higher wages than 86 percent of agricultural workers and 46 percent of industrial workers. The average family income of workers in the sugarcane industry was higher than 50 percent of Brazilian families. Additionally, the seasonality of jobs in the industry has been declining since the 1980s. By the late 1990s the industry was responsible for 650,000 direct jobs, 940,000 indirect jobs and an

129 Moran (2009)
130 BP (2011)
131 Brown (2010)
132 Measured by area harvested: soybeans, sugarcane, maize and rice. FAO (2011)
133 From 49 - 84% more labour intensive that maize and 300% more than soybeans. Geller (1985) 148
134 Pereira (1985) in Kojima and Johnson (2005) 100
135 Goldemberg (1999) 10
136 Macedo (2007) 212, Winfield (2008)
137 Silva (2007) in Sorvik (2011) 101
138 Unless otherwise states all figures quoted in this section are taken from Macedo (2007) 199 – 233

estimated 1,800,000 induced jobs. And in 2005, 980,000 people were directly employed in the industry, with an increasingly larger proportion of jobs coming from the industrial production of ethanol than in the production of sugarcane.

A much more recent (2010) study[139] further corroborates that in the past decade in the State of Sao Paulo, municipalities with sugarcane and ethanol distilleries had higher incomes and human development indicators than those with only primary agriculture. The 2005 Brazilian national survey (PNAD)[140] revealed that in Sao Paulo agricultural wages were almost double the monthly national average, at BR 820 versus BR 462. A similar trend is observed with industrial workers in the ethanol industry who in Sao Paulo made BR 1196 versus the average industrial wage of BR 770 per month, almost one-third above the average.

In addition to direct monetary remuneration, the industry also contributes to other aspects of social development in the communities where it operates[141]. Special legislation enacted by the government requires 1 percent of the net sugarcane price and 2 percent of net ethanol price be channeled into the various benefits of sugarcane workers[142]. The sugar and ethanol industry together maintain more than 600 schools, 200 daycare units and 300 ambulatory care units. In Sao Paulo-based companies, additional benefits for workers were very common: more than 80 percent received health and dental care, transportation and life insurance, and meals and pharmaceutical care. Further, more than 84 percent have profit-sharing programs, provide accommodations and have daycare units.

4.7.2 Caveat

Despite the positive socioeconoimc aspects of the program, it should be considered firstly (1.) that a number of international agencies have raised concerns about reports of abusive labour practices within the industry, and secondly (2.) increased mechanization, especially by larger producers, is leading to reduced labour requirements despite growing production.

As recently as 2008 a Brazilian NGO published a 55-page report that highlighted specific instances of worker abuse and exploitation in both the Sao Paulo and North-east areas[143]. More recently (2008 and 2011), concerns have also been raised about the general working conditions of cane workers, which arguable have not improved much in the last hundred years.[144] The working conditions in the fields are arduous and there are significant health risks that emerge due to repetitive motion, intense physical exertion and air pollution from preparatory burning of cane. In 2005, there were a reported 10 cane cutter deaths caused by high worker demands[145].

Both the adaption of mechanical harvesters to Brazilian conditions and recent government policies promoting this mechanization have created daunting prospects for the job creation aspect of sugarcane production. Recently, the Brazilian government introduced legislation requiring the adoption of harvesting machines on flat lands by 2014. It is estimated that this

[139] Martinelli et al. (2010)
[140] Macedo (2007) 37
[141] ibid. 223 – 224
[142] Goldemberg (2009)
[143] Biondi (2008)
[144] Hermele (2011), Martinelli and Filoso (2008) 893 - 894
[145] Rocah et al. (2010) 978

move will eliminate 150,000 jobs by 2014[146]. Automated harvesters are both more environmentally friendly because cane does not have to be burned before harvesting, and are also much more economically efficient[147]. The immediate effects of mechanization, even without legislation, are evident in the industry even today. In Sao Pualo where mechanized harvesting now accounts for 60 percent of sugarcane produced, and since 2007, this has led to the displacement of more than 40,000 cane cutters, only 10 percent of which have been relocated to other jobs within the industry[148].

[146] SCA (2011)
[147] Guilhoto (2002)
[148] SCA (2011)

5 Critical factors in the Development of the Brazilian Situation

There are a multitude of factors that have led to the current state of the ethanol system in Brazil. The gradual increase in the profitability of ethanol is in large part due to cost reductions brought about by technological and managerial innovations[149]. The development of these innovations took place over the length of the ethanol program, and were due both to learning-by-doing as well as concerted R&D efforts. In order to sustain these innovation processes over time required sustained demand for ethanol and the central coordination of the market. And in this regard, automobile technology and government policy over the past 35 years have been crucial. Because of the multifaceted and interconnected nature of the factors leading to the development of the Brazilian model, this section will be divided into five parts as follows:

5.1 A review of the innovations that have taken place in the various stages of sugarcane production. Particular emphasis is given to these innovations because feedstock costs currently represents the largest cost component in the production of ethanol. And it is the measure that will subsequently be used in this study to analyze transferability of the Brazilian System in Section 6.

5.2 A brief review of the efficiencies gained in industrial ethanol production. Less emphasis will be placed on this section, because it has fewer stages than sugarcane production. And more importantly, because the physical nature of the industrial technology makes these advances easier to transfer, as opposed to more knowledge intensive technological processes, such as crop breeding.

5.3 An illustration of the development and role of electricity cogeneration in improving production efficiencies.

5.4 An analysis of how government policy has helped to shape supply, demand and industry innovation.

5.5 An explanation as to how dual sugar and ethanol production has lead to the economic versatility of the industry

5.6 An analysis on the effect of Flexible-Fuel Vehicles on the industry. This will be the final aspect to be addressed because it is the most recent development and has had profound effect on the recent revitalization of local ethanol demand and production.

5.1 Innovation in Sugarcane Production*

The technological sophistication of the ethanol program has developed significantly since its start in 1975. Utilizing the concept of progress ratios[150], Goldemberg[151] demonstrated the rate of technology improvement in ethanol from 1985 - 2002 had outpaced those in other major renewable technology such as wind and solar. Based on this technological improvement, the

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[149] Goldemberg (2004)

[150] The Progress ratio of the technology is the variation of prices in accordance to the cumulative sales, and is a measure of the evolution of technological efficiency over time.

[151] Goldemberg (2004) 302

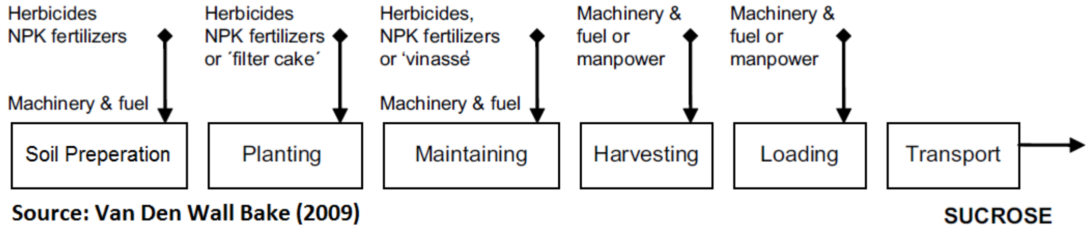
holistic cost of producing ethanol was reduced by roughly 70 percent from the inception of the program to its end in 1999[152]. In an exceptional debut work, Van Den Wall Bake[153] carries this analysis further and disaggregates the relative efficiency contributions of *sugarcane production* and *ethanol production*. The main conclusion of his work is that "cost reductions in the sugarcane production actually follow a steeper experience curve[154], thus making 'cane the key' factor behind the overall cost reductions, especially through achieving increasing yields per hectare."[155] This assertion is particularly important for this study, and is one of the foundations upon which the quantitative analysis in Section 6 is based.

Therefore, given that (1.) the majority of cost reductions in the aggregate ethanol production process have come from innovations in cane production and (2.) that this is assertion upon which the subsequent empirical analysis is based, the underlying technological factors responsible for this efficiency will be expounded upon.

Sugarcane production can be roughly broken down into a simple six stage process (See Figure 15). Along this process, there are five major cost areas that producers face, these are: (1.) land rents, (2.) soil preparation, (3.) crop maintenance, (4.) harvesting and (5.) cane loading and transportation. In this section any references not specifically otherwise quoted are drawn from Van Den Wall Bakes 2006 study.

Figure 15.

Simplified overview of sugarcane production.



Source: Van Den Wall Bake (2009)

5.1.1 Land rents

Over the thirty year period under analysis land rent costs reported by cane producers have fallen by roughly twenty percent. This is explained by the purchase of sugarcane lands by large industry companies in an attempt to vertically integrate their production chain. Since the beginning of the program property owned by companies in the industry had increased by more than 10 percent up to 2004[156]. Much of these purchases occurred during the deregulation of the industry and the removal of government assistance, and can be viewed as an attempt by industry to maintain stability in the production process.

[152] Van Den Wall Bake (2009) 645
[153] ibid. (2009)
[154] A steeper experience curve implies that as cumulative production increases the cost of production is falling rapidly.
[155] ibid. 656
[156] Van Den Wall Bake (2006) 43

5.1.2 Soil preparation

In Brazil the ratoon[157] system is used for growing sugarcane. This basically means that the same plant is harvested several times. This is possible because only the top of the plant is cut, leaving the lower part and the root uncut. Over time however, yields begin to drop the longer a single crop is continuously re-harvested. The replanting of new plants and the necessary soil preparation that accompanies it are expensive processes that represent a large capital investment by producers. Recently, however, developments in sugarcane crop varieties have led to longer periods of re-harvest, and therefore fewer instances of replanting for a given period. Whereas ratoon systems used to be limited to 3-4 years at the beginning of the program, they are now reaching 5-7 years without significant loss of sucrose content. Much of this increase in longevity is based on the development of better crop varieties, as well as a more *diversified* pool of crop varieties which reduces the incidence of diseases within the cane population. Currently in Brazil, there are more than 500 commercial varieties of cane, of which 20 varieties are used in 80 percent of the cane area[158]. At the start of the program, 80% of cane planted was a single variety. Today the most of any variety planted is 12 percent of total land area harvested.

5.1.3 Crop Maintenance

In terms of crop maintenance, the major costs to producers where herbicides and fertilizers, 55 percent; machinery, 35 percent; and labour, 10 percent. The application of vinasse, which is a nutrient rich byproduct from cane processing, has greatly reduced the fertilizer costs to producers. The adaption of this industrial waste was orchestrated by the research done by the Sugarcane Technology Center CTC[159]. And currently about 30% of cane fields have adopted its use. The application of machinery also became a critical factor. It has reduced labour costs in the application of fertilizers and herbicides by more than 50 percent between 1987 and 2003[160]

5.1.4 Harvesting

The adoption of mechanized harvesting was late to arrive in Brazil due to its often hilly terrain as well as an abundance of cheap labour. However in the 1990s investments in R&D by the largest industry producers led to the adaption of Australian mechanical harvesters to suit Brazilian conditions. These adapted harvesters have the capacity to harvest between 80 and 100 Tonnes of Cane (TC)/hour compared to between 8 and 10 TC/day for manual workers. At these rates the machines are able to easily displace approximately 90 manual harvesters, not taking into account that they can be run for 24 hours a day, which also has advantages given the nature of the industrial processes involved in ethanol production. Additionally, because many of these harvesters fulfill both the cutting and transport functions, they are able to supply cane more quickly, thereby reducing the amount of sugars lost due to lag time.

[157] Ratoon - a new crop (especially of rice, bananas, or sugar cane) that grows from the stubble of the crop already harvested (Oxford Dictionary)
[158] Xavier (2007) 9
[159] This is the English translation of: Centro de Tecnologia Canavieira.
[160] Van Den Wall Bake (2006) 42

Because of these developments, the government has kept labour costs relatively low in order to prevent the displacement of too many workers in the industry. And as of 2006, 60-70 percent of cane is still cut manually. However even in this aspect, efficiency improvements have been achieved due to competition based management strategies. These strategies have led to roughly a doubling of efficiency in manual can harvesting from 4.5- 6 TC/labourer/day in 1977 to 9.86TC/labourer/day at the present time.

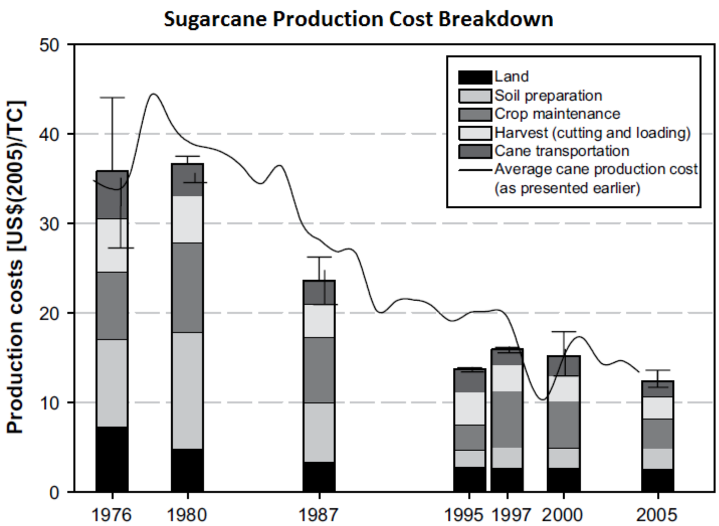
5.1.5 Transport

In order to take advantage of economies of scale in the processing of sugarcane it is important that large areas of cane be accessed quickly. In this regard the Brazilian industry has also taken steps to improve its efficiency. Larger trucks are employed the capacity of trucks has increased by more than 400 % since 1977. More than this however, their efficiency has dramatically increased as well from 30-60TC/truck/day to 246-343TC/truck/day in 2004, an increase of more than 467%. In addition to increasing the amount carried by trucks, logistics systems have also been employed to increase efficiency along with less breakdowns and faster loading and unloading mechanisms.

One recent study[161] of the use of precisions agricultural technology in Sao Paulo found adoption rates of this technology to be above 56 percent. It was further established that those companies that did employ this technology achieved managerial improvements, higher sugarcane yields, lower costs, minimization of environmental impacts and improvements in sugarcane sucrose content.

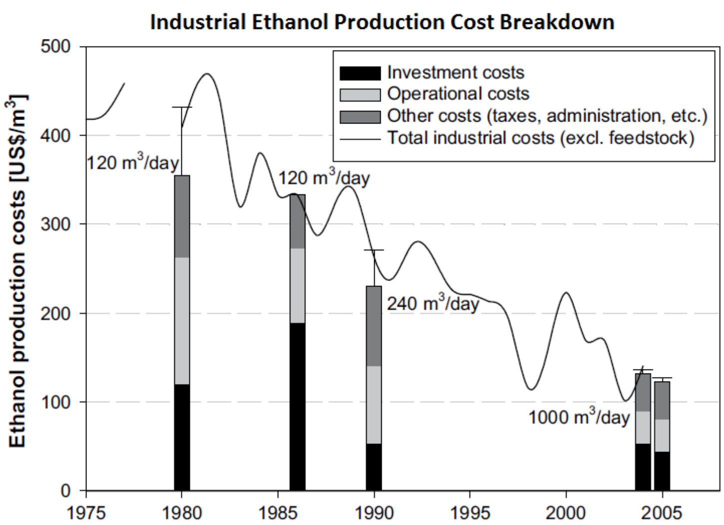
The cumulative result of these various efficiency developments in sugarcane production are summarized below in Figure 16.

Figure 16.



Note: The lines on tops of bars represent error markers
Source: Van Den Wall Bake (2009)

Figure 17.



Note: Excludes feedstock costs
Source: Van Den Wall Bake (2009)

[161] Silva (2011)

5.2 Innovations in Ethanol Production

As afore mentioned, the cost efficiency of the ethanol production process has improved markedly as well. In this circumstance, however in addition to technological improvements, various financial considerations have also contributed to the reduction in costs (See Figure 17). The main contributors to industrial performance were found to be increased sugarcane milling capacity, sucrose extraction and fermentation performance[162]. With regard to milling capacity, three main innovations led to higher efficiency: continuous feeding, increased pressure on the mills[163], and more advanced cane juice recovery systems. The major innovation in terms of fermentation was the adoption of more efficient yeast that sped up the fermentation process and enabled continuous fermentation, both of which significantly reduced the costs involved in tank purchase, maintenance and cooling[164].

Here, it is important to note that the difference in the kind of technology that has contributed to the developments in the efficiency. In the case of sugarcane production, the innovations are more based on procedural methodology and specific knowledge, while in the industrial component is more based on more physical mechanical technology.

5.3 Electricity Cogeneration

One important aspect of efficiency improvement that is not directly related to cane cultivation or ethanol production is the generation of electricity and heat from the sugarcane byproduct, bagasse[165]. As of 2005, Brazilian mills and distilleries were almost entirely energy independent, with a few efficient enough to sell surplus electricity into the grid[166]. Currently, overall electricity generation by the sugarcane sector represents 1.32 percent of total installed capacity in the country[167] This is also significant environmentally, as the fact that sugarcane trash can be used as a fuels source for the processing of ethanol has significant implications for the fuel's overall GHG balances[168].

This process takes advantage of the fact there is more energy contained in the bagasse of the sugarcane than in the subsequent ethanol produced form the juice of the sugarcane[169]. When these cane residues are burned, they provide heat for the industrial process involved in both sugar and ethanol production, and can also generate electricity by creating steam to power dynamos. Efficiencies in this area has greatly increased when the commercial sale of surplus energy was introduced in 1997[170].Using available technologies it is currently possible to generate excess electricity worth approximately 30 percent of the combined sugar and ethanol sales[171]. A recent 2011 study[172] has demonstrated that projected return on investment for a

[162] Van Den Wall Bake (2009) 652
[163] Mills are use to crush sugarcane, thereby extracting its sugar-rich juices. Increased pressure in this case corresponds to applying a higher force to the cane.
[164] ibid. 653
[165] Kojima and Johnson (2005) 4, Goldemberg (2006) 3: "Cost reduction was highly influenced by the use of sugarcane bagasse for energy production."
[166] Kojima and Johnson (2005) 24
[167] Martines-Filho et al. (2006) 96
[168] Sebara and Macedo (2011) 424
[169] Moreira (2000) 47
[170] Kojima and Johnson (2005) 4
[171] Macedo (2007) 193

commercial steam power plants in Brazil averages about 23.2 percent return on investment, which is considerable even for the high interest rates in Brazil[173].

5.4 Government Policy

The previous sections highlighted exactly how Brazilian firms were able to reduce costs and increase efficiency across the length of their production chain. As impressive as these developments were however, much of the progress achieved find finds its roots in incentives created by government assistance programs in various forms. And indeed, no country has ever been able to launch a successful biofuels program without active government support beyond the regulatory role[174]. This therefore makes the Brazilian story as much about effective policy instruments as efficient technological innovation.

In 1975 the Proalcool program was created to coordinate all aspects of government's ethanol strategy. This program affected every important aspect of the incorporation of ethanol into the national matrix. It was instrumental in increasing both the production and consumption of ethanol, as well as in supporting the development of the technology that made commercialization possible.

The main components of this program were as follows[175]:

1. A guaranteed market for producers. The government encouraged the production of ethanol by guaranteeing that the state-owned oil company, PETROBRAS, would purchase of a given quota of ethanol at a price above the cost of production. This agreement started at the beginning of the program and lasted until 1985.

2. Subsidized Credit for agriculture and industry. Credit was offered to agricultural and industrial ethanol interests at interest rates substantially below market and with sizable grace periods for repayment[176]. These loans amounted to USD 2 billion, in historical dollars and accounted for an estimated 29 percent of the total investment needed to reach current ethanol production capacities.

3. Discounts for Consumers. During the first phase of the program the price of ethanol to consumers was set at 59 percent the price of gasoline, making it a much cheaper alternative on a per mileage basis. This measure was essentially paid for by increased consumer taxes on gasoline, which brought the final price to approximately twice that as the United States[177]. This policy was accompanied by a government mandate that all petrol stations had to offer ethanol as well gasoline fuels[178] leading to the elimination of highly polluting 'super' gasoline containing lead additives. In addition to this the annual licensing fee for ethanol cars was reduced[179].

[172] Sebara and Macedo (2011) 421
[173] FXSTREET (2011), Coelho (2006) 11
[174] Kojima and Johnson (2005) 5
[175] Goldemberg (1999), Puppim de Oliveira (2002)
[176] Puppim de Oliveira (2002) 143
[177] Goldemberg (1999) 232
[178] Goldemberg (2006) 2
[179] Van Den Wall Bake (200) 646

4. Banning of ethanol imports. As an incentive to encourage further private investment in the development of national ethanol capacity, the government enacted legislation prohibiting the importation of ethanol, except under emergency situations. Thought this measure was never needed in actuality, its effect on investors was surely real.

5. Incentivized research and development. The government offered financial incentives to universities, research institutes, and companies for the development of ethanol technologies.

Several exhaustive accounts of the ethanol program are available[180], however in essence the government was critical in the development of the industry, most critically between the period 1975 -1990. During this period, the government created the market for ethanol by creating both artificial demand and supply funded through government taxes. Efficiencies in the industry were actively promoted through concerted R&D efforts as well as by financing the expansion of operations geared at improving economies of scale. By the 1990s when much of the government support was removed from the industry, the market had reached a point where it could sustain itself, and the removal of government support actually lead to significantly increased efficiency development.

5.5 Versatility of Production between Sugar and Ethanol

Another key factor in development of the program is that most sugarcane mills in Brazil are actually mill/distillery complexes, and therefore have the ability to switch between sugar and ethanol production. As of 2004, about 25 percent of ethanol plants were autonomous ethanol-only distilleries, while the remaining 75 percent were mill/distilleries with the ability to produce both sugar and ethanol[181]. At any given time, these mill/distilleries have the ability to shift between a 40 - 60 percent mix[182] of ethanol production versus sugar. This limitation exists because of economic interdependencies between the two processes, involving the utilization of molasses, a low-value sugar by-product, as a feedstock for higher-value ethanol. This system has significant profitability advantages for mill owners, and consequently for the survival of the industry as a whole. One of the critical factors that contributed to the beginning of the ethanol program, was in fact a precipitous fall in the price of sugarcane in the face of rising oil prices.

This versatility of production helps to stabilize the supply of sugarcane. This is because the volatility of commodity prices, represents a risk to producers. The ability to produce for two distinct markets reduces the risk of being overwhelmingly affected by price reductions in any one market, as the options still exists to sell into the next.

However, it should be noted that despite being beneficial to the producers these two commodities, this situation can often be detrimental to consumers. This is because instead of prices being determined mainly by the cost of production, now they are also affected by fluctuation in demand for the competing product. The aggregate effect of this more complex relationship is demand shortages and consequent price fluctuations which are disruptive to markets. This issue is further complicated by the fact that Brazil has a 25 percent ethanol blending requirement for commercial gasoline. Without this requirement, during times when

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[180] Rosillio-Calle (1998), Goldemberg (1999), Puppim de Oliveira (2002)
[181] Kojima and Johnson (2005) 244
[182] Winfield (2008)

ethanol is in short supply, consumers could simply switch to gasoline to avoid increased prices. However because of the blending requirements, increases in the price of ethanol also affect the final price of gasoline, though to a lesser degree than the price of pure ethanol.

5.6 Flex Fuel Vehicles

Finally, Flex-fuel vehicles (FFVs) have been critical in the revival of the industry to the point of its current success. They represent a marked improvement in their ethanol-only counterparts[183] that were developed early in the Brazilian Ethanol Program. These cars have been important to the ethanol industry because they provide a large and constant market for ethanol, but unlike their predecessors are not crippled during periods of low ethanol production.

In the mid 1980s, more than three-quarters of new cars in Brazil ran strictly on ethanol, utilizing what are known as neat ethanol engines[184]. However, the sharp sugar price rises that occurred in the early 1990s dramatically altered the production economics of ethanol for local growers. Because most producers had the ability to switch between sugar and ethanol production, the sudden price rise in sugar led to rapid increases in the production of sugar[185]. This however, dramatically reduced the availability of ethanol to the general consumer, with the effect of rapidly increasing ethanol prices at the pump[186]. The situation was dire as much of the Brazilian fleet had become locked into ethanol as its primary fuel source. The government was forced to import ethanol to keep the transport industry going. Somewhat ironically, during the crisis Brazil became the biggest net importer of ethanol in the world[187]. In addition to this oil prices dropped significantly and were sustained through most of the 1990s, thereby increasing the relative expense of the government support of the system. The repercussion on neat ethanol engines was swift. By the end of the 1990s sales of ethanol-only cars, not surprisingly, accounted for less than one percent of total annual car sales.

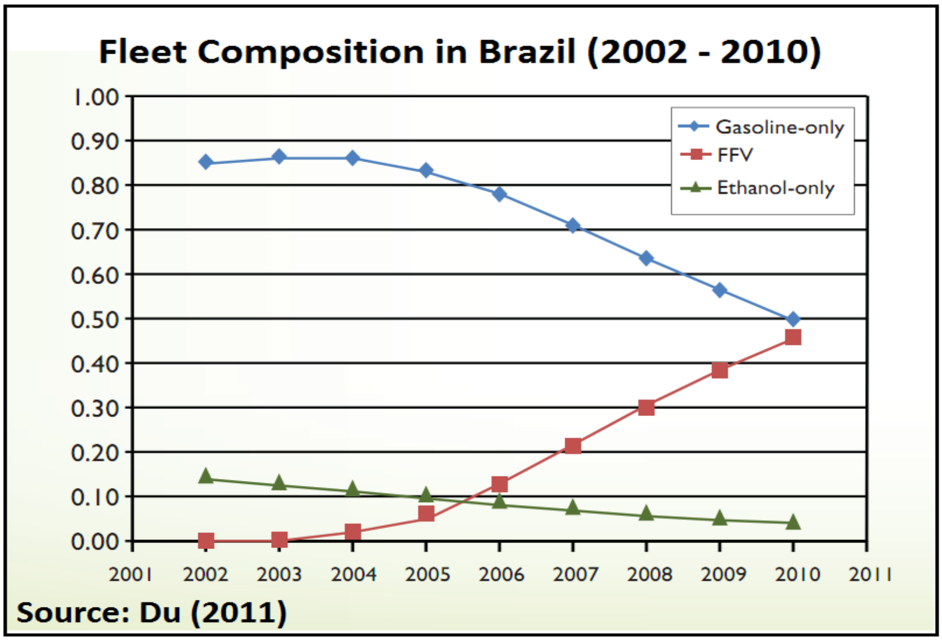
The Flex-fuel revolution started in Brazil in 2003, when Volkswagen do Brasil[188] introduced the Golf Total Flex, the first commercial vehicle capable of running on any mixture of gasoline and ethanol. Equally important is that these cars are no more expensive than their conventional gasoline-fueled equivalents[189]. This development has reinvigorated ethanol producers because it provides them with a much larger market when compared with the use of ethanol as a fuel additive only up to 25 percent. As of 2006, approximately 70 percent of new cars sold in Brazil were FFVs, and consequently ethanol now accounts for 40 percent of driving fuel in Brazil[190].

As of 2010, about half of light-vehicles in Brazil were FFVs, and the proportion of gasoline-only and ethanol-only vehicles were on a significant decline (See Figure 18). Since 2003, the introduction of this technology has significantly expanded the market for ethanol. This has happened at such a rapid pace that demand for ethanol has outstripped supply and created shortages, so much so that as of January 2011 the government temporarily reduced the

[183] Technically known as neat ethanol-powered vehicles.
[184] Xavier (2007) 5
[185] Hira and Olivera (2009) 2454
[186] Van Den Wall Bake (2006) 20
[187] Xavier (2007) 5
[188] The Brazilian subsidiary of the Volkswagen Group.
[189] IEA (2006) 6
[190] ibid.

mandatory proportion of ethanol in gasoline from 25 to 20 percent[191] in an attempt to ease demand. Though this development is perhaps immediately daunting, the wider and more stable market provided by FFV gives producers more incentives to expand production capacity and further reduce costs.

Figure 18.



[191] Dantas and Cortes (2010)

6 Evaluating the Brazilian System in other Developing Countries

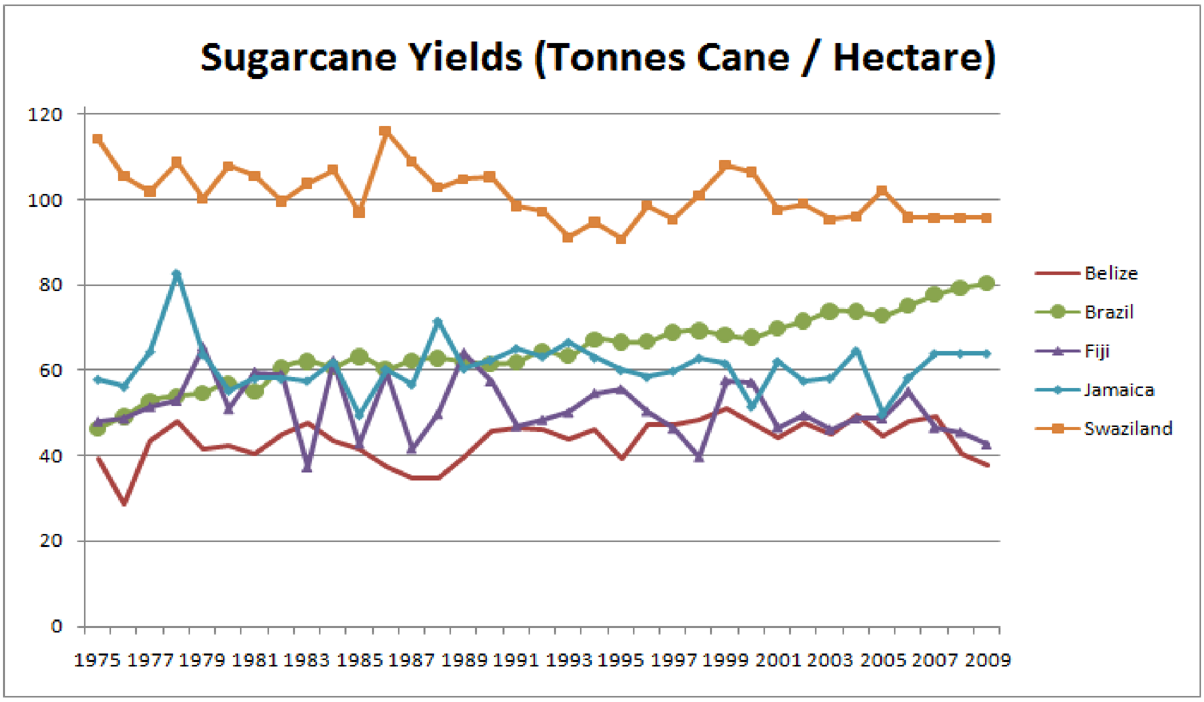
The key fact underpinning this quantitative analysis is that sugarcane production costs are the major determinant of the final cost of ethanol. This fact is supported throughout the prominent ethanol literature[192]. More recently, Van Den Wall Bake[193] has demonstrated that increased technological efficiency in sugarcane production has been the major driver in the reductions of the price of Brazilian ethanol over the years, and that these advances are mainly represented in increased cane yields[194]. This is the justification behind the subsequent analysis of the progression of sugarcane yields in the study sample.

6.1 Results

6.1.1 Historical Development of Sugarcane Yields

When the FAO data is analyzed, stark differences become apparent in the performance of Brazil's sugarcane industry and those of the other developing countries being investigated. The most revealing comparison is of how sugarcane yields per hectare have progressed over the thirty year period since the Brazilian ethanol program started. These results are expressed graphically in Figure 19 and Figure 20. The first graph demonstrates that the soil and climatic conditions in Brazil are by no means exceptional, and at the beginning of the sample Brazil had the second lowest cane yields of the sample of five countries. The position has, however, been subsequently reversed; as Brazil has managed to attain higher yield than all other countries in the sample, except for Swaziland which enjoys exceptional productive climatic conditions. Given these results and the significant variable of Brazil's ethanol program, it can be argued that the application of more advanced technology in Brazil has lead to a significant increase in their yields of sugarcane per hectare.

Figure 19.



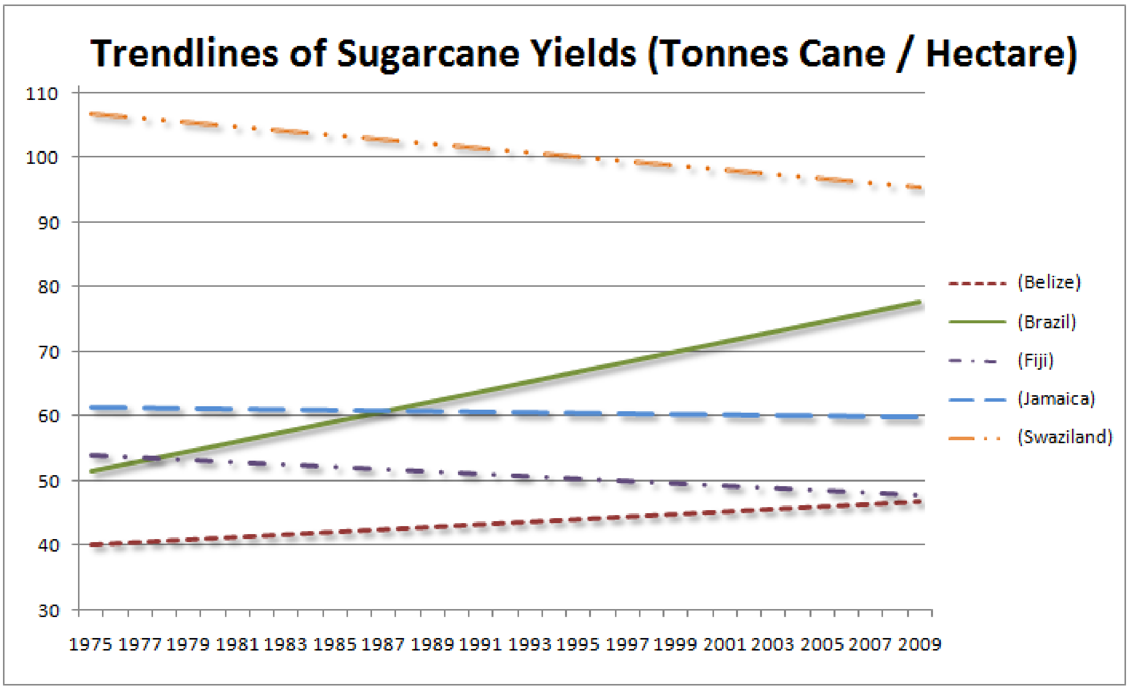
[192] Goldemberg (1999), Kajima and Johnson (2005), Macedo (2007), Bain (2007)

[193] Van Den Wall Bake (2006, 2009)

[194] "Feedstock production costs predominantly depend on agricultural yields" Van Den Wall Bake (2009) 653, Goldemberg (2006) 3

Figure 20, which represents the trend lines of the progression of yields per hectare, further clarifies the Brazil's dramatic productivity gains. Taking a four year average of yields both at the beginning and end of the sample period, 1975 – 2009, demonstrates that Brazil has managed to increase yields by more than 54 percent. While, with the exception of Belize, which had a growth rate of just below 10 percent, all other countries in the study, showed *negative growth* in this measure of productivity: Fiji -5.5, Jamaica -4.6 and Swaziland -11 percent. Interestingly, it was those countries that had the highest yields in 1975, when technological application was arguable equal between the countries, which showed the least development in productivity.

Figure 20.



What is further interesting is that in most countries in the study lands used for sugarcane cultivation either declined or remained fairly constant, increasing less than 25 percent, with the exceptions of Brazil and Swaziland, which increased 332 and 214 percent respectively. the land dedicated or sugarcane cultivation either declined or remained fairly constant (See Appendix Figure 24). When this fact is coupled with declining cane yields, it can be inferred that the lower yields per hectare were not due to the expansion of production onto less productive lands[195]. This, however, could perhaps be the situation in Swaziland where there has been a sharp increase in land dedicated to sugarcane farming since 2003, which coincides with a decline in yields over the same period. This further highlights that the defining factor in the success of Brazil has *not* been superior soil or climate conditions.

This analysis between Brazil and the comparison countries of the study has shown that the productivity of the land in Brazil is modest to average at best. This is based on comparison of

[195] As an increase in less productive lands would bring down the average productivity of all land considered in a given sample. Further, it can be assumed that an expansion of crop land would occur on less productive lands, and those that are most productive would already be gainfully employed.

yields between the countries in the period before the development of Brazil's technology. In fact, if yield data is considered back to the beginning of the 1960s, the land utilized for sugarcane in Brazil actually had the poorest yields of any country in the study (See Appendix Figure 25). However, by the end of 2009, Brazil has managed to outperform all of the countries in this study, with the exception of Swaziland due to the extraordinary yields that its land and climate allow for.

6.1.2 Historical Development of Worker Productivity

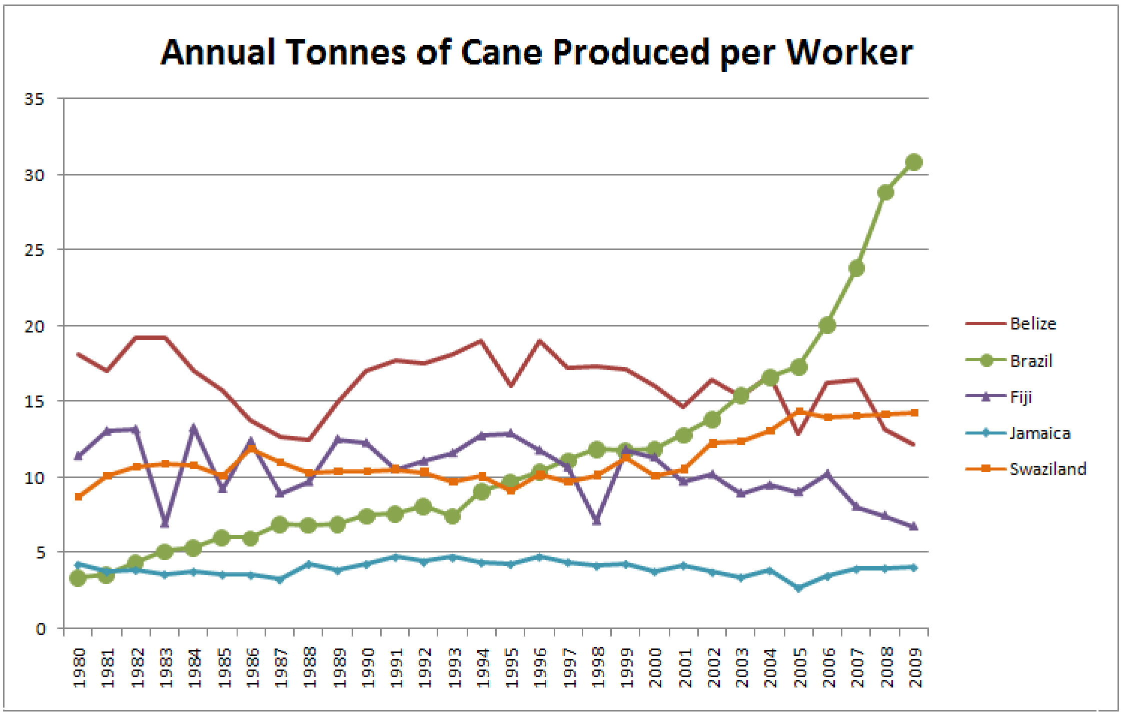
Further insight into the impact of technology in Brazil can be garnered by analyzing the productivity of *sugarcane workers* across the different countries is considered. The data is based on FAO data on specific sugarcane production statistics, but on *general* agricultural population statistics (as is elaborated in detail in the methodology section along with other fundamental assumptions). Therefore, because this population data is for *all* agricultural workers, and not sugarcane workers specifically, an *exact* representation of the state of the industry cannot be rendered based on this data. Nonetheless, the analysis does provide insight into the *general* trends that are occurring in each of the countries.

This analysis is based on traditional economic theory, where the level of output (Y) is a function of capital (K), technology (E) and labour (L):

$$Y= f(K, E \times L)$$

By taking the rate of change of output (Y) with labour (L), an approximation of the capital accumulation in the industry (K) and technology (E) can be derived. This definition of technology however is not constrained to engineering techniques and scientific knowledge, but rather encompasses non-tangible assets such as management practices and organization structure. These results are presented in Figure 21.

Figure 21.



Note: This graph uses total agricultural labour as an approximation of the sugarcane workers in each of the constituent studies (Further details and underlying assumptions are given in the methodology section).

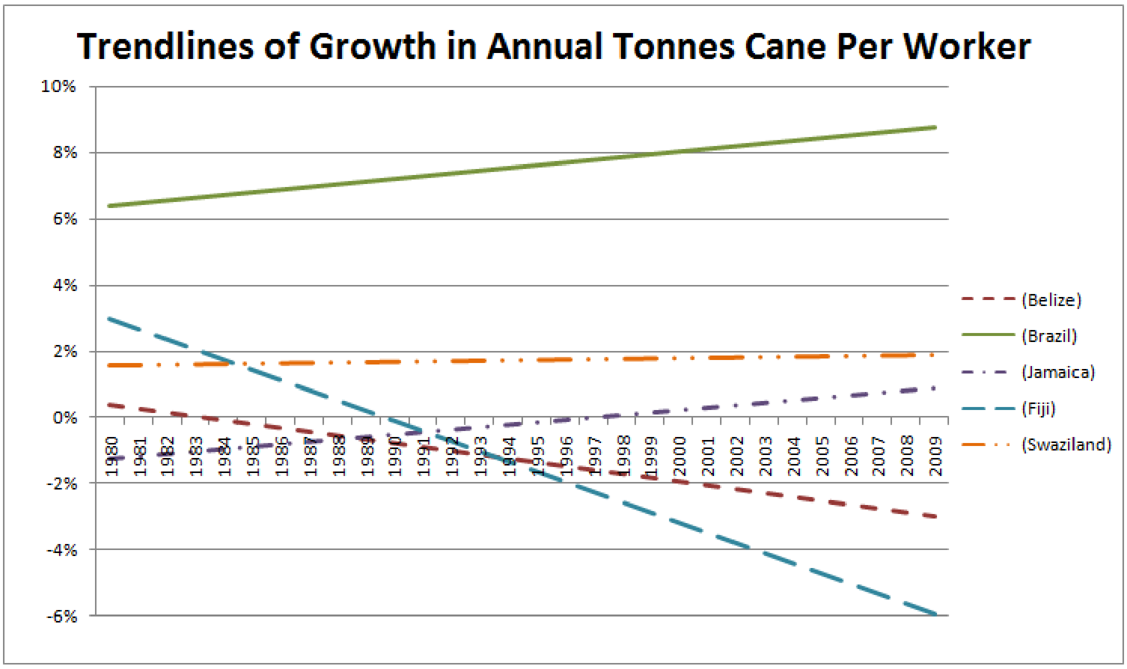
This analysis shows that the labour productivity gains in Brazil are in the region of 800 percent over the period. While in other countries in the study labour productivity has remained relatively constant throughout the period with a tendency towards declining rates towards the end of the period. A marked deviation from this general trend is observed in Swaziland where labour productivity has increased roughly 40 percent over the past ten years. This could be due to the introduction of experienced multinational firms into the local market, as well as government initiatives to increase the share and productivity of small farmers in the industry, conclusive answers however were not available in the literature reviewed.

Interestingly, the use of *total* agricultural workers in place of only sugarcane workers should have the effect of reducing the output per worker in economies where sugarcane production is not the major agricultural employer[196]. Of the countries in the study, it is Brazil where sugarcane occupies the smallest proportion of agricultural land (See Appendix Figure 26). Surprisingly however, its performance is still dramatic compared to the comparison countries.

Additionally, despite the assumed distortionary effect of the aggregate agricultural population, the trends observed in Brazil, seem to fit the increased mechanization and recent high rates of labour displacement that are addressed in Section 4.7 on employment.

Nonetheless, to try and limit the distortionary effect of the worker sample, the data has been expressed in terms of growth rates represented by trendlines for simplicity. In this form, the data should indicate more clearly the rate at which worker productivity has been growing, which is a more comparable ground for comparison (See Figure 22).

Figure 22.



Again, the results are explicit, and demonstrate an annual positive growth in worker productivity in Brazil of between 6 and 9 percent. While of the comparison countries, only Swaziland displays positive growth though modest, at 2 percent

[196] As the denominator, *Number of Workers*, would be larger.

6.1.3 Simple Feasibility Analysis of Ethanol Production in Comparison Countries

Based on the results from the previous two sub-sections, it is arguable that (1.) Brazil has exhibited strong growth in productivity related to sugarcane its counterparts in the study have not and (2.) that this strong growth is based on the development of Brazilian technology. If a third factor (3.), the transferability of this technology is assumed, then this presents an opportunity to perform a rough evaluation the feasibility of ethanol production in the comparison studies.

In Brazil, sugarcane prices per tonne, adjusted for inflation, have fallen by 65 percent[197] during the period 1976 to 2005, with even greater price reductions estimated in 2020. Based on this percentage price reduction, a simple two scenario analysis will be performed on the comparison countries. The first is a *conservative scenario* in which a 35 percent cost reduction is assumed, as reasonably speaking technology is never perfectly transferable. And the Second is a *optimistic scenario,* whereby full transfer of technology is assumed.

In this analysis, prices paid to producers have been used as a proxy for the cost of production of sugarcane. This, again, is not a perfect method of analysis as several factors can affect the prices offered to producers, but nonetheless offers some insight into the potential of the technology. Further, the costs of ethanol production estimated in this study are very much in line with those used in other recent studies[198]. The 5-year period was selected to start in 2004 as this was the first year that ethanol became commercially competitive with gasoline[199]. Given that ethanol has remained commercially viable in Brazil since that time, the average of prices in Brazil for this period have been selected as the benchmark cost that other countries must meet in order to also achieve feasibility. These results are reported in Figure 23.

Figure 23. Non-rigorous Feasibility Assessment of Ethanol Production in Comparison Countries.

	Production Price (USD / Tonne of Cane)		
	5 Year Average 2004-2008	Conservative 35 Percent Reduction	Optimistic 65 Percent Reduction
Brazil	15.46	-	-
Belize	22.78	14.80	7.97
Fiji	31.98	20.78	11.19
Jamaica	43.08	28.00	15.07
Mozambique / Swaziland	10.6	6.89	3.71

The analysis revealed that even at current productivity levels Moqambique/Swaziland should be able to produce ethanol competitively, this is not surprising given the demonstrated high productivity of farmlands in Swaziland, and their status is a low cost producer of cane. Under the conservative scenario, Belize, a medium-cost producer, also managed to undercut the Brazilian average. While Fiji another medium-cost and Jamaica a high-cost producer were still

[197] From USD 35.77/TC in 1976 to USD 13.09 in 2005. Van Den Wall Bake (2009) 653
[198] Van Den Wall Bake (2009) 65
[199] See section 3 for more details.

not close to feasibility levels. Not surprisingly, under the perhaps overly “optimistic” scenario all countries in the study were able to produce sugarcane at prices low enough to make sugarcane profitable versus gasoline.

These results demonstrate that even with a moderately successful rate of technology transfer, there exists a reasonable potential for low and medium-cost producers of sugarcane to successfully produce ethanol commercially. Additionally, however, based on the results, it could be argued that there is even perhaps potential for high-cost producers, such as Jamaica, given a serious enough commitment from government and private enterprise.

7 Discussion and Conclusion

7.1 Discussion

The above analysis is admittedly non-rigorous. This however does not imply that the results are not significant, but rather that further study is warranted. This is especially true in with respect to two underlying assumptions of the model. These are, (1.) the suitability of Brazilian technology in other countries, and (2.) the extent to which technology is actually transferable given the limiting factors listed in Section 2.2.2 on Technology Transfer Theories.

Despite similarities in the base productivity of land that have been used in this study, the possibility still exists that there are dramatic differences in the actual circumstances of production. This situation that exists even within Brazil, where harvesting technologies developed in Sao Paulo, have not diffused to the traditional sugarcane regions of the North East, as they are ill-suited to the mountainous terrain there[200]. This dilemma could be applied to a number of the aspects of the Brazilian system, such as the foreign applicability of cane varieties developed specifically for Brazil and the compatibility of distilleries designed for Brazilian-style factories with the varying industrial setups around the globe.

In this regard, the adaption of the Brazilian technology to specific regional conditions will be essential to the transferability of the system, as it is largely this technology that will determine the program's final profitability. This adaption of Brazilian technology and techniques however requires a fundamental understanding of their functioning, and context within the larger system. And in this regard, the volume of information about the Brazilian system is still relatively limited, as serious international interest in the system have only solidified since 2004 with ethanol's demonstrated economic competitiveness with gasoline.

Even as access to codified information grows however, there are still other geographic, cultural, and developmental barriers to the efficient spread of the technology. Take Swaziland for instance. This study has demonstrated that there is considerable potential for ethanol production in this country because it can produce ethanol at costs even below that of Brazil, using very rudimentary agricultural technology. However the significant physical, cultural and linguistic distances between the two countries significantly limits the potential for spontaneous knowledge diffusion. Further, even with specific concerted research into Brazilian technology, the extent to which Swaziland, a less-developed agrarian-based society, has the absorptive capacity to replicate the performance of an industrialized and rapidly growing country such as Brazil is questionable.

This is however, not to say that replication is impossible in this circumstance. But rather that is should be delayed to a later positions on the S-shaped curve in Figure 8, when countries with similar geography and economic development to Brazil have already begun the replication process. This is because as the network of sugarcane-ethanol producers begins to grow the cost of transferring the technology will be reduced and the number of services aimed at facilitating transfer would have increased.

In the initial stages of technology transfer support from the Brazilian government and Brazilian ethanol firms in particular will be imperative, due to their monopoly on both information and

[200] Sorvik (2011)

technology. Interestingly, such a process of expanding global ethanol markets would in fact be beneficial to these Brazilian interests. This is because with increased foreign export capacity Brazil would be able to smooth out its own volatile domestic supply of ethanol through imports, as well as to further develop the international ethanol market which is also immature and prone to volatility due to the concentration of supply from Brazil. Additional benefits could also be garnered from the sale of ethanol related technology in which Brazil is an undisputed leader.

Interestingly, such a situation has already begun to unfold between Brazil and the Dominican Republic, a country with similar geography and level of development[201]. As recently as 2011, Brazilian ethanol technology manufactures were offering 'goodwill' packages that included up to 80 percent financing of the value of equipment, consulting and installation[202]. To be sure, this is a positive step towards replication, however in the author's opinion; successful wide-scale replication of the system will need to be based on joint ventures with large Brazilian ethanol companies with both the technical ability and capital required to develop new markets.

Finally, economies of scale are considered an important aspect of the cost reductions in Brazil, especially in the industrial component of production[203]. For the purposes of this study, it was assumed that small size was a hindrance to the effective development of economies of scale. The literature reviewed, however, is not explicit on the ideal size of a given ethanol operation. In section 3.4.3 of the Methodology, it is argued that the countries in this study are several times larger than some of the most productive districts in Sao Paulo. In this regard, the island of Mauritius offers important insights. It has a much smaller land mass than any of the countries in this study, but managed to significantly increase its labour productivity in the industry and raise its cane yields by more than 25% over the same period considered in this study. Further, Mauritius actually developed the electricity cogeneration currently in use in Brazil today[204]. The example of this small island therefore shows that despite small size both technological adoption and development are possible. (See Appendix section 2 for further discussion on Mauritius.)

7.2 Conclusion and Application of the Study

The Brazilian ethanol experience has contributed positively to the economic and socioeconomic development of Brazil. It has produced the first renewable fuel that is competitive with petroleum, and represents an eloquent solution to the growing scarcity of oil and its detrimental environmental effects. The system is not a *perfect* solution to our dependence on oil for transportation; in its development there have been environmental, social and economic setbacks. However, in its totality, it remains the best example of an effective large-scale biofuel system that exists today, which warrants its replication in other countries. For geographic, economic and political reasons, developing countries with a history of sugarcane production are the most poised to benefit from this opportunity.

[201] With Brazil currently ranked at 73rd and the Dominican Republic at 88th. UNDP (2010)
[202] Kadala (2011)
[203] Goldemberg (2006), Van Den Wall Bake (2009)
[204] Deepchand (2005)

This study has empirically demonstrated that (1.) other developing countries have land as productive for growing sugarcane as that in Brazil, (2.) Brazil's efficiency is based on technological innovation, and (3.) given the transfer and adaption of this technology the Brazilian system is applicable in countries that are low to medium cost producers of sugar cane.

Though theoretical arguments for replication are sound, the practical feasibility of transfer at this point remains untested. Certainly, more rigorous empirical research is needed in accurately accessing the feasibility of the Brazilian model in *specific* countries. To this end, this author's hope that this study will act as a starting point for more detailed studies and promote further interest in the Brazilian system to developing world governments and private companies.

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9 Appendix

9.1 Basic Facts about Sugarcane and Ethanol

Sugarcane[205] *(Saccharum officinarum*) is a sugar-rich agricultural crop which grows in warm regions[206]. Sugarcane has been traditionally used as the main input for the production of commercial sugar, and is currently the source of most of the world's sugar, followed by the sugar beet. More recently however, sugarcane crops have also been used in the commercial production of ethanol (ethyl alcohol) or more specifically bioethanol[207]. The industrial process required for ethanol production shares certain initial steps with that for sugar production, and therefore sugar mills can be adapted to produce ethanol relatively easily[208].

This ethanol can be used as substitute to gasoline, either as an additive in conventional Otto cycle engines or as a standalone fuel in engines that have been specifically designed for this purpose. Per volume unit, ethanol contains about 30 percent less energy content than pure conventional gasoline, and so is slightly more restrictive for long distance journeys. However, apart from this, there are no other significant performance differences between the two fuels.

Ethanol has two major advantages over gasoline as a transport fuel: (1.) it is renewable and (2.) it is more environmentally friendly. Because ethanol is derived from plants, it is considered a renewable source of energy, limited only by the availability of land for the growth of its feedstock. Ethanol also has the advantage of being a carbon neutral fuel, as the amount of carbon emitted from its combustion is subsequently sequestered by new sugarcane crops. In addition to this it also produces significantly fewer air pollutants during combustion when compared to gasoline.

Sugarcane is currently grown in over a hundred countries, with Brazil being by far the largest producer. Bioethanol is currently produced from a number of different feedstocks[209], but the vast majority of production is generated from corn, sugarcane and sugar beets, in the USA, Brazil and the EU respectively.

9.2 Economies of scale, Innovation and the Small Island of Mauritius.

The case of Mauritian sugarcane industry is an interesting one. It was excluded from the countries in the main part of this study because of the impressive developments that the country has made in its sugarcane industry and because they have already begun to establish an ethanol program there[210]. Mauritius is a very small island, roughly one-eighth the size of the smallest country in this study, Jamaica. However, despite this limited size, the island nation was able to increase yields by roughly 25 percent between the period 1961 and 2009, demonstrating that there is indeed scope for increased production efficiencies on a smaller scale than the Brazilian example. Similar to the Brazilian example in many ways, the success of

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[205] Is also referred to as "sugar cane" in many sources. The Oxford Dictionary, a British source, separates the two words: "sugar cane," while the Merriam-Webster, an American source, conjoins them into a single word "sugarcane." For the purposes of this study, the latter will be used.

[206] Roughly speaking this encompasses regions of latitude below 30 degrees Celsius.

[207] The classification for ethanol derived from plants as opposed to synthetic ethanol, which is derived industrially.

[208] Goldemberg (2009), 23

[209] Including rye, sweet sorghum, wood, whey, potatoes, grass among other sources.

[210] Lane (2007), GOM (2005)

the Mauritian example can also be connected with technology. Organized sugarcane research commenced more than a hundred years ago, with a focus on breeding, nutrition, plant protection and the processing of sugarcane. This legacy was solidified in the Mauritius Sugar Industry Research Institute (MSIRI) which was founded in 1953. Interestingly however, it was not founded by the government, but rather a collection of private interests in the sugar industry[211]. Today the MSIRI boasts an impressive industry of services ranging from geographic information systems, irrigation, land preparation and plant breeding to advisory services on mechanization, technology and engineering[212].

In tandem with Mauritius' technical prowess, the island's relative success in the sugarcane industry is also due to constant efforts by government and the industry to maintain the industry. In recent history the island boasts a slew of national industry strategy reports focused on sustaining and improving the profitability of the industry[213]

Appendix Figure 24. Percentage Change in Sugarcane Area

countries	country codes	item	item codes	element	element codes	1975	2009	percentage change
Brazil	21	Sugar cane	156	Area Harvested (Ha)	31	1969230	8514370	332%
Belize	23	Sugar cane	156	Area Harvested (Ha)	31	20234	24292	20%
Fiji	66	Sugar cane	156	Area Harvested (Ha)	31	44921	49000	9%
Jamaica	109	Sugar cane	156	Area Harvested (Ha)	31	61915	30800	-50%
Swaziland	209	Sugar cane	156	Area Harvested (Ha)	31	16579	52000	214%

Source: FAO (2011)

Appendix Figure 25. Sugarcane Yields (Hg/Ha) the Five Comparison Countries 1962-1975

countries	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Belize	502120	439153	522102	527682	567488	502163	414703	444375	569723	536815	502161	549599	502189	393242
Brazil	426385	422282	436982	444864	463390	458640	454195	450015	462303	465164	472117	469649	464939	464773
Fiji	522118	666928	566363	516134	514063	493617	619511	505039	625551	537531	512093	550561	478836	480870
Jamaica	544818	780302	769406	795200	805653	740618	728873	718036	707155	694929	704136	628900	615483	578137
Swaziland	988513	558173	783473	715610	1190975	1163414	1024169	1033198	1205611	1068025	1165142	1033640	1075930	1141383

Source: (FOA 2011)

211 Larson (2001) 28
212 MSIRI (2011)
213 GOM (2005)

Appendix Figure 26. Share of Agricultural Land Dedicated to Sugarcane Production 1980 and 2009

	Hectares	1980	2009	Percentage Changes
Brazil	Total Area	49618048	65342482	32
Brazil	Sugarcane Area	2607630	8514370	227
Brazil	**Sugarcane Proportion**	**5,3**	**13,0**	**148**
Belize	Total Area	47801	82863	73
Belize	Sugarcane Area	24281	24292	0
Belize	**Sugarcane Proportion**	**50,8**	**29,3**	**-42**
Fiji	Total Area	85391	140597	65
Fiji	Sugarcane Area	66000	49000	-26
Fiji	**Sugarcane Proportion**	**77,3**	**34,9**	**-55**
Jamaica	Total Area	187471	160022	-40
Jamaica	Sugarcane Area	51000	30800	-15
Jamaica	**Sugarcane Proportion**	**27,2**	**19,2**	**-29**
Swaziland	Total Area	158373	146327	-8
Swaziland	Sugarcane Area	25829	52000	101
Swaziland	**Sugarcane Proportion**	**16,3**	**35,5**	**118**