8-2016

# Economic viability of flexible biogas pumps in Bangladesh

Saima A. Matin

*Purdue University*

## Recommended Citation

Matin, Saima A., "Economic viability of flexible biogas pumps in Bangladesh" (2016). *Open Access Theses*. 954.
https://docs.lib.purdue.edu/open_access_theses/954

# PURDUE UNIVERSITY
# GRADUATE SCHOOL
# Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Saima A. Matin

Entitled

ECONOMIC VIABILITY OF FLEXIBLE BIOGAS PUMPS IN BANGLADESH

For the degree of Master of Science

Is approved by the final examining committee:

| | |
|---|---|
| Chair<br>Juan P Sesmero | |
| Co-chair<br>Benjamin M Gramig | |
| Co-chair<br>Gerald E Shively | |

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy of Integrity in Research" and the use of copyright material.

Approved by Major Professor(s): Juan P Sesmero

Approved by: Kenneth A Foster 6/30/2016

Head of the Departmental Graduate Program Date

# ECONOMIC VIABILITY OF FLEXIBLE BIOGAS PUMPS IN BANGLADESH

A Thesis
Submitted to the Faculty
of
Purdue University
by
Saima A. Matin

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science

August 2016
Purdue University
West Lafayette, Indiana

# TABLE OF CONTENTS

# LIST OF TABLES

# TABLE OF FIGURES

# ABSTRACT

Matin, Saima. M.S., Purdue University, August 2016. Economic Viability of Flexible
Biogas Pumps in Bangladesh. Major Professor: Juan P. Sesmero.

This study examines the economic viability of flexible irrigation pumps that can run on biogas as well as diesel fuel in Bangladesh. Such examination faces two main hurdles. First, the ease with which farmers running flexible pumps can switch from one energy source to another is unknown and perhaps highly heterogeneous. Second, diesel prices in Bangladesh are volatile and limited information precludes direct estimation of their probability distribution. We address the first issue by evaluating the economics of flexible pumps for varying degrees of inter-fuel substitutability. To deal with the second issue, we model the probability distribution of Bangladeshi diesel prices conditional on prices in India (these markets are integrated) plus a directly estimated distribution of the error-in-prediction. Our analysis identifies conditions (patterns in diesel markets, inter-fuel substitutability, and policy) that would render flexible pumps economically attractive. Results show that flexible pumps can generate large benefits for Bangladeshi farmers.

# CHAPTER 1. INTRODUCTION

Agriculture plays a major role in the growth and stability of the economy of Bangladesh, contributing 20% to the national GDP, and providing employment for 63% of the population. Of the country's arable land, 33% is under single cropping, 45% under double cropping, 12% triple cropping and 10% is cultivable waste and currently fallow land (FAO STAT, 2007). Irrigation is a key agricultural input in Bangladesh, provided high rainfall variability driven by the monsoon phenomenon. Though the country has abundant surface water resources, particularly in the monsoon season, its flat deltaic topography and the instability of major rivers make large irrigation systems both technically difficult and costly (FAO STAT, 2007).

Rice is considered a typical staple food for the people of Bangladesh, and it constitutes about 90% of the total food grain production (Huda, 2001). Boro, winter season, (in which some varieties of rice are widely grown) alone contributed and continues to contribute the highest share of total rice production since 1998-99 (BER, 2007). Therefore, high productivity of boro season is key to overcome food deficiency in the country. Rice cultivation during boro season starts from October to March and it grows completely under irrigated conditions. Therefore, irrigation plays a vital role in the country's agriculture, food and labor sectors.

For a land sparse country with a population expected to increase to 175 million by 2025, Bangladesh faces the challenges inherent in intensifying agriculture and maintaining self-sufficiency in food grains. Recently, the Bangladesh Water Development Board (BWDB) has taken a critical step forward to introduce a new approach in the south-eastern part of the country. It will improve maintenance of current major irrigation systems by assessing, planning, financing, and implementing the operations. If successfully implemented it will have a profound impact on food security, water use efficiency and sustainable growth of the country (ADB Annual Report, 2012).

In Bangladesh, about 94% of the irrigated land is under small and minor irrigation devices such as shallow tube wells, deep tube wells, low lift pumps, manual and indigenous pumps. According to a recent survey, water is being lifted in this country through 4.7 million shallow tube wells, 26,704 deep tube wells, 56,829 low lift pumps, 142,132 manual pumps, and more than 565,000 indigenous water lifting devices (Banglapedia, 2015). Nearly 22% of farm households now own 1.3 million shallow tube wells that provide irrigation to 10 million to 15 million farm households (Hossain, 2009). But sub-optimal use of these irrigation devices and unplanned cropping activities has resulted in low irrigation coverage. With proper utilization and improved management, 4 to 5 million hectares of land can be irrigated using this number of devices. Yet, only 3.12 million hectares are currently irrigated, resulting in an irrigation efficiency of about 30% (Banglapedia, 2015).

Availability of energy at reasonable cost is key for irrigation, as pumps run on one type of energy or another. Electricity supply in Bangladesh is typically insufficient to cover demand. Total electricity demand is 6000 MW, whereas total production amounts to 4000-

4600 MW (Biswas et al., 2011). As of 2014, only around 55% of the urban population in Bangladesh has access to electricity (Energypedia, 2016). Government-imposed upper limits on price results in power outages that cause frequent disruptions in irrigation. Yet, until not long ago, irrigation pumps were to a large extent driven by electricity due to its relatively low cost. Recently, a large number of pumps have been converted to diesel. But diesel price is volatile and can get, at times, prohibitively high. For example, diesel fuel cost rose from BDT 16 in 2000 to BDT 61 in 2012 per litre (Mujeri, Chowdhury and Shahana, 2013). Under current conditions in energy supply, renewable energy conversion technologies may offer an attractive alternative to conventional, fossil fuel-based energy sources.

The Bangladeshi government has already started to address these challenges by supporting development of renewable energy resources such as biomass, biogas, solar and wind energy. Irrigation pumps powered by renewable energy sources have been successfully deployed in other developing countries. One of the most common options has been solar pumps. For instance, solar pumps have been successfully disseminated in Benin, a region with little accessibility to grid electricity and where groundwater is too deep to access using traditional pumps for the study (Burney et al., 2009). Solar pumps are also increasingly popular in India and Bangladesh, where electricity grid coverage is very limited (World Bank, 2015). But there are some disadvantages associated with these pumps as well. The pumps can only be used during certain periods of the day. In particular, they can typically run from 10 am to 4 pm, when solar radiation is highest but evaporation is also highest, reducing the application efficiency. In addition, energy shortages associated with dependence on solar radiation may result in water deficiency for the crop (The Hindu, 2013)

Biogas, an emerging renewable energy source, uses materials such as cow waste and rice husks, which are abundant in developing countries, like Bangladesh. Small plants run by households can produce biogas. More importantly, a new “flexible” technology is now available, that can allow the irrigation pumps to switch between diesel and biogas. The goal of our study is to investigate the economics of adopting flexible irrigation pumps in Bangladesh. Two important features complicate the analysis. First, historical data on diesel price in Bangladesh are very limited. Second, the speed with which farmers can switch fuel sources in response to price swings is unknown. We address the first by modeling the probability distribution of diesel prices in Bangladesh as a function of: 1) the estimated distribution of prices in India, and 2) an error-in-prediction term, the distribution of which is also estimated. Finally we estimate a generalized logistic function that captures varying degrees of responsiveness of farmers to swings in relative prices of energy sources.

# CHAPTER 2.  PROMISING ASPECTS OF BIOGAS IN BANGLADESH

Biogas has been around in Bangladesh for a decade and it is an increasingly popular energy source, specifically in rural areas. The first floating drum biogas plant, which is mainly used for digesting animal waste, was established in 1972 at Bangladesh Agricultural University (BAU). Many government institutions such as the Local Government Engineering Department (LGED), Department of Environment (DOE), Bangladesh Agricultural Development Corporation (BADC) and NGOs like BRAC, and Thengamara Mohila Sabuj Sangha (TMSS) had successfully constructed almost 30,000 biogas-based installations (biogas is mainly used for cooking purposes) in different parts of the country by 2004 (REEIN, 2004). One of the reasons for this is that agricultural operations (e.g., ploughing and harvesting) are not mechanized, so livestock is mainly used for such operations. Therefore, a relatively large amount of livestock waste is available for biogas production.

Bangladesh is also the 6th largest producer of rice in the world, producing around 34 million metric tons per year (FAO STAT, 2012). Rice husk is a major by-product of rice and it has been considered a waste in the past. Rice husk has also been increasingly used for biogas production in Bangladesh. Infrastructure Development Company Limited (IDCOL) financed the first and only power plant based on biomass gasification with a capacity of 250 kW at Kapasia, Gazipur district. Construction of this plant benefited from concessionary loans and grants provided by IDCOL, IDA, UN and the Global Environmental Facility. The plant uses locally available agricultural residues (primarily rice husk) as fuel for power generation. The project started commercial operation in 2007. Around 20% of rice husk is made up of ash and the ash coming from the gasifier contains 10 to 15% carbon by weight. The ash-laden water can be used as organic fertilizer or for land filling. The plant has on site storage facility for ash. Char can be transformed into charcoal, which is used as a domestic fuel for cooking and heating. Tar can be either recycled or burnt in the gasifier or used as black paint for wood typically used in boats and wooden structures. Tar is also used for construction of roads. The plant has onsite storage capacity to deposit waste water which needs to be changed every three months (IDCOL, 2013).

Early adoption was hampered by people’s misconceptions about biogas. As noted by Forida Yesmin, a local official for Grameen Shakti (a non-profit village renewable energy scheme linked to the micro credit lender Grameen Bank), it was generally believed that biogas would contaminate their dwellings and food, and even cause explosions. But evidence suggests that these fears were eventually overcome, resulting in increased adoption of biogas. The number of biogas users in Gazipur district has increased from around 200 in 2010 to 450 in 2015, according to (Grameen Shakti, 2012). Under the National Domestic Biogas and Manure Program (NDBMP) implemented by IDCOL, about 5,700 biogas plants have been constructed in Bangladesh in the year of 2010, shown in Figure 1 (IDCOL, 2013).

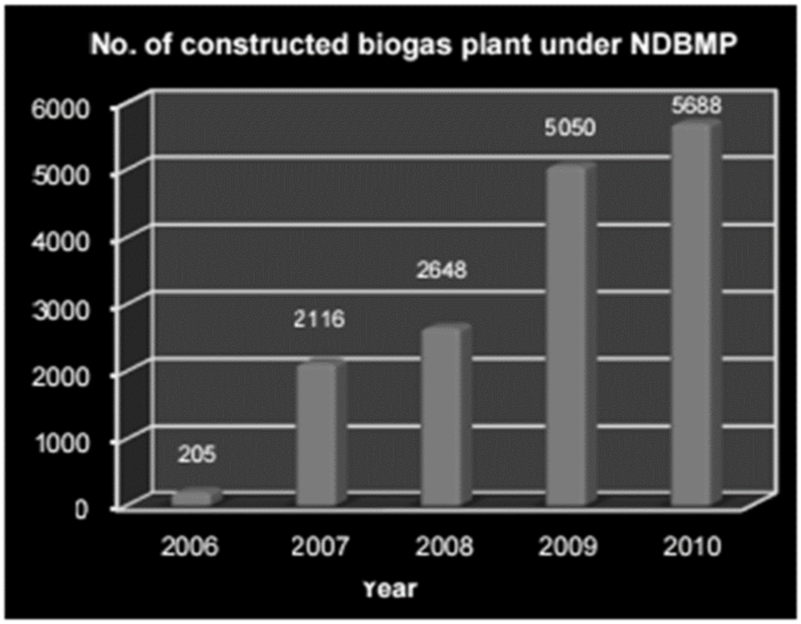

Figure 1: Biogas Plants Construction in Bangladesh under NDBMP

The United Nations and a number of NGOs have also undertaken massive development projects in Bangladesh, which resulted in 41,000 biogas plants using either animal wastes or rice husks as raw materials (Islam, 2009). These small biogas plants are being used primarily for cooking purposes. There is potential to produce 2.7 billion $m^3$ biogas from 4 million small-scale biogas plants using livestock waste in Bangladesh (Bahauddin and Salahuddin, 2012).

The Bangladeshi government has a comprehensive program that supports modification of petrol/diesel-based 4-stroke engines to also run on compressed natural gas (CNG) in private vehicles (Iqbal, Iqbal and Salahuddin, 2011). The conversion technology enables low maintenance and reduces fuel cost up to 60% (Navana, 2011). The program consists of tax breaks to vehicle owners who implemented the modification to run their vehicles on flexible engines. So far, about 194,000 vehicles have been converted (Iqbal, Iqbal and Salahuddin, 2011).

This technological conversion can also be used to modify diesel-fueled irrigation pumps to run on CNG, and more specifically compressed biogas. A key advantage of modified engines is their flexibility in terms of the energy source used, which is important when volatility in relative prices is high. In particular, the modified engines allow users to run the pump on biogas when diesel prices are high, and switch back to diesel when prices are low enough to make it less costly than biogas. Therefore, a critical factor in the economics of flexible pumps is the speed with which users can adjust fuel source to price swings in combination with the frequency and magnitude of such price swings. Our analysis captures this along with other key aspects of the transition from conventional to flexible pumps.

# CHAPTER 3. LITERATURE REVIEW

## 3.1 General Literature on Energy/Irrigations Problems in Bangladesh

The development of small-scale irrigation is considered a vital part of the Bangladeshi Government's strategy for agricultural development (FAO STAT, 2016). Large scale irrigation (conducted through major canals) currently only covers 6% of total irrigated land. The other 94% is irrigated through systems deemed minor or small scale. They consist of low lift pumps (LLPs: power operated centrifugal pumps drawing water from rivers, creeks and ponds), shallow tube-wells (STWs: with a motorized suction mode pumping unit), deep tube-wells (DTWs: with a power operated force mode pumping unit), manually operated pumps (MOPs: extracting water from a shallow tube-well), and traditional systems (FAO STAT, 2016).

During the dry season, the water level sometimes falls beyond the suction level of LLPs. However, it is possible to pull water by placing STWs in a pit. A STW in a pit is called a deep-set shallow tube-well (DSSTW) or a very deep-set shallow tube-well (VDSSTW). If static water levels fall further (over 10.7 m), a submersible or vertical turbine (FMTW: force mode tube-well) is required to fix this issue. STW, DTW and FMTW that are driven by motors/pumps account for over 80% of total irrigation (FAO STAT, 2016). This implies that accessibility to energy to lift water up is of the upmost importance for agricultural irrigators. Parvin and Rahman (2009) conducted a study focusing on the spatial pattern of irrigated agriculture in Bangladesh and its impact on food grain production during the past three decades. The study revealed a strong correlation between productivity of Boro rice production and food security. The study also showed a strong correlation between Boro rice production and irrigation; in fact it found a correlation of 0.98 between irrigation and Boro rice production implying that virtually all Boro rice is produced under irrigation and virtually all irrigated areas produce Boro rice (the remaining irrigation water usage is typically allocated to wheat and other winter crops). These links underscore the importance of irrigation on food security in Bangladesh. Therefore not only access to irrigation but the cost at which farmers access it are key to their livelihoods.

Farmers in Bangladesh have typically relied on irrigation pumps that run either on electricity or diesel fuel. Currently, there are about 1.34 million diesel pumps and 270,000 electric-run pumps in Bangladesh. Every year, diesel pumps consume 1 million tons of diesel (World Bank, 2015). Recognizing the important role of irrigation on food security, and the importance of the cost of diesel on irrigation, the Bangladeshi Government subsidizes diesel fuel. But regardless of the cost, transporting diesel fuel to agricultural lands is not always easy and its supply can be unpredictable. Poor farmers often face less than competitive diesel markets in which middlemen charge higher diesel prices during times of peak irrigation demand, adversely affecting the profitability of farming (World Bank, 2015). Other disadvantages of diesel pumps are: 1) these pumps frequently break down and have higher maintenance costs (World Bank, 2015) and 2) greenhouse gas emissions adversely affect the environment.

## 3.2 Recent Developments on Biogas and Flexible Pumps

A previous study (Kabir, Palash and Bauer, 2012) conducted a cost-benefit analysis on biogas plants, though not pumps, in Bangladesh. As biogas is viewed as an innovative and promising option towards a plausible solution to the existing energy problems in Bangladesh, this study examined the cost-capacity relationship of biogas plants, while also analyzing their financial and economic feasibility. Data were collected from 150 biogas plants from four districts of Bangladesh. The sample included three types of plants: small, medium and large. Measures of economic performance such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), and Net Benefit Increase (NBI) were used to evaluate their economic feasibility. Multiple scenarios were considered in this evaluation. Plants were compared under the presence and absence of adoption subsidies and carbon trading schemes. They were also compared including and excluding health benefits and income generated from time savings.

Results in Kabir, Palash and Bauer (2012) suggest that biogas plants seem to be economically viable in Bangladesh. But they also indicate that upfront capital required for investment may constitute a significant hurdle for potential adopters. Therefore, subsidies and credit played a vital role in adoption. This study also concludes that there is great potential in Bangladesh for adoption of biogas plants, especially in livestock producing areas (Kabir, Palash and Bauer, 2012).

In addition to livestock waste, biomass can be used as feedstock for the production of compressed gas. Biomass gasification, which is a new and promising technology in Bangladesh, has been used to produce electricity, a very scarce resource in the Bangladeshi country side. Ferdous et al. (2014) studies the availability, proper selection and quality of biomass throughout the country and utilization of by-product released by the biogas plant. The first biomass power plant in Bangladesh was installed in Kapasia and generates power from rice husk. Installation and operation of this plant has been considered a milestone in the development of renewable energy in Bangladesh. The authors also conclude that, while promising, these sources of energy require government support; both in terms of financial and human capital.

The advent of biogas production is being combined with engine modification technologies to convert traditional agricultural irrigation pumps to flexible ones that could run on either compressed gas or diesel. Several programs supporting deployment of these technologies have been implemented in developing regions of the world. The next sections survey such experiences and their performance.

## 3.3 Analyses of Biogas-fueled Irrigation Pumps

Teleghani and Kia (2003) conducted a techno-economic analysis of irrigation pumps run on biogas produced in the city of Saveh, 150 km from Tehran, Iran. The authors discuss the economic, social and health effects of the biogas plant. The plant produced biogas not only to power irrigation pumps but also to be used as fertilizer. Irrigation pumps powered with biogas extracted, on average, 31,000 $m^3$ of water per year. Pakistan, an energy scarce country is also using biogas to satisfy energy requirements of rural areas.

One drawback of biogas observed by (Taleghani and Kia, 2003) was the limited geographical scope of distribution networks. This constrains the area that can be served by a biogas producing plant. However, distribution has been greatly improved in recent years by the introduction of bottling. A case study conducted by (Ilyas, 2006) analyses a model to bottle the biogas in cylinders and then carry them to rural areas. The study found that use of bottled biogas could result in significant cost savings and employment opportunities.

Purohit and Kandpal (2007) conducted a techno-economic evaluation of biogas-only water pumping systems in India. Both electricity and diesel are being used as the main energy sources for irrigation pumps in India. The objective of their paper was not only to examine the economic viability of this technology but also quantify the potential reduction in the amount of $CO_2$ released into the atmosphere. Results show that biogas irrigation pumps can be an economically attractive alternative to conventional technologies. The authors recommended that efforts should be made for large-scale dissemination of community biogas based water pumping systems in different parts of India. However, the authors did not consider the randomness of diesel price and the impact of diesel price changes on the economic viability of biogas driven pump.

Abdel-Galil et al. (2008) tested an innovative method for handling, storing and utilizing biogas in Egypt to power irrigation pumps. Starting with gasoline as fuel, a spark ignition engine was modified to allow the irrigation pump to run on biogas. Then an inner tube (filled with biogas by using a modified car compressor) of tractor tire was used to transfer the biogas from the digester to the pump. The study undertook a comparison between biogas and liquid fuels (kerosene and gasoline). Results showed that the introduction of biogas capabilities reduced energy consumption by 80% when compared to conventional energy sources, under a 2500-rpm engine speed. The total pump efficiency of biogas operation was about 60%.

In Bangladesh the history of flexible irrigation pumps is a very recent one. In 2014, Practical Action Bangladesh, (WAME, 2014) implemented a biogas fueled irrigation pump pilot project in the Faridpur district. This region has dry season from April to June when the water level in both surface and underground sources decrease. This makes irrigation physically difficult and economically costly as it requires more energy and manpower. There are currently 300 small-scale (1.2 cubic meters to 4.8 cubic meters) biogas plants in the district, though not all of them are actively used. Biogas produced with these plants is mostly used as a backstop technology; they are used to replace other fuel sources such as wood, dry leaves or cow waste when they are not available. But they usually are. As a result, they often find it convenient to shut down the plant instead of paying for repair and maintenance costs.

Practical Action, Bangladesh is now working to add more value to biogas. Specifically, using biogas to run irrigation pumps. People under the project are using dual engines where biogas and diesel are mixed in a fixed ratio, but biogas is used as primary fuel. These engines use 400 kg paddy per hour, which costs BDT 35-45. Beneficiaries are using 3 inch boring pipe in deep tube wells, with which they can irrigate their land during the dry season. Once more, the diesel savings associated with these pumps look promising. The NGO is now expanding support by providing decentralized technical solutions to the end users. The goal of the NGO is to reach 500,000 beneficiaries within the next 5 years.

Dual engines permit use of biogas and diesel in a fixed proportion. Therefore they are limiting in the sense that the user cannot switch between energy sources in response to changes in relative prices. This study focuses on the economic viability of flexible pumps, as opposed to dual ones. While flexible pumps have been adopted in India and Egypt, they have yet to penetrate the market in Bangladesh despite promising supply of feedstocks (biomass and livestock waste). Our analysis aims at filling the informational gap regarding the economic viability of flexible pumps in Bangladesh.

# CHAPTER 4.  METHODOLOGY

## 4.1 The Model

We consider two types of pumps in our study, a conventional pump and a flexible pump. We refer to the typical diesel-driven irrigation pump used for irrigation in Bangladesh as the conventional pump. We focus on diesel-powered pumps (as opposed to electricity-powered ones) as they constitute the overwhelming majority of currently operated pumps. We define a flexible pump as the conventional pump with an added mechanism, which enables the pump to be run with compressed biogas, as well as diesel.

Our goal in this study is to compare the conventional and flexible pumps based on their cost to extract a unit of water from a given source. We assume that it requires exactly the same amount of energy (mega joules) to extract a fixed amount of water irrespective of the fuel. A typical conventional pump irrigates on an average 25 hectares of land annually in Bangladesh (AQUASTAT, 2011). Therefore, we calculate the cost per unit of energy (BDT/mega joules) under each type of pump with a coverage of 25 hectares. We start with the premise that farmers will be more likely to adopt a flexible pump if the per unit energy cost of pumping water ($C_f$) is lower than that of pumping with a conventional technology ($C_c$); in other words, flexible pumps will be attractive insofar as they generate savings on water pumping:

$$f(C) = C_c - C_f = \begin{cases} < 0 & \mathit{Flex\ results\ in\ increased\ cost\ of\ pumping} \\ \geq 0 & \mathit{Flex\ generates\ savings} \end{cases} \tag{1}$$

The per unit cost of pumping under the conventional pump can be written as:

$$C_c = FC_c + VC_c, \tag{2}$$

and the cost under the flexible pump is:

$$C_f = (1 - u)C_c + uC_b, \tag{3}$$

where $C_c$ is as defined before and $C_b$ is the cost per unit of water pumped when the flexible pump completely runs on biogas:

$$C_b = FC_b + VC_b. \tag{4}$$

The parameter $u$ denotes what fraction of biogas in total energy used by the flexible pump. The support of $u$ is [0, 1], where $u = 0$ means that the flexible pump completely runs on diesel and $u = 1$ means it runs completely on biogas. $FC_k$ and $VC_k$ denote the (annualized) fixed and variable costs: $k = b$ when the pump runs on biogas, and $k = c$ when the pump runs on diesel.

Combining equations 1 and 3, we re-write equation 1 as follows:

$$f(C) = u\,(C_c - C_b) \tag{5}$$

The usage parameter, $u$, is not a constant in our model. It depends on the per unit energy cost difference, $C_c - C_b$, as well as the flexibility allowed by the pumping technology. For example, if $C_c$ is substantially lower than $C_b$ then $u$ will probably tend to 0. Conversely if $C_c$ is substantially higher than $C_b$ then $u$ will probably tend to 1. But small price swings around $C_c - C_b$ may not trigger large behavioral changes. This would suggest a non-linear relationship between the fraction of energy from biogas and the cost difference. Hence, we model the usage parameter with a logistic function that captures potential non-linearity or rigidities in behavioral responses and, also, the expected asymptotic behavior of the fraction $u$:

$$u = \frac{1}{1+e^{-k(C_c - C_b)}} \tag{6}$$

By using a logistic function we restrict the fraction $u$ to the interval [0, 1] and the behavioral response to changes in relative water pumping costs (i.e. the inter-fuel substitutability) is fully captured by a single parameter, $k$.

The cost of extracting water using diesel depends on the diesel price, which can vary widely over time. Therefore the cost per unit of energy with a diesel-fueled pump can be, at times, higher or lower than that with biogas. A flexible pump allows the irrigator to switch between energy sources, so as to use the least expensive one. The parameter $k$ captures the speed of fuel switching. Higher $k$ means faster response. This parameter is influenced by the ease with which the technology allows the switch. But it is also influenced by behavioral factors including farmers' information and responsiveness. These may in turn be influenced by his/her characteristics (e.g. age, education, and experience), financial constraints, and farm size (van Winsen et al., 2014).

Figure 2 illustrates how the fraction of total energy coming from biogas responds to changes in the relative cost of diesel under alternative levels of flexibility. When the farmer using a flexible pump is completely unresponsive to changes in cost ($k = 0$), the logistic function converges to a straight line at a predetermined fraction, $u = 0.5$. As flexibility increases the logistic function becomes positively sloped, and the inflection

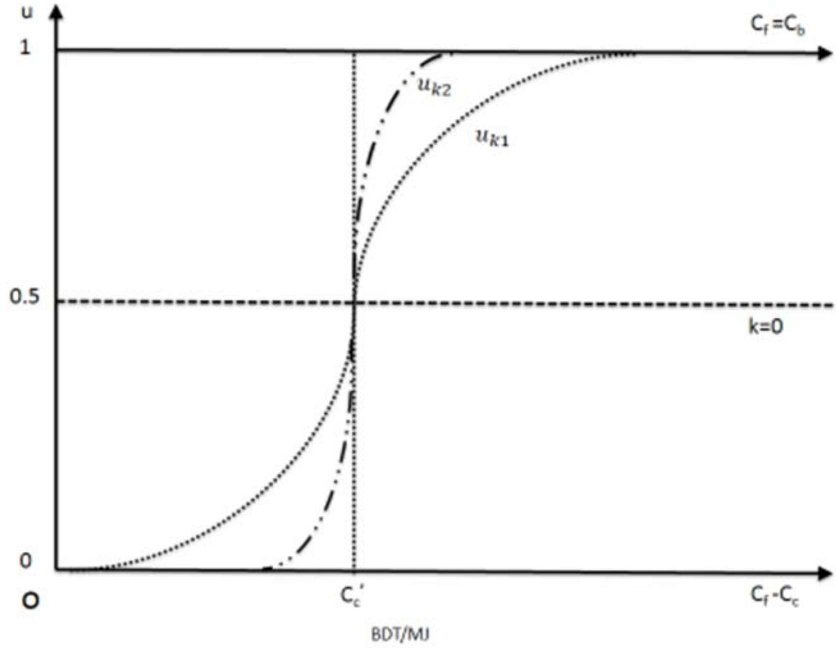

Figure 2: Relative Cost of Biogas and Fuel Mix under Low and High Flexibility

point is always located at the coordinates $C_c - C_b = 0$ and $u = 0.5$. Moreover, as $k$ increases (e.g. from $k1$ to $k2$ in Figure 2) the portions of the curve to the left and right of the inflection point move closer to zero. Asymptotically, when flexibility is perfect ($k = \infty$), $u = 0$ if $C_c < C_b$, $u = 1$ if $C_c > C_b$, and $u \in [0,1]$ if $C_c = C_b$; so the logistic curve converges to a staircase function.

Figure 3 illustrates the cost of irrigation under the conventional and flexible technologies. Under the conventional technology, diesel is the only energy source used. Therefore the cost of water extraction is equal to $C_c$, which is represented by the 45° line in Figure 3. On the other hand, when the farmer uses a flexible technology the cost curve will depend upon the ease with which the farmer switches from diesel to biogas. Under zero flexibility ($k = 0$), the cost per unit of water extracted is the simple average between

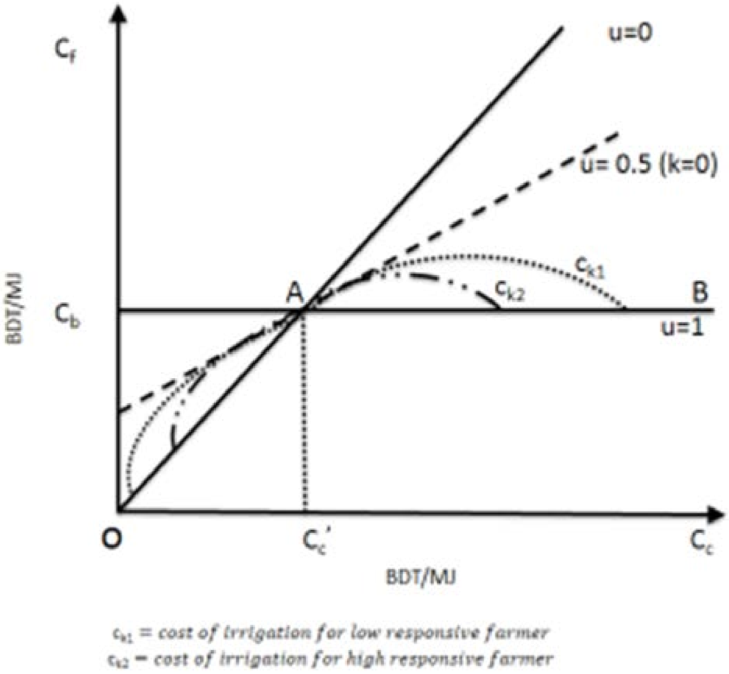

Figure 3: Relationship between Costs and Usage Parameter

the extraction cost using diesel and the cost using biogas. This is lower (higher) than the cost with a conventional pump if diesel is more (less) costly than biogas. Under $k = 0$ biogas constitutes 50% of total energy used. Therefore, when diesel is cheap the conventional pump results in savings (relative to the flexible) as it uses only the cheaper energy source (diesel). Savings from the conventional pump are captured in Figure 3 by the vertical distance between the dashed straight line and the 45$^{o}$ line to the left of $C_c{}'$.

When farmers can switch from one source to another in response to prices ($k > 0$), the per unit cost of extraction is lower than the one achieved under $k = 0$. Take for instance a flexibility of $k1$. As illustrated in Figure 2, when the cost of using diesel is low the farmer will reduce the fraction of biogas in the fuel mix below 50%. The magnitude of that reduction will depend on the ease with which substitution takes place; the higher $k$ the lower the share of biogas in the mix when $C_c < C_b$. Therefore the per unit cost of extraction will be a weighted average between $C_c$ and $C_b$, with a higher weight on $C_c$, the cheaper source. This will be lower than the simple average under $k = 0$. This is illustrated by concave cost curves in Figure 3. The higher the flexibility, the lower the cost; which is why the curve $c_{k2}$ is below $c_{k1}$ (k2>k1).

In figure 3, point A ($C_c = C_b$) coincides with the inflection point of the logistic curve in Figure 2, regardless of the value of $k$. Moreover, the distance between a curve with $k > 0$ and the line when $k = 0$, represents the savings associated with flexibility. These savings increase when the cost of diesel is very large or very small. Savings vanish when $C_c = C_b$, in which case the per unit cost of extraction is independent of the biogas fraction. But the use of a flexible pump will still result in higher irrigation cost than a conventional one when the cost of diesel is lower than the cost of biogas at pump level. This is because the conventional pump relies completely on the cheaper energy source. Nevertheless, as flexibility grows without bound ($k \to \infty$), the logistic function in Figure 2 converges to a staircase function with a jump at $C_c - C_b = 0$, and the cost curve in Figure 3 converges to the piecewise linear function OAB.

### 4.2. Calculating Cost Parameter Values

The cost of extracting water with a flexible pump is comprised of the cost of producing and delivering the biogas to the pump, and the (annualized) cost of converting the pump to make it flexible. The former includes two parts: i) producing biogas in a biogas plant and ii) delivering the produced biogas to the flexible pump. The (annualized) cost of installing the biogas plant, producing the biogas, and delivering it to the user. We calculate the annualized capital cost ($CC_b$), maintenance cost ($MC_b$), annual input energy cost in order to run the biogas plant ($EC_b$), cost of compressing/bottling biogas ($BC_b$) and transportation cost of bottled biogas to the pumps ($TC_b$) in order to calculate the total biogas cost at the pump. Next, we convert the plant's energy output from m$^3$/day to mega joules ($EO_{plant}$) per year, so that cost of extracting water can be expressed on an energy basis.

For pumps to become flexible, a conversion mechanism needs to be added that allows a conventional pump to be able to run with biogas. So, we calculate the annualized cost of converting a conventional pump to a flexible pump ($XC_b$) and then divided it by the pump's annual energy consumption ($EO_{pump}$) to obtain the per unit energy cost. Therefore, both terms of equation (4) can be expanded to:

$$FC_b = (CC_b + MC_b)/EO_{plant} \qquad (7)$$

$$VC_b = \frac{EC_b+BC_b+TC_b}{EO_{plant}} + X\,C_b/EO_{pump} \qquad (8)$$

Similarly, we calculate the per unit energy cost of a conventional pump. In this case, we do not need to calculate the cost of diesel production because the cost of extracting, processing, and transporting diesel fuel are already included in the diesel fuel price ($P$). At first, we use the data to obtain how much diesel fuel in liters ($DQ$) is usually required annually at a typical pump coverage area (25 hectare) in Bangladesh (AQUASTAT, 2011). We calculate the energy equivalent of that amount of fuel ($EO_{diesel}$). Considering the capital and maintenance cost of an irrigation pump, both terms of equation (2) can be expanded to:

$$FC_c = (CC_c + MC_c)/EO_{diesel} \qquad (9)$$

$$VC_c = DQ * P/EO_{diesel} \qquad (10)$$

The values of the above mentioned parameters are given in Table 1.

Table 1: Parameter Values (Annualized)

| **Parameter** | **Unit** | **Value** | **Source** |
|---|---|---|---|
| **$FC_b$** | BDT*/MJ** | .59 | Author's calculations |
| **$CC_b$** | BDT | 4397.23 | Kabir, Palash and Bauer, 2012 |
| **$MC_b$** | BDT | 1986.36 | Kabir, Palash and Bauer, 2012 |
| **$VC_b$** | BDT/MJ | .90 | Author's calculations |
| **$EC_b$** | BDT | 2477.52 | DESCO, 2015 |
| **$BC_b$** | BDT | 4055.55 | Kapdi et al, 2006 |
| **$TC_b$** | BDT | 2063.88 | D'Sa and Murthy, 2004; author's calculations |
| **$EO_{plant}$** | MJ | 10731 | Islam, 2011 |
| **$XC_b$** | BDT | 34252.6 | Times of India |
| **$EO_{pump}$** | MJ | 352745.86 | Author's calculations |
| **$FC_c$** | BDT/MJ | .02 | Author's calculations |
| **$CC_c$** | BDT | 7626.47 | Valle et al, 2014 |
| **$MC_c$** | BDT | 1591.24 | Author's calculations |
| **$VC_c$** | BDT/MJ | Random/Simulated | Author's calculations |
| **DQ** | Liter | 8305.15 | Islam, 2011 |
| **P** | BDT | Simulated | Global Petrol Prices, 2016; author's calculations |
| **$EO_{diesel}$** | MJ | 298154 | Author's calculations |
| **$C_b$** | BDT/MJ | 1.49 | Author's calculation |
| **$C_f$** | BDT/MJ | Simulated | Author's calculations |
| **$C_c$** | BDT/MJ | Simulated | Author's calculations |

*BDT= Bangladeshi Currency (1 USD= 78.28 BDT)

**MJ= Mega joules

In Bangladesh, there are typically three types of plants available for biogas generation. The small, medium and large plants generate 2.4, 3.2 and 4.8 m$^3$/day of biogas respectively. The investment cost for such small, medium and large plants are BDT 29,949 ($382), BDT 31,909 ($407) and BDT 41,972 ($535) respectively (Kabir, Palash and Bauer, 2012) .The most commonly used plants in rural Bangladesh are small and medium, due to capital constraints and ease of maintenance. For our study, we consider only the small plant. The investment for such a plant is divided into two parts: a total of BDT 21,249 is financed through a loan, and the other part, BDT 8700, is covered by a government subsidy (Kabir, Palash and Bauer, 2012) .We annualize investment costs under the assumption that the plant's life period is 15 years using a discount rate of 12% (Kabir, Palash and Bauer, 2012).

$$CC_b = \frac{Asset\ Price * Discount\ Rate}{1-(1+Discount\ Rate)^{-No.of\ periods}} = \ 4397.24\ \text{BDT} \tag{11}$$

Following Kandpal, Bharati and Sinha (1991) we take 4% of annualized investment/capital cost ($CC_b$) to calculate the annual maintenance cost. The total annual operating cost using cow waste includes the daily amount of waste required for the plant ($W$) and the price of the fresh waste ($P_{wdu}$) per kg. Therefore, total annual maintenance and operating cost, $MC_b = 365 * W * P_{wdu} + 0.04 * CC_b$, is BDT 1986 for the small plant. Moreover, $W = 2.4 * 6$ kg, is the quantity of wet waste required per day to produce 2.4 m$^3$ of gas (it takes 6 kg of cow waste to generate 1 m$^3$), $P_{wdu} = 0.18 + 0.15 = 0.33$, where 0.18 is the price of fresh cow waste and 0.15 is the opportunity cost of cow waste per kg (Singh and Sooch, 2004).

For a plant with a capacity of 60 m$^3$, the total input energy (electricity) required per day for purification and compression is 2.5 kW (Ilyas, 2006). Applying the data to our plant capacity of 2.4 m$^3$, we obtain input energy per kilowatt as 0.1 kW/day or 3 kWh/month.

This amounts to 206 BDT/month as per the monthly electricity rate of 3.82 BDT/kWh, meter charge of BDT 125, demand and service charges of BDT 70 (DESCO, 2015). The annual input energy, $EC_b$ amounts to BDT 206 *12=2,477.

As originally generated by the plant, biogas cannot be used to run a pump under normal atmospheric pressure. Hence, biogas needs to be compressed, bottled and transported to the pump. For a small plant, the annual generation of biogas is 876 $m^3$ (2.4*365). Standard practice is to compress 5.4 $m^3$ of gas into one 3.5 kg cylinder (Ilyas, 2006). So a small biogas plant produces 162 cylinders in a year. As per Kapdi et al. (2006) our annual bottling cost, $BC_b$ for 162 cylinders is BDT 4,050.

In Bangladesh, villages are clustered in unions. The United Nations Development Program (UNDP) reports that the average union size in Bangladesh is 33 $km^2$. On average, each union consists of 15 villages, each covering an average area of about 2 $km^2$. Assuming biogas cylinders will be generated and used within a village distance between biogas plant and irrigation pumps is roughly 2 km (UPGP, 2012). Using per unit transportation cost is BDT 1.82/ kg-km (D’Sa and Murthy, 2004), transportation cost for each cylinder is BDT 12.74 and for 162 cylinders, yearly transportation cost, $TC_b$ is 162*12.74= BDT 2063.88.

All of these cost components can be summed up following equations 7 and 8. This results in the total annual cost for generating biogas at pump level, BDT 14,975 that covers 25 hectares of land.

## 4.3 Pumping Cost with Conventional Pump

Bangladesh imports 3.5 million tonnes of oil annually against its demand of around 4.3 million tonnes. Despite the shortage in domestic supply revealed by these figures, the

Bangladesh Petroleum Corporation, Bangladesh's sole oil importer and distributor, pays BDT 33.44/litre as a subsidy for diesel (Reuters, 2011).

During peak growing season, irrigating a total of 3,400,000 hectares of land requires 900,000 tons of diesel. A typical pump's irrigation coverage is 25 hectares. That is, it requires 8,305 liters of diesel ($DQ$) annually. At the pump level, a typical diesel pump results in a capital cost ($CC_c$) of BDT 7,626, and maintenance cost ($MC_c$) of BDT 1,591 (Valle et al., 2014). Conventional pumps consume 35.9 MJ equivalent of energy per 1 litre of diesel. Therefore to irrigate 25 hectares, a conventional pump requires 298,154 MJ of energy annually ($EO_{diesel}$=8,305 * 35.9). The overall cost of pumping with a conventional engine will of course depend upon the price of diesel.

## 4.4. Pumping Cost with Flexible Pump

A 2.4 m$^3$–capacity plant generates 10731 MJ annually (Ilyas, 2006), denoted as $EO_{plant}$. As we have calculated in the previous section, the total cost of producing and transporting biogas to a pump is BDT 1.40 per MJ of energy. However, for that pump to run on biogas, we need to consider a conversion cost. In other words, a conversion kit that will enable a pump to run on biogas needs to be installed. A standard 15 hp conversion kit costs BDT 118,724 and has a life period of 5 years. As before, we annualize the cost, which is BDT 32,935. The annual maintenance cost is BDT 1,317, which is 4% of the annualized capital cost. Therefore, the total annualized conversion cost ($XC_b$) is equal to BDT 34,252. With the conversion kit, a flexible pump generates

352,746 MJ of equivalent energy ($EO_{pump}$). The annualized conversion cost is therefore 0.097 BDT/MJ.

Combining the cost of producing and transporting biogas from the plant to the pump with the cost of converting the pump, we estimate that the total cost of one MJ of energy from biogas ($C_b$) is 1.49 BDT/MJ. To evaluate the economic attractiveness of flexible pumps the cost per unit of energy from biogas and diesel need to be quantified and compared. But in contrast with the case of biogas, where production and transportation costs are largely stable, the cost per unit of energy from diesel is highly volatile. This is because diesel prices are subject to drastic swings in accordance with global fossil energy markets. In other words, diesel prices are random. Therefore calculation of the cost of energy from diesel requires estimation of the probability distribution of diesel prices.

## 4.5 Estimating Distribution of Diesel Prices in Bangladesh

Data on diesel prices in Bangladesh is limited. Historical diesel prices in Bangladesh can only be found on a yearly basis, and from 2006 to 2013. Since the amount of data is insufficient to fit a distribution, we use data from a market that is relatively integrated to that of Bangladesh, India. We obtained historical diesel prices in India, which are reported on a monthly basis. Figure 4 shows the historical prices of diesel in India from 2006 to 2015. We observe that there is a price spike in June 2008.

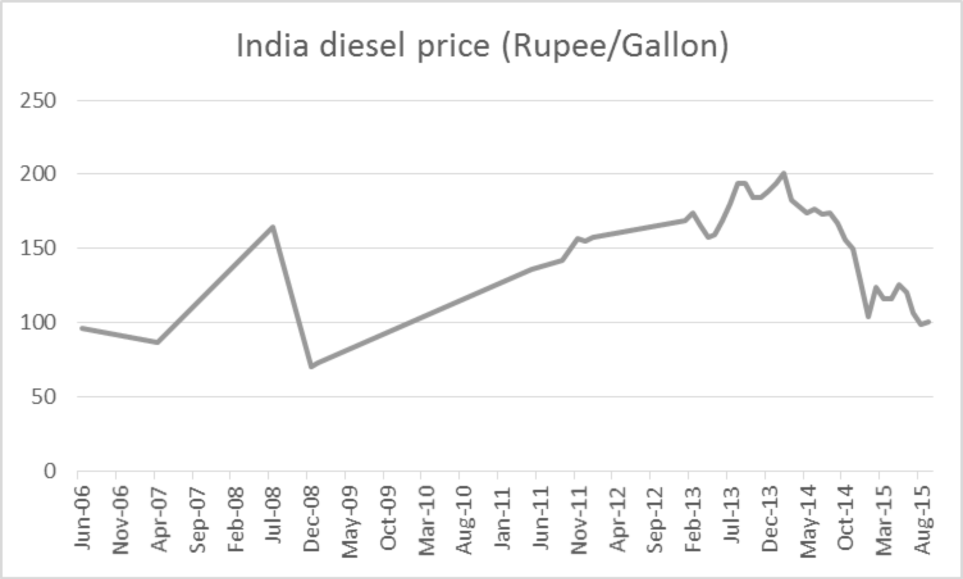

Figure 4: Historical Price of Diesel in India

After that, there is a steady growth of diesel prices from December 2008 to February 2013. The volatility of price is generally high but particularly so after 2012.

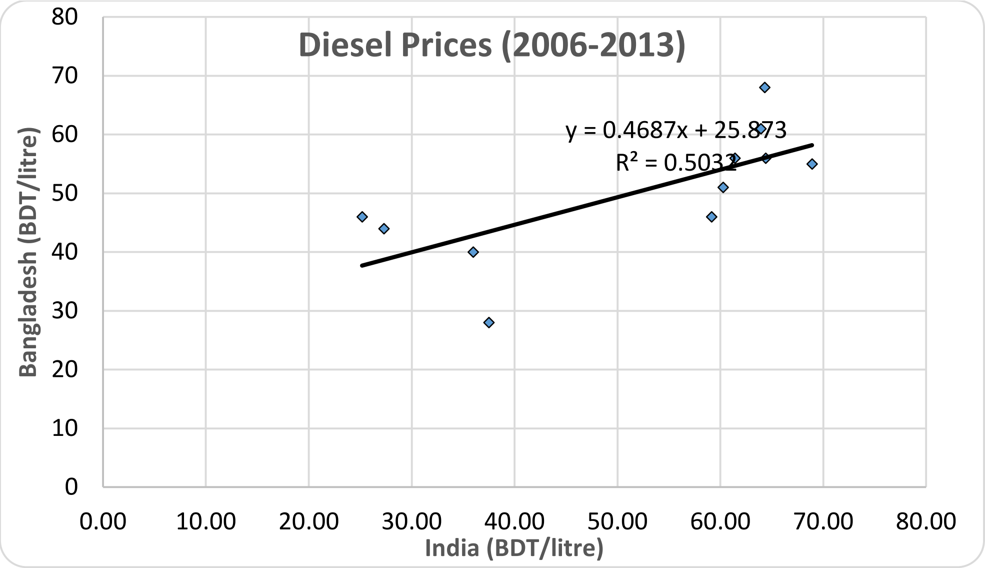

Figure 5: Diesel Price Relationship

Next we calculate the correlation between diesel prices in Bangladesh and India, by regressing the former against the latter. We do so based on annual data from 2006 to 2013. Results are reported in Figure 5. The analysis reveals a strong, though not perfect correlation between price series. In particular variation in the price of diesel in India explain about half of the variation of the price in Bangladesh. This correlation is statistically significant at 1% level with a standard deviation of 0.16. Using regression coefficients, we model monthly diesel price in Bangladesh as follows:

$$P = 25.873 + 0\ .467 * P_i + \ \varepsilon \qquad (12)$$

There are two sources of randomness included in equation (12); diesel price in India ($P_i$), and the error-in-prediction term ($\varepsilon$). We exploit a richer history of price data in India to directly estimate a probability distribution for $P_i$. Following typical assumptions behind ordinary least square regressions, the error-in-prediction term is normally distributed with mean zero and variance estimated based on observations in the sample. In particular, we calculate the variance of the sample error by summing the squared differences between the predicted and actual diesel prices of Bangladesh corresponding to diesel prices of India. The calculated variance is $\sigma^2 = 66$.

To estimate the probability distribution of $P_i$, we fit multiple parametric specifications to historical data and compare their performance based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The procedure indicates that a triangular distribution with min= 20.27, mode=64.31 and max=70.28 constitutes the best fit to these data and results in an AIC statistic of 326.57 and BIC

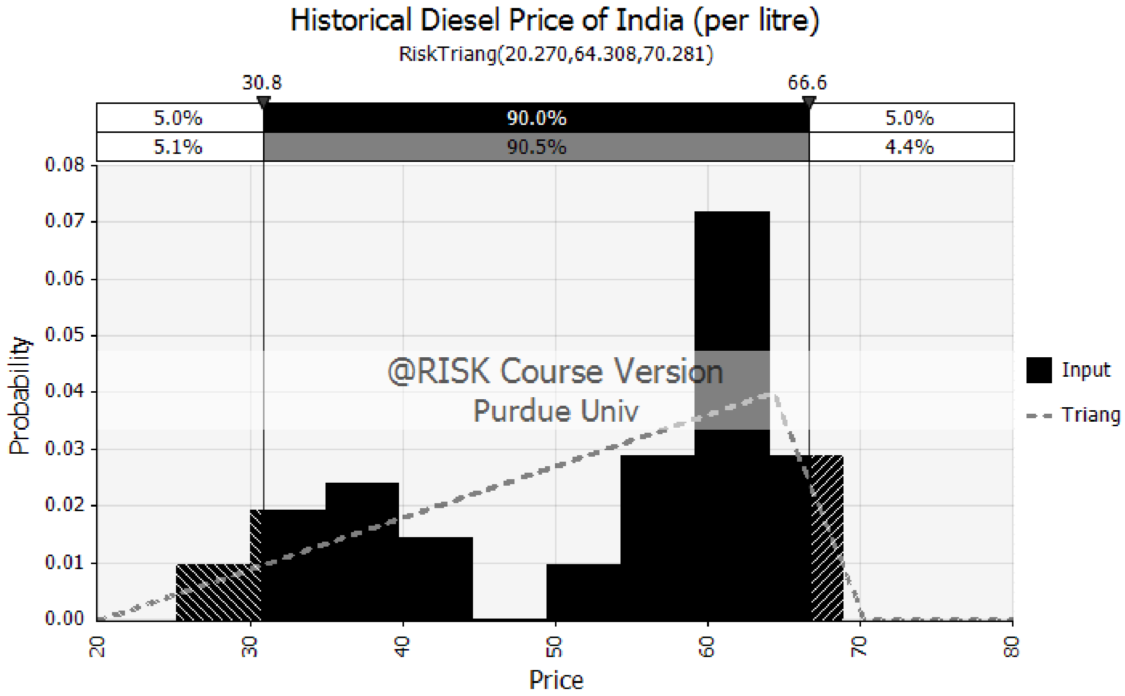

Figure 6: Probability Distribution of Historic Diesel Price of India with Fitted Triangular Distribution

statistic of 331.24. A histogram of historical data and the fitted distribution are displayed in Figure 6. A noticeable property of the fitted distribution is its positive skewness. In particular, the mode is closer to the maximum than to the minimum of the distribution. This is consistent with prior expectations as prices were consistently high over the 2008-2015 period.

# CHAPTER 5. SIMULATION AND RESULTS

Our goal is to examine the economic viability of flexible pumps over conventional ones. We base this comparison on the cost of energy under a conventional pump relative to the cost of energy under a flexible pump. This difference, which one can think of as savings attained through adoption of flexible pumps, was denoted by $f(c)$ in equation (5). According to equation (5), savings from flexible pumps depend upon three important factors. First, the cost of biogas $C_b$ which is constant and equal to 1.49 BDT/MJ. Second, the cost of energy with a conventional pump $C_c$ which is a function of the random diesel price described by equation (12). And third, the usage parameter $u$, which is a function of inter-fuel substitutability $k$ and the diesel price; such function is portrayed in equation (6).

Therefore, it should be clear that savings from adoption of a flexible pump, are themselves random. And that such randomness is driven by random diesel prices. Therefore we generate a probability distribution of savings $f(c)$ and evaluate the economic attractiveness of flexible pumps in a stochastic setting. The procedure to generate a distribution of $f(c)$ is as follows. First, we generate random draws of monthly diesel prices in India using the fitted triangular probability distribution function. Simultaneously, we generate random draws from the fitted normal distribution of the error-in-prediction term. Using equation (12), these random occurrences are translated into random values of diesel price in Bangladesh. Multiple parametric approximations of

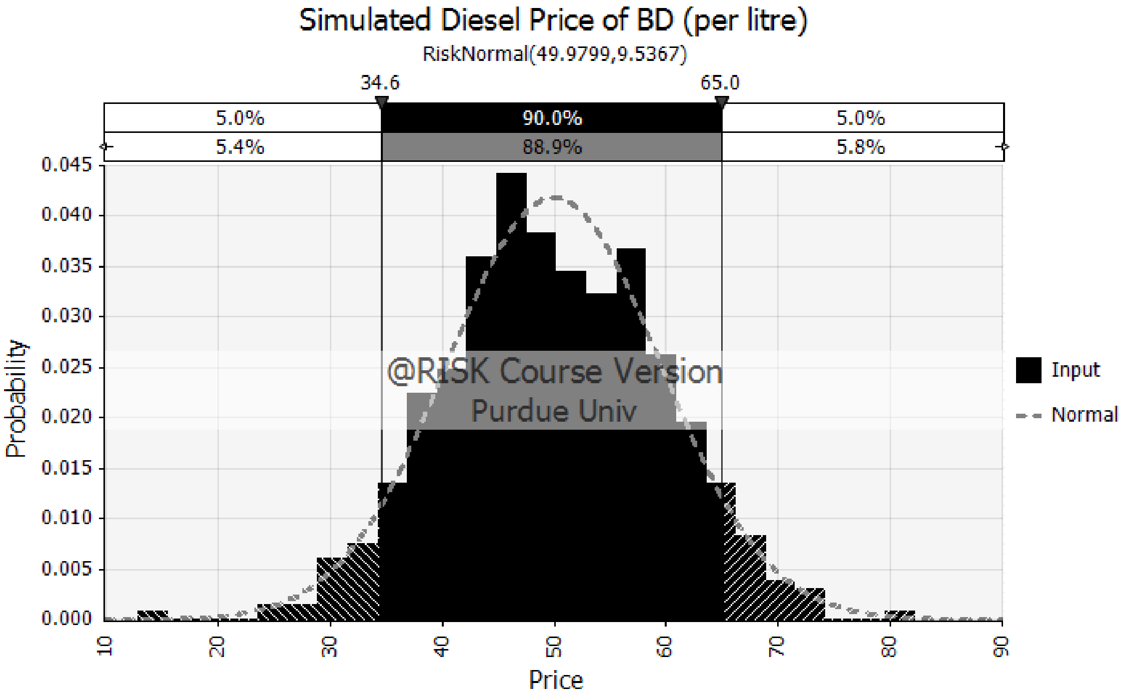

Figure 7: Probability Distribution of Simulated Diesel Price of Bangladesh with Fitted Normal Distribution

probability density functions are then fitted to simulated Bangladeshi prices and the superior one is identified based on AIC and BIC statistics. Simulated values and estimated distribution are depicted in Figure 7.

Then equation (6) and a combination of equations (2), (9) and (10) are used to translate diesel prices in Bangladesh to different values of $u$ and $C_c$ respectively, which can ultimately be mapped to values of $f(c)$. The collection of random occurrences of $f(c)$ is used to estimate a cumulative distribution function depicting the probability that the flexible pump will result in savings for the farmer, and how different factors affect such probability. We focus our attention on three key parameters: inter-fuel substitutability, policy (subsidies on both diesel and biogas), and patterns of diesel prices.

We examine the role of inter-fuel substitutability by generating cumulative distribution functions (CDFs) of savings from flexible pumps for a range of values of k in equation (6). Different values of $k$ will affect the shape of the logistic function, which in turn influences savings through equation (5). We then analyze the importance of policy by generating CDFs of savings under different scenarios of subsidies to both energy sources. Finally, we evaluate the importance of patterns of diesel prices by generating CDFs under alternative scenarios regarding the volatility of Bangladeshi diesel prices.

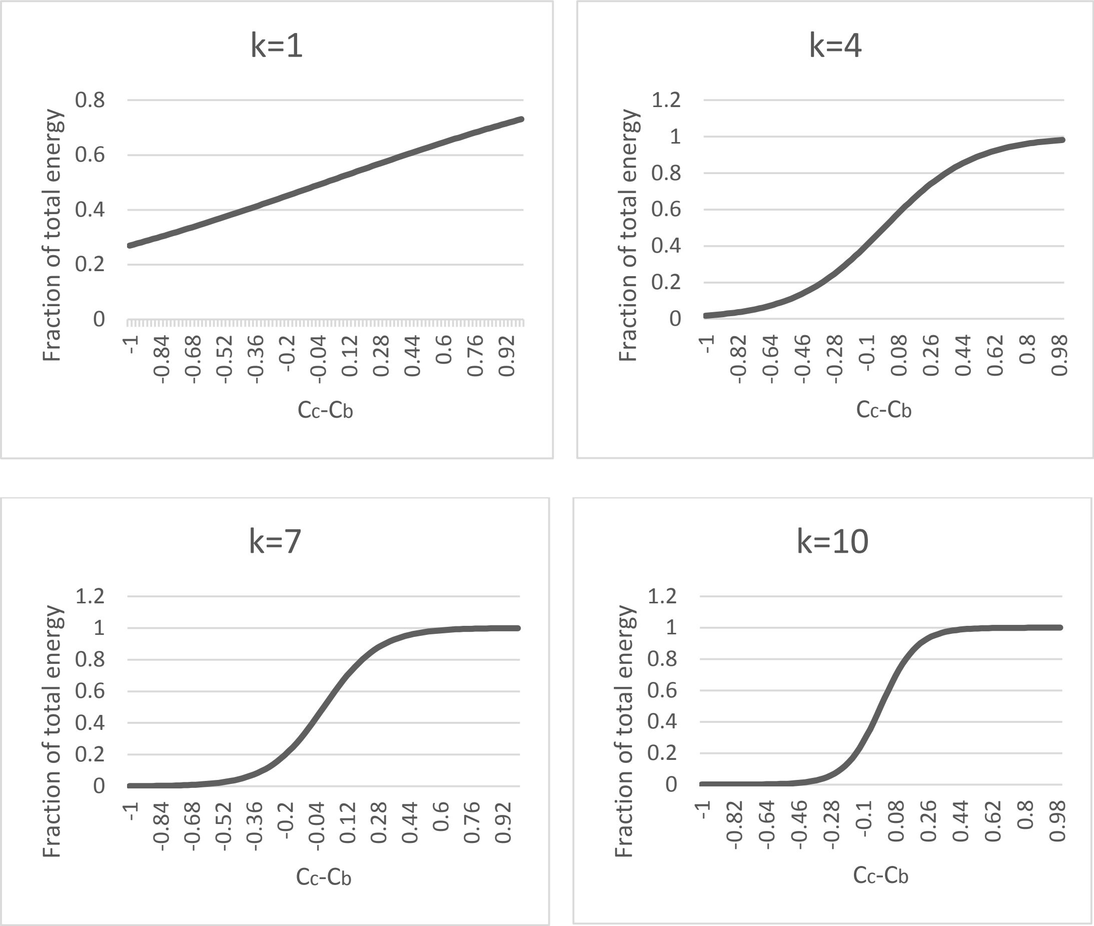

Figure 8. Different Values of Parameter k, under the Logistic Function

### 5.1. Inter-fuel Substitutability and the Economics of Flexible Pumps

The logistic function (6) describes a farmer's choice of fuel mix. Several curves are depicted in Figure 8 which correspond to different values of substitutability, $k$. The Y-axis in Figure 8 depicts the fraction of total energy used by the pump coming from biogas. The X-axis depicts the cost of diesel (per unit of MJ) relative to the cost of biogas (also on a MJ basis). Four interior (neither zero nor infinite) cases are depicted in this figure, $k \in \{1, 4, 7, 10\}$. Figure 8 illustrates how greater inter-fuel substitutability allows the farmer to more appropriately respond to changing economic conditions. Under a large $k$ the farmer can quickly reduce the fraction of total energy composed of biogas if biogas is relatively expensive, and quickly increase such fraction when biogas is relatively cheap.

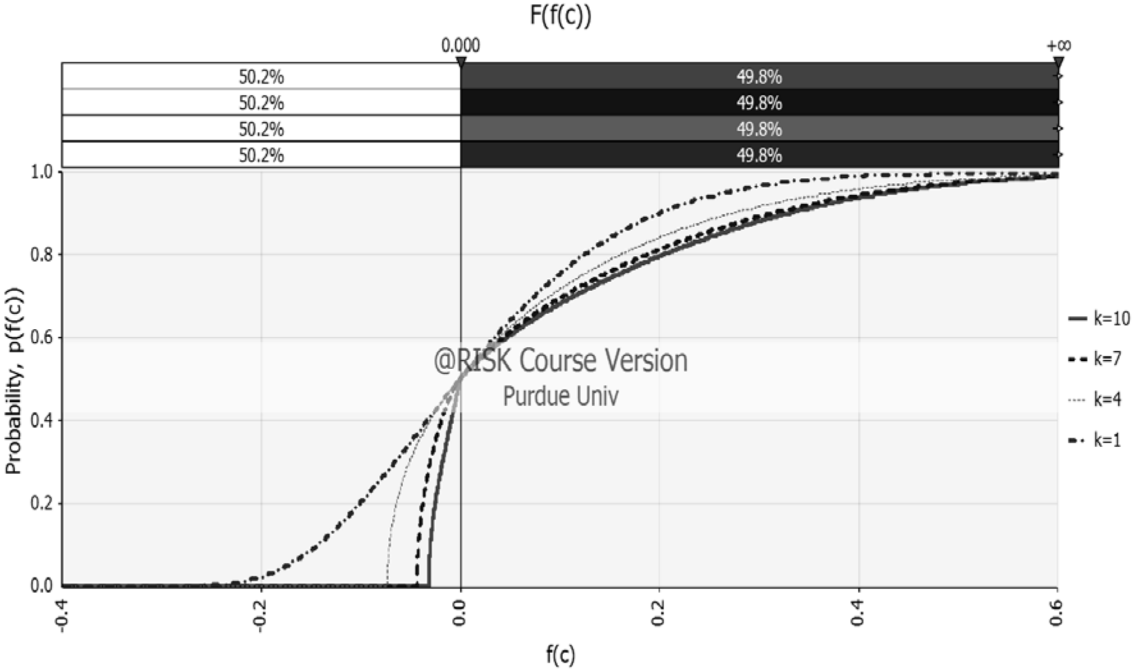

Figure 9: Probability of Savings with Flexible Pump

We examine the effect of inter-fuel substitution by constructing CDFs under different levels of $k$ and comparing them. To isolate the effect of substitutability on the economics of flexible pumps we keep policy and diesel market conditions constant at current levels. More specifically, we analyze a situation in which a subsidy on diesel consumption is in place as it is currently the case in Bangladesh. We also assume that the distribution of monthly Bangladeshi diesel prices is governed by a normal distribution with mean 50 BDT/litre and variance 9.5 BDT/litre, which is the distribution recovered based on historical data.

Results from the analysis are displayed in Figure 9, we observe that regardless of substitutability, the inflection point occurs at the same level, roughly 51%. That means that a flexible pump is 49% likely to generate savings for the farmer. But the most important effect of flexible pumps is regarding downside risk (probability of negative savings) and upside potential (probability of high positive savings), given randomness in diesel prices. The CDF of savings under low inter-fuel substitutability shows that there is a 1% probability that a flexible pump will result in increased cost of .20 cents or more. There is also a 10% probability that a flexible pump will result in savings of .20 cents or more.

On the other hand, under high inter-fuel substitutability there is a 0% probability that a flexible pump will result in increased cost (negative savings) .20 cents or more. Moreover, there is a 20% probability that a flexible pump will result in savings of .20 cents or more. These figures demonstrate that increased inter-fuel substitutability both: 1) reduces the downside risk of investment in flexible pumps, and 2) increases the upside potential of savings from a flexible pump. As inter-fuel substitutability tends to infinity (diesel and biogas are perfect substitutes) the probability that a flexible pump will result in increased water extraction cost relative to a conventional one converges to 0%, while generating a substantial upside potential.

This study did not consider dual pumps, which also uses two types of fuels but in a fixed proportion. This is slightly different from the scenario of our flexible pump with $k = 0$ because under current assumption, that would result in a 50%/50% fuel mix. In contrast the dual pumps use mostly biogas. In Bangladesh, the Government undertook a two-year pilot project in 2007 to convert conventional pumps to dual fuel pumps which uses 95% CNG and 5% diesel (ICC, 2007). The investment cost for such pump is estimated between BDT 12,000 and BDT 15,000 and the conversion kit cost about BDT 5,000. An economic feasibility analysis by (Ehsan and Bhuiyan, 2010) under different load conditions reported that a mixture of 88% CNG with 12% diesel achieves savings of 51% of irrigation cost compared to the conventional pump.

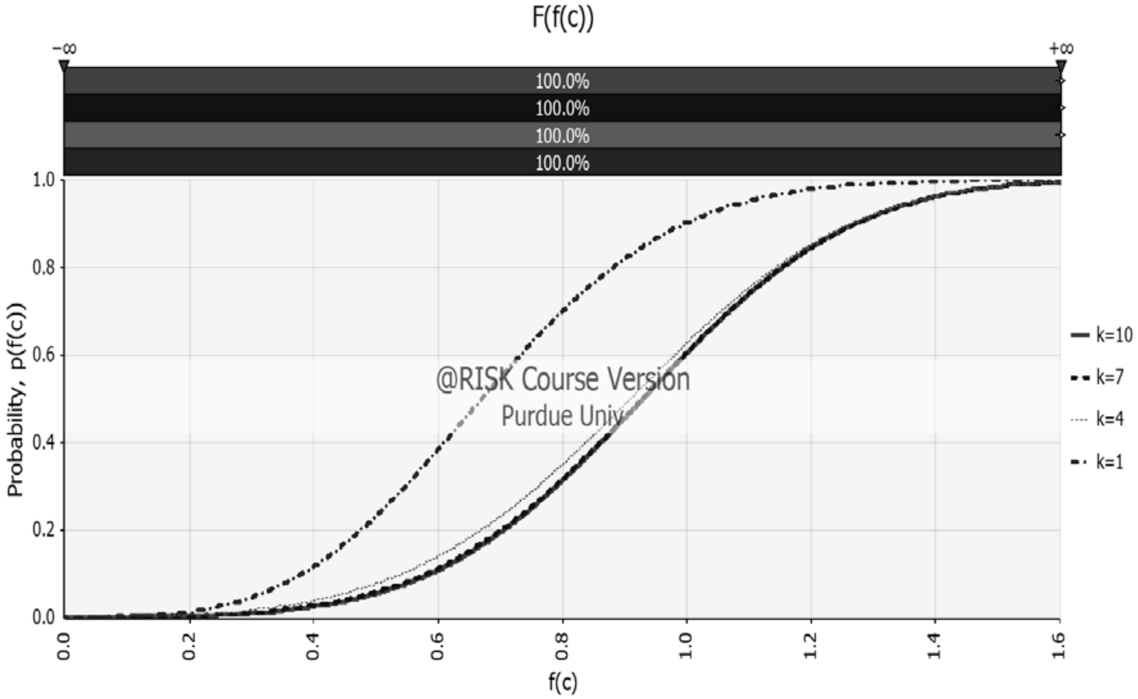

Figure 10: Probability that Flexible Pump will Reduce Cost of Pumping Water without Diesel Subsidy

However, the authors did not considered the impact of diesel prices changes and the availability of CNG. As we have mentioned, that CNG converted cars are becoming popular in Bangladesh but the supply of CNG stations are confined in the major cities and along the highways. There are only 400 CNG stations all over Bangladesh (Ehsan and Bhuiyan, 2010), so the availability of CNG as well as diesel is limited to urban areas whereas almost all of the irrigation is done in the rural areas. That is why, flexible pumps are more economically attractive than the dual fuel pumps.

## 5.2. Policy and the Economics of Flexible Pumps

A subsidy on diesel fuel is currently in effect in Bangladesh. Such subsidy currently amounts to BDT 33 per litre (Kapdi et al, 2006); an amount that constitutes roughly 35% of per unit energy cost for conventional pumps. We first examine the effect of removing the subsidy currently provided by the Bangladeshi government. Removal of this subsidy shifts the probability distribution of diesel prices to the right. It does not affect the volatility of such prices, but it does affect the level. As a result removal of the subsidy enhances the economics of flexible pumps as shown in Figure 10.

After the subsidy is removed, Figure 10 reveals that there would be a 100% probability that flexible pumps will generate savings for the farmer. Moreover, there would be a 50% chance that the flexible pump generates savings for BDT 0.9 or more per unit of energy (MJ). This results in substantial savings for the farmer. In fact, if a farmer uses a flexible pump instead of a conventional one, savings of BDT 0.9 per unit of energy would translate into a 48% reduction in total energy cost.

Removing the diesel subsidy may adversely impact the wellbeing of farmers that are already in a vulnerable situation. One alternative is the addition of a subsidy (or tax break) to biogas, leaving the diesel subsidy in place. Subsidizing biogas while keeping the diesel subsidy simply amounts to a reduction in the *net* diesel subsidy. And it improves the economics of flexible pumps without worsening the financial situation of farmers. Providing tax breaks for farmers investing in the conversion kit for the pump and/or the biogas plant itself will reduce the cost of biogas and increase the likelihood of savings from adoption of a flexible pump. The subsidy required to attain a certain probability that adoption of a flexible pump will result in savings under alternative inter-fuel substitutability levels are depicted in Table 2.

Table 2: Subsidy that Makes Flex pump 66.5%, 83%, and 100% Likely to Generate Savings

| Probability of savings | Inter-fuel substitutability (k) | | | |
|---|---|---|---|---|
| | 1 | 4 | 7 | 10 |
| 66.5 | 3.8% | 3.3% | 2.0% | 1.3% |
| 83 | 8.8% | 5.5% | 3.2% | 2.0% |
| 100 | 20.3% | 10.0% | 7.0% | 2.5% |

Figure 9 reveals there is a 49% probability that flexible pumps will result in savings in the absence of a subsidy to that technology. Table 2 focuses on probability thresholds between 50% and 100%. We divide this range in three equal parts and examine the 66.5%, 83%, and 100% probability thresholds. Table 2 reports, for a probability threshold $x$ and inter-fuel substitutability $y$, the subsidy (expressed in percentage of per unit cost of energy with flexible pump) required to make a pump with flexibility $y$, $x\%$ likely to generate savings.

Table 2 shows that, in order to achieve 83% probability of savings with high inter-fuel substitutability ($k = 10$), a 2.0% of the cost of flexible pumps must be subsidized. But that subsidy must raise to 9%, if substitutability is limited ($k = 1$). Under risk aversion, farmers may require an even higher probability of positive outcomes before they take the risk associated with investment in a conversion kit and a biogas plant. If they require biogas pumps to generate savings with certainty (100%), then the subsidy would range from 2.5% under high substitutability to about 20% under limited substitutability. Conversely, a subsidy of 1.3% is necessary to achieve a 66% likelihood of savings if flexibility is high; and that subsidy raises to almost 4% if flexibility is very low.

Table 2 also reveals interesting interplays between substitutability, probability thresholds, and subsidies. For a given probability threshold, increases in substitutability lower the subsidy. But the magnitude of such reduction is much larger at higher thresholds. Take for instance the 66% threshold. The difference between the least and most flexible pump is only 2.5%. But such difference at the 100% threshold is 18%. Therefore increased flexibility may have a large impact among risk averse farmers who will require a high probability of savings before they undertake the investment associated with a flexible pump. Risk averse investors typically correlated with certain demographic characteristics such as older, lower income, less educated farmers.

A key implication of the pattern of subsidies shown in Table 2 is that small increases in the subsidy may attain substantial increases in the probability that a flexible pump will generate savings, if inter-fuel substitutability is high. But this observation does not hold when inter-fuel substitutability is limited. Take for instance the case where $k = 10$. A surge in 1.2% in the subsidy (from 1.3% to 2.5%) is sufficient to increase the probability that flexible pumps will generate positive savings from 66% to 100%. On the other hand, when $k = 1$, a surge in 16.5% in the subsidy is required to attain such effect.

## 5.3. Diesel Market and the Economics of Flexible pumps

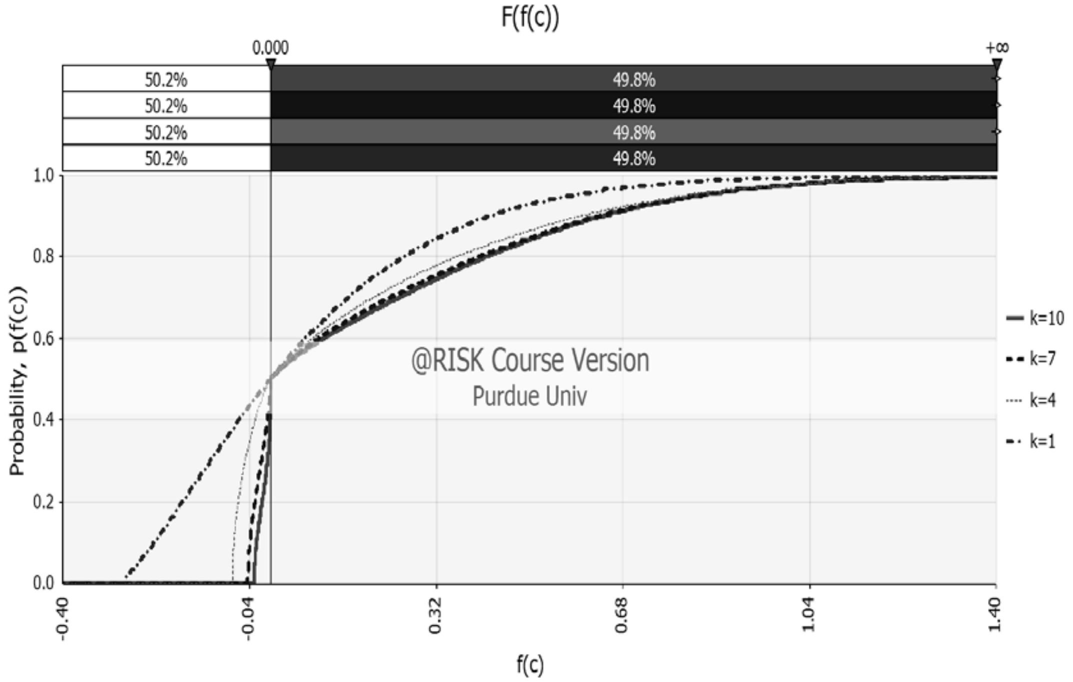

Figure 11: Sensitivity Analysis, with Higher Variance of Sample Error of Diesel Prices

There are two sources of randomness affecting diesel prices in Bangladesh; conditions in the global fossil fuel markets and features that are idiosyncratic to diesel markets in Bangladesh. The former is captured (through prices in India) by the intercept and slope of equation (12), as well as the parameters of the probability distribution of the price in India.

The latter are captured by the distribution of error term. In this section, we investigate how the volatility of prices in the Bangladeshi market affects the economics of flexible pumps. We do so by obtaining CDFs of savings from flexible pumps under different values of $\sigma^2$, the variance of the error-in-prediction term. Furthermore, for this part of the analysis we assume current policy conditions in Bangladesh (subsidy on diesel prices and no subsidy on flexible pumps).

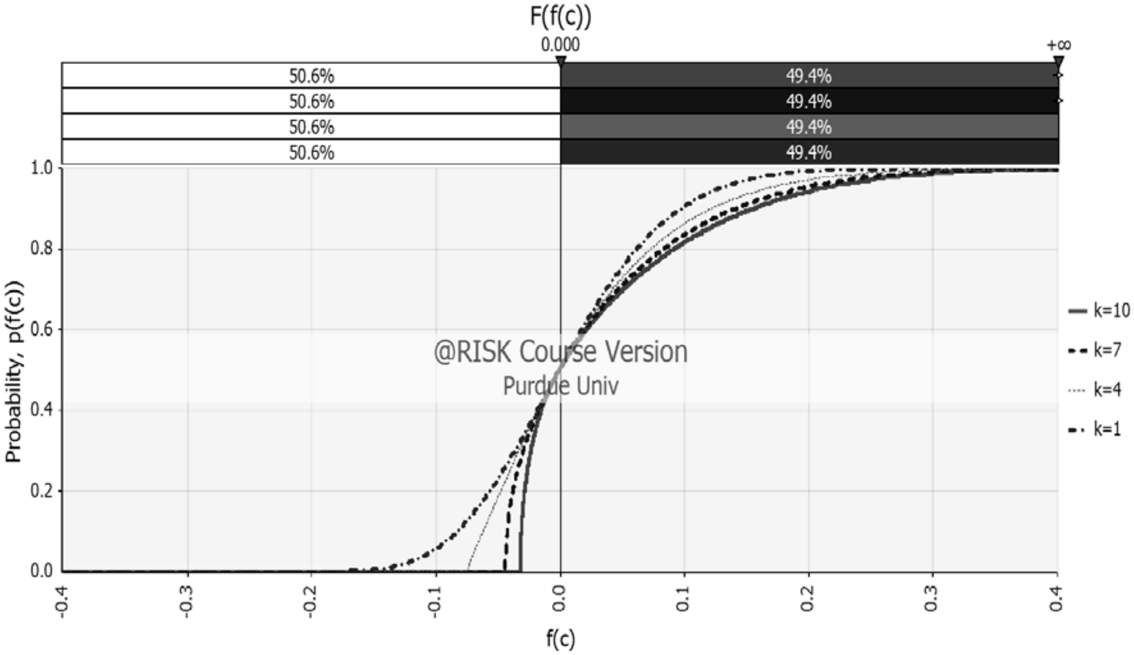

Figure 12: Sensitivity Analysis, with Lower Variance of Sample Error of Diesel Prices

Results under high and low volatility are reported in Figures 11 and 12 respectively. Increased volatility enhances the economics of flexible pumps under high inter-fuel substitutability. Specifically Figures 11 and 12 reveal that increased volatility leaves downside risk virtually unaffected, while greatly increasing upside potential. This is because, under high flexibility, farmers can quickly switch to diesel when it is very cheap, and switch back to biogas when it is expensive.

On the other hand, when substitutability is low an increase in diesel price volatility has an ambiguous effect on the economics of flexible pumps. On one hand, it increases upside potential because there is a higher probability the diesel prices will be very high. On the other hand it also increases downside risk because there is a high probability that diesel prices will be very low, and the farmer can only partially substitute away from diesel due to limited flexibility. Therefore the effect of volatility in diesel price hinges upon inter-fuel substitutability. But generally speaking, the increase in volatility of diesel prices observed in recent years is likely to encourage adoption of flexible.

# CHAPTER 6. CONCLUSION AND POLICY IMPLICATIONS

Irrigation plays and will continue to play a vital role in agricultural development in Bangladesh. But farmers face challenging conditions due to drastic swings in diesel prices, the main source of energy for pumps. Flexible pumps that can switch between diesel and biogas produced from animal waste seem a promising technology to alleviate the aforementioned challenges. Yet the economic viability of these pumps remains an under-investigated issue. The objective of this study is to determine the likelihood that such pumps will result in savings for the farmers by reducing the cost of extraction water from underground or surface sources.

Due to scarcity of price data in Bangladesh, we estimated the probability distribution of these prices by regressing them against prices in India (a market highly correlated to that in Bangladesh), and including an error-in-prediction term which probability distribution is also estimated. The model also accounts for the fact that farmers may not be able to quickly respond to changes in the cost of diesel relative to biogas, resulting in varying degrees of inter-fuel substitutability.

Our results suggest that the flexible pump is 49% likely to result in savings (relative to a conventional one) under current policy and market conditions. If the subsidy on diesel currently in effect in Bangladesh is removed, that probability raises to 100% (flexible plants will result in saving for the adopting farmer with certainty). Increased inter-fuel substitutability does not affect the probability of savings, but it does affect downside risk and upside potential. It reduces the former, while increasing the latter. In other words, flexible pumps are economically more attractive as inter-fuel substitutability increases. Increased flexibility also improves the cost-effectiveness of government policies; i.e. smaller subsidies have equally enhancing effects on the economics of flexible pumps.

These results have important implications for policy. First, flexible pumps seem to be already relatively attractive despite the fact that currently polices favor conventional diesel-powered pumps. So removing some of those policies may in fact be sufficient for widespread adoption of flexible pumps. But removing current diesel subsidies may also have negative impacts on farmers' livelihoods. So subsidizing part of the cost of flexible pumps may greatly encourage adoption, while still helping vulnerable farmers.

Another important implication of our results is that fiscal policies to encourage adoption of flexible pumps (reductions in diesel subsidies or subsidizing flexible pumps) should be designed in isolation from policies affecting inter-fuel substitutability. Since increased substitutability improves the cost-effectiveness of fiscal incentives, it may be convenient to implement a mix of both policies. Policies that can increase flexibility include those that enhance farmers' information so that they are aware of market conditions in real time, as well as technological and transportation infrastructure that farmers can use to better exploit arbitrage opportunities (to identify and use cheaper energy sources whenever available).

# BIBLIOGRAPHY

# BIBLIOGRAPHY

Abdel-Galil, Ashrf, et al. "Biogas utilization for powering water irrigation pump”, 2008.

ADB Annual Report 2012. http://www.adb.org/documents/adb-annual-report-2012

Alam, M. S., et al. "Institutional backup towards food security in Bangladesh." Proceedings BKAS 13th National Conference and Seminar on Climate Changes: Food Security in Bangladesh. Vol. 13. 2008.

Bahauddin, Khalid Md, and Tariq Md Salahuddin. "Prospect and trend of renewable energy and its technology towards climate change mitigation and sustainable development in Bangladesh." International Journal of Advanced Renewable Energy Research 1.3 (2012): 156-166.

Bangladesh Economic Review (BER), Bangladesh Economic Survey, 2005, Finance Division, Ministry of Finance, Government of Bangladesh, Dhaka, Bangladesh, 2007.

Bangladesh- Irrigation in Southern and Eastern Asia in Figures- AQUASTAT Survey-201, Table.5 pg.10, 2011 http://www.fao.org/nr/water/aquastat/countries_regions/bgd/BGD-CP_eng.pdf

Bangladesh raises fuels prices to cut subsidy. Reuters. May 2011. http://in.reuters.com/article/2011/05/06/idINIndia-56817120110506

Biswas, Md M., et al. "Prospects of renewable energy and energy storage systems in Bangladesh and developing economics." *Global Journal of Researches in Engineering (GJRE)* 11.5 (2011): 23-31.

Burney et al. Solar-powered drip irrigation enhances food security in the Sudano-Sahel. December 14, 2009.

D’sa, Antonette, and KV Narasimha Murthy. "Report on the use of LPG as a domestic cooking fuel option in India." International Energy Initiative, Bangalore (2004): 17-19.

Ehsan, Md, and Shafiquzzaman Bhuiyan. "Dual fuel performance of a small diesel engine for applications with less frequent load variations." Int. J. Mech. Mechatron. Eng 9.10 (2010): 30-39.

Energypedia: Bangladesh Energy Situation, 2016 http://energypedia.info/wiki/Bangladesh_Energy_Situation

FAO STAT 2016. http://www.fao.org/nr/water/espim/country/bangladesh/index.stm

FAO STAT 2012. http://faostat.fao.org/site/339/default.aspx

FAO STAT 2007. ftp://ftp.fao.org/docrep/fao/010/a1200e/a1200e00.pdf

Ferdous, Md Sadek, et al. "A case study on present scenario of biomass energy in bangladesh and its future prospect." Green Energy and Technology (ICGET), 2014 2nd International Conference on. IEEE, 2014.

Global Petrol prices 2016. Bangladesh. http://www.globalpetrolprices.com/diesel_prices/

Grameen Shakti. 2012. http://www.grameen.com/index.php?option=com_content&task=view&id=1283&Itemid=1058

G. Sathyamoorthi “Solar powered irrigation pumpset has its limitations, say farmers.” The Hindu, 2013. http://www.thehindu.com/news/cities/Tiruchirapalli/solarpowered-irrigation-pumpset-has-its-limitations-say-farmers/article4724126.ece

Hossain, Mahabub. The impact of shallow tube wells and boro rice on food security in Bangladesh. Vol. 917. Intl Food Policy Res Inst, 2009.

IDCOL. Renewable Energy. 250 kW Biomass Based Power Plant Project. 2013. http://foundation.e-arttic.com/wiki/tiki-index.php?page=IDCOL%3A+Renewable+Energy+Projects

IDCOL: Biogas Audit Bangladesh 2011-2013 http://www.idcol.org/notice/86e1c7700f88b15452435d90c762ec68.pdf

Ilyas, Syed Zafar. "A case study to bottle the biogas in cylinders as source of power for rural industries development in Pakistan." *World Applied Sciences Journal* 1.2 (2006): 127-130.

International Chamber of Commerce (ICC), Bangladesh, 2007 http://iccbangladesh.org.bd/view_latest.php?NewsID=310&page=555

Iqbal Salma, Iqbal M, Salahuddin AFM. “Present Scenario of Compressed Natural Gas (CNG) as a Vehicular fuel in Bangladesh” Proceedings 2nd International Conference on Industrial Engineering and Operations Management (IEOM), 2011. http://www.iieom.org/ieom2011/pdfs/IEOM034.pdf

Irrigation. Banglapedia. 2015. http://en.banglapedia.org/index.php?title=Irrigation

Kabir, H., Palash M.S., and Bauer, S. "Appraisal of domestic biogas plants in Bangladesh." *Bangladesh Journal of Agricultural Economics* 35.1-2 (2012)

Kandpal, C., Bharati. J. and Sinha, C.S. (1991). Economics of Family Sized Biogas Plants in India. Energy Conversation Management, 32: 101-13.

Kapdi, Shyam S., et al. "Upgrading biogas for utilization as a vehicle fuel." *As. J. Energy Env* 7.04 (2006): 387-393.

Mujeri, M. K., Chowdhury, T. T., & Shahana, S. Energy Subsidies in Bangladesh: A profile of groups vulnerable to reform. Research Report). Geneva: Global Subsidies Initiative, International Institute for Sustainable Development, 2013. https://www.iisd.org/gsi/sites/default/files/ffs_stakeholders_bangladesh.pdf

M. Z. Huda, “Regional development of irrigation technologies and its impact on food grain production in Bangladesh,” MS Thesis, Department of Agricultural Economics, BAU Mymensingh, Bangladesh, 2001.

Navana CNG Limited, 2011. http://www.navanacng.com/cng_petrol_driven_vehicle_conversion.php

Parvin, Lovely, and M. Wakilur Rahman. "Impact of irrigation on food security in Bangladesh for the past three decades." Journal of Water Resource and Protection 3 (2009): 216-225.

Purohit, Pallav, and Tara Chandra Kandpal. "Techno-economics of biogas-based water pumping in India: an attempt to internalize CO 2 emissions mitigation and other economic benefits." *Renewable and Sustainable Energy Reviews* 11.6 (2007): 1208-1226.

Renewable Energy and Environmental Information Network (REEIN), 2004. http://www.reein.org/

Sharif Islam. “Renewable Energy Development in Bangladesh”. Spain, 2009. http://www.sari.sarienergy.org/PageFiles/What_We_Do/activities/renewable_spain_oct_2009/Presentations/Bangladesh_Renewable_Energy_development.pdf

Singh K. J., Sooch S. S., 2004. Comparative study of economics of different models of family size biogas plants for state of Punjab, India. Energy Conversion & Management 45:1329-1341.

Syful Islam, Bangladesh backs solar pumps to expand irrigation. Thomson Reuters Foundation. (2011)

Taleghani, Giti, and Akbar Shabani Kia. "Technical–economical analysis of the Saveh biogas power plant." *Renewable Energy* 30.3 (2005): 441-446

Tariff rate, Dhaka Electric Supply Company Limited, 2015 https://www.desco.org.bd/?page=tariff-rate

UPGP Project Document, 2012 http://www.bd.undp.org/content/dam/bangladesh/docs/Projects/UPGP/UPGP%20Project%20Document.pdf

Valle et al. Axial flow pumps can reduce energy use and costs for low-lift surface water irrigation in Bangladesh. USAID. Research Report No.1. Cereal Systems Initiative for South Asia Mechanization and Irrigation (CSISA-MI) Project. 2014.

van Winsen, Frankwin, et al. "Determinants of risk behaviour: effects of perceived risks and risk attitude on farmer's adoption of risk management strategies." Journal of Risk Research (2014).

van Winsen, Frankwin, et al. "Determinants of risk behaviour: effects of perceived risks and risk attitude on farmer's adoption of risk management strategies." Journal of Risk Research (2014).

WAME: Energy for Poor People from Biogas. Bangladesh. (2014) http://www.wame2015.org/case-study/1096/

World Bank. "Solar powered pumps reduce irrigation costs in Bangladesh". September 2015. http://www.worldbank.org/en/results/2015/09/08/solar-powered-pumps-reduce-irrigation-costs-bangladesh