

ABSTRACT

Title of dissertation: LEARNING-BY-DOING AND CONTRACTS IN NEW
 AGRICULTURAL INDUSTRIES

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The dissertation develops a theoretical model to examine the effects of limited liability contracting on learning-by-doing and capital investment within a new agricultural industry. The theoretical model applies to many new bio-based industries, where novel crops are being used to produce goods, such as chemicals and energy, which would not be considered traditional agriculture.

Limited-liability contracts create an environment of moral hazard in learning investment and adverse selection in the production of the intermediate good. These two features of the contracting environment present difficulties for the principal to benefit from the learning-induced cost reductions realized at the intermediate stage of production. Thus, the principal under-invests in the industry and requires less of the intermediate good. Reduced feedstock orders decrease the incentives for the agent to invest in learning, and so the ultimate cost of production of the intermediate good is higher than optimal.

The dissertation adapts the theoretical model to construct a simulation of investment and production decisions within an industry for the generation of electricity

using biomass. The results of the simulation show that an industry formed around limited liability contracts realizes project scales 25-30% smaller than optimal. Learning-induced cost reductions in the production of biomass are 20% less than predicted by engineering analyses. Limited-liability contracts raise the price paid by the principal for the feedstock by 25% above optimal. The analysis reveals that the price of electricity necessary for a project to break even is 5% higher under limited liability contracts. Sensitivity analysis illustrates that the problem of underinvestment increases under conditions favorable to grower learning.

A capital subsidy paid to processors that invest in technology encourages overinvestment in capital relative to feedstock utilization. The Renewable Energy Production Credit or a feedstock subsidy paid to growers increase project scales by about 30%, yet they are still 20% smaller than optimal. These subsidies do not have a significant impact on the price of the feedstock to the processor. The government may seek to explore policies that encourage forward vertical integration in the industry.

LEARNING-BY-DOING AND CONTRACTS
IN NEW AGRICULTURAL INDUSTRIES

by

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Dedication

To Denise,
my wife and best friend.
Without her love and support
this dissertation would not exist.

And to our children, Sam and Abigail,
who make life interesting and fun.

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Chapter 1. Introduction

Bio-based products and bioenergy offer promising new markets to agricultural producers. The new industries emerging from these products are likely to exhibit a learning curve in the early stages of development, i.e. costs of production will decrease over time as producers gain experience in production. The prospect of learning-induced cost reductions has implications for these new industries in that they affect the timing and magnitude of investments necessary for industry formation. In some cases, these learning-induced cost reductions will play a crucial role in determining the profitability and ultimate viability of the new industry.

However, contractual problems may present obstacles for the establishment of these industries. The lack of alternative markets for growers, the need for specific investments and uncertainty about the viability of the new industries imply that relationships between growers and processors will be governed by long-term contracts. Limitations in the contractual arrangements may prohibit industries from realizing the full economic benefits accrued through learning. As a result, contracting will lead to inefficient ex ante investments as compared to the first best and the resulting industry will realize lower profits than the socially optimal outcome. The reduced level of expected profits could be a major impediment to the emergence of these new industries.

The dissertation examines the nature and extent of this potential problem using a multiple period model of investment and production in a new industry involved with bio-based products and energy in which agents make specific investments before the occurrence of production and the resolution of uncertainty about the magnitude of future learning-induced cost reductions. Growers adopt novel and unconventional crops while

processors incur large investments in processing capacity. The lack of alternative markets for the novel crops and the high adjustment costs faced by the processor have the effect of locking the agents into a relationship. The model pertains to situations like molecular farming, where growers produce transgenic crops and a “biorefinery” extracts the pharmaceutical chemicals from the crops, or biomass electricity, where growers produce switchgrass and a generator converts the crop to electric power.

The first part of the dissertation presents the theoretical basis for the analysis. In Chapter 2, the discussion motivates the theoretical analysis with a description of the salient features of new agricultural industries that are likely to affect their governance structures. New agricultural industries are characterized by novel crops and advanced processing technologies, which necessitate specific investments on the part of growers and processors alike. This feature, combined with temporal considerations and uncertainty, is likely to play a large role in determining the ultimate structure of the industry.

Another important feature of new agricultural industries is that they are likely to exhibit learning-by-doing, where costs of producing the intermediate and final goods decline as producers gain experience. Chapter 2 includes a discussion of learning-by-doing and a review of the literature concerning the phenomenon. The typical model found in the literature for an industry that exhibits learning assumes that a single agent (producer) undertakes the production and investment decisions that directly affect learning. The agents also own all of the assets of production and receive the full marginal benefit of their actions. The literature has not addressed the issue of coordination of private investments among agents that induce learning and the

appropriate organization of the production of intermediate goods in cases where learning is important.

Furthermore, the types of investments undertaken by growers that bring about higher levels of learning about particular crops are generally unobservable. These investments are oftentimes non-monetary in nature, pertaining to the care in making cropping decisions and the amount of time observing crop performance under various conditions. The magnitude of cost reductions that occur due to learning is also private information of the grower. As a result, the processor faces a contracting environment characterized by both moral hazard (in learning investment) and adverse selection (in production).

Uncertainty about the future costs of producing novel crops and the profitability of the new industry as a whole further constrains the contracting environment. At present, a spot market for many of the novel crops is non-existent. The processor, therefore, must offer contracts that are designed to induce grower participation by offering protection to growers from negative outcomes; such as those where experience-driven cost reductions are not achieved. By restricting the contract set to those that limit the liability of the grower, the processor ensures adequate expected feedstock production and thereby protects his capital investment. Chapter 2 continues with a discussion of the literature on contracting with moral hazard and adverse selection and limited liability contracting. The chapter concludes with a summary of the dissertation's contribution to the literature.

Chapter 3 contains the core of the theoretical portion, a construction of a two-period model to analyze a limited liability contractual arrangement between two risk-

neutral agents in an industry where one agent experiences learning-by-doing and the other wishes to benefit from the resultant cost reductions. The contract must achieve two objectives: (1) create incentives for the grower to exert learning effort, or invest in learning, and (2) elicit truthful revelation of cost reductions that occur from that learning investment. In order to achieve the two objectives, the contract must promise bonus payments, or learning rent, to growers that realize higher levels of learning.

In general, the analysis reveals that the principal (the processor with a large capital investment) is unable to appropriate the gains from learning-by-doing. This results from the combined hidden action and hidden information problem. In order to induce learning effort and elicit information from the agent about the learning that has occurred, the principal must make the agent the residual claimant of any of the learning-induced cost reductions due to his efforts. The payment of learning rents to growers with high levels of learning induces the processor to contract for underproduction of the crop relative to the first best for any given level of capital investment. This, in turn, elicits under-investment in learning on the part of the grower. Processors, therefore, do not make an efficient investment in capital, resulting in a suboptimal industry size that is potentially unprofitable.

Chapter 3 also includes a discussion of the implications of the model. Here, alternative forms of industry organization are described and discussed. The potential merits of a vertically integrated industry are explored. In particular, the discussion highlights the possibilities for further research in the area of forward vertical integration, whereby a cooperative of growers invests in the processing technology.

The remaining chapters of the dissertation present the empirical application of the theoretical analysis. These chapters constitute a case study of the biomass for electricity generation. Chapter 4 describes the current state of the biomass for electricity generation, the potential societal benefits of the industry, and some predictions from the literature about the industry's viability. This description is followed by a qualitative analysis of the existing contractual arrangements within the industry. In the qualitative analysis, current contracts illustrate the potential difficulties facing the industry in becoming competitive with other sources of electricity.

Chapter 5 consists of the construction of an empirical counterpart to the theoretical model of Chapter 3. For this empirical construction, a processor seeks to invest in a biomass generation facility that use advanced gasification technology to be located in the North Central Region of the United States. For each element of the theoretical model, Chapter 5 designates and provides justification for functional form, reports on the availability of data, and provides parameter estimates for costs and production. The chapter concludes with a calibration of the model via comparison with current estimates from the literature of break-even prices and minimum scale of generation.

Chapter 6 presents the results from the empirical model. The results confirm the qualitative results from Chapter 3, showing that limited liability contracts impose a significant cost to the industry and may hinder initial investment on the part of the processor. The chapter also includes a sensitivity analysis of the model to three parameters: price of electricity, responsiveness of cost to learning effort, and marginal disutility of learning effort.

The final segment of the empirical analysis explores the policy implications of the results. The potential environmental and rural development benefits arising from a biomass for electricity sector may justify government intervention to foster the emergence of the industry. A few policies are currently in place or have been proposed to assist the development of the industry. Three of these policy prescriptions are analyzed: the renewable energy production incentive credit (REPI), a subsidy for biomass production, and a subsidy for generation capacity investment. In general, the policy analysis shows that the REPI and feedstock subsidy each mitigate a portion of the distortion between first and second best outcomes. However, the amount of learning that arises may not be sufficient to render a viable industry. The analysis also determines that a capital subsidy would not perform as well, and may create perverse incentives for investment and production within the industry.

Chapter 7 presents some concluding remarks to the dissertation. Further implications of the model are discussed. The chapter also discusses possible directions for future research that have been revealed by the current analysis.

Chapter 2. Literature Review

Traditionally, agriculture and agricultural industries have been concerned with the production of food, food products, and animal feed. Many new agricultural industries will form around the production of non-traditional agricultural products, such as chemicals, pharmaceuticals, energy, and fuels. The crops proposed for these industries are oftentimes unfamiliar to current agricultural producers and require sophisticated processing technologies to extract the marketable product. Thus, emerging agricultural industries necessitate specific investments on the part of both the grower and the processor.

It is likely that as growers become more familiar with new crops and processors with new technologies, production efficiency will increase. This effect of learning by doing is likely to play a role in the development of these new industries. In the case of biomass for energy, for example, industry analysts expect cost reductions to occur in the production of crops as growers assimilate advances from research and development. Experience has also shown that renewable energy technologies, such as that to be used by the processor, exhibit a learning curve, i.e. costs decline with increasing experience (McDonald and Schrattenholzer). Indeed, many feasibility studies for biomass energy and other renewable sources present potential cost reductions as evidence that the industry may be viable at a future date. (Marrison & Larson, Graham et al.)

The markets for processed bio-products are likely to feature greater competition than the market for intermediate goods. Energy producers, for instance, must compete with other sources of energy (fossil fuels and other renewable sources). Bio-chemical and bio-pharmaceutical producers must compete with producers that employ

conventional technologies. Faced with lower cost competitors in the market for their final products, processors will be forced to pass learning-induced cost savings to the final consumer of the good. Growers, though, may not face similar market conditions, and therefore may not pass learning-induced savings associated with the intermediate good to the processor. Transportation costs associated with new agricultural crops, among other factors discussed later in this chapter, may limit entry into the thereby limiting the amount of competition for the intermediate good supplied to the processors. These factors could create a disincentive for growers to reduce crop prices to processors as the cost of producing the crop declines. If the market for the final good is particularly competitive, as in the case of electricity, then the inability of the processor to pass the cost savings realized by the grower onto the final consumer may prove detrimental to the viability of the new agricultural industry. Furthermore, the inability of the processor to appropriate the gains from learning presents an obstacle to the initial investment in the industry, potentially depriving society of certain environmental amenities, as well as reducing the welfare of rural communities that could reap economic benefits.

An investigation of the extant literature reveals that many of the characteristics of the problem described here have been previously addressed. The literature discusses and analyses several implications of learning by doing in new industries. The literature also contains exhaustive analyses of the implications of moral hazard and adverse selection in procurement contracts. However, much of the literature concerning learning has dealt with the implications of learning-induced cost reductions on market structure, i.e. competition among producers, and market entry. Much of the literature on contracts

between agents when there is potential for future cost reductions focuses on cases of government procurement of products and services from the private sector.

The literature has not fully addressed several issues intrinsic to the problem at hand, such as the issue of coordination of private investments among agents that induce learning and the appropriate organization of the production of intermediate goods in cases where learning is important. Specifically, the literature does not contain an application of contracting with learning to the formation of a new industry nor does it contain an empirical investigation of the implications for contractual agreements on learning in new industries.

This chapter reviews three strands of literature that are relevant to this dissertation. The first section of the chapter discusses the literature concerning industry traits and their implications for the organization between stages of production within the industry. The second section discusses learning and its implications for new industries. The third and final section considers the problems of moral hazard and adverse selection in contractual environments.

Structure of New Industry

Several characteristics of new agricultural industries will likely influence the optimal governance structure. New agricultural industries feature relationship-specific investments for producing and processing novel crops, poorly developed markets for those crops, and uncertainty in agricultural production. Each of these characteristics has significant implications for industrial organization. Combined, these characteristics imply that new agricultural industries may benefit from vertical coordination between stages of production, either through vertical integration or through long-term contracting.

Relationship-specific assets are those that have little or no value outside of an economic relationship. Relationship specific assets expose investors to the risk of opportunism on the part of trading partners. As a result, agents may be hesitant to invest in specific assets without assurances (by way of a contract) of a future market for a good. Williamson categorizes relationship-specific investments as dedicated assets, location specific asset, and physical specific assets.

Most of the investments necessary for a new agricultural industry to take shape may be characterized as *dedicated assets*. Growers are not likely to begin production of novel crops without the assurance that a processing facility will be built to procure and market those crops, and processors are not likely to construct a facility without the assurance that growers will produce the novel crops. Once an agreement is made to form a new agricultural project, it is possible that a significant amount of time passes before production of crops and bio-products occurs. Some processing facilities may take years to construct, particularly those requiring sophisticated technologies. In many cases, the novel crops may take several years to reach the level of maturity necessary for use as an input to production. During this phase, growers dedicate all their physical and human assets to the production of crops that likely have little value to any other user than the future processor. In addition, any experience gained in the production of those crops may be considered a dedicated asset, as that knowledge has no value to other industries and may not be transferable to the production of other crops.

Investments are *site specific* when agents must locate near each other for the purposes of minimizing inventory or transportation costs. The bulkiness of crops results in high costs of transportation of biomass. These costs could comprise a significant

portion of the costs of production of bio-products, thereby limiting the distance that can exist between the processors and the growers. Due to the need to minimize transportation costs, the processor and growers are engaged in a so-called cheek-by-jowl arrangement and the processing facility must be located in close proximity to the growers of crops.

In addition to site specificity, the processors' technologies may be characterized by a high degree of *physical asset specificity*. The quality of biomass varies considerably from region to region. Energy content, impurities, moisture content, nutrient content are all examples of properties that fluctuate due to the quality of soil and climate in which they are grown, as well as the cropping practices of agricultural producers. Sophisticated processing technologies may require adjustments to tolerate the particular nature of the biomass supplied by the producer. Some technologies may be designed from the onset to handle the quality of biomass inherent to a specific region, or growing area. The costs to the processor will depend on the level and precision of adjustments made to the technology. Greater specialization of the technology confers a higher degree of physical asset specificity on the processor's investment.

Temporal considerations may also play an important role in the organization of new agricultural industry. In addition to a time lag before crops reach a level of maturity necessary for use as an input to production, a processor may require a supply of biomass over a long period of time, possibly decades. This implies the need for a supply arrangement between growers and processors that exceed the length of typical agricultural contracts. Long-term contracting is currently uncommon in United States agriculture, and in those sectors where it does exist "long-term" is defined in terms of four to seven years.

The presence of relationship-specific investments suggest that vertical integration or a form of contracting will be preferred to the development of a spot market (Williamson, Joskow (1985, 1990), Wolak). Uncertainty in agricultural production, uncertainty about the extent of cost reductions through learning and uncertainty in the markets for energy resources suggest that contract breach may pose a problem under certain conditions. Joskow (1985, 1990) has shown that long-term contracts have proven effective and resilient to breach in the minemouth-coal electricity generation industry. In minemouth coal, uncertainty results from the variability in the price of the final product, electricity. However, contracts are designed such that the price of coal may be adjusted regularly for changes in the market for electricity. Although some variability exists in the costs of producing the coal for use in generation, this variability is directly related to the rate of inflation. As a result, the price of coal may also be adjusted regularly for inflation within the industrial sector.

In contrast, agricultural production is subject to persistent randomness due to changes in weather and growing conditions. In a new agricultural industry, uncertainty results from this randomness, as well as in variability in the value of the crop to the processor and in the probability of learning-induced cost reductions. It may be difficult to develop a contract that allows for feedstock price adjustment that accounts for the various avenues of uncertainty. Additionally, growers have a number of outside opportunities, such as the production of conventional crops or participation in the Conservation Reserve Program (CRP), which may make them unwilling to take on the risk of producing a novel crop.

In these industries, it is more plausible that uncertainty will impinge upon the willingness of agents to enter into contractual arrangements from the onset. To induce grower participation in the new industry, processors may need to shield growers from all or most of the risk associated with novel crop adoption. Thus, the industry may need to rely on limited liability contracts in the early stages of formation.

Learning by Doing

The phenomenon of decreasing production costs with increasing experience was first observed in the production of airframes. Engineers documented a precise inverse relationship between the number of labor-hours used in the production of an airframe and the number of airframes that had already been produced. This effect has since been observed in other industries and has been attributed to learning-by-doing, or production experience within an industry.

Kenneth Arrow formalized the effect in his seminal work on the economic implications of learning where he uses cumulative production experience as a proxy for learning. Arrow (1962) applied his analysis to the problem of economic growth, attempting to endogenize changes in productivity within an economy using a variable representing experience. This work has inspired a strand of literature that extends beyond the original macroeconomic focus, covering a wide range of economic environments where learning may have a significant impact.

Rosen (1972) was perhaps the first to formalize a microeconomic model of learning. He proposed a model of learning-by-doing for an individual firm where learning is an output of a joint production process. Rosen considers the case where learning is entirely proprietary, i.e. firm-specific and non-transferable. Here, knowledge

that results from learning is closely aligned with entrepreneurship, or the ability to “organize and maintain complex production processes that take fuller advantage of possibilities for economizing through specialization of function and division of labor within the firm.” Rosen’s model focuses on the intertemporal allocation of resources by a firm that realizes cost reductions from learning. The main conclusion of the analysis is that the firm finds it profitable to incur present costs associated with learning in order to reduce future costs associated with input use.

Spence (1982) considered the implications of learning by firms in the context of a competitive marketplace. Spence identifies the analogy of learning-by-doing and increasing returns to scale. Because learning is directly related to the total quantity of a firm’s experience, industry costs are minimized with a single producer. A social optimum is achieved with single producer that sets price equal to marginal cost. However, a single producer creates a monopoly and so a tradeoff exists between price competition and costs.

Subsequent analyses have extended and modified the models of Rosen and Spence using a variety of techniques that include discrete (Petraakis et al.) and continuous dynamic optimization (Brueckner & Raymon), over finite (Ghemawat & Spence) and infinite horizons (Mookherjee & Ray.) These analyses have examined a number of permutations associated with market and cost structures, that include the impact of learning spillovers between firms (Fudenberg & Tirole, Ghemwat & Spence), the potential for collusive price paths (Mookherjee & Ray), and the significance of increasing versus constant marginal costs of production (Petraakis).

Although the list above is not exhaustive, the models all share some common elements. One common element of these models is that they assume a single agent (producer) undertakes the production and investment decisions that directly affect learning. These “learner” agents own all of the assets of production and receive the full marginal benefit of their actions (Rosen, Fudenberg, Spence, Brueckner and Raymon).

One aspect not addressed in the literature is the issue of learning when it occurs at the intermediate stage of production within a vertically coordinated industry. In particular, the literature has not addressed the coordination of private investments among agents that induce learning and the appropriate organization of the production of intermediate goods in cases where learning is important. For new agricultural industries, it is unlikely that one agent will make all of the relevant decisions. That is, it is unlikely that one agent will make all decisions pertaining to investment in growing and processing of the crops, as well as production of the intermediate and final goods. Coordination between phases of production will be necessary

Another common facet of the models is that learning is essentially a costless endeavor, the result of a joint production process. These existing models of learning-by-doing follow Arrow’s lead and focus on learning as it relates to cumulative input use or output production. However, Arrow offers an alternative definition of learning that does not preclude the existence of learning costs. In his words, learning may occur through the “attempt to solve a problem and therefore only takes place during activity.”

In new agricultural industries, some learning will be costless to the private sector, as it will result from the transfer of research and development efforts from the public to the private sectors. This learning may include knowledge about new crop hybrids,

planting techniques, and harvest timing that arise from genetic and agronomic studies. However, any production cost reductions that occur from this transfer will depend on the ability of growers to incorporate research developments. It has been observed that agriculture is characterized by heterogeneity of agents and resources. As a result, agricultural production displays site specificity, agriculture varies from site to site, and is therefore highly dependent on management (Lichtenberg). Learning in new agricultural industries is also likely to be site specific, dependent on the resource base of a particular region and grower. Thus, even the transfer public sector learning will require effort on the part of the growers to modify and adapt the knowledge to their particular conditions and experience.

A significant portion of learning will occur from the entrepreneurship, in Rosen's terminology, of the growers themselves. A critical period for many biomass crops is the establishment phase, the early period of cultivation. During this period, management practices may have a substantial impact on yields during the harvest period. As an example, poor management in the establishment of a perennial crop stand, such as those used in biomass energy, has significant consequences by reducing the yields for several seasons of production (Sanderson et al.) During this phase, learning occurs through the diligence of the grower in observing crop responses to inputs and land quality and making appropriate adjustments in cropping practices. This entrepreneurial learning in agriculture is related to a grower's experience with the novel crop. However, the crops are not harvested during the establishment phase when learning occurs and so one cannot relate this learning to cumulative output of the grower. Thus learning in this phase will

be directly related to some effort exerted by the grower, which cannot be measured by cumulative output.

In a sense, there may be two phases of learning in agriculture. For each crop stand, there is learning associated with the establishment of the crop; one may designate this as intra-period learning. There is also learning that may extend beyond the life of a particular crop stand that is linked to total experience, or inter-period learning. For two reasons, intra-period learning during the establishment phase may matter the most for the initial development of new agricultural industries. First, it is difficult to forecast economic conditions over a long horizon. In order to make appropriate investments in a new industry, decisions will be based on short-term forecasts of crop productivity. These short-term forecasts are based on outcomes from management during the establishment phase of the crop stand. Second, if establishment practices affect the productivity of the crop stand over several years, then profitability of the industry will also be affected over several years, or the lifespan of the crop stand. Thus, profits and losses of the industry are magnified in that they extend over the period of a lifespan of a crop stand, or at least over a period of a few years needed to establish a new crop stand. Early losses in the industry may serve as a signal to investors that there will be an extended period of losses due to poor crop productivity. Investors may decide to abandon the new industry rather than take a “wait and see” approach to determine if cost reductions occur from continued production.

This intra-period learning may best be modeled as an investment in time and care on the part of the grower. These investments are oftentimes non-monetary in nature. As stated before, these activities may pertain to the care in making cropping decisions or the

amount of time observing crop performance under various conditions. The challenge, then, lies in the forming contractual arrangements that induce the appropriate level of this learning investment on the part of the grower that lead to cost reductions to be enjoyed by the industry as a whole.

Moral Hazard and Adverse Selection in Contracts

The types of investments and activities undertaken by agents to induce higher levels of learning are generally unobservable. In addition, the magnitude of cost reductions that occur due to learning is the private information of the grower. This poses two problems to the processor when offering a contract to the grower. Because the processor cannot observe the effort exerted by the grower that may lead to cost reductions, the processor faces a hidden action problem. In addition, the processor can not observe the actual realization of learning, i.e. the true cost of production, and so the processor faces a hidden information problem. The contracting environment is thus characterized by both moral hazard in learning investment and adverse selection in production. This environment creates a problem where a new industry may be unable to appropriate the gains from grower learning, thereby hindering the formation and development of a viable industry.

Uncertainty about the future costs of producing novel crops and the profitability of the industry as a whole further constrains the contracting environment. For many of these emerging industries, spot markets for the biomass crops are non-existent. In addition, the notion of producing pharmaceuticals or electricity from biomass is foreign to many, especially within the United States, and may even appear “faddish” to many agricultural producers. The processor, therefore, must offer contracts that are designed to

induce grower participation by offering protection to growers from negative outcomes; such as those where experience-driven cost reductions are not achieved. By restricting the contract set to those that limit the liability of the grower, the processor ensures adequate expected feedstock production and thereby protects his capital investment.

The literature on investments on the part of agents under contracts with asymmetric information is vast. However, a handful of the analyses contained in the literature summarize the basic results of contracting in this environment. In general, the issue of investment that leads to cost reductions, i.e. the learning investment, has been placed in the context of a regulator and a firm or in the context of government procurement. In the case of the regulated firm, the government must set a policy based on the firm's cost. As an example, a regulatory agency may set the price for electricity for a utility that serves a particular region. In addition, the firm may engage in activities that lead to the reduction of future costs. These activities are unobservable and the resulting costs are unverifiable. The government or regulator would like to take advantage of any cost reductions accrued to the firm.

In problems of this type, the government must rely on a menu of contracts, or price-quantity pairs, from which the firm selects once it observes its true costs of production. The regulated price-quantity pairs must be attractive enough to allow the utility some profit, as well as create incentives for investing in learning. Yet the price-quantity pairs must also be such that they benefit the utility's customers. The regulator requires information from the utility, yet the firm has an incentive to misrepresent this information. The menu of contracts relies on the reported type of the regulated firm because the true type of the firm is unobservable by the regulator. By the revelation

principle, the regulator may restrict the menu of choices to those that are incentive compatible and elicit truthful revelation of cost by the regulated firm. (Myerson) In general, the firm has an advantage over the regulator in that it possesses private information about costs. This allows the firm to extract rent, “information rent”, from the regulator. The payment of information rent elicits a truthful revelation from the firm. The need to pay information rent prohibits attainment of a first best outcome.

In one of the earliest models of this form, Baron & Besanko include research and development on the part of the firm. In a two-period model, the regulator wishes to elicit truthful revelation of costs in both the first and second periods, as well as influence the firm’s level of investment in R & D in the first period. The results depend on the level of correlation that exists between first and second period costs to the firm. In the case where costs are correlated, such as may occur in learning by doing, contracts of this sort do not allow for attainment of first best levels of investment in research by the firm. Ex ante contracts also do not allow for the regulator to set the optimal price for the firm’s regulated product in the second period. This result has been reproduced by other analysts, notably Laffont and Tirole.

Sappington examined the issue of limited liability contracts under asymmetric information. Here, there is no investment on the part of the firm, so there is no moral hazard complicating the contractual environment. However, there is uncertainty about the cost of production in the second period and the purchasing entity guarantees a minimal payment to the producing firm. The cost of producing the good is private information of the firm. Sappington invokes the revelation principle and restricts his attention to the set of contracts that elicit truthful revelation. The main effect of limiting

liability is to increase the amount of information rent paid to the firm for the traded good. In general, the contract offers the greatest per unit price for the good plus the largest absolute information rent to the firm when it realizes the lowest possible cost of production. In order to receive the payment, the firm must also produce the largest quantity of the good at the lowest per unit cost. This practice of increasing the payment, information rent, and the quantity accordingly, as the firm cost declines, creates an incentive compatible mechanism. However, limited liability does not allow for a contract that punishes poorly performing firms. Information rent is always non-negative under limited liability, and so production is skewed downward away from the first best.

Laffont and Martimort generalize the results of Baron & Besanko and Sappington. In the generalized model, a firm is offered a limited liability contract in the first-period that elicits investment in cost-reducing activities. As expected, a first best is unattainable. Investment in cost reductions is less than first best, and the contract elicits underproduction over the entire range of outcomes, except the worst.

More recently, Osmundsen proposed of model of learning-by-doing under contracts by expanding upon the Baron-Besanko framework. In this model, second-period cost reductions depend on first-period output. However, the model employs the Arrow technique of using cumulative output as a measure of learning. The contract in this environment uses countervailing incentives to elicit lower costs in the second period. If the firm reports high costs in the first period, by choosing low levels of production, then it will face higher costs of production and extract lower rent from the regulator in the second-period. There exists a tradeoff for the firm between first period and second

period revelation of costs which, under certain conditions of the distribution of efficiency types, may allow the regulator to attain a solution closer to the first best outcome.

Contribution to the Literature

The need for location and relationship-specific assets, combined with temporal considerations, imply that new agricultural industries will be governed by some form of long-term contracting. Uncertainty about the prospect of the industry and unfamiliarity with novel crops may deter involvement on the part of growers without some form of payment guarantees. On the other hand, this unfamiliarity underlies the potential for learning within the industry that may reduce the cost of producing the novel crops.

Learning requires effort on the part of the grower. This effort is, in general, unobservable by the processor and therefore non-contractible. The resulting cost reductions are private information of the grower and therefore unverifiable by the processor. Thus, new agricultural industries are likely to exhibit moral hazard in learning effort, as well as adverse selection in the production of the intermediate good.

Although the problem of limited liability contracts in the presence of moral hazard and adverse selection has been explored in the literature, the contracts have been limited to the case where the principal (government, regulator, procuring agent) does not make an investment. The size of projects in these models is exogenous to the model, or irrelevant. In the case of new agricultural industries, the principal is a processor that must determine the size of the project, as well as the quantity of the intermediate good for use in production of the final good. This dissertation presents a model similar to that of Laffont and Tirole, yet modified to include an investment in processing capacity on the part of the principal.

In addition, the dissertation contributes an empirical application of the model that quantifies the inefficiencies that arise from this contracting environment. The empirical application allows for a better understanding of how these contracts may impinge upon the viability of a new agricultural industry by creating an additional obstacle to initial investment.

Chapter 3. Theoretical Model

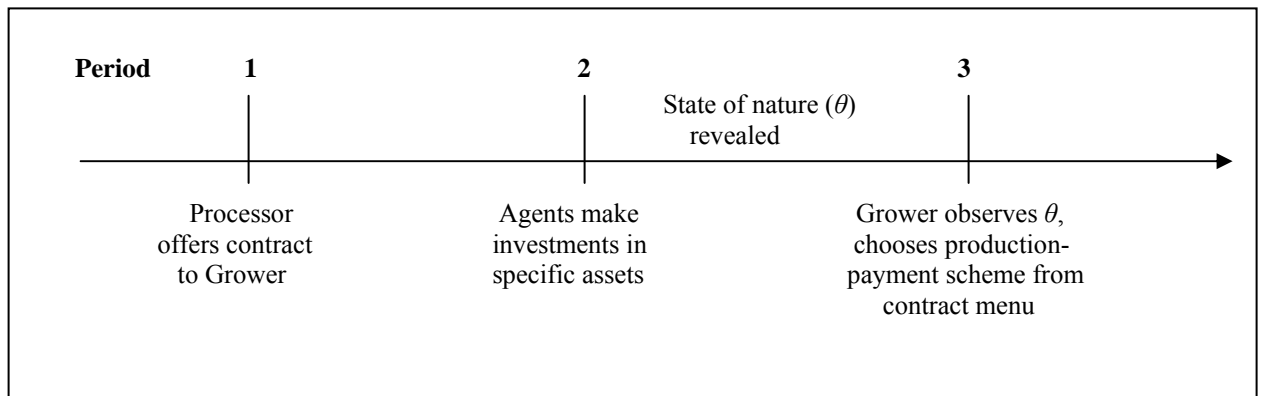
Analysis of the impact of limited liability contracts on learning within a new industry proceeds via construction of a theoretical model. In the model, a processor (the principal) wishes to enter a contractual relationship with a producer of an intermediate good. The producer of the intermediate good may be a grower or a cooperative of growers acting as a single grower (the agent) that cultivates a new agricultural crop. Due to the specificity of the relationship that arises between the two parties, the processor and grower wish to secure an agreement before making investments and producing output. A timeline of the model is appears in Figure 1.

In the first period, the processor offers a contract to the grower. The contract consists of a menu of production and payment options from which the grower will choose at a later date. In the second period, both parties make investments in relationship-specific assets. The processor invests in physical capital, such as a processing facility, that requires feedstock from the grower. The grower undertakes investments that are unobservable and unverifiable. These investments in learning, have a direct impact on the grower's future production costs. Many of these investments are non-monetary, as they may include the amount of time spent by the grower in observing crop responses to certain inputs and determining optimal soil conditions for growth or the amount of care taken in making appropriate cropping decisions.

Despite the level of investment undertaken by the grower, there is always a possibility that no cost reductions will result. Agricultural uncertainty is always present and in any period poor growing conditions may overshadow any benefits accrued through experience. The impact of the learning investment is probabilistic and affects only the

distribution of the costs; the ultimate impact on future costs is uncertain. Learning investments, therefore, only increase the probability that costs will be reduced at a future date. In the third, and final, period, the grower observes the resulting costs and chooses a production level and corresponding payment from the contract menu that was offered in the first period. Trade occurs between the processor and grower.

Figure 1. Timeline of the Model



Both the processor and the agent are risk-neutral agents. The investment made by the processor is much larger, in monetary terms, than that of the grower and so the processor faces much higher adjustment costs than the grower. It is assumed in the model that the grower has no conversion costs, i.e. she may switch costlessly from the project crop, which has uncertain value, to another commodity, of certain value. The relative magnitude of investments combined with the outside option of the grower places the burden on the processor to ensure a future supply of feedstock. In order to induce adequate grower participation, a contract must be written that satisfies the grower in all states of nature, i.e., one that limits the grower's liability in bad states of nature yet offers adequate incentives for grower to invest and produce at near-optimal levels. Thus, the grower acts risk neutral toward outcomes where her income is at least equal to her outside option.

Consider the grower's production technology. The cost of producing crops is stochastic, dependent on the level of production, q , and the state of nature, θ . The investment made by the grower, e , may be viewed as the quality of management or entrepreneurship effort exerted by the growers in production. Although this investment does not directly affect costs, it has an impact on the distribution of the state of nature. In other words, a high level of investment increases the probability of a favorable state of nature, where learning has resulted in significant cost reductions. Cost, $C(q, \theta)$, is increasing and convex in crop production and decreasing in the state of nature. Using subscripts to denote partial derivatives, this may be summarized as: $C_1(q, \theta) > 0$, $C_{11}(q, \theta) > 0$, $C_2(q, \theta) < 0$, $C_{22}(q, \theta) > 0$. The marginal cost of production also decreases in favorable states of nature, $C_{12}(q, \theta) < 0$.

The state of nature may take any value in the support, $\theta \in [\underline{\theta}, \bar{\theta}]$, where $\underline{\theta}$ is the worst state of nature. The cumulative distribution, $G(q, \theta)$, and probability density, $g(q, \theta)$, of θ are conditional on investment where

$$G_e(\theta|e) = \frac{\partial G(\theta|e)}{\partial e} \leq 0 \quad \forall \theta \in (\underline{\theta}, \bar{\theta}),$$

and investment has no effect on the supports of the distribution,

$$G_e(\bar{\theta}|e) = G_e(\underline{\theta}|e) = 0.$$

In addition, the probability distribution exhibits diminishing marginal returns to investment at higher levels of learning investment,

$$G_{ee}(\theta|e) = \frac{\partial G_e(\theta|e)}{\partial e} \geq 0 \quad \forall \theta \in (\underline{\theta}, \bar{\theta})$$

The processor creates a final good using capital, K , and the grower's output, q . The production function, $f(K, q)$, is increasing and concave in both arguments, $f_i(\cdot) > 0$,

$f_{11}(\cdot) < 0, f_2(\cdot) > 0, f_{22}(\cdot) < 0$, and the inputs are complementary, $f_{12}(\cdot) > 0$. The cost of physical capital is represented as r , on the monetary value per unit of processing. The processor faces an output price, p , for the final good.

First Best Solution

As a benchmark for the analysis, consider the first best levels of production and investment. A number of benchmarks may be chosen for this analysis; in particular one may choose to consider the outcome of the industry under a governance structure, such as another form of contract or some form of vertical integration. The first best outcome serves as the benchmark primarily because the analysis in the dissertation is, in part, a response to engineering analyses of new agricultural industries. These analyses implicitly assume first best conditions: full, symmetric information; a single agent that makes all investment and production decisions; and, a single agent that receives the full marginal benefit of all investments. The benefits, both direct and ancillary, of these new industries are often based on these engineering assumptions. By reproducing engineering analyses through a first best regime and comparing them to a limited-liability contracting regime, one may better understand the magnitude of overestimation (underestimation) of the benefits (costs) reported in those analyses.

In a first best regime, a social planner chooses production that maximizes total surplus. The optimal level of production in each state of the world is selected ex post, i.e. after the resolution of uncertainty about over the state of nature, or the level of realized production costs.

$$V^{FB} = \max_q \{pf(K, q) - C(q, \theta)\}$$

This implies that the marginal cost of producing the intermediate good (the crop) must equal the marginal benefit of producing the final good in every state of nature.

$$\frac{\partial V^{FB}}{\partial q} = pf_2(K, q) - C_1(q, \theta) = 0 \quad \forall \theta \quad (1)$$

The first order condition produces a best response function for crop production based on the level of capital invested and the state of nature, $q(K, \theta)$, which may be used ex ante to solve for the optimal level of investments in capital and learning. The planner maximizes expected surplus,

$$U^{FB} = \max_{K, e} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, \theta)) - C(q(K, \theta), \theta)] dG(\theta|e) - rK - e \right\}.$$

The first order conditions for the ex ante maximization are,

$$\frac{\partial U^{FB}}{\partial K} = \int_{\underline{\theta}}^{\bar{\theta}} \left[pf_1(K, q(K, \theta)) + (pf_2(K, q(K, \theta)) - C_1(q(K, \theta), \theta)) \frac{\partial q}{\partial K} \right] dG(\theta|e) - r = 0 \quad (2)$$

$$\frac{\partial U^{FB}}{\partial e} = \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, \theta)) - C(q(K, \theta), \theta)] dG_e(\theta|e) - 1 = 0 \quad (3)$$

Applying the relationship found in equation (1) to the first-order condition for capital investment simplifies equation (2) to the following:

$$\frac{\partial U^{FB}}{\partial K} = \int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, \theta)) dG(\theta|e) - r = 0$$

In words, the level of capital investment should be chosen at the point where the expected marginal value product of capital equals the marginal cost of investing in that capital.

The first-order condition for learning effort (3) simplifies upon integration by parts followed by application of equation (1). Using the following identity,

$$\int u dv = uv - \int v du$$

and defining u and v as follows,

$$u = pf(K, q(K, \theta)) - C(q(K, \theta), \theta)$$

$$dv = dG_e(\theta|e)$$

equation (3) implies that,

$$[pf(K, q(K, \theta)) - C(q(K, \theta), \theta)]G_e(\theta|e) \Big|_{\theta=\underline{\theta}}^{\theta=\bar{\theta}}$$

$$- \int_{\underline{\theta}}^{\bar{\theta}} [pf_2(K, q(K, \theta)) - C_1(q(K, \theta), \theta) - C_2(q(K, \theta), \theta)]G_e(\theta|e) d\theta - 1 = 0$$

Applying condition (1) and the condition, stated earlier, that investment has no impact on the supports of the distribution, equation (3) reduces to,

$$\frac{\partial U^{FB}}{\partial e} = \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, \theta), \theta)G_e(\theta|e) d\theta - 1 = 0$$

Similar to the condition for capital investment, the condition above states that amount of effort put forth in learning should be chosen at the point where the expected marginal decrease in feedstock production cost associated with learning equals the marginal cost of learning effort. Equations (1)-(3) will be used later in the analysis to compare the first best results with those investment levels obtained in a contractual environment.

In order to ensure an optimal solution, the benefit function, or the social planner's objective function, must also satisfy certain concavity requirements. Ex post, the benefit function must be concave in the level of feedstock production. Ex ante, the benefit function must be concave in the levels of investment in capital and learning. In the interest of conserving space, a full derivation and discussion of the sufficient conditions to ensure optimality appear in Appendix A.

Contracting Solution

The contractual environment is characterized by ex ante moral hazard and ex post adverse selection. Ex ante, the principal wishes to elicit optimal investment choice by the agent, which is a hidden action. The optimal level of investment may not be achievable due to the need to induce grower participation in the new project. When the grower has an outside option, such as a conventional crop, she may choose to enter into a joint project only when offered a guarantee that her income will be at least as great as that she could realize from the conventional crop. This imposes a constraint on the principal to offer a limited liability contract that ensures the grower at least his reservation utility (the value of the other commodity) in all states of nature. In a sense, the grower acts as though she has infinite risk aversion below her reservation utility. The need to limit liability to the grower reduces the overall power of the contract, thereby reducing incentives to invest in learning.

The principal also offers a contract to elicit optimal production levels given the ex post level of learning that has occurred. A number of mechanisms may achieve this end, but by the revelation principle the analysis simplifies by restricting the solution to a contract that elicits truthful revelation of costs. Myerson shows that there exists a mechanism that elicits a truthful reporting strategy and performs at least as well as all other mechanisms. The state of nature is hidden information, observed only by the grower. This further constrains the principal, who must now offer extra incentives to elicit truthful information from the grower, i.e. learning rents. The following model is similar to one presented by Laffont and Tirole. It differs in that the principal also has an investment choice.

The principal, faced with ex post adverse selection, offers a contract of payment and production schedules designed to elicit truthful revelation of the state of nature by the agent. Payment for crop production consists a variable portion, w that depends on the level of production, q . After the resolution of the state of nature, the agent indirectly reveals the actual state of nature through her choice of q from the contract menu. For a payment-production scheme for the “announced” state of nature, $\hat{\theta}$, an agent of type θ will find that her best response is to announce the true state of nature. The choice of production, therefore, depends on the state of nature and so production may be represented by $q(\theta)$. The variable portion of the payment that is dependent on q is therefore also dependent on the reported state of nature and may be represented by $w(\hat{\theta})$. The utility (ex post) of an agent (grower) of type θ that has announced, through her choice of contract option, that she is type $\hat{\theta}$ is

$$V^G(\hat{\theta}, \theta) = w(\hat{\theta}) - C(q(\hat{\theta}), \theta).$$

Therefore the contract must be designed so that a grower maximizes her utility through truthful revelation and the grower has no incentive to falsify her type. These conditions (4) formally appear below.

$$\frac{\partial V^G(\hat{\theta}, \theta)}{\partial \hat{\theta}} = w_{\theta}(\hat{\theta}) - C_1(q(\hat{\theta}), \theta)_{q_{\theta}}(\hat{\theta}) = 0$$

$$\left. \begin{aligned} w(\theta) - C(q(\theta), \theta) &\geq w(\theta') - C(q(\theta'), \theta) \\ w(\theta') - C(q(\theta'), \theta') &\geq w(\theta) - C(q(\theta), \theta') \end{aligned} \right\} \forall \theta \neq \theta' \quad (4)$$

To ensure that the grower achieves a maximum, the second-order condition with respect to announced type must be non-positive,

$$\frac{\partial^2 V^G(\hat{\theta}, \theta)}{\partial \hat{\theta}^2} = w_{\theta\theta}(\hat{\theta}) - C_{11}(q(\hat{\theta}), \theta)q_{\theta}(\hat{\theta})^2 - C_1(q(\hat{\theta}), \theta)q_{\theta\theta}(\hat{\theta}) \leq 0.$$

Incentive compatibility of the contract implies that the conditions (4) hold in all states of nature. Truthful revelation therefore implies that $\hat{\theta} = \theta$ and so $U^G(\hat{\theta}, \theta) = U^G(\theta, \theta)$. Therefore, differentiation of condition (4) with respect to the state of nature results in the following:

$$\frac{\partial^2 V^G(\theta, \theta)}{\partial \theta^2} = w_{\theta\theta}(\theta) - C_{11}(q(\theta), \theta)q_{\theta}(\theta)^2 - C_1(q(\theta), \theta)q_{\theta\theta}(\theta) - C_{12}(q(\theta), \theta)q_{\theta}(\theta) = 0$$

Substitution of the second-order condition with respect to announced type implies that, for the condition to hold $C_{12}(q(\theta), \theta)q_{\theta}(\theta) \leq 0$, and so, therefore, $q_{\theta}(\theta) \geq 0$. In words, if a separating equilibrium exists whereby each state of nature is associated with a unique production level, the production level increases monotonically with the state of nature. The generator will offer a contract that elicits greater production of feedstock in better states of nature.

Differentiation of the grower's utility function over type and application of the envelope theorem yields,

$$\frac{\partial V^G(\theta, \theta)}{\partial \theta} = w_{\theta}(\theta) - C_1(q(\theta), \theta)q_{\theta}(\theta) - C_2(q(\theta), \theta) = -C_2(q(\theta), \theta) \quad (5)$$

In other words, the increase in utility to the grower that arises from an increase in the state of nature is equal in magnitude to the marginal decrease in feedstock production cost that occurs. Although it is possible to elicit truthful revelation through a mechanism that demands greater output in better states of nature, the revelation comes at a cost greater than the marginal cost of producing the additional output.

This cost, or learning rent, may be found by deriving an expression for the the payment scheme. An expression for the total payment given to the grower in a particular state of nature, $w(\theta)$, may be found by integrating the first part of condition (4) over types:

$$\int_{\underline{\theta}}^{\theta} [w_{\theta}(\theta) - C_1(q(\theta), \theta)q_{\theta}(\theta)]d\theta = w(\theta) - w(\underline{\theta}) - \int_{\underline{\theta}}^{\theta} C_1(q(\theta), \theta)q_{\theta}(\theta)d\theta = 0$$

The first part of condition (4) equals zero in all states of nature. In addition, one may apply the following identity,

$$\frac{dC(q, \theta)}{d\theta} = C_1(q(\theta), \theta)q_{\theta}(\theta) + C_2(q(\theta), \theta),$$

so that the expression for the total payment reduces to:

$$w(\theta) = w(\underline{\theta}) - C(q(\underline{\theta}), \underline{\theta}) + C(q(\theta), \theta) - \int_{\underline{\theta}}^{\theta} C_2(q(z), z)dz$$

The other crop commodity that may be grown by the agent has no value to the principal but it plays a role in determining the grower's reservation utility, Π . This implies that the contract must satisfy (ex ante) the following participation constraint,

$$V^G(\theta, \theta) = w(\theta) - C(q(\theta), \theta) \geq \Pi \quad \forall \theta \tag{6}$$

In order to minimize the total amount of rents that the processor must pay for truthful revelation, the payment is designed so that equation (6) holds at equality in the worst state of nature.

$$V^G(\underline{\theta}, \underline{\theta}) = w(\underline{\theta}) - C(q(\underline{\theta}), \underline{\theta}) = \Pi \tag{7}$$

Substitution of this condition into the expression for total payment to the grower results in

$$w(\theta) = \Pi + C(q(\theta), \theta) - \int_{\underline{\theta}}^{\theta} C_2(q(z), z) dz \quad (8)$$

Information rents to the grower are represented by the last element of equation (8) and are equivalent to all of the learning rents, i.e. all of the cost reductions attributable to the investments in learning that the grower has made. In effect, the payment to the grower takes the form of a cost-plus reimbursement scheme, whereby the processor pays the grower the opportunity costs of her resources (land, labor), the production costs of the crop, plus an additional amount (learning rent) to induce higher levels of production in more favorable states of nature.

Optimal ex ante investment by the grower is represented by

$$e = \arg \max_a \int_{\underline{\theta}}^{\bar{\theta}} [w(\theta) - C(q(\theta), \theta)] dG(\theta|a) - a,$$

which implies that equation (3), the first-order condition for grower investment in the social optimum, must hold in the contractual environment. Using integration by parts, as before, the first-order condition reduces to:

$$\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e(\theta|e) d\theta - 1 = 0$$

When solving for optimal level of production, the processor must take into account this condition – the moral hazard in investment constraint. Adding the constraint to the processor's profit maximization problem allows the processor to solve for the grower's equilibrium choice of learning investment, i.e. the grower's best response to the contractual terms. The processor's problem, therefore, is

$$U^P = \max_{K, e, q(\theta)} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(\theta)) - w(\theta)] dG(\theta|e) - rK \right\} \text{ s.t. } \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e(\theta|e) d\theta - 1 = 0$$

The processor Lagrangian, after appropriate substitutions and rearrangement of terms, may be written as,

$$\mathcal{L} = \max_{K, e, q(\theta)} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} \left[pf(K, q(\theta)) - C(q(\theta), \theta) + \int_{\underline{\theta}}^{\theta} C_2(q(\theta), \theta) d\theta \right] dG(\theta|e) + \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e d\theta - 1 \right] - \Pi - rK \right\}.$$

Integrating by parts the final term within the first set of brackets (above), the Lagrangian may be further simplified as,

$$\mathcal{L} = \max_{K, e, q(\theta)} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} \left[pf(K, q(\theta)) - C(q(\theta), \theta) + C_2(q(\theta), \theta) \frac{1 - G(\theta|e)}{g(\theta|e)} \right] dG(\theta|e) + \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e d\theta \right] - \lambda - \Pi - rK \right\}$$

where λ represents the shadow price of the grower investment constraint. The four first-order conditions to the problem are:

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial q(\theta)} &= pf_2(K, q(\theta)) - C_1(q(\theta), \theta) + C_{21}(q(\theta), \theta) \left[\frac{1 - G(\theta|e) + \lambda G_e(\theta|e)}{g(\theta|e)} \right] \\ &= 0 \quad \forall \theta \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial e} &= \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(\theta)) - C(q(\theta), \theta)] dG_e(\theta|e) - \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e(\theta|e) d\theta + \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_{ee} d\theta \right] \\ &= 0 \end{aligned} \quad (10)$$

$$\frac{\partial \mathcal{L}}{\partial K} = \int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(\theta)) dG(\theta|e) - r = 0 \quad (11)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e(\theta|e) d\theta - 1 = 0 \quad (12)$$

Inspection of the first-order conditions under limited liability contracts reveal that the first best solution is not achieved. Condition (9) reveals that the quantity of the intermediate good, the feedstock for the processor, is not selected at the level where the marginal value product of the input equals the marginal cost of procuring the input. An

additional term appears in the first best condition for feedstock production that creates a distortion between first and second best outcomes.

Additional terms also appear in the condition for the learning investment, implying that limited liability contracts also distort the level of effort taken by the grower in learning. Condition (11) appears identical to the first best solution for the optimal level of capital investment. However, the production schedule for the intermediate good appears as an argument of the production function for the final good. By condition (9), the production schedules are not the same in the first and second best solutions. Therefore, a distortion must also exist in the level of capital investment undertaken by the processor.

Alternatively, the processor's problem may be written as a two-stage problem. The first stage of the problem may be solved using optimal control of the feedstock production over states of nature. The second stage of the problem may be solved using static optimization for the investments in capital and learning. The Hamiltonian for the optimal control problem and a more formal treatment of the optimal solution is presented in Appendix A. In addition, the Appendix also includes a discussion of the second-order conditions necessary to ensure optimality of the solution to the processor's problem.

Comparison of Contracting Solution with the First Best

In this section of the chapter, the first-order conditions are analyzed to ascertain the direction of the inefficiency in learning effort and feedstock production that occurs under contracting. Is there overproduction or underproduction of feedstock under contracts relative to the first best? Is there too much learning effort, or too little, put forth under contracts? In addition, the analysis determines if there exists an effect of these

inefficiencies on the overall scale of the project. Do these inefficiencies also create inefficiency in capital investment under contracts relative to the first best? If so, is there an overinvestment in capital or an underinvestment?

To answer the questions about the direction of distortions between first and second best outcomes, the analysis first compares crop production levels between the first and second best outcomes. This is accomplished by identifying the wedge term in the first-order condition for feedstock production and determining that it is positive in sign, implying underproduction of feedstock. Further, a monotonicity condition is imposed to ensure a separating equilibrium. This condition allows for determination of the relative level of underproduction over the states of nature. The second part of the analysis identifies a positive correlation at the optimum between the investment in learning and the level of feedstock production. This correlation allows for determination of underinvestment in learning on the part of grower. The final part of the analysis identifies a positive correlation at the optimum between the investment in capital with the learning investment and feedstock production schedule. This correlation completes the analysis with the determination that there is also underinvestment in capital on the part of the processor.

Proposition 1. For a given level of capital investment, the optimal limited-liability contracts elicits underproduction of the intermediate good in all states of nature, except for the most favorable.

The analysis begins with a comparison of crop production levels between the two regimes through rearrangement of equation (9). Equation (9) states that the optimal contract will elicit production of q for each θ such that the following holds:

$$\frac{\partial \mathcal{L}}{\partial q(\theta)} = (pf_2(K, q(\theta)) - C_1(q(\theta), \theta)) + \Phi(\theta, e) = 0 \quad \forall \theta$$

where

$$\Phi(\theta, e) = C_{21}(q(\theta), \theta) \left[\frac{1 - G(\theta|e) + \lambda G_e(\theta|e)}{g(\theta|e)} \right]$$

represents the wedge that exists between the optimal production level that occurs in the first best and the optimal level that occurs under contracting. The level of feedstock is chosen so that the marginal value product of the input equals the marginal cost of producing the input plus the wedge term, which may be thought of as the marginal cost of mitigating moral hazard in the learning investment and adverse selection in the input's production. This additional cost term creates a distortion between the level of feedstock that would be selected under first best conditions and that chosen under limited liability contracts.

In order to ascertain if there is too much or little of the feedstock produced relative to the first best, one must first determine the sign of this “wedge” term. First, restrictions are imposed. To ensure a separating equilibrium, we assume that the expression within the brackets of the wedge term is monotonic in the state of nature. Evaluating the expressions at the worst and best states of nature, one finds the following:

$$\left. \frac{1 - G(\theta|e) + \lambda G_e(\theta|e)}{g(\theta|e)} \right|_{\theta=\bar{\theta}} = 0$$

$$\left. \frac{1 - G(\theta|e) + \lambda G_e(\theta|e)}{g(\theta|e)} \right|_{\theta=\underline{\theta}} = \frac{1}{g(\theta|e)}$$

Monotonicity implies that the value of the expression above must fall within the

range $\left[0, \frac{1}{g(\theta|e)} \right]$, and so must be positive for the entire range of values in $[\underline{\theta}, \bar{\theta}]$. In

addition, assumptions on the cost function impose $C_{12}(q, \theta) < 0$. Monotonicity, combined

with assumptions on the cost function and the distribution of θ allow us to state that $\Phi(\theta, e)$ is weakly negative for all values of θ . It is strictly negative for all θ except $\bar{\theta}$ (the best state of nature), where it is equal to zero. This implies that, for a given level of K , the optimal contract will elicit underproduction of q in all realized states of nature except the most favorable.

Proposition 2. For a given level of capital investment, limited liability contracts elicit underinvestment in learning on the part of the grower.

It is now determined if the levels of capital investment and learning effort differ between the two regimes. In order to extend the analysis in this manner, equation (9) is first solved qualitatively for the second-best levels of crop production given K and e . That is, we must determine an expression for feedstock as a function of the ex ante investment levels and the revealed state of nature: $q(K, e; \theta)$. To facilitate comparisons between the first best and second-best levels of investment and production, we denote first best levels by an asterisk (*) and second-best levels by a tilde (~) and define $q^* \equiv q(K^*, \theta)$ and $\tilde{q} \equiv q(\tilde{K}, \tilde{e}; \theta)$.

Consider the grower's learning investment decision. A qualitative analysis of the level of investment as compared to the first best may be done via inspection of equation (3), the first-order condition for grower investment in the first best. Differentiation of the constraint by $q(\theta)$ and by e results in the following expressions (13).

$$\left. \begin{aligned} \frac{\partial}{\partial q(\theta)} \left(\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, \theta), \theta) G_e(\theta|e) d\theta - 1 \right) &= \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, \theta), \theta) G_e(\theta|e) d\theta > 0 \\ \frac{\partial}{\partial e} \left(\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, \theta), \theta) G_e(\theta|e) d\theta - 1 \right) &= \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_{ee}(\theta|e) d\theta < 0 \end{aligned} \right\} \quad (13)$$

The two conditions in (13) imply that there is a positive correlation between feedstock production and learning investment at the optimum. In order for the condition (3) to hold with equality, an increase in production must be accompanied by a corresponding increase in investment in learning. Because it has already been determined that the optimal contract elicits underproduction (relative to the first best) for a given K in nearly all states of nature, then (13) implies that the contract elicits a corresponding level of investment in learning that is less than that of the first best for a given K . In other words, if the second-best level of investment in capital were equal to the first best ($\tilde{K} = K^*$), then there would be underproduction of feedstock ($\tilde{q} < q^*$) and under-investment in learning relative to the first best ($\tilde{e} < e^*$).

Proposition 3. Limited liability contracts elicit underproduction in processing capacity on the part of the principal.

Now consider the final piece of this puzzle, the processor's investment in capital. In order to determine the relationship between \tilde{K} and K^* we must analyze the first-order condition for capital investment in the first best. Similar to the analysis of the grower decision, we may differentiate condition (2) by the investment and production variables.

$$\left. \begin{aligned}
 \frac{\partial}{\partial q} \left[\int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, \theta)) dG(\theta|e) - r \right] &= \int_{\underline{\theta}}^{\bar{\theta}} pf_{12}(K, q(K, \theta)) dG(\theta|e) > 0 \\
 \frac{\partial}{\partial e} \left[\int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, \theta)) dG(\theta|e) - r \right] &= \int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, \theta)) dG_e(\theta|e) \\
 &= - \int_{\underline{\theta}}^{\bar{\theta}} pf_{12}(K, q(K, \theta)) q_{\theta}(K, \theta) G_e(\theta|e) d\theta > 0 \\
 \frac{\partial}{\partial K} \left[\int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, \theta)) dG(\theta|e) - r \right] &= \int_{\underline{\theta}}^{\bar{\theta}} \left[pf_{11}(K, q(K, \theta)) + pf_{12}(K, q(K, \theta)) \frac{\partial q}{\partial K} \right] dG(\theta|e) < 0
 \end{aligned} \right\} \tag{14}$$

The set of conditions (14) rules out the case where $\tilde{K} = K^*$, $\tilde{q} < q^*$, and $\tilde{e} < e^*$.

The first two expressions of (14) imply that increases in both learning investment and feedstock production must also be accompanied by an increase in capital investment. Therefore, when \tilde{q} and \tilde{e} are less than the first best, then \tilde{K} must also be less than the first best for condition (2) to hold at equality. Therefore, second-best levels of investment in both capital and learning are inefficient relative to the first best. For any given level of capital investment, there will be under-investment in learning and underproduction of feedstock relative to the first best. Due to the expectation that overall levels of feedstock and learning will be low, the processor under-invests in capital, and so the second-best project scale is smaller than the first best.

Intuitively, the problem of under-investment in learning within the industry occurs because the processor must pay an information rent to the grower for production of the intermediate good. As shown in the analysis, the information rent is directly related to the amount of learning-induced cost reductions that occur in a given state of nature. In order to elicit truthful revelation, and induce investment in learning, the processor must pay these so-called learning rents to the grower. As a result, the feedstock price to the processor remains relatively high as compared to the first best, despite cost reductions that occur due to learning.

Better states of nature correspond to greater magnitudes of learning-induced cost reductions. Better states of nature also correspond to larger payments of learning rent to the grower. In order to elicit greater production in better states of nature the processor must make it unattractive for a low cost producer to mimic a high cost producer. This requires the processor to pay larger bonus payments in the form of learning rents in better

states of nature. The increasing size of the learning rent increases the overall cost of feedstock to the processor. To compensate for the increasing magnitude of learning rent in better states of nature, the processor reduces the feedstock procured in all states of nature except for the best. The distortion between first best and second best levels of feedstock production decreases monotonically in magnitude from a maximum in the worst state of nature to zero in the best state.

To some extent, the problem of moral hazard in learning investment reduces the size of the wedge between first best and second best feedstock output. This can be verified by examining the wedge term, $\Phi(\theta, e)$. One element of this term represents the

distortion arising from moral hazard $\left(\frac{\lambda G_e(\theta|e)}{g(\theta|e)} \right)$ and another represents the distortion

arising from adverse selection $\left(\frac{1 - G(\theta|e)}{g(\theta|e)} \right)$. The term related to moral hazard is negative,

whereas the term related to adverse selection is positive. Because the wedge term is positive, the moral hazard distortion serves to reduce the size of the wedge and the adverse selection distortion serves to increase the size of the wedge. The size of the wedge in feedstock production is directly related to the size of the learning rent given to the grower. To overcome adverse selection, the processor pays learning rent to the grower. In order to reduce the expected burden arising from payment of learning rent, the processor reduces the amount of feedstock procured in each state of nature, except the best. However, the processor adjusts the reduction in feedstock production in order to induce investment in learning by the grower.

Overall, the processor expects to pay a higher price for the feedstock than would have been paid in a first best situation. As a result, capital investment becomes less attractive to the processor relative to the first best, and so the processor invests in a smaller facility. The smaller facility requires less feedstock. Reduced orders for feedstock production reduce the size of the payments to growers in all states of nature. The reduced expected compensation diminishes the incentives for growers to invest in learning, resulting in higher costs of production for the feedstock.¹

Implications for New Agricultural Industries

The model clearly shows that limited liability contracts do not achieve a first best solution. Under limited liability contracts, growers are compensated for production costs and opportunity costs, and are given a bonus payment representing learning rent. Thus, limited liability contracts increase the total price of the intermediate good to the processor. To reduce the expected cost of the feedstock, the processor reduces contract orders for the procurement of the intermediate good, as well as the size of the capital investment. Reduced orders for feedstock production diminish the overall power of the contracts by reducing incentives for growers to invest in learning. The ultimate result is a project that is smaller in scale than that which would arise under the first best.

This result has a number of implications for new agricultural industries. Limited-liability contracts have the effect of ensuring project participation on the part of growers, which assures the processor a source for the intermediate good. However, the higher cost for the feedstock that results from this arrangement will affect the profitability of the project. If the processor produces a final good in a competitive market, the project may

¹ A similar result may be found using a first-order Taylor approximation around the first best of the set of first-order conditions. The analysis has been suppressed from this draft to conserve space.

not be viable. This high cost of feedstock may also discourage processors from investing in the biomass project and selecting a more conventional means of production that does not require a biomass crop. The new industry may not get off the ground, which may deprive some rural communities of a means for economic development. Certain environmental benefits may also not be realized.

Perhaps other contractual arrangements are possible that allow for assurances to both the grower and processor that would induce greater investment in these new industries. Future research in this area is necessary to determine the efficacy of other contract forms and coordination schemes on the scale and viability of new agricultural projects. For example, a possible topic for research would examine the performance of an ex post contract, i.e. a contract or menu of contracts that is offered after investments are made. It has been shown that ex ante limited liability contracts offer the grower incentives for investment in learning. However, they also increase the expense to the processor of the intermediate good. Would an ex post contract reduce the price paid for the feedstock while reducing the incentives for learning? Is there an overall increase or decrease in the efficiency of investments and production levels? Perhaps other commitment devices would lead to efficiency gains. Would anything be gained by the processor acting as a Stackelberg leader and making investments before offering contracts to the grower?

A first best solution may be achievable in a perfectly competitive market for the intermediate good. Under perfect competition, growers would offer the intermediate good at marginal cost of production, thereby revealing the level of learning that has occurred. Competition would also create the appropriate incentives for growers to invest

in learning. In new agricultural industries, such as the biomass for electricity generation industry, a perfectly competitive environment does not exist. The need for specific investments on the part of growers and processors, among other features of the industry, necessitate long-term contracts. Furthermore, the location specificity of the investments that restrict the market area of an individual project could prohibit the formation of competition once the markets for biomass feedstock become more developed.

Repeated interactions between the processor and the grower may offer a solution to the problem of industry viability. After the industry has been established, then there may be potential for a processor to extract more of the rents from learning, thereby increasing the value of capital investment. Oftentimes, crop rotation schedules will be shorter than the planning horizon of the processor. As such, there may be several contracting periods over the lifespan of a processing facility. In subsequent contracting periods, processors may be able to elicit information about cost reductions through a competitive bidding process. Allowing new growers to enter in the bidding process may force incumbent growers to bid truthfully, enabling the processor to extract learning rents from the less efficient growers. If a processor could be relatively certain that a competitive bid process could be implemented successfully, then perhaps they may be willing to invest greater resources into the industry. Successful implementation of a competitive bidding process requires freedom of entry of new growers into the process. Entry may be limited due to transportation costs that restrict the expanse of the growing area. Established grower cooperatives may also restrict new membership. This may be a fruitful avenue for future research.

Vertical integration within the industry offers another potential solution to the problem of industry viability. However, vertical integration does not come without another, and potentially more significant, set of problems. Williamson theorized that a decision on organizational form would involve a trade-off between potential diseconomies of vertical integration and costs of transacting in the marketplace. For many new agricultural industries, diseconomies of backward vertical integration (processor acquiring grower) may occur due to geographical reasons. Large processing facilities require vast tracts of land for crop production. The processor would require a team of grower-managers to oversee crop production. Here, the situation is identical to the original contracting problem with moral hazard and adverse selection. The processor will need to offer a wage contract identical to that under contracting – a base pay with bonuses for better outcomes – resulting in an inefficient industry. The problem may not be solved by backward integration.

Another scenario may be forward vertical integration where a cooperative of growers invests in processing technology. Under the information structure, forward vertical integration enables the growers to internalize both investment decisions – capital and learning – and appropriate all of the returns from those investments. A first best solution may be achievable if the expected profitability of the industry is greater than the grower's outside option. Problems may arise, however, when industry profits turn out to be lower than expected, particularly if growers require a government bailout from a failed biomass project.

Forward vertical integration offers a number of possible extensions to the research. In particular, are the incentives within a cooperative sufficient to induce

efficient levels of learning and appropriate levels of feedstock? Will project size differ under a vertically integrated industry from the limited liability contract outcome? How will grower risk aversion affect the project under forward vertical integration? Subsequent chapters of the dissertation explore in greater depth the issues concerning alternative contracting arrangements, coordination schemes, and vertical integration in new agricultural industries. The discussion is placed in the context of the biomass for electricity generation industry. Examination of this specific industry allows for clearer insight into the implications of the theoretical model.

Chapter 4. The Case of Biomass for Electricity Generation

The theoretical model developed in Chapter 3 may be applied to a whole class of new industries. Many new agricultural industries exhibit the requisite features: two-sided specific investments, the prospect for cost reductions through learning, uncertainty in outcomes, and the potential need to minimize the risk to the producer of the intermediate good. This chapter presents a case study of a specific industry: the use of closed-loop biomass for electricity generation.

Biomass electricity production holds the promise of a sustainable, environment-friendly energy source and a means for rural economic development. Biomass for electricity generation has garnered increased interest in recent years as a means of reducing carbon dioxide emissions and replacing a diminishing fossil fuel supply. When grown in a sustainable manner, biomass is a renewable energy resource that results, at worst, in no net emission of greenhouse gases and may well result in a net reduction in atmospheric carbon due to sequestration in roots (Bransby, McLaughlin, and Parrish 1998). In addition, biomass energy systems offer other potential environmental and economic benefits, such as protection of watersheds and highly erodible agricultural lands, creation of new markets for agricultural products and revitalization of rural economies (Graham, Lichtenberg, Roningen, Shapouri, and Walsh 1995).

Biomass energy plantations serve a dual role in the reduction of carbon emissions. There will be a direct reduction in greenhouse gases through substitution of fossil fuels in electricity production and there will be an indirect reduction in emissions through the increase in ability of agricultural land to sequester carbon. Biomass energy initiatives may be helpful in bridging the gap between European Union and United States over

international agreements on carbon gas emissions. Perennial crops used for biomass power, like switchgrass and willow trees, provide year-round vegetative cover. As a result, they protect against soil erosion and prevent watershed deterioration. Energy crops are also resistant against floods. In the aftermath of the Mississippi River floods of 1993, there has been controversy concerning the use of land in the flood plain for agricultural purposes. Conversion of the flood plain to perennial energy crops could relieve tension over the management of the Missouri and Mississippi Rivers.

The presence of relationship-specific assets and intertemporal considerations such as the frequency and duration of the relationships between energy crop growers and electricity generators necessitate the formation of long-term contractual relationships. Growers are not likely to begin production of energy crops without the assurance that a generation facility will be built, and generators are not likely to construct a facility without the assurance that growers will produce energy crops. After an agreement is made to form a biomass electricity generation system, a significant amount of time passes before production of electricity occurs. The generating facility must be constructed and, in most cases, the energy crops take several years to reach the level of maturity necessary for use as fuel input. During this phase, growers dedicate all their physical and human assets to the production of crops that likely have little value to any other user than the generator. In addition, any experience gained in the production of energy crops may have little or no value to other industries and may not be transferable to the production of other crops. In addition, the bulkiness of energy crops results in high costs of transportation of biomass. These costs comprise a significant portion of the costs of production of electricity using energy crops and limit the distance that can exist between the generators

and the growers (Larson & Marrison, Marrison and Larson). Due to the need to minimize transportation costs, the generating facility must be located in close proximity to the growers of energy crops. As in many electricity-generating technologies, production also exhibits a certain degree of increasing returns to scale. This implies that for biomass, a trade-off exists between economies of scale in production and diseconomies of scale in transportation.

In addition to site specificity, the generators' technology may be characterized by a high degree of physical asset specificity. Biomass may be used in one of several manners to generate electricity, from simple co-firing with coal to a more complex process of gasification with a combined-cycle generation. As the technology becomes more complex along this spectrum, capital costs and thermal efficiency increase. Yet, the technology also becomes more specialized in terms of being less able to accept fuel other than biomass. In simpler technologies, a relatively small capital investment is required on the part of the generator and biomass and fossil fuels act as near-perfect substitutes. In more complex technologies, the use of biomass requires specially designed turbines made of unconventional materials. Although it may be theoretically possible for a generator to use natural gas in a system designed for biomass, such a substitution cannot be made without loss in engineering efficiency and resulting loss in competitiveness.

Many crops used for the production of electricity are perennial crops that require a period of two to five years of cultivation to reach a level of maturity necessary for use as a fuel input. This implies that an agreement to generate electricity via biomass must be made years before actual production commences in order to assure adequate supply of feedstock. In addition, electricity generation requires a significant investment in physical

capital. Typically, a productive lifetime of thirty to forty years is required to recoup the costs of investment. The generator must therefore arrange for fuel supply over a long period of time. On the part of the grower, energy crop production exists in cycles of seven years (switchgrasses) to fifteen years (poplars and willows). It is likely that generators will wish to forge relationships with growers that extend over several crop production cycles.

In general, the current costs of producing biomass have been too high to elicit significant investment in this industry on the part of generators. However, learning-by-doing will play an important role in the development of biomass electricity feedstock production. Energy planners often cite the important role that learning-by-doing will have on the ability of renewable energy technologies to compete with fossil fuel technologies in the long run.

Graham et al.'s (1995) estimates of crop yields and production costs over the next twenty years show the potential value of learning to the emerging industry. A modest program in research and development is expected to increase switchgrass yields in the North Central region by 14% in 2005 and 42% in 2020. These values correspond to decreases in production costs of 10% in 2005 and 24% in 2020. In monetary terms, switchgrass production costs could drop from \$3.15 per gigajoule (GJ) in 2000 to \$2.84 in 2005 and \$2.39 in 2020². In comparison, the average price for natural gas to electric utilities has ranged from about \$2.41 per GJ in 1999 to about \$4.00 per GJ in 2000 (Energy Information Administration 2001b).

Much of the learning with perennial crops used in energy production is likely to occur during the establishment phase. This learning will be site-specific and depend

² All monetary values expressed in 2001 U.S. dollars.

greatly on the management of the growers involved. Sanderson et al. (1996) report that failure to quickly establish a productive stand of switchgrass within 1 year of seeding reduces the viability of using the crop as an energy feedstock. They cite planting methods as an important factor contributing to stand failures. Other biomass energy crops, such as willow and poplar, have been shown to be especially susceptible to early establishment practices (Downing and Graham, Wright.) Measures to control weeds and pests will be especially important and may be very specific to regions or individual fields (Wright.) Although switchgrass is generally considered a resilient crop that is able to grow on marginal lands, it has been shown to be responsive to fertilizer applications and sensitive to the timing and application of fertilizer and pesticides.

A number of U.S. government agencies, particularly the Departments of Agriculture and Energy, are already involved in efforts at promoting the use of biomass for electricity generation through the Biobased Products and Bioenergy Initiative³. The initiative has resulted in a number of joint ventures involving industry, government, farming and research organizations to fund research, development and demonstration projects for bioenergy systems. Examples of these ventures include The Salix Consortium, comprised of over twenty organizations, that aims to establish willow tree energy crop plantations in the upper Midwest and Northeastern regions of the country; and the Chariton Valley Biomass Project that aims to establish a market for switchgrass to support a 35 mega-watt electric generation facility in South Central Iowa. The initiative was formed by executive order in 1999 to triple the use of bio-based products

³ Participating federal agencies also include the Departments of the Interior, Commerce and Treasury, the National Science Foundation, the Environmental Protection Agency, the Office of Science Technology and Policy, the Office of the Federal Environmental Executive, the Office of Management and Budget, and the Tennessee Valley Authority.

and bioenergy in the United States by 2010, with the goal of expanding economic and trade opportunities for agricultural producers.

These projects typically rely on short-term and long-term contracts between growers and processors. The contracts in use by these projects have been designed primarily to induce grower participation. Typical energy crops, such as switchgrass and willow trees, are perennial and require more than one growing season to reach maturity before they are viable for use in electricity generation. Growers have therefore been hesitant to commit land for up to ten years to a crop that has no alternative use and that creates no return on investment before the second or third year of growth. As a result, contracts offer a number of provisions to the growers that include partial to full reimbursement of crop establishment costs, minimum crop price guarantees, as well as a share of the energy tax credits accrued by the utility for renewable energy production.

Utilities involved in these projects have thus far limited their use of biomass to direct combustion in conjunction with another fuel, such as coal. This requires a modest investment to modify existing capital to accommodate the use of biomass in generation facilities. Significant improvements in the energy conversion efficiency of biomass, and hence reductions in marginal cost of generation, may be attained through the use of more sophisticated technologies which, in contrast to co-firing, require a substantial investment on the part of utilities in relationship-specific capital. These new technologies, such as gasification of energy crop hybrids, are likely to place biomass on a more competitive level with traditional fossil fuels (Larson and Marrison, Paisley and Anson).

The arrangements between generators and growers will affect the extent of learning that will occur and, therefore, the magnitude of future cost reductions in the

industry. This suggests that the organization of biomass electricity systems will determine the ability of the industry to compete in the long term. Several researchers have pointed out the potential problems of organizing the new industry as a potential obstacle to the creation of a viable biomass electricity sector (Costello and Finnell, Rösch and Kaltschmitt, Roos et al.). To date, there has been no serious discussion in the literature about the possible structure of the biomass electricity industry and the impact that various structures may have on costs of production, investment decisions (including those pertaining to production experience, i.e. learning), and economic efficiency.

The estimates by Graham et al. suggest that it may be optimal for a risk-neutral agent to invest in a large scale biomass generation facility several years before the costs of producing the crops falls below current fossil fuel prices. This would be true if the investor had the ability to make all investment and production decisions, and so is able to appropriate the gains from learning. However, in a contractual environment described above, where some of the investment decisions are unobservable and the resulting cost reductions are unverifiable, then it may be impossible for the generator to appropriate any of these rents. In some cases, it may be optimal for the generator to not invest in biomass technology at all.

Current predictions about the industry based on these analyses may be too optimistic. Consider the feasibility analyses of the biomass for electricity industry. Many of these analyses (Graham et al., Larson & Marrison) assume some form of cost reductions will occur on the part of switchgrass production. In their models, the reductions come from exogenous research and development programs. A fundamental flaw of these models is the assumption that the transfer of R & D to the growers will

costless and fully assimilated. The ability to substitute private learning by the grower with public R & D will be constrained by the heterogeneity that exists in agriculture. The conditions for agricultural production vary considerably from site to site. Agriculture is site-specific due to the variations in climate and resource quality, which makes agricultural production highly dependent on management. (Lichtenberg) Advances in plant sciences and genetics may bring about cost reductions in biomass production through the introduction of new crop hybrids and cropping techniques. However, learning in new agricultural industries is also likely to be site specific, and so the transfer public sector learning will require effort on the part of the growers to modify and adapt the knowledge to their particular conditions and experience.

In addition, the development of supply curves (Graham et al.) based on expected cost reductions assumes that growers will pass cost reductions on to the processor. This only occurs under certain conditions with perfect competition. The salient features of biomass electricity generation throw doubt upon the ability of this industry to develop a competitive market for biomass fuel. As described earlier, the need for specific investments, the geographic limitations imposed by transportation costs, and the need to offer assurances of future trade between processors and growers all point to an industry arranged around long-term contracts that restrict the potential for competition between growers. Long-term contracts for biomass supply imply that the cost reductions may not be costlessly passed on to the processor.

The theoretical model presented in Chapter 3 illustrates the difficulties inherent in contracting for an industry with the characteristics of biomass for electricity generation. To summarize, limited liability arrangements offer assurances to the grower in the form

of minimum payments and to the processor in the form of guaranteed feedstock supply. However, these assurances come at the cost of reduced project scale and inefficient levels of investment in learning. Overall, the project that arises from a limited liability arrangement may be too small to and costly to be viable. These arrangements pose an obstacle to the success of new agricultural industries.

Currently, a wide assortment of arrangements exists between processors and growers for new biomass electricity projects.⁴ Some of these arrangements are essentially limited liability contracts. Other arrangements force growers to take on some risk. However, many of these arrangements will exhibit some elements of moral hazard and adverse selection that result in sub-optimal investment and production decisions. Learning effort on the part of growers will be restrained, ultimately affecting the viability of the industry. The following paragraphs describe various elements of the biomass energy project arrangements and how these elements may impinge upon the viability of the industry. These include the use of contracts linked to participation in the Conservation Reserve Program; the use of bonuses for early adopters and rewards for productivity; the use of stiff penalties for contract breach; the use of minimum price for the feedstock; and the use of production quotas based on share ownership in a grower cooperative.

Many biomass projects now operate under some form a limited liability arrangement. One example of this is the set of producers that have contracts linked to participation in the Conservation Reserve Program (CRP). Under the CRP, growers take land out of production for conservation. They then receive a payment related to the opportunity cost. Biomass projects like Chariton Valley have enlisted farmers in CRP.

⁴ This discussion is based on correspondence with Dr. Mark Downing of Oak Ridge National Laboratories.

In the contracts, CRP growers are allowed to sell switchgrass in exchange for forgoing part of the CRP payment. It is likely that these farmers will only choose to harvest and sell switchgrass if the price of switchgrass exceeds the CRP payment. This implies that growers will only participate when reimbursed opportunity cost, as well as production costs.

In one set of agreements, growers are paid bonuses to enlist in a project (“early adopter” bonuses, guaranteed reversion costs, and are rewarded for productivity. Early adopter bonuses may encourage those that expect lower costs in the future to join projects first. However, it is not clear if these bonuses lead to incentives to exert effort that increase the probability of cost reductions. Do these bonuses only encourage those growers of initial high ability to enroll in the projects? Do they encourage lower ability growers to enroll and then invest in learning? Greater detail of this arrangement is necessary to determine the effect of these bonuses. If, for example, the bonuses are meted out by a competitive process, they may induce efficient investment in learning.

Most agreements within the new industry, even those that force the grower to take on some of the risk, reimburse 50% or more of the establishment costs to the grower. One set of agreements guarantees reimbursement of reversion costs, the cost of reverting production out of energy crop production. In a sense, these reimbursements reduce the risk taken on by the farmer by mitigating the effect of specific investments. Specific investments lock agents into a relationship. By removing some of the costs of the specific investment, a grower may experience less apprehension at joining biomass projects. However, the reduction of risk to the grower increases the problem of moral hazard in learning investment and may lead to inefficient exertion of learning effort.

Another set of agreements sets a minimum level of effort in cultivation and harvesting, as well as severe penalties for breaking with the contract. Yet, establishing a minimum amount of effort does not necessarily induce optimal effort. A penalty for contract breach, however, should have a positive effect on the learning investment in that it increases the risk to the grower of realizing a poor state of nature, or high costs of production. If the grower realizes a high cost of producing the feedstock, she may wish to renege on the agreement and leave the biomass project. The penalty increases the cost of renegeing and encourages the grower to take actions that increase the probability of realizing low costs of production.

Rewarding for productivity may also elicit greater learning effort, but how is this implemented? A reward for productivity implies the need to elicit truthful revelation on the part of the grower through her choice of payment and quantity in a contract menu. This is similar to a mechanism used to overcome adverse selection. This mechanism causes much of the distortion between first and second best outcomes described by the theory. Therefore, the rewards for productivity translate to learning rent that increases the price of the feedstock to the grower. The increased price reduces feedstock quantity procured, which reduces incentives to invest in processing capacity, which reduces incentives to invest in learning.

Focus groups conducted in Florida reveal that utilities prefer to conduct business with a cooperative of growers and have no desire to pursue supply agreements with individual growers. Growers, in turn, have no desire to invest in biomass without a long term agreement. Currently, growers supplying eucalyptus and other tree materials to a Florida utility are paid a price linked to the price of fossil fuels, biomass quality, and

renewable energy subsidies. The agreement only appears to limit liability to the grower cooperative with a minimum price for the feedstock. However, the utility has made no significant investment in biomass specific technology. It is unclear how much biomass is being used in this project or how many growers are involved.

Despite the variety of arrangements within the industry, there appears to be one common element of these projects. The projects all seem to be characterized by small levels of investment in specific assets on the part of the processors. Most utilities that employ biomass for the generation of electricity use a co-firing technology. These technologies allow the utility the ability to burn biomass in conjunction with another fuel, such as coal. The utilities, therefore, enjoy a luxury of flexibility in the use of input fuel. Engineering analyses, however, suggest that greater conversion efficiencies for biomass fuel, and therefore lower marginal costs of production for electricity, are achievable with more sophisticated gasification technologies. These sophisticated technologies require a greater amount of specific investment by the processor. Part of the reason for this lack of investment rests in uncertainty about the technology. However, part of the reason rests on the high cost of biomass feedstock relative to fossil fuels. Perhaps if generators could expect a greater degree of cost reductions in biomass feedstock, they would be less hesitant to invest in large-scale biomass-specific generation technology. Current agreements may not be sufficient to ensure that generators appropriate the gains from grower learning.

The potential for backward vertical integration to resolve the problem of underinvestment may be limited within the biomass electricity industry. The industry is likely to be characterized by diseconomies of backward vertical integration (generator

acquiring grower) due to geographical reasons. As an example, consider a 100 megawatt (MW) generating facility using gasification technology. Calculations using published estimates of switchgrass yields (Turhollow 1994) and technical efficiencies (Larson and Marrison 1997) suggest that 50,000 to 150,000 acres of land would be needed to produce the energy crops to supply a power plant. This large plantation requires an enormous amount of management effort. Based on the average size of a farm in Iowa of 300 to 500 acres, the firm could potentially require 100 to 200 crop managers and operators. In a world where employees are guaranteed a minimum wage, the firm is likely to encounter similar problems of moral hazard and adverse selection between firm management and farm employee as could be encountered between processor and grower.

The use of cooperatives in more than one project suggests the possibility of forward vertical integration within the industry. Perhaps, a cooperative producing energy crops may decide at a future date to take on the processing phase of production. At this point, the cooperative may choose to invest in a suitable biomass-specific technology to increase the value of their energy crop production.

There appears to be one encouraging development in the industry in the area of cooperatives. In one project, the growers purchase shares in a cooperative. Each grower is then allowed to sell a quantity of biomass proportional to the number of shares owned in the cooperative. The price at which they sell the biomass is fixed in any given year, yet negotiable annually. Buying shares in the cooperative allows growers to take on some of the risk associated with these projects. By linking the quantity to be delivered to the amount of shares purchase, growers may be forced to compete with each other to enter the market. Growers with the ability to reduce costs will be able to buy more

shares, or pay a higher price for those shares. The need to recoup the cost of the shares then induces exertion of learning effort.

Future research is needed on the issue of forward vertical integration and grower cooperatives. Perhaps these organizations create the proper incentives needed to induce investment in learning within the industry, as well as allow the industry to reap the full marginal benefit of this learning investment. However, more research is needed to determine if and how these vertically integrated cooperatives would be able to overcome the same obstacles facing the industry. In particular, how will vertical integration mitigate the risk aversion growers currently have toward enrolling in these biomass projects?

Chapter 5. Empirical Model

This chapter describes the construction of an empirical counterpart to the theoretical model developed in Chapter 3. To illustrate the impact of limited liability contracts on the viability of new agricultural industries, an empirical model simulates the investment and production decisions and outcomes from an emerging agricultural industry: biomass for electricity industry. As described earlier, several projects are currently underway to establish biomass electricity as a new market for agricultural producers, particularly in the North Central and Southeastern regions of the United States. The basis for the simulation in this and the subsequent chapter arises from ongoing efforts in the Chariton Valley of Iowa to establish a sustainable biomass electricity project using local growers to produce switchgrass.

Current analyses of projects like Chariton Valley implicitly assume that growers will only participate in these projects if they are reimbursed for production and opportunity costs (Brummer et al.) This assumption suggests the use of limited liability contractual arrangements within the industry. Indeed, there is evidence from a survey of Florida landowners that they would not be willing to invest in biomass production unless they are assured of the availability of markets and granted some certainty about the costs of production and returns. Contracts in Chariton Valley are linked to the Conservation Reserve Program (CRP). The CRP offers incentives to growers to not harvest crops on their land. This incentive equates to the opportunity cost of land to the landowner. Under the contract, growers are allowed to harvest and to sell switchgrass in exchange for a portion of the CRP payments. Due to the assurance of the CRP payments, growers are likely only to sell switchgrass if the payment exceeds the CRP payment. In spirit, this is

a limited liability contract for the production of switchgrass. The policy of reimbursement of all costs incurred by the grower constitutes a limited liability agreement between the processor and grower. Therefore, the biomass electricity serves as an excellent candidate for the empirical application of the theoretical model.

Data from the Chariton Valley project allows for reasonable approximations of feedstock production costs, transportation costs, and opportunity costs to growers. This data also allows for estimation of switchgrass yields, as well as storage costs and losses. Data from the engineering literature allows for estimation of capital investment costs and energy conversion efficiencies. The scenario for the simulation posits a wholesale electricity producer siting a facility in the North Central United States. The producer wishes to invest in biomass gasification technology for use with an energy crop suitable for cultivation in the region: switchgrass. The processor chooses investment in capacity as a best response to the grower's investment in learning. For the analysis, trade occurs between processor and grower under a limited-liability agreement. Each of the sections below discusses segment of the theoretical model in terms of its empirical counterpart.

The Processor

The construction begins with elements of the model that pertain to the processor: the production function for electricity generation, cost function for the capital investment, and cost function for the transportation of biomass fuel to the facility.

Production function for electricity generation

The engineering literature primarily relies on a fixed proportions technology to represent the generation of electricity. This representation, however, is not suitable for the present analysis since it does not allow for variability in the choice of the amount of

generation capacity used at any given point in time. Additionally, a fixed proportions technology does not meet the necessary conditions for the theoretical model. In particular, it is not differentiable at all levels of capital (K) and feedstock (q).

A quadratic representation of the processor technology was chosen for a number of reasons. The quadratic production function (15) is a flexible functional form. In addition, within appropriate ranges for capital and feedstock, the quadratic form accurately predicts output from various levels of capital and feedstock, allows for replication of results from the literature when engineering assumptions are imposed, and allows for tractable analysis of the theoretical model in both the first best and contracting scenarios.⁵ Also, the form selected implies that both inputs, capital and feedstock, are essential to the production of electricity, i.e. $f(0,0) = 0$.

$$f(K, q) = \alpha_1 K + \alpha_2 q + \alpha_3 K^2 + \alpha_4 q^2 + \alpha_5 Kq \quad (15)$$

Data from the engineering literature concerning the conversion efficiency of existing biomass facilities in Europe (Dornburg) allow for a determination of the parameters (α) of the production function. The conversion efficiency was used to determine the electricity that can be produced from various levels of capital and feedstock. A Leontief production function (16) was used to determine the output of electricity from approximately 6000 pairs of capital and feedstock levels.

$$y = \max\{\eta K, \zeta q\} \quad (16)$$

⁵ Other functional forms were explored for use in the simulation. These include the constant elasticity of substitution, transcendental logarithm, quadratic, and Mitscherliche-Baule functional forms (a differentiable form that exhibits a production plateau.) Some of these form led to expressions that could not be inverted for solving first-order conditions. Others led to expressions that when combined with a probability distribution could not be solved for expected values.

In the production function (16), η and ζ represent conversion factors accounting for the engineering efficiency of the technology, total hours of operation, and the energy content of switchgrass. Engineering efficiency of the technology varies with the level of capital and ranges from a low of 32% conversion of biomass energy to electricity at 10 MW, to a high of 44% at 170 MW. Capital investment (K) varies from 10-megawatt (MW) capacity to 300 MW and for each level of K , feedstock (q) ranges from a level that would sustain the facility at 50% capacity usage to a level that surpasses capacity by approximately 40%. The resulting set of inputs and outputs were fit to the quadratic form using ordinary least squares. Parameter estimates from the quadratic fit are reported in Table 1. The R^2 for the estimation is about 0.995.

Table 1. Regression results for Production Function

Parameter	Estimate	Standard Error	t-Statistic
α_1	4.655×10^6	63998	72.7
α_2	815.74	14.60	55.9
α_3	-35,757	398	-89.9
α_4	-0.00152	0.000013	-118.9
α_5	14.686	0.142	103.1

The parameters of the production function must be such that the following hold in the relevant range of input values.

$$f_1(K, q) = \alpha_1 + 2\alpha_3K + \alpha_5q = 4,655,000 - 71,514K + 14.686q \geq 0$$

$$f_2(K, q) = \alpha_2 + 2\alpha_4q + \alpha_5K = 815.74 - 0.00304q + 14.686K \geq 0$$

In addition, the following verifies that the production function is concave and complementary in the inputs, as specified in the theoretical model:

$$\begin{aligned}
f_{11}(K, q) &= 2\alpha_3 = -71,514 < 0 \\
f_{22}(K, q) &= 2\alpha_4 = -0.00304 < 0 \\
f_{12}(K, q) &= \alpha_5 = 14.686 > 0 \\
f_{11}(K, q)f_{22}(K, q) - f_{12}(K, q)^2 &= 4\alpha_3\alpha_4 - \alpha_5^2 = 1.724 > 0
\end{aligned}$$

Investment function for capital

Larson and Marrison estimate the unit cost of generation capital⁶ per kilowatt (kW) of capacity, in 1994 US dollars, as:

$$\$/kW = 1400 + 47198MW^{-1.56} \quad (17)$$

Adjusting to 2003 dollars using a GDP deflator for capital cost⁷ and annualizing using a capital charge rate equal to 0.101,⁸ the annualized cost of capital investment per megawatt (MW) of capacity (K) is:

$$r(K) = 141400K + 5576210K^{-0.56} \quad (18)$$

Equation (18) describes a technology that exhibits a form of increasing returns to scale. In this form, the model has difficulty converging on a reasonable solution. Part of the difficulty is due to the non-integer exponent on capital in (18), and part of the difficulty is due to the increasing returns over the entire range of capital. To correct this problem, a cubic form was selected that would facilitate calculation. This form also limits increasing returns to select range of capital, exhibiting decreasing returns at higher levels of capital. Equation (18) is used to generate a set of points for a smoothing regression. The cost equation was fit to an equation cubic in capital (K). The final equation for the capital cost

⁶ Costs based on pressurized biomass integrated-gasifier/gas turbine combined cycle (HP BIG/GTCC) technology.

⁷ The GDP deflator for capital cost is taken from the National Aeronautics and Space Administration (<http://www.jsc.nasa.gov/bu2/inflateGDP.html>) and is equal to 1.1725.

⁸ Larson and Marrison use a capital charge rate of 0.101, as suggested by the Electric Power Research Institute. This rate assumes a utility-financed renewable energy power plant with a 30-year life, 6.2% real pretax discount rate, and 38% income tax.

is displayed below. The adjusted R^2 for the equation is 0.987. Standard errors for the parameter estimates are in parentheses below the estimates.

$$r(K) = 18667.3 K - 406.64 K^2 + 0.805 K^3$$

(3632) (37.1) (0.09)

Transportation Costs for Feedstock

The average cost of transporting feedstock from the production area to the generation facility increases with the size of the facility. Consider a facility located at the center of a large area of farmland involved in feedstock production. As the size of the facility increases, the radius of the production area increases. As one moves outward from the facility, each successive ring of production contains greater amounts of farmland. Therefore, an increase in the size of the facility necessarily increases the average distance of transport for each ton of feedstock.

Current arrangements place the responsibility for transportation costs on the processor. Several estimates for costs per ton per kilometer of travel exist in the literature. Two of those estimates were considered for the analysis those from Larson & Marrison and those reported by the Chariton Valley Project (Brummer et al.) In general, the transportation costs consist of a fixed cost and a variable cost. The Larson & Marrison estimates appear to have a lower fixed cost portion and higher variable cost portion than those of the Chariton Valley reports.

In the reasonable range of feedstock production for facilities ranging from 150 MW to 300MW, the Chariton Valley estimates of cost are approximately 30-40% higher than Larson & Marrison. However, Larson & Marrison costs are estimates based on reports in the engineering literature. The Chariton Valley estimates are based on actual experiences with transporting switchgrass in Iowa. Therefore, in order to present a more

realistic portrayal of the industry and to produce conservative estimates of the industry viability, the Chariton Valley reports of transportation costs were used for the simulation.

The fixed and variable costs of transportation are determined using those values reported by the Chariton Valley Project coordinator: \$155 to \$200 per trip, with sites 26 to 66 miles from the facility. Solving two equations with two unknowns results in an equation for the cost per metric tonne of feedstock as a function of distance (D) in kilometers.

$$\text{Cost per tonne} = 7.69 + 0.043D \quad (19)$$

In order for the processor to use this formula in planning, she requires a relationship between size of the facility and distance for transportation. French derives this relationship and estimates the average distance per unit of feedstock to a processor, assuming a uniform density of cultivation surrounding the facility and a rectangular grid of roads for trucking. This is a reasonable approximation for the purposes of this simulation:

$$D = 0.4714 \frac{q^{1/2}}{P_0^{1/2}} \quad (20)$$

where, D is the average distance from the facility in kilometers, q represents the total quantity of feedstock necessary to supply the processing facility in metric tonnes, and P_0 represents the planting density (yield) of the feedstock in tonnes/hectare. Agronomic analyses report average yields of switchgrass in Iowa (Lemus et al.) to be approximately nine (9) tonnes per hectare. Combining equations (6) and (7), and converting to miles, acres, and short tons, results in:

$$T(q) = 7.0q + 0.0004q^{3/2} \quad (21)$$

Once again, to ensure reasonable tractability, the simulation uses a quadratic approximation of the relationship (21). A linear regression of transportation costs on feedstock and the square of feedstock produces the equation for use in the simulation. Results from the regression are displayed below. The adjusted R^2 for the regression is 0.96. Standard errors appear in the parentheses below parameter estimates.

$$T(q) = \underset{(0.004)}{7.167} q + \underset{(2 \times 10^{-9})}{2.19 \times 10^{-7}} q^2$$

The Grower

The construction of the model continues with elements of the model that pertain to the grower: the cost function for the production of switchgrass, the probability of cost reductions due to learning effort, and the cost or disutility function of learning effort.

Cost function for feedstock production

Participants in the Chariton Valley Project have recently reported costs for the production of switchgrass. These reported costs are high relative to previous estimates in the literature (Walsh and Graham). However, previous estimates are based primarily on experimental plot studies and so Chariton Valley estimates are likely to be a more accurate representation of true costs of producing switchgrass. These estimates also allow for a conservative estimate of the viability of the industry.

Walsh and Graham report estimated and actual yields of switchgrass on lands of varying quality in Iowa and the North Central Region of the US. Recent analyses of crop yields from Iowa plots (Lemus et al.) correspond closely with previous yield estimates. Lemus et al. report switchgrass biomass yields from 1998 to 2001 ranging from 6.4 to 11.8 tonnes per hectare, with a mean value of 9.0 tonnes per hectare. Walsh and Graham estimate a range of switchgrass yields for the North Central region which has an average

yield of about 9.4 tonnes per hectare. Walsh and Graham yield estimates are used in the estimation of costs of switchgrass for two reasons: they are possibly more representative of the variability of growing conditions in the North Central region, and the average value does not differ greatly from those experienced recently in Iowa. Walsh and Graham report greater variation of yields, which represent yields for a larger region (North Central) than those reported in Lemus et al. This allows for a wider range in cost estimates to be used in calculating an average cost of production for the region.

The basic cost function used in the simulation takes the following linear form:

$$C(q) = c_0 q$$

where c_0 represents the average cost of switchgrass production. A linear cost function for crop production allows for the disentanglement of production costs and transportation costs for switchgrass delivery. A strictly convex cost function implies that cost of production varies due to changes in land quality and opportunity costs. Due to the importance of transportation costs, a ton of switchgrass produced on high quality land far from the generation facility may not be as expensive to produce as a ton produced on low quality land close to the facility. Thus, determination of the delivered price of a particular ton of switchgrass requires knowledge of the distribution of land in a particular region. A specific site has not been selected for this analysis and so the distribution of land quality is not known. Therefore to keep the analysis applicable to more general region, a linear cost function has been used.

To calculate the average price of switchgrass for the North Central region, the analysis employs a technique similar to that used by Graham et al in the estimation of a biomass supply curve. Graham et al. construct a supply curve for switchgrass biomass in

the North Central region. They use data on land quality (land capability class), yields, production costs, and average rental rates of land as reported in the 12th sign-up of the CRP (Osborn et al.) to determine the quantity of switchgrass produced at a price that is competitive with other uses of the resources for production. For the analysis of this dissertation, production costs and rental rates have been calibrated to those reported in Brummer et al. For instance, 12th-signup CRP rental rates range in value from \$10 to \$125 per acre. Brummer et al. reports rental rates for two qualities of land \$185 and \$123 per hectare, or about \$75 and \$50 per acre. The set of values in CRP sign-up were then adjusted proportionally so that the highest value would correspond with the high value reported by Brummer, so that the final range of rental rates was \$6 to \$75. Cost of production in the Chariton Valley report does not vary by land quality, and it equals about \$176 per acre. In addition, the analysis accounts for storage costs of \$10 per ton of switchgrass to be stored at a centralized location that results in about 2% loss of biomass. Using the distribution of land and rental rates, an average cost for the Chariton Valley region, including opportunity costs, is \$65.04 per ton of switchgrass, or $c_0 = \$65.04$.

Probability of learning

As described in the theoretical model, the potential for learning in the production of feedstock may lead to reduced costs of production. This is modeled as an investment in learning, representing extra effort expended on the part of the grower in observing crop progress, adapting agricultural techniques, implementing proper crop management, etc. Despite the additional effort, reduction in costs is not certain. The expenditure of effort, however, makes it more likely that costs of production decline in the future.

Representation of probabilistic cost reductions occurs through modification of the cost function (above) to include a state of the world, θ , that is randomly distributed. Distribution of θ depends on the level of effort, e , where higher values for e imply a lower probability that θ takes on a value corresponding to low levels of cost reduction. One functional form that offers a relatively simple representation of cost reduction under uncertainty is:

$$C(q, \theta) = e^{\theta t} c_0 q$$

When the “damping parameter”, t , is less than zero, a higher value for θ results in lower costs of production. In the limit as θ approaches infinity, the cost of production approaches zero. Therefore, the selection of an appropriate probability distribution for θ is important and the choice of cost function will depend on the distribution of θ . For distributions that span the full range of positive values, one must ensure that there is little likelihood of being in a range of values that would allow for costless production of feedstock. This implies using a distribution weighted away from infinity, such as the exponential.

An attractive feature of this cost structure is that one may use moment generating functions ($M(t) = E[e^{\theta t}]$) for the chosen distribution of θ to determine closed-form solutions to expectations of the objective functions. The moment-generating function exists in closed form for the exponential distribution:

$$E[e^{\theta t}] = \frac{1}{1 - \beta t}$$

Learning investment, e , plays a role in the determination of the value of θ by acting as a parameter of the probability distribution. In the case of a single-parameter

distribution like the exponential, the learning investment can be represented by β , the parameter of the distribution. Through proper definition of learning effort, one can ensure that higher levels of investment lead to higher probability of low production costs.

The exponential distribution also exhibits the desired properties of a distribution function as outlined in the theoretical model. Defining learning investment in terms of β , one can show that an increase in β leads to a decrease in the probability that costs will be high and that this effect eventually decreases as β increases. Formally,

$$G(\theta|\beta) = 1 - e^{-\theta/\beta}$$

$$G_{\beta}(\theta|\beta) = -\frac{\theta e^{-\theta/\beta}}{\beta^2} \leq 0 \quad \forall \theta \geq 0, \beta > 0$$

$$G_{\beta\beta}(\theta|\beta) = \frac{2\theta e^{-\theta/\beta}}{\beta^3} - \frac{\theta^2 e^{-\theta/\beta}}{\beta^4} \geq 0 \quad \forall \beta \geq \frac{\theta}{2}$$

Using the moment-generating function, the expected cost of feedstock production is:

$$E[C(q, \theta)] = \frac{c_0 q}{1 - \beta t}$$

This expression simplifies the evaluation of expectations that occur in both the grower and processor objective functions. The sensitivity of expected production costs to the learning investment, or elasticity of learning investment, varies with the value of the parameter, t . This parameter, the damping parameter, represents the responsiveness of switchgrass production cost to the effort exerted toward learning, β . Thus, the model simulation employs several values for the damping parameter to evaluate the industry under several plausible regimes. To preserve the relationship of decreasing expected costs with increasing learning effort, the damping parameter must be negative.

The set of values for the damping parameter were chosen so that the expected reduction in costs, when learning effort $\beta=100$, roughly ranged from about 10% when $t=-0.001$, to about 50% when $t=-0.009$. The damping parameter values are taken from the set $\{-0.001, -0.003, -0.005, -0.007, -0.009\}$.

Cost of learning investment

The learning investment, β , is loosely defined in the simulation. The simulation seeks to determine the relative scale of learning investment under different scenarios and regimes. Learning effort has been described earlier as the additional care that is taken by a grower to observe and monitor crop development and to adjust actions based on input responses. As such, the disutility of learning effort may be calibrated to some form of managerial cost. However, the learning investment determined in the simulation should not be interpreted as any particular quantity of cost or effort, such as a wage rate or hours of labor. It should be interpreted as an indicator of the relative amount of effort chosen under different scenarios and regimes. The usefulness of this measure is found in comparison between first best and contracting scenarios.

An estimate for management needs is loosely based on Larson and Marrison estimates for the optimal scale of the project, or about 270 MW. A facility of this size requires about 1,100,000 tons per year of switchgrass, which may be produced on an estimated 220,000 acres of land. Assuming an average farm size of 350 acres (as in the case of the Chariton Valley), then this implies a minimum of 625 farms will be employed in the production of energy crops. If one assumes that one manager is needed per farm to exert the learning effort, then this translates to about 2000 hours of management per year per farm. The establishment phase in which the effort must be exerted is approximately

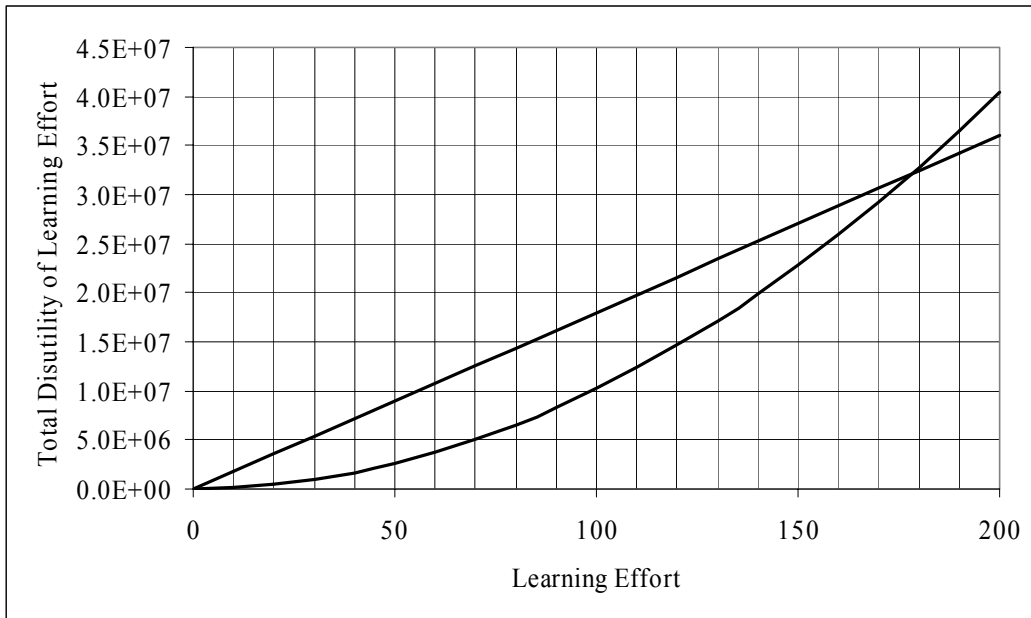
two years. Thus, two years of effort on the part of 625 managers annualized over the thirty-year lifespan of the generation facility equates to almost 180,000 hours of learning effort.

Multiplying learning effort, β , by 180,000 hours would result in a linear estimate of the total learning investment. In order to ensure convexity in the cost of learning effort, the linear relationship was approximated by a quadratic relationship through an appropriate choice of a learning parameter (ι). The learning parameter appears in the quadratic expression below and conveys a sense of the marginal disutility of learning effort. The disutility of learning effort, d , is a function of the learning parameter and the amount of learning effort selected.

$$d(\beta) = \iota\left(\beta + \frac{\beta^2}{2}\right)$$

Values for ι were selected so that the value of above quadratic expression would roughly equal $180,000\beta$ at levels of β in the range of 0 to 200. A plot of the two expressions where $\iota=2000$ is shown below. The linear expression intersects the quadratic expression at approximately $\beta=150$. Higher values of the parameter drive the intersection point to lower values of e . For the simulation, values for ι come from the set $\{1000, 2000, 3000, 4000, 5000\}$.

Graph 1. Linear and quadratic representations of the disutility of learning



Calibration of Full Model

Comparison of the empirical model's results under engineering assumptions with those results found in the literature help to determine the validity of the model's calibration. Larson & Marrison estimate the minimum cost of electricity (break-even price) and the optimal size of facility at the break-even price for facilities sited in North Central and Southeast US, as well as some regions in Brazil. For the North Central Region, they report the minimum cost of electricity for HP BIG/GTCC to be 6.2 ¢/kWh from a 269 MW facility. Projecting to 2020, where they estimate yields to increase by 15%, the minimum cost of electricity is 5.4 ¢/kWh from a 290 MW facility. These values adjusted to 2003 dollars, using an inflator of 1.1725, equal 7.27 and 6.32 ¢/kWh.

The results emanate from a model that assumes full information, a single agent, and exogenous learning (no learning investment.) Imposition of the same assumptions to the simulation allows for a replication of engineering results found in the literature. This

so-called “engineering scenario” uses the basic linear production cost function with no probabilistic element for possible cost reductions. As a result, there is no learning investment ($\beta = 0$) and there is no moral hazard. For sensitivity analysis, the scenario employs three values for the average cost of feedstock production: c_0 , $0.85c_0$, and $0.75c_0$. Table 2 displays the results of the simulation: break-even price (p_{BE}), optimal plant size, annual feedstock utilization, and capacity utilization. The table also displays the results of Larson & Marrison’s analysis for ease of comparison.

Table 2. Results from engineering scenario compared to results in literature

Crop cost	Calibration Results				Larson & Marrison Results			
	p_{BE} (€/kWh)	K (MW)	q (tons)	Capacity Used	p_{BE} (€/kWh)	K (MW)	q (tons)	Capacity Used
c_0	6.38	208	849,500	80%	7.27	269	1,163,300	85%
$0.85 c_0$	5.87	221	928,800	83%	6.32	290	1,254,200	85%
$0.75 c_0$	5.52	227	974,200	84%	-	-	-	-

The results from the simulation hew closely to those found in the literature. The break-even prices are approximately 15% smaller than those found in Larson, and the plant sizes are approximately 20% smaller. A number of reasons exist for the discrepancy: (1) choice of a quadratic production function over a fixed proportions technology which allows capacity utilization to vary, (2) feedstock costs reported from the Chariton Valley project are actually higher than the estimates used by Larson, (3) the use of quadratic and cubic approximations for transportation and capital costs, and (4) a combination of factors that might affect economies of scale between the present model and the engineering specification.

Despite the differences, the results fall within the expected range of values for a biomass project. The simulation appears to be reasonably well calibrated. This exercise

in validation allows for greater confidence in the results derived from the simulation when engineering assumptions are lifted.

Chapter 6. Results and Policy Implications

The empirical model developed in the previous chapter allows for practical application of the theory outlined in Chapter 3. A possible candidate for the application of the model is the biomass for electricity industry. As described earlier, the industry widely anticipates that *de facto* limited liability arrangements will be necessary to ensure grower participation by growers in energy projects. At current biomass production costs, it is questionable whether biomass will be competitive with other fuels, such as natural gas, for the production of electricity. However, industry analysts contend that cost reductions in the production of biomass feedstock, such as switchgrass, are likely as the industry evolves. The theory outlined earlier throws into doubt the ability of the industry to profit from these cost reductions when limited liability arrangements govern trade between processors and growers.

This chapter illustrates empirically the potential effect of limited liability arrangements on the viability of the nascent industry. The following analysis includes quantification of the potential efficiency losses via numerical simulation of a biomass electricity industry structured on limited-liability contracts for feedstock procurement. Efficiency losses are conveyed via comparison between a first best regime, i.e. single agent acts as grower and processor, and a contracting regime. These losses appear as differences between regimes of a number of project attributes, such as break-even price and scale of individual biomass electricity projects, learning in switchgrass production and cost reductions, and profitability.

This chapter first uses the model to establish a baseline case for a biomass electricity project situated in the North Central region of the United States. After

establishment of the baseline, the chapter presents a sensitivity of the model's results to changes in the relevant parameters: price, learning investment cost, and responsiveness of cost to learning investment. The chapter then presents the effect of three possible policy alternatives to support the emerging industry: a renewable energy production incentive (REPI) credit, a crop subsidy, and a capital subsidy.

All solutions presented in this chapter have been obtained using *Mathematica*[®] 5.0. Appendix B contains a subset of the *Mathematica*[®] notebooks with algorithms used to derive the solutions. Appendix C contains the verification that the solutions presented here meet first-order and second-order conditions necessary for a local maximum.

Baseline Case

Establishment of the baseline project results from an appropriate selection of three parameters: responsiveness of cost to learning effort (t), relative disutility of learning effort (ι), and the price of electricity (p). Several initial analyses (not shown here) tested the impact of the two parameters related to learning effort on the achieved level of cost reductions for a typical project. The cost reductions were then compared to those that are expected in the literature. The baseline values for these parameter ($t=-0.003$ and $\iota=2000$) result in levels of cost reductions that parallel those assumed possible by Larson & Marrison and Graham et al. Prior analyses in the literature have analyzed industry viability under a scenario where crop yields increase by approximately 25% over a ten to twenty year period of research and development. This roughly converts to a 15-20% reduction in production costs. Using the values for the learning-related parameters, the model determined break-even prices for the project under first best and contracting

regimes. These break-even prices are the prices used for the baseline case of a biomass electricity project.

Table 3 presents the characteristics of the baseline project under first best and contracting regimes. To construct the table, the break-even price for the project under contracts was determined, i.e. the price of electricity at which the processor makes zero profit. The optimal level of investments in learning and capital, as well as feedstock utilization, are determined at this break-even price in both the first best and limited liability contracting regimes. Under baseline parameters, the first best project scale is a facility of about 330 megawatt (MW) capacity that uses 1.5 million tons of switchgrass per year. The learning effort exerted in the first best results in an expected switchgrass production cost reduction of approximately 22%.

In addition to the outcomes under the two regimes, Table 3 presents the distortion that arises under contracts as compared to the first best. This distortion is presented as the ratio of investments and production under contracts to the first best. The baseline project under contracts features a marked reduction in the scale of investments (K , β) and switchgrass usage (q). Capital investment and feedstock use are approximately 35-40% less than the first best. The learning effort under contracts is about 65% of that under the first best, which results in an expected switchgrass production cost reduction of about 16%. In addition, processor profits are \$8,700,000 less under limited liability contracts than under first best conditions.

Switchgrass production costs decrease by about \$4/ton more under the first best than under contracting. However, the effect of contracting on the viability of the project extends beyond the level of crop cost reductions that occur. A critical element for

industry viability is the extent to which learning-induced crop reductions are passed from the grower onto the processor. To examine this point, we must also look not only at the cost of production, but also at the prices paid by the processor for the delivered switchgrass. As reported earlier, the cost of producing a ton of switchgrass before any learning (ex ante) is approximately \$65.04, inclusive of storage costs and possible storage losses. Because of learning under contracts, the cost of producing the feedstock in the expected state of nature⁹ reduces to \$54.84. The processor, in contrast, faces a price in the expected state of nature of \$64.53.

In this state of nature, the processor pays a price to the grower that differs from the ex ante price by less than 1%. Although the grower expects a total reduction of \$10.20 in the cost of producing a ton of switchgrass due to learning, the processor only expects to realize a reduction of \$0.51 in the price per ton of switchgrass. The grower passes only about 5% of the total cost reduction to the processor and retains the remaining 95% as profit. Essentially, the price paid by the processor for the switchgrass includes a 15% learning rent for the grower. Because of the ability of the grower to extract information rent under a limited liability contract, a mere 6% difference in cost reduction between the two regimes results in a nearly 40% downward distortion in project size.

The increased price paid by the processor for feedstock under limited liability also affects the capacity utilization of the processor investment in capital. Capacity utilization is defined the amount of electricity generated by the inputs divided by the maximum

⁹ Here the expected state of nature is used in lieu of expected value to facilitate computation. Although possible to calculate the expected value of feedstock and feedstock costs, the calculation is complex and requires significant computational power. The difference between the expected value and the value in the expected state, in this context, is small. Also, for the purpose of the comparison presented here, the marginal cost of computation far exceeds the marginal value of determining the expected value.

amount of electricity that may be produced with the available capital, or $f(K, q)/\eta K$. The individual terms used in the expression for capacity utilization are defined in Chapter 5. Most engineering analyses implicitly assume a fixed proportions technology by explicitly constraining the level of capacity utilization for the analysis. Larson and Marrison call this a capacity factor and fix it at 85%. The baseline results from the simulation indicate that capacity utilization is in the approximate range assumed in engineering analyses. The results also show that the increase in prices caused by limited liability contracts decreases capacity utilization by about 10% from the first best.

Table 3. Comparison of Baseline under first best and contracts

	Processor Profit (\$/year)	K (MW)	β	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)	Price of biomass (\$/ton)
First Best	\$ 8,747,000	332	92.61	1,525,000	90%	14.11	\$50.92
Contracts	\$ -	212	62.01	863,000	80%	10.21	\$64.53
Ratio	-	64%	67%	57%	89%	72%	127%

The preceding comparison of the project in the first best and under limited liability contracts was conducted at the break-even electricity price in the contracting regime, 6.36 cents per kilowatt-hour. At this price, the project under contracts derives no profit for the processor. By definition, limited liability contracts guarantee the grower a non-negative profit. At this break-even price, though, the project will only be marginally viable, perhaps operating only in periods of high demand for electricity. In a first best world, the same price generates almost \$9,000,000 in profits for the processor.

Contracts also affect the viability of the project. One may measure the effect of contracts on viability through changes in the break-even electricity price. Table 4 displays a comparison of break-even prices of the project under first best and second best regimes. In addition to the prices, the table presents the investment and production

levels, as well as percentage of cost reduction related to learning effort. The break-even price under first best is about 6.02 ¢/kWh, a level that is about 5% lower than that which occurs under contracts. Although the first best project may still only be marginally viable, the price difference of nearly one-third cent per kilowatt-hour may be crucial in a deregulated competitive wholesale market.

Even at its lower break-even price, the first best project exceeds the contracts counterpart by nearly 30% in scale and almost 50% in expected switchgrass usage. The reduction in the price of the feedstock is also greater under the first best than under contracts by about 20%, or \$2.50 per ton produced. Under the first best, the investor in capital (the processor) is able to appropriate the benefits from learning under the first best to achieve greater viability and profitability than under contracts.

Table 4. Comparative viability of the Project under first best and contracts

	p_{BE} (\$/year)	K (MW)	β	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)
First best	6.02	282	80.75	1250000	87%	12.68
Contracts	6.36	212	62.01	863000	80%	10.21
Ratio		75%	77%	69%	92%	81%

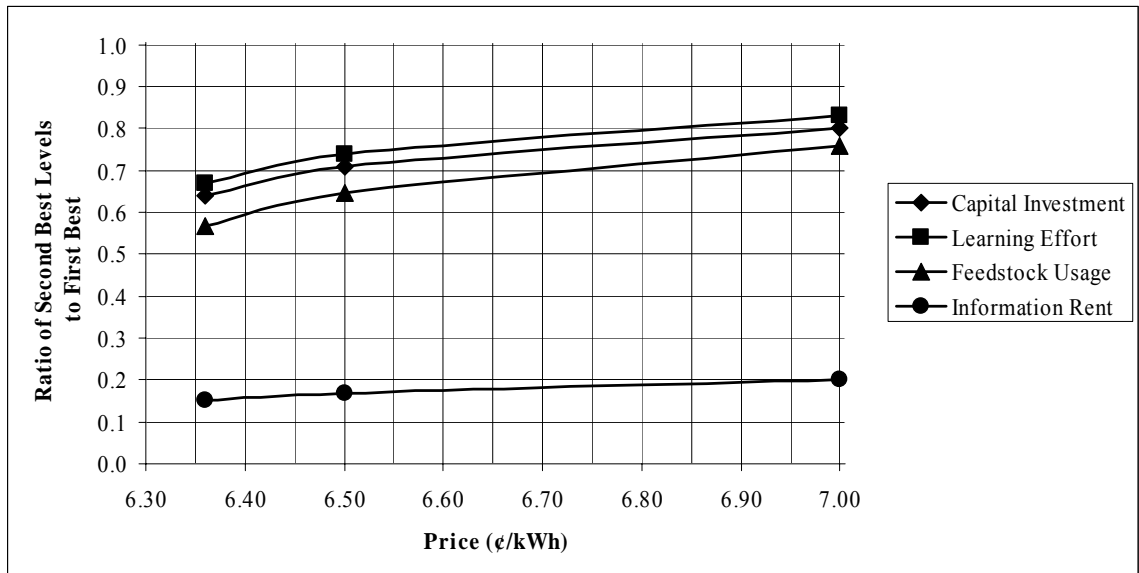
Sensitivity Analysis

Sensitivity to Price

To ascertain the sensitivity of the model to the price of electricity, the baseline model was evaluated at three separate prices: the 6.36 ¢/kWh break-even price of before, as well as 6.5 ¢/kWh and 7.0 ¢/kWh. As one would expect, an increase in price increases the overall profitability of the project in both the first best and contracting regimes. In addition, the increased profitability increases the incentives to invest in learning, which increases the likelihood of cost reductions in feedstock production.

Increases in profitability reduce the inefficiencies caused by limited liability contracting. Graph 2 depicts the changes in distortion between regimes that arise from an increase in price. On the graph, three lines represent the relative distortion for each of the capital and learning investments, as well as expected switchgrass utilization. Each line plots the ratios of first best levels to contracting levels for each of the choice variables. The graph clearly shows that as price increases, the ratios become larger. This implies that the size of the distortion between first and second best reduces as the profitability of the project increases. At the lowest price ($p=6.36$), the contracting levels of capital investment, learning effort, and feedstock usage amount to 55-65% of first best levels. At the highest price ($p=7.0$), those ratios increase to 75-95%.

Graph 2. Effect of Price of Electricity on Contract Efficiency



The fourth line of the graph represents the percentage of the price paid by the processor that constitutes information rents above the cost of producing the feedstock. As price increases, the learning investment also increases, which increases the increased likelihood of cost reductions. The increased possibility of reductions, in turn, results in

larger information rents paid to the grower. As discussed earlier, this information rent leads to a distortion between first and second best capital investment and expected feedstock usage. As the price increases from 6.36 to 7 ¢/kWh, the information rent portion of switchgrass price increases from 15% to 20%. Despite the increasing proportion spent on information rent, the processor is still able to contract a lower price for switchgrass at higher prices of electricity. As a result, the processor invests more, thereby reducing the distortion between first and second best.

In summary, higher prices for electricity translate into greater profitability for the project. As profitability increases, the processor is able to offer a contract that entices greater learning effort from the grower by paying more information rent, both in absolute magnitude and in percentage of overall price. This learning induces greater crop production cost reductions, and so the processor may negotiate a lower price for switchgrass. This ultimately results in a larger scale facility that uses greater quantities of feedstock.

Sensitivity to the Damping Parameter

A crucial parameter for the analysis is the damping parameter (t), or the responsiveness of crop production costs to learning effort. In this section of the sensitivity analysis, the value of this parameter ranges from -0.001 to -0.009. The impact of changes to the parameter is examined graphically, as before, in terms of the relative distortion that occurs between the first best and contracting regimes. As one would expect, increases in the responsiveness of crop costs to learning effort result in greater expected cost reductions in the project. This leads to greater learning effort exerted on

the part of the grower and lower prices for switchgrass paid by the processor. As a result, project scale increases, as well as profitability.

Increasing the magnitude of the damping parameter increases capital investment, learning investment, feedstock utilization, and overall profitability. Despite these, the distortion in capital investment and switchgrass usage increases with greater responsiveness of cost to learning effort. Graph 3 below depicts the distortion between the two regimes arising from increasing responsiveness to learning.

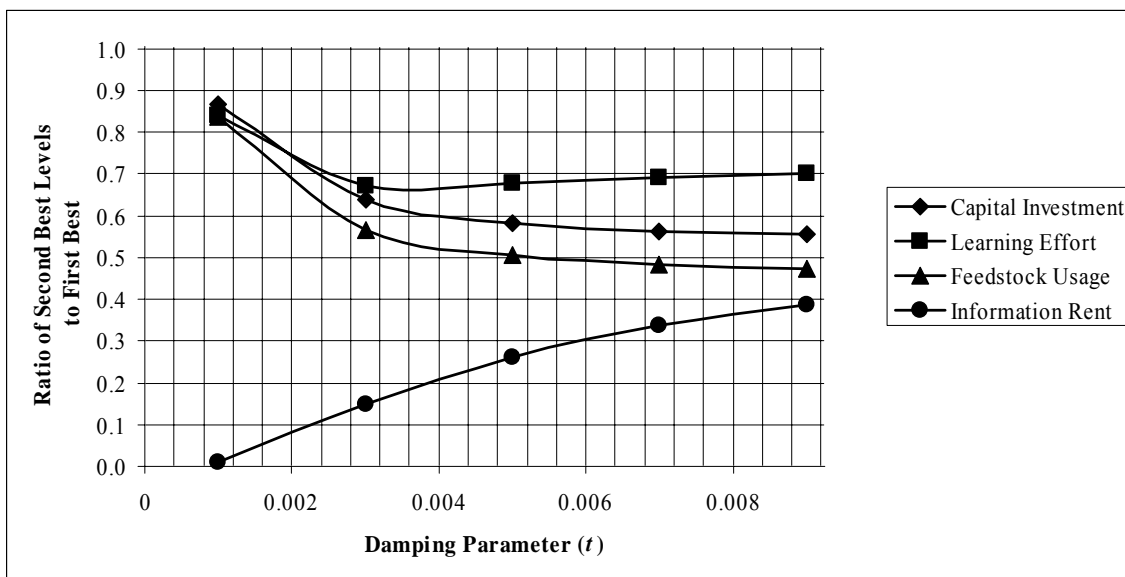
With exception to the lowest value of t , the learning effort distortion tends to decrease slightly as the magnitude of the parameter increases. This is due to learning investment increasing at a higher rate under limited liability contracts than under the first best. This is a result of the marginal diminishing returns to investment at higher levels of investment. Under the first best, learning investment levels reach relatively high levels ($\beta > 100$) at $t = -0.005$. Under limited liability contracts, the learning investment reaches moderate levels ($50 < \beta < 100$), and so there is a greater marginal response to increases in the learning investment under limited liability contracts than under the first best. Hence, the rate of increase in learning investment over t is greater under limited liability contracts than under first best, and the distortion between the two actually decreases in this range.

In the case of least responsiveness ($t = -0.001$), the level of distortion between first best and limited liability contracts is very small – the ratios between investment and production levels cluster around 85%. This is because very little cost reduction in switchgrass production occurs, resulting in a minimal share of switchgrass price spent as information rent to the grower. Movement to the right on the graph represents an

increase in the responsiveness of cost to learning effort or an increase in the magnitude of the damping parameter, which implies a greater likelihood of feedstock cost reductions per unit of learning effort. As the absolute value of the parameter increases, the distortion between first and second best increases. The relative size of contracting capital investment to first best falls to about 55%, and the relative quantity of feedstock usage falls to under 50%.

This increase in distortion is a result of information rents paid by the processor to the grower. In essence, the increased likelihood of cost reductions increases the value of private information held by the grower. As the value of private information increases, the processor must offer information rents that comprise larger shares of the price of switchgrass. The growing share of price devoted to information rent causes stickiness in the price of a ton of switchgrass, that is a decrease in the cost of producing the switchgrass is accompanied by disproportionately small decrease in the price of the switchgrass delivered to the processor. The relative lack of price reduction deters investment on the part of the processor, thereby increasing the distortion between first best and second-best levels of capital investment and expected feedstock usage.

Graph 3. Effect of Damping Parameter on Contract Efficiency



In contrast to the situation of increasing prices, the increased profitability due to increased cost responsiveness to learning does not result in a decrease in the distortion between first and second best. In the case of increasing electricity prices, the value marginal product of switchgrass increases for the processor. As a result, the processor is willing to pay the increase in information rent to procure the input to production. This willingness to pay on the part of the processor induces greater investment on the part of the grower that results in greater learning, lower feedstock prices, and greater profitability. In the case of increasing cost responsiveness to learning effort, the marginal value product of switchgrass does not increase for the processor. However, to entice the growers to invest in learning, the processor must be willing to pay a greater share of information rent to the grower. Paying more information rent reduces the cost of producing the feedstock by offering incentives to exert learning effort. Yet, the learning does not result in an overall price decrease to the processor.

The processor, therefore, does not have the incentive needed to invest in a larger facility and so feedstock usage and learning effort remain well below first best levels. The disincentives created for processor investment by limited liability contracts suggests the possibility of pursuing a policy to subsidize processor investment in capital. Analysis appearing later in the chapter explores the effect of such a policy on the distortions between first best and limited liability contracting outcomes.

Sensitivity to the Cost of Learning Effort

The final parameter for the sensitivity analysis is the learning parameter (ι) that is linked to the cost of learning effort exerted by the grower (β). As described earlier, the learning parameter has been calibrated using a measure of equivalent managerial cost needed to fund learning effort. However, this parameter in itself does not represent a dollar value; but it is a metric that facilitates a comparison of relative effort put forth under first best and contracting regimes. For this segment of the analysis, the parameter ranges in value from 1000 to 5000. An increase in the parameter represents an increase in the costliness, or disutility, of learning effort.

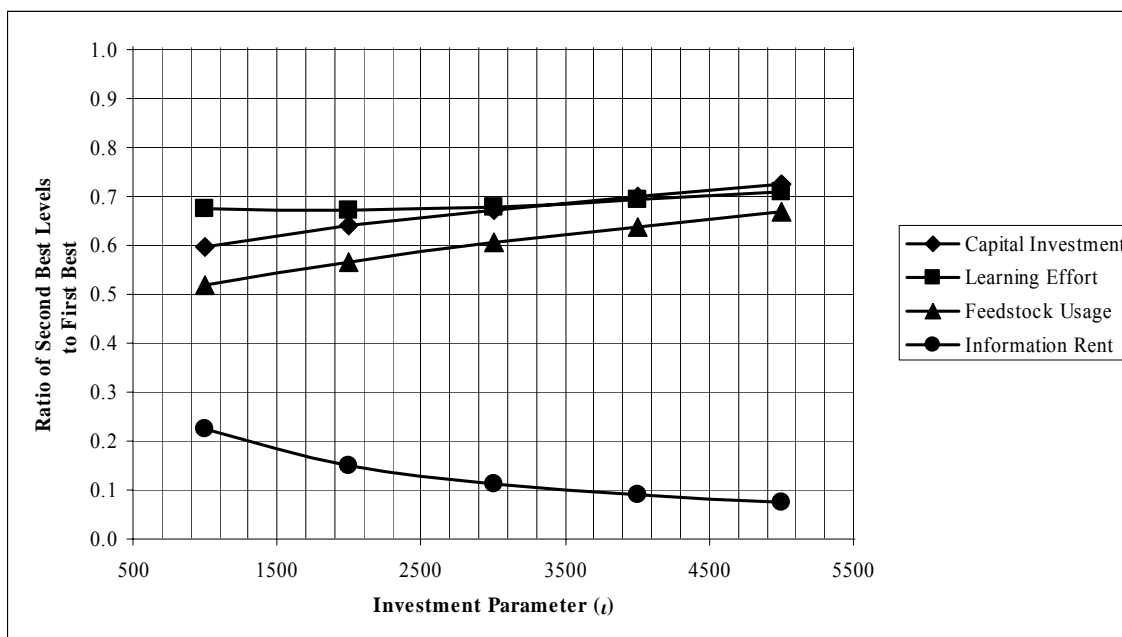
As one would expect, an increase in the parameter decreases the incentive to invest effort in learning, thereby decreasing the scale and profitability of biomass electricity projects. A larger parameter value implies a reduction in the elasticity of switchgrass production cost to learning effort, and is akin to a decrease in the absolute value of the damping parameter (t). With a reduced incentive to invest in learning comes a smaller reduction in production costs. The smaller reduction in cost is associated with a reduced value of information to the grower. The processor, therefore, does not need to pay a large share of switchgrass price devoted to information rent. Ultimately, the

reduction in information rent reduces the distortion between first best and second best outcomes.

An increase in the learning parameter increases the marginal disutility of effort. As the parameter increases the scale of all investments and production schedules decrease. However, these decreases do not occur at the same rate under the first best and second best regimes. The scale of the investments decrease more rapidly with increase in the parameter under limited liability contracts than under first best because of the amount of information (learning) rent paid to the grower declines. Therefore, relative investments in learning and capital investment, as well as feedstock production, increases with increases in the parameter.

In short, the distortion decreases with higher cost of learning effort. This effect is represented in Graph 4 below. As the parameter increases, the share of price for information rent decreases and the relative distortion decreases. At baseline ($\iota = 2000$), the information rent comprises about 15% the price of switchgrass paid by the processor, and the relative sizes of capital investment and feedstock usage are approximately 55-65%. Increasing the parameter to 5000 drives the information rent share to below 10%, and increases the relative size to about 65-75% of first best.

Graph 4. Effect of Cost of Effort on Contract Efficiency



Policy Analysis

The final segment of the empirical analysis explores the policy implications of the results using a comparison of the relative merits of various energy and agricultural policies. The potential environmental and rural development benefits arising from a biomass for electricity sector may justify government intervention to foster the emergence of the industry. A few policies are currently in place or have been proposed to assist the development of the industry. The analysis seeks to discover if any one of these policies is more effective at mitigating the inefficiencies created through limited liability contracts, thereby fostering a more competitive and sustainable industry.

Three policies are evaluated: the renewable energy production incentive credit (REPI), a crop subsidy paid to the grower, and a capital investment subsidy given to the processor. This section of the chapter is composed of five segments of the analysis, three of which examine each policy individually and the fourth compares the relative value of

the policies against each other. The fifth segment contains a discussion of other policy implications of the model and potential policy prescriptions.

Renewable Energy Production Incentive

The REPI was established in the Energy Policy Act of 1992 (42 U.S.C. 13317). This credit is a direct subsidy to producers of renewable energy that is proportional to the quantity of electricity produced by a renewable energy project. This credit was initially established at 1.5 ¢/kWh and adjusted annually for inflation. There have been calls to reauthorize the credit, which in 2003 dollars equals 1.85 ¢/kWh. A project is only eligible for the credit during the initial ten (10) years of operation. For the purpose of this analysis, which focuses on a single representative year of operation, the ten-year's worth of credit has been annualized over the entire thirty (30) year expected life of a biomass energy project. The resultant credit is valued at approximately 0.99 ¢/kWh.

Two effects of the REPI are evaluated: (1) the effect on project scale and profitability at baseline prices, and (2) the impact on project break-even prices. Table 5 below addresses the first effect. This table recreates Table 3 for the baseline case after incidence of the REPI credit. In comparison to the baseline case, the REPI reduces the distortion between first best and contract levels of investment and production. The relative size of the choice variables under limited liability contract vis-à-vis the first best range from 55%-65% at the baseline, but increase to the range of 80-85% when an REPI is offered to the processor. This effect could have been predicted based on the price sensitivity analysis above. Here, the marginal value product of switchgrass increases for the processor, which increases the processor's willingness to pay information rents to the grower. This willingness induces investment on the part of the grower and increases cost

reductions in switchgrass production. The amount by which switchgrass production cost falls is slightly greater than the amount by which learning rent increases. As a result, the overall price of switchgrass paid by the processor declines slightly.

Table 5. Comparison of Baseline Project with REPI Credit

	Processor Profit (\$/year)	K (MW)	β	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)	Price of biomass (\$/ton)
First Best	\$ 40,120,000	421	111.33	2,013,000	94%	16.33	\$48.70
Contracts	\$ 23,432,000	351	95.31	1,599,000	91%	14.50	\$64.50
Ratio	58%	83%	86%	79%	95%	89%	132%

The REPI credit also has the effect of increasing the intensity with which biomass feedstock is used by the processor for electricity generation. This is evident by the increase in capital-feedstock ratio, in terms of capacity utilization, over that in the baseline case. The REPI successfully increases capacity utilization by 5% in the first best and by over 10% in the limited liability contracting regime.

The REPI credit affects the viability of projects through a reduction in the break-even price of the facility. The impact of REPI on break-even price and project scale is reported in Table 6 below. In this case, the marginal value product of switchgrass to the processor is unaffected. In fact, the REPI's effect is to decrease the break-even price by an amount exactly equal to the REPI credit. This implies that the marginal value product of switchgrass is the same both with and without an REPI at their respective break-even prices. Essentially, Table 6 is identical to Table 4 with exception of the column for break-even price.

Table 6. Comparative viability of the Baseline Project with an REPI credit

	p_{BE} (\$/year)	K (MW)	β	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)
First best	5.03	282	80.75	1250000	87%	12.68
Contracts	5.35	212	62.01	863000	80%	10.21
Ratio		75%	77%	69%	92%	81%

The REPI has the effect of increasing the competitiveness of biomass electricity by reducing the break-even price of generation. However, the REPI does not reduce the inefficiency of limited liability contracting relative to the first best within the industry at their respective break-even prices. The REPI has no impact on the delivered price of feedstock paid by the processor, but it does increase the marginal value product of the feedstock. The REPI serves to shift downward the price at which the marginal value product of switchgrass equals the marginal cost of its procurement. Therefore only the break-even price changes under the REPI. There is no change in the level learning investment, nor the amount of learning-induced cost reductions, and so there is no change in the level of capital investment or feedstock usage by the facility.

Feedstock Production Subsidy

A subsidy paid directly to growers of the switchgrass could serve as an alternative to the REPI credit. The government may wish to pursue a feedstock subsidy in lieu of other payments, such as the Conservation Reserve Program. A policy such as this may be justified through the creation of environmental amenities and rural development benefits arising from a biomass electricity project.

Here, the feedstock subsidy (σ_F) is in terms of dollars per ton of switchgrass produced and is paid directly to the grower. To facilitate comparison of a feedstock subsidy with the REPI, the subsidy is calculated in two ways. First, the subsidy is

estimated at the amount necessary to attain an equivalent first best project scale as that which occurs under the baseline price plus an REPI credit. This feedstock subsidy is applied to the baseline project under first best and limited liability contracting regimes. Second, the subsidy is estimated at the amount necessary to attain the same break-even prices attained under the REPI program. Here, two subsidies are calculated, one to achieve the first best break even price of the baseline project plus an REPI and another to achieve the limited liability contracting break even price of the project plus an REPI.

Table 7 recreates the equivalent table for the REPI credit by displaying profit, capital investment, learning effort, switchgrass usage, and reduction in feedstock cost for the first best and contract regimes when a feedstock subsidy exists. The table also reports capacity utilization and the price of biomass feedstock in the expected state of nature under the two regimes. It appears that the feedstock subsidy has the same qualitative effect as the REPI in that it reduces the relative distortion between the two regimes as compared to the baseline. The subsidy to the grower reduces the pressure on prices paid by the processor to the grower, i.e. the processor does not need to offer as much payment to induce the same learning effort and truthful revelation as in the baseline. As a result, the processor can afford to purchase more feedstock and invest in a larger generation facility.

The feedstock subsidy also increases capacity utilization over the baseline case. The increased purchasing power of the processor for feedstock encourages greater intensity of feedstock usage in the generation of electricity. Thus, a generation facility of the same size uses greater amount of feedstock in the presence of a feedstock subsidy than without the subsidy. A subsidy of this sort would have the effect of generating

greater participation in a particular region in projects of this sort, for a given level of capital. Greater participation implies a greater potential for spillover effects that lead to economic development, such as labor employment and increased commerce. Greater feedstock intensity also implies more land in production and more substitution of fossil fuels for biomass, which has an impact on the potential for environmental benefits.

Table 7. Comparison of Baseline Project with feedstock subsidy

	Processor Profit (\$/year)	K (MW)	β	Q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)	Price of biomass (\$/ton)
First Best	\$ 39,300,000	421	113.38	2,063,000	96%	16.52	\$48.51
Contracts	\$ 22,066,000	350	97.34	1,628,000	91%	14.70	\$63.87
Ratio	56%	83%	86%	79%	95%	89%	131%

To evaluate the effect of the policy of viability of the project, one may examine the effect of the subsidy on break-even prices. Here, the subsidy needed to reach the REPI-induced break-even prices is estimated. By holding break-even price constant across policies, the investment and production levels may be compared under the different programs. One may thus see if one program is more effective at mitigating the inefficiency arising from the limited liability contracts.

Table 8 displays the result of the viability analysis. Essentially Table 6 from the REPI analysis is recreated with the respective values for an equivalent feedstock subsidy. From the results, one sees that the feedstock subsidy performs better than the REPI credit at attenuating the distortion between first and second best outcomes. The distortions under REPI at break-even prices are approximately 5% larger than those that occur under the feedstock subsidy. Paying the subsidy directly to the grower appears to mitigate, somewhat, the problem of information rent paid by the processor. In the case of the REPI, the processor is willing to pay the information rent to the grower due to an increase

in the marginal value product of switchgrass. In the case of the feedstock subsidy, the grower is willing to reduce the price of the switchgrass delivered to the processor. In a sense, the government takes on a portion of the information rent by paying a subsidy to the grower, reducing the overall burden to the processor and reducing (slightly) the distortion between first and second best outcomes.

Table 8. Comparative viability of the Baseline Project with a feedstock subsidy

	p_{BE} (\$/year)	K (MW)	B	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)
First best	5.03	292	85.80	1,353,000	91%	13.33
Contracts	5.35	232	69.68	1,000,000	85%	11.25
Ratio		79%	81%	74%	93%	84%

Capital Investment Subsidy

Another alternative policy is a capital investment subsidy paid directly to the processor, or investor in the renewable energy technology. This policy may be justified on the basis that the processor will be replacing fossil fuels with a renewable resource for the generation of electricity. The processor's investment may also have some ancillary rural development benefits through the creation of jobs and alternative agricultural markets for neighboring farmers.

The capital subsidy (σ_K) is in terms of dollars per megawatt of capacity investment in electricity generation and is paid directly to the processor. The analysis proceeds as before in that the subsidy is calculated in two ways. First, the subsidy is estimated at the amount necessary to attain an equivalent first best project scale as that which occurs under the baseline price plus an REPI credit. Second, the subsidy is

estimated at the amount necessary to attain the same break-even prices attained under the REPI program.

Table 9 resembles Tables 5 and 7 for the previous policies. Compared with the REPI, the capital subsidy appears to have a similar effect at attenuating the distortion between first and second best levels of capital investment and learning effort. However, the capital subsidy exacerbates the distortion in feedstock utilization. The capital subsidy decreases capacity utilization by the processor, reducing the relative usage of feedstock to capital in the generation of electricity. This does not bode well for using the policy over the REPI or feedstock subsidy to achieve environmental and economic benefits. The reduction in orders for switchgrass mitigates the information rent problem to a certain degree, which results in a reduction in the distortion between first and second best cost reduction that occur under the two regimes. However, this reduction in learning rent is achieved via reduced orders for feedstock production.

Table 9. Comparison of Baseline Project with capital subsidy

	Processor Profit (\$/year)	K (MW)	β	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)	Price of biomass (\$/ton)
First Best	\$ 40,330,000	421	109.67	1,962,000	92%	16.13	\$48.90
Contracts	\$ 24,532,000	352	93.69	1,271,000	71%	14.24	\$64.40
Ratio	61%	84%	85%	65%	77%	88%	132%

Table 10 resembles Tables 6 and 8 from before and displays the viability analysis under a capital subsidy. The break-even prices under REPI are now achieved via the capital subsidy to determine if there is an effect on the amount of distortion between the first and second best. Here the comparison reveals that the capital subsidy is ineffective at reducing the distortion between first and second best regimes.

At lower prices for electricity, the capital subsidy creates perverse incentives for the investor in electricity generation. A corner solution results from the empirical model, in that the generator invests the minimal amount possible in capacity and contracts for a minimal amount of feedstock from the grower. This, in turn, elicits the minimal amount of investment in learning on the part of the grower.

The minimum values for the choice variables are constrained by the physical model. In the model, the term for investment in learning appear in the denominator of parts of the objective function, thereby constraining learning investment from below at unity. The model also restricts the value for feedstock utilization to non-negative values in all states of the world. This constraint results in a constraint on the generation capital investment. The structure of the production function in the model may also be skewing the amount of feedstock utilization downward. At low levels of input use, the production function may allow for more substitution between capital and feedstock than one might reasonably expect from the true technology.

The results of the analysis of the capital subsidy indicate that the subsidy creates an Averch-Johnson effect, whereby the processor over-invests in capacity relative to biomass use in order to receive the subsidy payment. The policy rewards the processor for investing in the technology, but not for actually using the technology to generate electricity. On this basis, one may conclude that a capital subsidy would be inappropriate for addressing the problems created by limited-liability contracting and helping to jump-start the new industry.

Table 10. Comparative viability of the Baseline Project with a capital subsidy

	p_{BE} (\$/year)	K (MW)	β	q (tons/year)	Capacity utilization	Reduction in cost (\$/ton)
First best	5.03	263	72.27	1,060,000	79%	11.58
Contracts	5.35	52	1	10,400	4%	0.20
Ratio		20%	1%	1%	5%	2%

Comparison of Policy Alternatives

The final segment of this section consists of a side-by-side comparison of the previously mentioned policies in terms of the effectiveness at reducing the distortion created by contracts and the total cost of the policy to the government. Similar to above, the section includes two tables that present the policies on the basis of impact at baseline price of electricity, and on the basis of impact on viability. The total cost to the public sector in terms of the size of the subsidy per project is reported in each table to assist in making a final judgment about the effectiveness of each policy.

In the prior two sections, the size of a feedstock subsidy and a capital subsidy were determined that would achieve the same effect on first best capital investment as that under a REPI credit. The capital subsidy creates perverse incentives for the processor that reduces the intensity of feedstock usage for the projects. As the justification for public intervention relies on the potential for ancillary benefits that arise from the production and usage of biomass, one may safely eliminate the capital subsidy from consideration by public policy makers. This now allows for a comparison of the relative outcomes under limited liability contracting in the presence of the remaining two subsidies: REPI credit and feedstock subsidy.

Table 11 presents the contracting outcomes relative to the first best for the two policies. The first three columns of the table identify the policy, the unit cost of the

policy, and total resultant outlay for the policy, i.e. the cost to the government per project when it implements the policy. The next columns show the size of the project relative to the first best outcome, as well as the size of profits relative to the first best and switchgrass production cost reductions.

Table 11. Comparison of Policies at Baseline Price

	Unit Cost	Total Cost	Processor Profit	<i>K</i>	<i>B</i>	<i>q</i>	Reduction in cost
REPI	\$ 0.99/kWh	\$ 28,440,000	58%	83%	86%	79%	89%
σ_F	\$ 16.86/ton	\$ 27,446,000	56%	83%	86%	79%	89%

The results indicate that, at the baseline price of 6.36 ¢/kWh, each of the policies work equally as well at reducing the distortion in capital investment and learning effort created by limited liability contracts. It appears that the REPI is marginally better at reducing the distortion in project profits than the feedstock subsidization policy (about 2%.) However, re-examination of Tables 5 and 7 reveal that the feedstock subsidy leads to slightly larger investments in learning and larger decreases in biomass production costs. The processor also pays slightly less for feedstock in the expected state of nature with the feedstock subsidy than with the REPI.

The absolute magnitude of the difference in profit (as reported in Tables 5 and 7) is approximately \$1.3 million. The magnitude of the policy cost difference equals \$1 million. For an additional \$1 million dollars, the REPI credit generates \$1.3 million dollars in direct project benefits over the feedstock subsidy. In addition, \$1 of REPI credit generates approximately 82¢ of profit for the project, whereas a \$1 of feedstock subsidy generates about 80¢. Because of the relatively small differences in feedstock usage and project scale, one may assume that the ancillary benefits will be equivalent

under either policy. Therefore the REPI credit may be more attractive than the feedstock subsidy as an instrument to mitigate some of the impact of limited liability contracts and encourage investment within the industry.

A similar analysis may be conducted using the break-even price analyses from previous sections. In these sections, equivalent subsidies for feedstock and capital were estimated that would achieve the break-even price realized with a REPI credit. The subsidies and total costs of the programs appear in Table 10 below. The relative distortions of contracting outcomes to the first best also appear in the table.

At break-even prices, the profits under both policies are zero, so comparison may only be made on the basis of relative distortion to the first best outcome and absolute scale of the resultant project. Without considering the cost of the policies, it is clear that the REPI credit does not perform as well as the feedstock subsidy at the break-even price in terms of mitigating the negative impact of limited liability contracts. However, in terms of cost to the government of the policy, the REPI outperforms the feedstock subsidy by over \$2 million.

In weighing the cost and benefits, one must also consider the absolute scale that results under each policy. Ancillary environmental and economic benefits arising from the project will be directly related to the scale of the project in question. On this score, the feedstock subsidy surpasses the REPI credit. The feedstock subsidy creates incentives for investing in 20 MW of additional capacity over the REPI, which translates to over one hundred thousand additional tons of switchgrass used per annum.

One final comparison of the projects relates to the cost to government per ton of switchgrass produced. The feedstock subsidy equals \$18.46/ton. The REPI costs

\$16,130,000 and 863,000 tons of switchgrass are produced, which equals about \$18.69/ton. It appears that the cost per ton of switchgrass produced in these projects is less when the subsidy is paid directly to the grower than to the processor (in terms of the REPI.)

Table 12. Comparison of Policies to Achieve the 1st-best at Break-even Prices

	Unit Cost	Total Cost	<i>K</i>	<i>B</i>	<i>q</i>	Cost Reduction
REPI	\$ 0.99/kWh	\$ 16,130,000	75%	77%	69%	81%
σ_F	\$ 18.46/ton	\$ 18,470,000	79%	81%	74%	84%

Unfortunately, the results of the analysis do not clearly designate one policy as dominant over another. The REPI performs slightly better than the feedstock subsidy at a fixed price for electricity. However, the feedstock subsidy appears to perform better at break-even prices, in terms of feedstock utilization and realized cost reductions. The feedstock subsidy does lead to greater production of biomass under both scenarios and so a valuation of the additional environmental benefits of biomass production may be in order. A valuation of the ancillary benefits that result from the additional tons of switchgrass used under a feedstock subsidy is beyond the scope of this work. However, one may argue that the additional cost of the feedstock subsidy may well be worthwhile for its greater potential to include more growers and more land in productive agricultural activity.

Concluding Remarks

The results presented in this section clearly show that it will be difficult for biomass for electricity projects to be viable in the near future. This finding holds true even under first best conditions and is further compounded by the fact that the industry may use limited liability contracts during the establishment phase.

Consider the competitive price of electricity. The results of this chapter show that the price of electricity must be above 6 cents/kWh in a first best world and over 6.36 cents when limited-liability contracts are in place. The Energy Information Agency (EIA) reports that wholesale prices for electricity in 1999 (the most recent compilation of data available) ranged widely in value. These electricity prices are reported for the Pennsylvania-New Jersey-Maryland (PJM) and New England (NE) Independent System Operators (ISO) trading areas. This data is not available for the MidWest ISO. In general, the average monthly wholesale spot price ranged from about two (2) to four (4) cents per kWh. However, during the summer months, a period of peak demand, the average monthly spot prices reached as high as nine (9) cents/kWh. On a particularly hot day in August, the instantaneous spot prices reached a maximum of \$1.00/kWh over a period of several hours.

On an average price basis, biomass electricity may not be able to compete with other modes of electricity generation. On a marginal cost basis, there may be a niche market for biomass electricity. It may be possible for biomass to be profitable during summer months. However, the analysis contained in this chapter assumed year-round operation. This implies that the appropriate scale of projects should be much smaller than estimated in this analysis. There are also technological issues that must be resolved for a biomass facility to operate solely during periods of peak load. Ceramic materials used in the biomass gasification process do not tolerate alternating periods of heating and cooling without accelerated degradation. Perhaps the problem may be solved by minimizing the shutdown to once a year, allowing the facility to operate continuously during a three to four month period of anticipated high demand.

Consider the cost of other fuels used to generate electricity. EIA makes available data from Federal Energy Regulatory Commission (FERC) surveys of electric generation facilities¹⁰. Some of this data includes the cost of fuels to the electric facilities on an energy basis. In this data, the cost of fuels used for electricity generation is presented as a cost per unit of energy contained in the fuel. Although the reported cost does not take account of the efficiency of the technology to convert that energy into electricity, a quick comparison of fuels may still be made. The EIA reports that in 2002 (the earliest data available), coal ranged in cost from about 100 to 150 cents per million BTUs. For natural gas and various fuel oils, this cost ranged from 380 to 500 cents. Using the contract price of biomass determined earlier of approximately \$64, the biomass cost is about 400 cents per million BTU. If we use the price that would arise in the first best, this cost drops to 312 cents. These costs indicate that biomass is well within a competitive range for natural gas and fuel oils.

This suggests that there may be room for more improvement in the processing technology. The decision to invest in a particular type of generation facility does not hinge solely on fuel price. The cost of capital investment is also an important consideration. For the cases presented here, the cost of capital investment represents about 2¢/kWh. Based on the reported costs for fuels and electricity prices, one can infer that the capital costs for biomass may be significantly higher than that for natural gas. It may be wise to emphasize research and development on the processing side of this emerging industry, either to improve conversion efficiency or to reduce costs.

¹⁰ Form FERC-423 Database, "Monthly cost and quality of fuels for electric plants data." Available at <http://www.eia.doe.gov/cneaf/electricity/page/ferc423.html> [viewed May 2004].

Further increase in the costs of fossil fuels may spark a greater interest in biomass for electricity. Perhaps with an increase in the price of natural gas, a project may find it profitable to operate in the presence of one of the subsidies explored. In this case, short-lived limited liability contracts may be a feasible option to ensure that test projects may begin operating. In the case of the REPI, the subsidy expires after ten years of operation. A processor may want to explore the option of using a trial-run (ten-year) limited liability contract with the understanding of opening to the contract to a more competitive bidding process at the end of the trial period. The competition may be restricted due to concerns about transportation costs. Yet, certain growers who have experienced a greater share of learning may be able to offer more switchgrass at lower prices, thereby allowing the processor to appropriate some of the gains that occurred in the trial run.

A number of policy options are available for the public sector to pursue that may increase the viability of the industry, particularly in light of the potential benefits the industry may provide for the environment and rural economic development. The Renewable Energy Production Credit, which pays electricity generators a subsidy for each unit of output produced using renewable sources, serves to increase the overall scale of projects by about 30%. Yet, the projects under limited-liability contracts are still about 20% smaller than optimal. In addition, the credit actually increases the price of the feedstock to the processor due to the enhanced ability of the grower to extract learning rents from the processor. A similar effect occurs under a feedstock subsidy, which would pay growers a subsidy for each unit of the biomass produced. One clear result from the analysis is that a capital subsidy, where the processor is given a subsidy per unit of

capacity investment, is not an effective policy for the mitigation of inefficiency arising from limited-liability contracts. The capital subsidy encourages processors to over-invest in capital relative to feedstock utilization. Lower prices for electricity magnify this Averch-Johnson effect.

Both the REPI and feedstock subsidy enhance the viability of their ability to reduce break-even prices of electricity. The REPI reduces the break-even price by about 15% from the baseline. A feedstock subsidy could achieve the same effect at a cost to the government about 10-15% greater than the REPI. However, a feedstock subsidy encourages greater capacity utilization on the part of the processor, or feedstock to capital ratio.

Policy makers may choose to pursue other types of policies other than the subsidies detailed in this analysis. The theoretical model suggests that there may be value to encouraging vertical integration within the industry, particularly forward vertical integration on the part of grower cooperatives. Here, government intervention may be needed to assist grower cooperatives in choosing the appropriate technologies for generating electricity, hiring and training personnel to operate the generation facility, and securing purchasers for the electricity.

Alternatively, the government may intervene to arrange the coordination of the investments among processors and growers. An extreme example of this intervention would be direct government participation via investment in production capacity. Once a facility has been constructed, the government may auction contracts to growers for the supply of feedstock to the facility. A few years after the project has been established, perhaps at the beginning of the second growing cycle for switchgrass, the government

may auction the facility itself to a set of growers. If growers know in advance of these auctions, it may create competition among growers to reduce costs and induce incentives for the investment in learning. The competition generated by the auctions themselves may also elicit truthful revelation of production costs, thereby allowing the processor to benefit from the learning-induced cost reductions.

Chapter 7. Conclusion

The issues of coordination and organization of agents within new industries have previously been identified as potential obstacles to the formation and viability of new agricultural industries, particularly in the case of biomass energy production. However, this dissertation represents the first theoretical investigation into the implications of these obstacles for investment within new agricultural industries and empirical estimation of the magnitude of the issues' impacts on profitability in the biomass energy sector.

The dissertation combines three distinct areas of economic thought to develop a theoretical model for the examination of the effects of limited liability contracting on learning by doing and capital investment within a new agricultural industry. The first area of economic thought pertains to the characteristics of many new agricultural industries, specifically asset specificity, temporal considerations, and multiple facets of uncertainty. The combinations of these features within new agricultural industries indicate that there may be a need for the industry to rely on long-term contracts that extend a certain amount of protection to both a grower's and a processor's investments.

The second area of economic thought pertains to the issue of learning-by-doing. Novel industries are likely to exhibit learning in the early phases of development, whereby costs of production decrease as agents acquire more experience. Some of this learning may come in the form of public research and development freely transferred to the public sector via new crop hybrids and advanced cropping techniques. Some of this learning may also come from repetition in production, i.e. costs decline with cumulative production experience. Yet, a significant portion of this learning will not be costless and

will require additional exertion of effort, or a learning investment, on the part of growers to observe, monitor, and adjust the conditions for optimal crop cultivation.

The third area of economic thought concerns the impact of contracts on the investments of agents within a principal-agent framework. Contracts that extend guarantees to agents in a new agricultural industry, some of which include limited-liability contracts, have serious consequences for the incentives to invest in these industries. For the most part, the literature has focused on the effect of limited-liability contracts on investments undertaken by the agent, or in the case of new agricultural industries, the grower. However, the results of learning investments within the industry will have value to both the agent (grower) that undergoes learning and the principal (processor) that uses the intermediate good produced by the agent. The literature on learning has not explored the issue where the transfer of cost reductions in the production of an intermediate good to a processor may be necessary for viability of the industry in the production of a final good. Nor has the literature explored the potential impact of limited-liability contracts on investments when the principal, as well as the agent, has an investment decision.

The theoretical model in the dissertation illustrates the impact of limited-liability contracts in a new industry where learning may be important. Limited-liability contracts create an environment of moral hazard in learning investment and adverse selection in the production of the intermediate good. These two features of the contracting environment present difficulties for the principal to benefit from the learning-induced cost reductions realized at the intermediate stage of production. Thus, the principal under-invests in the industry and requires less of the intermediate good. Reduced feedstock orders decrease

the incentives for the agent to invest in learning, and so the ultimate cost of production of the intermediate good is higher than optimal. Underinvestment may prevent new agricultural industries, specifically those that face stiff competition in the market for the final goods, from achieving profitability. In some cases, the obstacles created by moral hazard and adverse selection may prevent investment in the industry altogether.

The theoretical model may be applied to any industry where a new technique has been devised to produce a good and where the market for the good is well-developed and competitive. This is true for many new bio-based industries, where novel crops are being used to produce goods, such as chemicals and energy, which would not be considered traditional agriculture. The dissertation applies the theoretical model to one of these new industries, the generation of electricity using biomass. Via simulation of the investment and production within the industry, the model allows for quantification of the inefficiencies that may arise from limited liability contracting.

In general, the new industry realizes project scales 25-30% smaller than optimal. In addition, the cost reductions in the production of the biomass feedstock are not as great under limited liability, which are about 20% less than what has predicted by typical engineering analyses. Contracts also raise the price paid by the principal for the feedstock due to the need to pay learning rents, which is about 25% higher under limited liability contracts than the optimal. The most significant finding of the analysis is the resulting break-even price for electricity. The price of electricity necessary for a biomass electricity project to produce zero profit is about 5% higher under limited liability contracts than under the first best. In the competitive market for electricity, this small difference may have serious implications for the industry's ability to compete. Perhaps,

if the cost of other fuel sources continues to climb rapidly, such as natural gas, then biomass may become more attractive. However, investors may not want to pin their hopes on the ability of the industry to reap the gains of learning-by-doing.

A number of policy options are available for the public sector to pursue that may increase the viability of the industry, particularly in light of the potential benefits the industry may provide for the environment and rural economic development. Of these policies, a capital subsidy paid to processors that invest in renewable energy technology is clearly not worth pursuing by policy makers. The policy merely encourages over-investment in capital relative to feedstock utilization. This has the effect of reducing electricity output and biomass production, which reduces the ancillary benefits of biomass electricity. The Renewable Energy Production Credit paid to the processor per unit of electricity generated and a feedstock subsidy paid to growers per unit of biomass produced, however, serve to increase the overall scale of projects by about 30%. Yet, even with these policies, the projects under limited-liability contracts are still about 20% smaller than optimal. In addition, these subsidies do not significantly decrease the price of the feedstock to the processor.

Both the REPI and feedstock subsidy enhance the viability of their ability to reduce break-even prices of electricity. The REPI reduces the break-even price by about 15% from the baseline. A feedstock subsidy could achieve the same effect at a cost to the government about 10-15% greater than the REPI. However, a feedstock subsidy encourages greater capacity utilization on the part of the processor, or feedstock to capital ratio. On this basis, it may be more favorable to pursue a biomass feedstock

subsidization program to increase the potential for rural development through the intensification of electricity production within projects.

Alternatively, the government may choose to pursue a policy that encourages the formation of a vertically integrated industry through grower cooperative ownership of the processing stage. There may also be the possibility of pursuing other contractual arrangements and coordination schemes that allow for greater ability of all participants of a new agricultural industry to benefit from learning and the resulting cost reductions. It's not clear how these policies may be implemented, or what actions would be necessary on the part of policy makers to ensure their success.

These other governance structures and policies may prove to be fruitful avenues of research for those interested in ensuring that new agricultural industries emerge and attain some level of long-term viability. This research must continue to address the issues highlighted by the present analysis, mainly those of risk aversion on the part of growers and processors in making specific investments and the ability of mechanisms to elicit appropriate levels of those investments. Learning within new agricultural industries provides hope that these industries may be profitable in the near future and competitive with other means of production. These industries offer environmental amenities that may benefit all of society and offer economic benefits that may increase the welfare of rural communities. However, industry organization may prevent the realization of any of these benefits unless the industry, or perhaps the government, is able to find some other suitable arrangement that provides certain guarantees to investor-participants while allowing all participants to profit from learning.

Appendix A: Necessary Conditions for Optimal Solutions to the First Best and Limited-Liability Contracting Problems

First Best Regime

An optimal solution to the First Best problem described in Chapter 3 implies that the following second order conditions hold:

$$\frac{\partial^2 U}{\partial K^2} = \int_{\underline{\theta}}^{\bar{\theta}} \left[pf_{11}(K, q(K, \theta)) + pf_{12}(K, q(K, \theta)) \frac{\partial q}{\partial K} \right] dG(\theta|e) \leq 0$$

$$\frac{\partial^2 U}{\partial e^2} = \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_{ee}(\theta|e) d\theta \leq 0$$

The implicit function theorem allows for derivation of an expression for $\frac{\partial q}{\partial K}$. Total differentiation of the first order condition for the intermediate good, equation (1), results in,

$$[pf_{22}(K, q) - C_{11}(q, \theta)]dq + [pf_{21}(K, q)]dK = 0,$$

and so,

$$\frac{dq}{dK} = \frac{-pf_{21}(K, q)}{pf_{22}(K, q) - C_{11}(q, \theta)}$$

This expression may be substituted into the second-order condition for capital investment:

$$\int_{\underline{\theta}}^{\bar{\theta}} \left[pf_{11}(K, q) - \frac{pf_{21}(K, q)^2}{pf_{22}(K, q) - C_{11}(q, \theta)} \right] dG(\theta|e) \leq 0$$

By Young's Theorem, $pf_{21}(K, q) = pf_{12}(K, q)$, and so rearrangement of the condition yields,

$$\int_{\underline{\theta}}^{\bar{\theta}} \frac{p^2 [f_{11}(K, q)f_{22}(K, q) - f_{12}(K, q)f_{21}(K, q)] - pC_{11}(q, \theta)}{pf_{22}(K, q) - C_{11}(q, \theta)} g(\theta|e) d\theta \leq 0$$

Concavity of the production function $f(K, q)$ in the inputs implies that,

$$\begin{aligned} f_{11}(K, q) &\leq 0 \\ f_{22}(K, q) &\leq 0 \\ f_{11}(K, q)f_{22}(K, q) - f_{12}(K, q)f_{21}(K, q) &\geq 0 \end{aligned}$$

Combined with convexity of the cost function, $C_{11}(q, \theta) \geq 0$, the denominator above is nonpositive, or:

$$pf_{22}(K, q) - C_{11}(q, \theta) \leq 0$$

Thus, to ensure optimal solution the numerator above must be nonnegative, or the cost function for the input production must be sufficiently convex to ensure optimality of the solution.

$$p^2 [f_{11}(K, q)f_{22}(K, q) - f_{12}(K, q)f_{21}(K, q)] - pf_{11}(K, q)C_{11}(q, \theta) \geq 0$$

which implies,

$$f_{11}(K, q)f_{22}(K, q) - f_{12}(K, q)f_{21}(K, q) \geq \frac{f_{11}(K, q)C_{11}(q, \theta)}{p}$$

A cost function that is linear in q guarantees that the condition holds.

Additionally, the following condition must hold for concavity of the social planner's

objective function:

$$\frac{\partial^2 U}{\partial K^2} \frac{\partial^2 U}{\partial e^2} - \frac{\partial^2 U}{\partial K \partial e} \frac{\partial^2 U}{\partial e \partial K} \geq 0$$

The cross partial derivatives in the condition above equals,

$$\frac{\partial^2 U}{\partial K \partial e} = \int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, \theta)) dG_e(\theta|e)$$

$$\frac{\partial^2 U}{\partial e \partial K} = \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, \theta), \theta) \frac{\partial q}{\partial K} G_e(\theta|e) d\theta = \int_{\underline{\theta}}^{\bar{\theta}} \frac{-pf_{21}(K, q)C_{21}(q(K, \theta), \theta)}{pf_{22}(K, q) - C_{11}(q, \theta)} G_e(\theta|e) d\theta$$

By Young's Theorem, the cross-partials are equal, so either of the two conditions above may be used to verify that second order conditions hold at the solution to ensure optimality.

Limited Liability Contracting Regime

The processor problem under limited liability contracts may be solved in two stages. The first stage involves solution to a constrained optimal control problem to determine the production schedule over the states of nature, $q(\theta)$. The constraint to the problem represents the moral hazard in learning investment:

$$\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(\theta), \theta) G_e(\theta|e) d\theta - 1 = 0$$

The above constraint may be reformulated as a differential equation, with boundary conditions, for a state variable, $\kappa(\theta)$, within the optimal control framework (Léonard and Van Long). We may define the following:

$$\dot{\kappa}(\theta) = C_2(q(\theta), \theta) G_e(\theta|e)$$

$$\kappa(\bar{\theta}) = 1$$

$$\kappa(\underline{\theta}) = 0$$

The Hamiltonian for the problem, then, is

$$\mathcal{H} = [pf(K, q(\theta)) - C(q(\theta), \theta)]g(\theta|e) + C_2(q(\theta), \theta)[1 - G(\theta|e)] + \lambda(\theta)C_2(q(\theta), \theta)G_e(\theta|e)$$

By the maximum principle, the necessary first-order conditions for the processor problem are,

$$\begin{aligned}\frac{\partial \mathcal{H}}{\partial q} &= [pf_2(K, q) - C_1(q, \theta)]g(\theta|e) + C_{21}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)] = 0 \\ \dot{\lambda}(\theta) &= -\frac{\partial \mathcal{H}}{\partial \kappa} = 0 \\ \dot{\kappa}(\theta) &= \frac{\partial \mathcal{H}}{\partial \lambda} = C_2(q(\theta), \theta)G_e(\theta|e)\end{aligned}$$

The above conditions imply that the co-state variable, λ , is a constant over the entire range of states of nature.

When the Hamiltonian is jointly concave in the control and the state variables (q, κ) then the above conditions are sufficient conditions to ensure optimality of the solution. Joint concavity implies the following:

$$\begin{aligned}\frac{\partial^2 \mathcal{H}}{\partial q^2} &\leq 0 \\ \frac{\partial^2 \mathcal{H}}{\partial \kappa^2} &\leq 0 \\ \frac{\partial^2 \mathcal{H}}{\partial q^2} \frac{\partial^2 \mathcal{H}}{\partial \kappa^2} - \frac{\partial^2 \mathcal{H}}{\partial q \partial \kappa} \frac{\partial^2 \mathcal{H}}{\partial \kappa \partial q} &\leq 0\end{aligned}$$

The derivatives of the Hamiltonian with respect to the state variable is zero, as are all other derivatives associated with the state variable. Thus, the only condition of concern is the following:

$$\frac{\partial^2 \mathcal{H}}{\partial q^2} = pf_{22}(K, q) - C_{11}(q, \theta) + C_{211}(q, \theta) \left[\frac{1 - G(\theta|e) + \lambda G_e(\theta|e)}{g(\theta|e)} \right] \leq 0$$

In the case of a linear cost function, the condition reduces to,

$$pf_{22}(K, q) \leq 0,$$

which is ensured by concavity of the production function.

Once the optimal production schedule is determined, $q(K, e, \lambda, \theta)$, it may be substituted into the second stage of the problem. The second stage involves static

optimization of the processor Lagrangean over the levels of investment in capital (K) and learning (e):

$$\mathcal{L} = \max_{K,e} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} \left[pf(K, q(K, e, \lambda, \theta)) - C(q(K, e, \lambda, \theta), \theta) + C_2(q(K, e, \lambda, \theta), \theta) \frac{1 - G(\theta|e)}{g(\theta|e)} \right] dG(\theta|e) \right. \\ \left. + \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \lambda, \theta), \theta) G_e d\theta \right] - \lambda - \Pi - rK \right\}$$

Application of the envelope theorem allows for determination of the first-order conditions for investments at the optimal production schedule:

$$\frac{\partial \mathcal{L}}{\partial e} = \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, e, \lambda, \theta)) - C(q(K, e, \lambda, \theta), \theta)] dG_e(\theta|e) - \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \lambda, \theta), \theta) G_e(\theta|e) d\theta \\ + \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \lambda, \theta), \theta) G_{ee} d\theta \right] = 0$$

$$\frac{\partial \mathcal{L}}{\partial K} = \int_{\underline{\theta}}^{\bar{\theta}} pf_1(K, q(K, e, \lambda, \theta)) dG(\theta|e) - r = 0$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \lambda, \theta), \theta) G_e d\theta - 1 = 0$$

A sufficient condition for a local maximum of the problem is that the determinant of Hessian matrix of the Lagrangean be negative. For a constrained maximization with m choice variables and n equality constraints, sufficiency is ensured when the last $(n-m)$ principal minors of the Hessian matrix alternate in sign, where the first of those principal minors has the sign equal to $(-1)^{m+1}$ (Léonard and Van Long). In this case, there are 2 choice variables and 1 equality constraint, which means that the last principal minor, $n-m=1$, must be negative. The final principal minor is the determinant of the Hessian matrix.

If we define the function, h , to represent the constraint, so that

$$h(K, e) = \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_e d\theta - 1 = 0,$$

then the Hessian for the problem is:

$$H = \begin{bmatrix} 0 & \frac{\partial h}{\partial K} & \frac{\partial h}{\partial e} \\ \frac{\partial h}{\partial K} & \frac{\partial^2 \mathcal{L}}{\partial K^2} & \frac{\partial^2 \mathcal{L}}{\partial K \partial e} \\ \frac{\partial h}{\partial e} & \frac{\partial^2 \mathcal{L}}{\partial e \partial K} & \frac{\partial^2 \mathcal{L}}{\partial e^2} \end{bmatrix}$$

Sufficiency implies that,

$$-\frac{\partial h}{\partial K} \left\| \begin{array}{cc} \frac{\partial h}{\partial K} & \frac{\partial^2 \mathcal{L}}{\partial K \partial e} \\ \frac{\partial h}{\partial e} & \frac{\partial^2 \mathcal{L}}{\partial e^2} \end{array} \right\| + \frac{\partial h}{\partial e} \left\| \begin{array}{cc} \frac{\partial h}{\partial K} & \frac{\partial^2 \mathcal{L}}{\partial K^2} \\ \frac{\partial h}{\partial e} & \frac{\partial^2 \mathcal{L}}{\partial e \partial K} \end{array} \right\| < 0$$

where,

$$\left\| \begin{array}{cc} \frac{\partial h}{\partial K} & \frac{\partial^2 \mathcal{L}}{\partial K \partial e} \\ \frac{\partial h}{\partial e} & \frac{\partial^2 \mathcal{L}}{\partial e^2} \end{array} \right\| = \frac{\partial h}{\partial K} \frac{\partial^2 \mathcal{L}}{\partial e^2} - \frac{\partial^2 \mathcal{L}}{\partial K \partial e} \frac{\partial h}{\partial e}$$

$$\left\| \begin{array}{cc} \frac{\partial h}{\partial K} & \frac{\partial^2 \mathcal{L}}{\partial K^2} \\ \frac{\partial h}{\partial e} & \frac{\partial^2 \mathcal{L}}{\partial e \partial K} \end{array} \right\| = \frac{\partial h}{\partial K} \frac{\partial^2 \mathcal{L}}{\partial e \partial K} - \frac{\partial^2 \mathcal{L}}{\partial K^2} \frac{\partial h}{\partial e}$$

The second derivative with respect to the learning investment is derived below:

$$\begin{aligned}
\frac{\partial^2 \mathcal{L}}{\partial e^2} &= \int_{\underline{\theta}}^{\bar{\theta}} [pf_2(K, q(K, e, \theta)) - C_1(q(K, e, \theta), \theta)] \frac{\partial q}{\partial e} dG_e(\theta|e) \\
&+ \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, e, \theta)) - C(q(K, e, \theta), \theta)] dG_{ee}(\theta|e) \\
&- \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{\partial q}{\partial e} G_e(\theta|e) d\theta - \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{ee}(\theta|e) d\theta \\
&+ \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{\partial q}{\partial e} G_{ee} d\theta \right] + \lambda \left[\int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{eee} d\theta \right]
\end{aligned}$$

The second derivative with respect to capital investment is,

$$\frac{\partial^2 \mathcal{L}}{\partial K^2} = \left[\int_{\underline{\theta}}^{\bar{\theta}} pf_{11}(K, q(K, e, \theta)) + pf_{12}(K, q(K, e, \theta)) \frac{\partial q}{\partial K} \right] dG(\theta|e)$$

The cross-partial derivative is,

$$\frac{\partial^2 \mathcal{L}}{\partial K \partial e} = \int_{\underline{\theta}}^{\bar{\theta}} pf_{12}(K, q(K, e, \theta)) \frac{\partial q}{\partial e} dG(\theta|e)$$

Determination of $\frac{\partial q}{\partial K}$ and $\frac{\partial q}{\partial e}$ proceeds via total differentiation of the first-order

condition for the control variable q :

$$\begin{aligned}
&\{ [pf_{22}(K, q) - C_{11}(q, \theta)] g(\theta|e) + C_{211}(q, \theta) [1 - G(\theta|e) + \lambda G_e(\theta|e)] \} dq \\
&+ [pf_{12}(K, q) g(\theta|e)] dK \\
&+ \{ [pf_2(K, q) - C_1(q, \theta)] g_e(\theta|e) + C_{21}(q, \theta) [-G_e(\theta|e) + \lambda G_{ee}(\theta|e)] \} de = 0
\end{aligned}$$

Setting $de=0$ allows one to solve for $\frac{\partial q}{\partial K}$ and setting $dK=0$ allows one to solve for $\frac{\partial q}{\partial e}$.

$$\frac{\partial q}{\partial K} = \frac{-pf_{12}(K, q) g(\theta|e)}{[pf_{22}(K, q) - C_{11}(q, \theta)] g(\theta|e) + C_{211}(q, \theta) [1 - G(\theta|e) + \lambda G_e(\theta|e)]}$$

$$\frac{\partial q}{\partial e} = - \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{[pf_{22}(K, q) - C_{11}(q, \theta)]g(\theta|e) + C_{211}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)]}$$

Application of the envelope theorem and substitution for the partial derivatives of q with respect to K and e give the set of second derivatives:

$$\begin{aligned} \frac{\partial^2 \mathcal{L}}{\partial e^2} &= \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, e, \theta)) - C(q(K, e, \theta), \theta)] dG_{ee}(\theta|e) \\ &+ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{[pf_{22}(K, q) - C_{11}(q, \theta)]g(\theta|e) + C_{211}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)]} G_e(\theta|e) d\theta \\ &- \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{ee}(\theta|e) d\theta \\ &- \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{[pf_{22}(K, q) - C_{11}(q, \theta)]g(\theta|e) + C_{211}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)]} G_{ee} d\theta \right\} \\ &+ \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{eee} d\theta \right\} \end{aligned}$$

$$\frac{\partial^2 \mathcal{L}}{\partial K^2} = \int_{\underline{\theta}}^{\bar{\theta}} \left\{ \frac{pf_{11}(K, q(K, e, \theta))}{[pf_{22}(K, q) - C_{11}(q, \theta)]g(\theta|e) + C_{211}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)]} - \frac{pf_{12}(K, q)^2 g(\theta|e)}{[pf_{22}(K, q) - C_{11}(q, \theta)]g(\theta|e) + C_{211}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)]} \right\} dG(\theta|e)$$

$$\frac{\partial^2 \mathcal{L}}{\partial K \partial e} = - \int_{\underline{\theta}}^{\bar{\theta}} pf_{12}(K, q(\theta)) \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{[pf_{22}(K, q) - C_{11}(q, \theta)]g(\theta|e) + C_{211}(q, \theta)[1 - G(\theta|e) + \lambda G_e(\theta|e)]} dG(\theta|e)$$

In the case of a linear cost function for the production of the intermediate good, $C_{11}(q, \theta)=0$ and $C_{211}(q, \theta)$. Thus, the second derivatives with respect to capital and learning reduce to:

$$\begin{aligned}
\frac{\partial^2 \mathcal{L}}{\partial e^2} &= \int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, e, \theta)) - C(q(K, e, \theta), \theta)] dG_{ee}(\theta|e) \\
&+ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q)g(\theta|e)} G_e(\theta|e) d\theta \\
&- \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q)g(\theta|e)} G_{ee} d\theta \right\} \\
&- \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{ee}(\theta|e) d\theta \\
&+ \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{eee} d\theta \right\}
\end{aligned}$$

$$\frac{\partial^2 \mathcal{L}}{\partial K^2} = \int_{\underline{\theta}}^{\bar{\theta}} \left\{ pf_{11}(K, q(K, e, \theta)) - \frac{pf_{12}(K, q)^2 g(\theta|e)}{pf_{22}(K, q)g(\theta|e)} \right\} dG(\theta|e)$$

Integration by parts allows for further simplification of the second derivative for learning investment.

$$\begin{aligned}
&\int_{\underline{\theta}}^{\bar{\theta}} [pf(K, q(K, e, \theta)) - C(q(K, e, \theta), \theta)] dG_{ee}(\theta|e) \\
&= [pf(K, q(K, \theta)) - C(q(K, \theta), \theta)] G_{ee}(\theta|e) \Big|_{\theta=\underline{\theta}}^{\theta=\bar{\theta}} \\
&- \int_{\underline{\theta}}^{\bar{\theta}} \{ [pf_2(K, q(K, e, \theta)) - C_1(q(K, e, \theta), \theta)] \dot{q}(\theta) - C_2(q(K, e, \theta), \theta) \} G_{ee}(\theta|e) d\theta \\
&= [pf(K, q(K, \theta)) - C(q(K, \theta), \theta)] G_{ee}(\theta|e) \Big|_{\theta=\underline{\theta}}^{\theta=\bar{\theta}} + \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{ee}(\theta|e) d\theta
\end{aligned}$$

This reduces to:

$$\begin{aligned}
\frac{\partial^2 \mathcal{L}}{\partial e^2} &= [pf(K, q(K, \theta)) - C(q(K, \theta), \theta)] G_{ee}(\theta|e) \Big|_{\theta=\underline{\theta}}^{\theta=\bar{\theta}} \\
&+ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)] g_e(\theta|e) + C_{21}(q, \theta) [-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q) g(\theta|e)} G_e(\theta|e) d\theta \\
&- \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)] g_e(\theta|e) + C_{21}(q, \theta) [-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q) g(\theta|e)} G_{ee} d\theta \right\} \\
&+ \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{eee} d\theta \right\}
\end{aligned}$$

The model assumes that investment has no effect on the supports of the distribution, which implies $G_e(\bar{\theta}|e) = G_e(\bar{\theta}|e')$ and $G_e(\underline{\theta}|e) = G_e(\underline{\theta}|e')$ for any pair of investments (e, e') .

This, in turn, implies that $G_{ee}(\bar{\theta}|e) = G_{ee}(\underline{\theta}|e) = 0$. Now the expression simplifies to:

$$\begin{aligned}
\frac{\partial^2 \mathcal{L}}{\partial e^2} &= \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)] g_e(\theta|e) + C_{21}(q, \theta) [-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q) g(\theta|e)} G_e(\theta|e) d\theta \\
&- \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)] g_e(\theta|e) + C_{21}(q, \theta) [-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q) g(\theta|e)} G_{ee} d\theta \right\} \\
&+ \lambda \left\{ \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{eee} d\theta \right\}
\end{aligned}$$

If we add one final assumption that the third-order effects of investment on probability are negligible, $G_{eee}(\theta|e) \approx 0$, then the second derivative of the Lagrangean with respect to learning investment is becomes:

$$\frac{\partial^2 \mathcal{L}}{\partial e^2} = (1 - \lambda) \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{[pf_2(K, q) - C_1(q, \theta)] g_e(\theta|e) + C_{21}(q, \theta) [-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q) g(\theta|e)} G_e(\theta|e) d\theta$$

A linear cost function simplifies the cross-partial derivative of the Lagrangean to:

$$\frac{\partial^2 \mathcal{L}}{\partial K \partial e} = - \int_{\underline{\theta}}^{\bar{\theta}} pf_{12}(K, q(\theta)) \frac{[pf_2(K, q) - C_1(q, \theta)]g_e(\theta|e) + C_{21}(q, \theta)[-G_e(\theta|e) + \lambda G_{ee}(\theta|e)]}{pf_{22}(K, q)g(\theta|e)} dG(\theta|e)$$

Earlier assumptions on the production function and the first-order condition for utilization of the intermediate good allows for signing the majority of the expression. However, the impact of learning investment on the probability density function, $g_e(\theta|e)$, depends on the state of nature. Because the impact of the learning investment on the cumulative distribution is negative, then this implies that $g_e(\theta|e)$ is positive at low states of nature and negative at high states. Without specification of functional forms, it does not appear possible to determine the sign of the cross-partial derivative.

Concavity of the production function in the inputs ensures that the second derivative with respect to capital is non-positive. The final stage to determine if second-order conditions are met under the assumptions of the model requires differentiation of the constraint of the Lagrangean, h . Differentiation of h with respect to the investments and simplification using a linear cost function results in,

$$\begin{aligned} \frac{\partial h(K, e)}{\partial K} &= \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{\partial q}{\partial K} G_e d\theta = 0 \\ \frac{\partial h(K, e)}{\partial e} &= \int_{\underline{\theta}}^{\bar{\theta}} C_{21}(q(K, e, \theta), \theta) \frac{\partial q}{\partial e} G_e d\theta + \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{ee} d\theta \\ &= \int_{\underline{\theta}}^{\bar{\theta}} C_2(q(K, e, \theta), \theta) G_{ee} d\theta \leq 0 \end{aligned}$$

Now that all of the derivatives have been signed, it is possible to determine if the determinant of the Hessian is negative. A complete expression for the determinant is:

$$\|H\| = \frac{\partial h}{\partial K} \left[\frac{\partial h}{\partial K} \frac{\partial^2 \mathcal{L}}{\partial e^2} - \frac{\partial^2 \mathcal{L}}{\partial K \partial e} \frac{\partial h}{\partial e} \right] + \frac{\partial h}{\partial e} \left[\frac{\partial h}{\partial K} \frac{\partial^2 \mathcal{L}}{\partial e \partial K} - \frac{\partial^2 \mathcal{L}}{\partial K^2} \frac{\partial h}{\partial e} \right]$$

The determinant of the Hessian must be positive. This condition ensures sufficiency. Determination of whether the condition is met in the solution is only possible once functional forms have been specified. Appendix C contains the verification of the second-order conditions as they pertain to the specified empirical model.

Appendix B. Sample Algorithms used in the Simulation

First Best Case

Define major elements of the model.

Production Function for Generation

$$f[\mathbf{K}_-, \mathbf{q}_-] := a_0 + a_1 * \mathbf{K} + a_2 * \mathbf{q} + a_3 * \mathbf{K}^2 + a_4 * \mathbf{q}^2 + a_5 * \mathbf{K} * \mathbf{q};$$

Transport and Capital Cost Functions

$$\begin{aligned} T[\mathbf{q}_-] &:= \tau_0 * \mathbf{q} + \tau_1 \mathbf{q}^2; \\ R[\mathbf{K}_-] &:= r_0 \mathbf{K} + r_1 \mathbf{K}^2 + r_2 \mathbf{K}^3; \end{aligned}$$

Cost Function for Feedstock

(* x is random variable representing state of the world *)

$$\begin{aligned} \text{Cunc}[\mathbf{q}_-, \mathbf{x}_-] &:= \text{Exp}[\mathbf{x} * \mathbf{t}] * c_0 \mathbf{q}; \\ \text{C2}[\mathbf{q}_-, \mathbf{x}_-] &:= \text{D}[\text{Cunc}[\theta, \xi], \xi] /. \{\theta \rightarrow \mathbf{q}, \xi \rightarrow \mathbf{x}\} \end{aligned}$$

Probability Distribution

```
Off[General::spell1, General::spell]
<< Statistics`ContinuousDistributions`
dist[B_] := ExponentialDistribution[A, B];
g[x_, B_] := PDF[dist[B], x]
ge[x_, B_] := D[g[\xi, \beta], \beta] /. {\xi -> x, \beta -> B}
G[x_, B_] := CDF[dist[B], x];
Ge[x_, B_] := D[G[\xi, \beta], \beta] /. {\xi -> x, \beta -> B}
Gee[x_, B_] := D[Ge[\xi, \beta], \beta] /. {\xi -> x, \beta -> B}
```

Value Function: Ex Post Profit

$$\text{VFB}[\mathbf{K}_-, \mathbf{q}_-, \mathbf{x}_-] := p f[\mathbf{K}, \mathbf{q}] - \text{Cunc}[\mathbf{q}, \mathbf{x}] - T[\mathbf{q}] + \sigma f \mathbf{q}$$

Optimal Production of Feedstock given Investment in Capital and State of Nature

$$\begin{aligned} \mathbf{qFBhat} &= \text{Solve}[\text{D}[\text{VFB}[\mathbf{K}, \theta, \xi], \theta] == 0, \theta][[1]]; \\ \text{QFB}[\mathbf{K}_-, \mathbf{x}_-] &:= (\theta /. \mathbf{qFBhat}) /. \{\mathbf{K} \rightarrow \mathbf{K}, \xi \rightarrow \mathbf{x}\} \end{aligned}$$

Expected Electricity Generation: Using Moment-generating function

f[K, QFB[K, x]] // Expand

$$\begin{aligned}
 & a_0 + a_1 K + a_3 K^2 + \frac{a_4 c_0^2 e^{2tx}}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_4 c_0 e^{tx} p}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 c_0 e^{tx} K p}{2(a_4 p - \tau_1)^2} + \\
 & \frac{a_2^2 a_4 p^2}{4(a_4 p - \tau_1)^2} + \frac{a_2 a_4 a_5 K p^2}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5^2 K^2 p^2}{4(a_4 p - \tau_1)^2} - \frac{a_4 c_0 e^{tx} \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_2 a_4 p \sigma f}{2(a_4 p - \tau_1)^2} + \\
 & \frac{a_4 a_5 K p \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_4 \sigma f^2}{4(a_4 p - \tau_1)^2} + \frac{a_4 c_0 e^{tx} \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_2 a_4 p \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 K p \tau_0}{2(a_4 p - \tau_1)^2} - \\
 & \frac{a_4 \sigma f \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 \tau_0^2}{4(a_4 p - \tau_1)^2} + \frac{a_2 c_0 e^{tx}}{2(a_4 p - \tau_1)} + \frac{a_5 c_0 e^{tx} K}{2(a_4 p - \tau_1)} - \frac{a_2^2 p}{2(a_4 p - \tau_1)} - \\
 & \frac{a_2 a_5 K p}{a_4 p - \tau_1} - \frac{a_5^2 K^2 p}{2(a_4 p - \tau_1)} - \frac{a_2 \sigma f}{2(a_4 p - \tau_1)} - \frac{a_5 K \sigma f}{2(a_4 p - \tau_1)} + \frac{a_2 \tau_0}{2(a_4 p - \tau_1)} + \frac{a_5 K \tau_0}{2(a_4 p - \tau_1)}
 \end{aligned}$$

% /. {e^{2tx} -> (1 - 2B t)^{-1}, e^{tx} -> (1 - B t)^{-1}}

$$\begin{aligned}
 & a_0 + a_1 K + a_3 K^2 + \frac{a_2^2 a_4 p^2}{4(a_4 p - \tau_1)^2} + \frac{a_2 a_4 a_5 K p^2}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5^2 K^2 p^2}{4(a_4 p - \tau_1)^2} + \frac{a_4 c_0^2}{4(1 - 2B t)(a_4 p - \tau_1)^2} - \\
 & \frac{a_2 a_4 c_0 p}{2(1 - B t)(a_4 p - \tau_1)^2} - \frac{a_4 a_5 c_0 K p}{2(1 - B t)(a_4 p - \tau_1)^2} + \frac{a_2 a_4 p \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5 K p \sigma f}{2(a_4 p - \tau_1)^2} - \\
 & \frac{a_4 c_0 \sigma f}{2(1 - B t)(a_4 p - \tau_1)^2} + \frac{a_4 \sigma f^2}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_4 p \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 K p \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 c_0 \tau_0}{2(1 - B t)(a_4 p - \tau_1)^2} - \\
 & \frac{a_4 \sigma f \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 \tau_0^2}{4(a_4 p - \tau_1)^2} - \frac{a_2^2 p}{2(a_4 p - \tau_1)} - \frac{a_2 a_5 K p}{a_4 p - \tau_1} - \frac{a_5^2 K^2 p}{2(a_4 p - \tau_1)} + \frac{a_2 c_0}{2(1 - B t)(a_4 p - \tau_1)} + \\
 & \frac{a_5 c_0 K}{2(1 - B t)(a_4 p - \tau_1)} - \frac{a_2 \sigma f}{2(a_4 p - \tau_1)} - \frac{a_5 K \sigma f}{2(a_4 p - \tau_1)} + \frac{a_2 \tau_0}{2(a_4 p - \tau_1)} + \frac{a_5 K \tau_0}{2(a_4 p - \tau_1)}
 \end{aligned}$$

$$\begin{aligned}
 \text{Ef}[K_, B_] := & a_0 + a_1 K + a_3 K^2 + \frac{a_2^2 a_4 p^2}{4(a_4 p - \tau_1)^2} + \frac{a_2 a_4 a_5 K p^2}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5^2 K^2 p^2}{4(a_4 p - \tau_1)^2} + \\
 & \frac{a_4 c_0^2}{4(1 - 2B t)(a_4 p - \tau_1)^2} - \frac{a_2 a_4 c_0 p}{2(1 - B t)(a_4 p - \tau_1)^2} - \frac{a_4 a_5 c_0 K p}{2(1 - B t)(a_4 p - \tau_1)^2} + \\
 & \frac{a_2 a_4 p \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5 K p \sigma f}{2(a_4 p - \tau_1)^2} - \frac{a_4 c_0 \sigma f}{2(1 - B t)(a_4 p - \tau_1)^2} + \frac{a_4 \sigma f^2}{4(a_4 p - \tau_1)^2} - \\
 & \frac{a_2 a_4 p \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 K p \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 c_0 \tau_0}{2(1 - B t)(a_4 p - \tau_1)^2} - \frac{a_4 \sigma f \tau_0}{2(a_4 p - \tau_1)^2} + \\
 & \frac{a_4 \tau_0^2}{4(a_4 p - \tau_1)^2} - \frac{a_2^2 p}{2(a_4 p - \tau_1)} - \frac{a_2 a_5 K p}{a_4 p - \tau_1} - \frac{a_5^2 K^2 p}{2(a_4 p - \tau_1)} + \frac{a_2 c_0}{2(1 - B t)(a_4 p - \tau_1)} + \\
 & \frac{a_5 c_0 K}{2(1 - B t)(a_4 p - \tau_1)} - \frac{a_2 \sigma f}{2(a_4 p - \tau_1)} - \frac{a_5 K \sigma f}{2(a_4 p - \tau_1)} + \frac{a_2 \tau_0}{2(a_4 p - \tau_1)} + \frac{a_5 K \tau_0}{2(a_4 p - \tau_1)}
 \end{aligned}$$

Expected Profit Function

ΓFB[K_, B_, x_] := Expand[VFB[K, QFB[K, x], x]]

$\Gamma\text{FB}[\mathbf{K}, \mathbf{B}, \mathbf{x}]$

$$\begin{aligned}
& a_0 p + a_1 K p + a_3 K^2 p + \frac{a_4 c_0^2 e^{2tx} p}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_4 c_0 e^{tx} p^2}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 c_0 e^{tx} K p^2}{2(a_4 p - \tau_1)^2} + \frac{a_2^2 a_4 p^3}{4(a_4 p - \tau_1)^2} + \\
& \frac{a_2 a_4 a_5 K p^3}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5^2 K^2 p^3}{4(a_4 p - \tau_1)^2} - \frac{a_4 c_0 e^{tx} p \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_2 a_4 p^2 \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5 K p^2 \sigma f}{2(a_4 p - \tau_1)^2} + \\
& \frac{a_4 p \sigma f^2}{4(a_4 p - \tau_1)^2} + \frac{a_4 c_0 e^{tx} p \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_2 a_4 p^2 \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 K p^2 \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_4 p \sigma f \tau_0}{2(a_4 p - \tau_1)^2} + \\
& \frac{a_4 p \tau_0^2}{4(a_4 p - \tau_1)^2} - \frac{c_0^2 e^{2tx}}{2(a_4 p - \tau_1)} + \frac{a_2 c_0 e^{tx} p}{a_4 p - \tau_1} + \frac{a_5 c_0 e^{tx} K p}{a_4 p - \tau_1} - \frac{a_2^2 p^2}{2(a_4 p - \tau_1)} - \frac{a_2 a_5 K p^2}{a_4 p - \tau_1} - \\
& \frac{a_5^2 K^2 p^2}{2(a_4 p - \tau_1)} + \frac{c_0 e^{tx} \sigma f}{a_4 p - \tau_1} - \frac{a_2 p \sigma f}{a_4 p - \tau_1} - \frac{a_5 K p \sigma f}{a_4 p - \tau_1} - \frac{\sigma f^2}{2(a_4 p - \tau_1)} - \frac{c_0 e^{tx} \tau_0}{a_4 p - \tau_1} + \frac{a_2 p \tau_0}{a_4 p - \tau_1} + \\
& \frac{a_5 K p \tau_0}{a_4 p - \tau_1} + \frac{\sigma f \tau_0}{a_4 p - \tau_1} - \frac{\tau_0^2}{2(a_4 p - \tau_1)} - \frac{c_0^2 e^{2tx} \tau_1}{4(a_4 p - \tau_1)^2} + \frac{a_2 c_0 e^{tx} p \tau_1}{2(a_4 p - \tau_1)^2} + \frac{a_5 c_0 e^{tx} K p \tau_1}{2(a_4 p - \tau_1)^2} - \\
& \frac{a_2^2 p^2 \tau_1}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_5 K p^2 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_5^2 K^2 p^2 \tau_1}{4(a_4 p - \tau_1)^2} + \frac{c_0 e^{tx} \sigma f \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_2 p \sigma f \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_5 K p \sigma f \tau_1}{2(a_4 p - \tau_1)^2} - \\
& \frac{\sigma f^2 \tau_1}{4(a_4 p - \tau_1)^2} - \frac{c_0 e^{tx} \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} + \frac{a_2 p \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} + \frac{a_5 K p \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} + \frac{\sigma f \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{\tau_0^2 \tau_1}{4(a_4 p - \tau_1)^2}
\end{aligned}$$

$\% /. \{e^{2tx} \rightarrow (1 - 2Bt)^{-1}, e^{tx} \rightarrow (1 - Bt)^{-1}\}$

$$\begin{aligned}
& a_0 p + a_1 K p + a_3 K^2 p + \frac{a_2^2 a_4 p^3}{4(a_4 p - \tau_1)^2} + \frac{a_2 a_4 a_5 K p^3}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5^2 K^2 p^3}{4(a_4 p - \tau_1)^2} + \frac{a_4 c_0^2 p}{4(1 - 2Bt)(a_4 p - \tau_1)^2} - \\
& \frac{a_2 a_4 c_0 p^2}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{a_4 a_5 c_0 K p^2}{2(1 - Bt)(a_4 p - \tau_1)^2} + \frac{a_2 a_4 p^2 \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5 K p^2 \sigma f}{2(a_4 p - \tau_1)^2} - \\
& \frac{a_4 c_0 p \sigma f}{2(1 - Bt)(a_4 p - \tau_1)^2} + \frac{a_4 p \sigma f^2}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_4 p^2 \tau_0}{2(a_4 p - \tau_1)^2} - \frac{a_4 a_5 K p^2 \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 c_0 p \tau_0}{2(1 - Bt)(a_4 p - \tau_1)^2} - \\
& \frac{a_4 p \sigma f \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 p \tau_0^2}{4(a_4 p - \tau_1)^2} - \frac{a_2^2 p^2}{2(a_4 p - \tau_1)} - \frac{a_2 a_5 K p^2}{a_4 p - \tau_1} - \frac{a_5^2 K^2 p^2}{2(a_4 p - \tau_1)} - \frac{c_0^2}{2(1 - 2Bt)(a_4 p - \tau_1)} + \\
& \frac{a_2 c_0 p}{(1 - Bt)(a_4 p - \tau_1)} + \frac{a_5 c_0 K p}{(1 - Bt)(a_4 p - \tau_1)} - \frac{a_2 p \sigma f}{a_4 p - \tau_1} - \frac{a_5 K p \sigma f}{a_4 p - \tau_1} + \frac{c_0 \sigma f}{(1 - Bt)(a_4 p - \tau_1)} - \\
& \frac{\sigma f^2}{2(a_4 p - \tau_1)} + \frac{a_2 p \tau_0}{a_4 p - \tau_1} + \frac{a_5 K p \tau_0}{a_4 p - \tau_1} - \frac{c_0 \tau_0}{(1 - Bt)(a_4 p - \tau_1)} + \frac{\sigma f \tau_0}{a_4 p - \tau_1} - \frac{\tau_0^2}{2(a_4 p - \tau_1)} - \\
& \frac{a_2^2 p^2 \tau_1}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_5 K p^2 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_5^2 K^2 p^2 \tau_1}{4(a_4 p - \tau_1)^2} - \frac{c_0^2 \tau_1}{4(1 - 2Bt)(a_4 p - \tau_1)^2} + \frac{a_2 c_0 p \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} + \\
& \frac{a_5 c_0 K p \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{a_2 p \sigma f \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_5 K p \sigma f \tau_1}{2(a_4 p - \tau_1)^2} + \frac{c_0 \sigma f \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{\sigma f^2 \tau_1}{4(a_4 p - \tau_1)^2} + \\
& \frac{a_2 p \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} + \frac{a_5 K p \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{c_0 \tau_0 \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} + \frac{\sigma f \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{\tau_0^2 \tau_1}{4(a_4 p - \tau_1)^2}
\end{aligned}$$

$$\begin{aligned}
x\tau\text{FB}[\underline{K}, \underline{B}] := & a_0 p + a_1 K p + a_3 K^2 p + \frac{a_2^2 a_4 p^3}{4(a_4 p - \tau_1)^2} + \frac{a_2 a_4 a_5 K p^3}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5^2 K^2 p^3}{4(a_4 p - \tau_1)^2} + \\
& \frac{a_4 c_0^2 p}{4(1 - 2Bt)(a_4 p - \tau_1)^2} - \frac{a_2 a_4 c_0 p^2}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{a_4 a_5 c_0 K p^2}{2(1 - Bt)(a_4 p - \tau_1)^2} + \\
& \frac{a_2 a_4 p^2 \sigma f}{2(a_4 p - \tau_1)^2} + \frac{a_4 a_5 K p^2 \sigma f}{2(a_4 p - \tau_1)^2} - \frac{a_4 c_0 p \sigma f}{2(1 - Bt)(a_4 p - \tau_1)^2} + \frac{a_4 p \sigma f^2}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_4 p^2 \tau_0}{2(a_4 p - \tau_1)^2} - \\
& \frac{a_4 a_5 K p^2 \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 c_0 p \tau_0}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{a_4 p \sigma f \tau_0}{2(a_4 p - \tau_1)^2} + \frac{a_4 p \tau_0^2}{4(a_4 p - \tau_1)^2} - \frac{a_2^2 p^2}{2(a_4 p - \tau_1)} - \\
& \frac{a_2 a_5 K p^2}{a_4 p - \tau_1} - \frac{a_5^2 K^2 p^2}{2(a_4 p - \tau_1)} - \frac{c_0^2}{2(1 - 2Bt)(a_4 p - \tau_1)} + \frac{a_2 c_0 p}{(1 - Bt)(a_4 p - \tau_1)} + \\
& \frac{a_5 c_0 K p}{(1 - Bt)(a_4 p - \tau_1)} - \frac{a_2 p \sigma f}{a_4 p - \tau_1} - \frac{a_5 K p \sigma f}{a_4 p - \tau_1} + \frac{c_0 \sigma f}{(1 - Bt)(a_4 p - \tau_1)} - \frac{\sigma f^2}{2(a_4 p - \tau_1)} + \\
& \frac{a_2 p \tau_0}{a_4 p - \tau_1} + \frac{a_5 K p \tau_0}{a_4 p - \tau_1} - \frac{c_0 \tau_0}{(1 - Bt)(a_4 p - \tau_1)} + \frac{\sigma f \tau_0}{a_4 p - \tau_1} - \frac{\tau_0^2}{2(a_4 p - \tau_1)} - \\
& \frac{a_2^2 p^2 \tau_1}{4(a_4 p - \tau_1)^2} - \frac{a_2 a_5 K p^2 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_5^2 K^2 p^2 \tau_1}{4(a_4 p - \tau_1)^2} - \frac{c_0^2 \tau_1}{4(1 - 2Bt)(a_4 p - \tau_1)^2} + \\
& \frac{a_2 c_0 p \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} + \frac{a_5 c_0 K p \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{a_2 p \sigma f \tau_1}{2(a_4 p - \tau_1)^2} - \frac{a_5 K p \sigma f \tau_1}{2(a_4 p - \tau_1)^2} + \\
& \frac{c_0 \sigma f \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} - \frac{\sigma f^2 \tau_1}{4(a_4 p - \tau_1)^2} + \frac{a_2 p \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} + \frac{a_5 K p \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} - \\
& \frac{c_0 \tau_0 \tau_1}{2(1 - Bt)(a_4 p - \tau_1)^2} + \frac{\sigma f \tau_0 \tau_1}{2(a_4 p - \tau_1)^2} - \frac{\tau_0^2 \tau_1}{4(a_4 p - \tau_1)^2} - R[K] + \sigma_k K - \iota \left(\frac{B^2}{2} + B \right)
\end{aligned}$$

Expected Costs of Feedstock Production, Expected Production, Expected Reduction in Costs

$$\begin{aligned}
\text{ECFB}[\underline{K}, \underline{B}] & := \text{Expand}[\text{Cunc}[\text{QFB}[\underline{K}, \underline{x}], \underline{x}]] /. \{e^{2tx} \rightarrow (1 - 2Bt)^{-1}, e^{tx} \rightarrow (1 - Bt)^{-1}\} \\
\text{EQFB}[\underline{K}, \underline{B}] & := \text{QFB}[\underline{K}, \underline{x}] /. \{e^{tx} \rightarrow (1 - Bt)^{-1}\} \\
\text{ECunc}[\underline{q}, \underline{B}] & := \text{Cunc}[\underline{q}, \underline{x}] /. \{e^{tx} \rightarrow (1 - Bt)^{-1}\} \\
\text{ER}[\underline{B}] & := 1/(1 - Bt)
\end{aligned}$$

Second-Order Condition for Capital

$$\text{Solve}[\text{D}[\text{D}[\text{x}\tau\text{FB}[\underline{K}, \underline{B}], \underline{K}], \underline{K}] = 0, \underline{K}]$$

$$\left\{ \left\{ \underline{K} \rightarrow \frac{4 a_3 a_4 p^2 - a_5^2 p^2 - 4 a_4 p r_1 - 4 a_3 p \tau_1 + 4 r_1 \tau_1}{12 r_2 (a_4 p - \tau_1)} \right\} \right\}$$

Parameters

(* Parameters of COST and PRODUCTION Functions *)

a0 = 0;
a1 = 4.655357384276914⁶;
a2 = 815.7420662122216;
a3 = -35757.06436566231;
a4 = -0.0015212658313828406;
a5 = 14.686413993115751;
c0 = 65.04;

(* Parameters of TRANSPORT and CAPITAL Costs *)

r0 = 1848191.14 * 0.101;
r1 = -4026.1237 * 0.101;
r2 = 7.969360393 * 0.101;
τ0 = 7.1664;
τ1 = 2.19426⁻⁰⁷;

(* Parameters for REPI, Feedstock, and Capital subsidies *)

REPI = 0;
σf = 0;
σk = 0;

Baseline Viability

Solution determined through search of price that achieves profit at or near zero with an operation and maintenance charge = 0.008 c/kWh.

t = 2000; t = -0.003; p = 0.0601823403 - 0.008;

NMaximize[{xτFB[K, B], B > 1 && K > $\frac{4 a_3 a_4 p^2 - a_5^2 p^2 - 4 a_4 p r_1 - 4 a_3 p \tau_1 + 4 r_1 \tau_1}{12 r_2 (a_4 p - \tau_1)}$ }, {K, B}]

{-0.240823, {B → 80.7519, K → 281.873}}

■ Expected Cost Reduction

(1 - ER[80.75192524275329]) c0

12.6836

- Expected Feedstock Production

EQFB[281.87311145864936, 80.75192524275329]

1.25036×10^6

Baseline at Contracting Break-Even Price

$t = 2000$; $t = -0.003$; $p = 0.063640637 - 0.008$;

NMaximize[{xτFB[K, B], B > 1 && K > $\frac{4 a^3 a^4 p^2 - a^5 p^2 - 4 a^4 p r_1 - 4 a^3 p \tau_1 + 4 r_1 \tau_1}{12 r_2 (a^4 p - \tau_1)}$ }, {K, B}]

{8.74686 × 10⁶, {B → 92.6117, K → 332.353}}

- Expected Cost Reduction

ER[92.61169722574058]

0.782574

$(1 - 0.783) c_0$

14.1137

- Expected Price Paid for Feedstock

$0.783 c_0$

50.9263

- Expected Feedstock Production

EQFB[332.3530455404039, 92.61169722574058]

1.52544×10^6

Limited-Liability Contracts Case

Define major elements of the model.

Production Function for Generation

$$f[\mathbf{K}_-, \mathbf{q}_-] := a_0 + a_1 * \mathbf{K} + a_2 * \mathbf{q} + a_3 * \mathbf{K}^2 + a_4 * \mathbf{q}^2 + a_5 * \mathbf{K} * \mathbf{q};$$

Transport and Capital Cost Functions

$$\begin{aligned} T[\mathbf{q}_-] &:= \tau_0 * \mathbf{q} + \tau_1 \mathbf{q}^2; \\ R[\mathbf{K}_-] &:= r_0 \mathbf{K} + r_1 \mathbf{K}^2 + r_2 \mathbf{K}^3; \end{aligned}$$

Cost Function for Feedstock

(* x is random variable representing state of the world *)

$$\begin{aligned} \text{Cunc}[\mathbf{q}_-, \mathbf{x}_-] &:= \text{Exp}[\mathbf{x} * \mathbf{t}] * c_0 \mathbf{q}; \\ \text{C2}[\mathbf{q}_-, \mathbf{x}_-] &:= \text{D}[\text{Cunc}[\theta, \xi], \xi] /. \{\theta \rightarrow \mathbf{q}, \xi \rightarrow \mathbf{x}\} \end{aligned}$$

Probability Distribution

```
Off[General::spell1, General::spell]
<< Statistics`ContinuousDistributions`
A = 1;
dist[B_] := GammaDistribution[A, B];
g[x_, B_] := PDF[dist[B], x]
ge[x_, B_] := D[g[\xi, \beta], \beta] /. {\xi -> x, \beta -> B}
G[x_, B_] := CDF[dist[B], x];
Ge[x_, B_] := D[G[\xi, \beta], \beta] /. {\xi -> x, \beta -> B}
Gee[x_, B_] := D[Ge[\xi, \beta], \beta] /. {\xi -> x, \beta -> B}
```

Value Function: Ex Post Profit

$$\begin{aligned} \Pi[\mathbf{K}_-, \mathbf{B}_-, \mathbf{q}_-, \mathbf{x}_-] &:= \\ &\text{Simplify}[\text{p f}[\mathbf{K}, \mathbf{q}] + \sigma \mathbf{f} \mathbf{q} - \text{Cunc}[\mathbf{q}, \mathbf{x}] - T[\mathbf{q}] + \text{C2}[\mathbf{q}, \mathbf{x}] * (1 - G[\mathbf{x}, \mathbf{B}]) / g[\mathbf{x}, \mathbf{B}]] \\ \text{V}[\mathbf{K}_-, \mathbf{B}_-, \mathbf{q}_-, \lambda_-, \mathbf{x}_-] &:= \Pi[\mathbf{K}, \mathbf{B}, \mathbf{q}, \mathbf{x}] + \lambda * \text{C2}[\mathbf{q}, \mathbf{x}] * \text{Ge}[\mathbf{x}, \mathbf{B}] / g[\mathbf{x}, \mathbf{B}] \end{aligned}$$

Optimal Production of Feedstock given Investment in Capital and State of Nature

$$\begin{aligned} \text{qhat} &= \text{Solve}[\text{D}[\text{V}[\mathbf{K}, \mathbf{B}, \theta, \mathbf{l}, \xi], \theta] == 0, \theta][[1]]; \\ \text{Q}[\mathbf{K}_-, \mathbf{B}_-, \lambda_-, \mathbf{x}_-] &:= (\theta /. \text{qhat}) /. \{\mathbf{K} \rightarrow \mathbf{K}, \mathbf{B} \rightarrow \mathbf{B}, \mathbf{l} \rightarrow \lambda, \xi \rightarrow \mathbf{x}\} \end{aligned}$$

Expected Production of Feedstock given Investment in Capital and Learning

Expand[Q[K, B, λ, x]] /. { $e^{2tx} x^2 \rightarrow B^2 A (A + 1) (1 - 2Bt)^{-(A+2)}$, $e^{2tx} x \rightarrow BA (1 - 2Bt)^{-(A+1)}$,
 $e^{tx} x \rightarrow BA (1 - Bt)^{-(A+1)}$, $e^{2tx} \rightarrow (1 - 2Bt)^{-A}$, $e^{tx} \rightarrow (1 - Bt)^{-A}$ } // **Simplify**

$$\frac{c0(1 - 2Bt + B^2 t^2 + t\lambda) - (-1 + Bt)^2 (a2p + a5Kp + \sigma f - \tau0)}{2(-1 + Bt)^2 (a4p - \tau1)}$$

$$EQ[K_, B_, \lambda_] := \frac{c0(1 - 2Bt + B^2 t^2 + t\lambda) - (-1 + Bt)^2 (a2p + a5Kp + \sigma f - \tau0)}{2(-1 + Bt)^2 (a4p - \tau1)}$$

Expected Profit Function

V[K, B, Q[K, B, λ, x], λ, x] // **Expand**

$$\begin{aligned} & -\frac{c0^2 e^{2tx}}{4(a4p - \tau1)} + \frac{a2c0 e^{tx} p}{2(a4p - \tau1)} + \frac{a5c0 e^{tx} Kp}{2(a4p - \tau1)} - \frac{a2^2 p^2}{4(a4p - \tau1)} + \frac{a0a4 p^2}{a4p - \tau1} + \frac{a1a4 Kp^2}{a4p - \tau1} - \\ & \frac{a2a5 Kp^2}{2(a4p - \tau1)} + \frac{a3a4 K^2 p^2}{a4p - \tau1} - \frac{a5^2 K^2 p^2}{4(a4p - \tau1)} + \frac{Bc0^2 e^{2tx} t}{2(a4p - \tau1)} - \frac{a2Bc0 e^{tx} pt}{2(a4p - \tau1)} - \frac{a5Bc0 e^{tx} Kpt}{2(a4p - \tau1)} - \\ & \frac{B^2 c0^2 e^{2tx} t^2}{4(a4p - \tau1)} - \frac{c0^2 e^{2tx} tx\lambda}{2B(a4p - \tau1)} + \frac{a2c0 e^{tx} ptx\lambda}{2B(a4p - \tau1)} + \frac{a5c0 e^{tx} Kptx\lambda}{2B(a4p - \tau1)} + \frac{c0^2 e^{2tx} t^2 x\lambda}{2(a4p - \tau1)} - \\ & \frac{c0^2 e^{2tx} t^2 x^2 \lambda^2}{4B^2(a4p - \tau1)} + \frac{c0 e^{tx} \sigma f}{2(a4p - \tau1)} - \frac{a2p \sigma f}{2(a4p - \tau1)} - \frac{a5Kp \sigma f}{2(a4p - \tau1)} - \frac{Bc0 e^{tx} t \sigma f}{2(a4p - \tau1)} + \\ & \frac{c0 e^{tx} tx\lambda \sigma f}{2B(a4p - \tau1)} - \frac{\sigma f^2}{4(a4p - \tau1)} - \frac{c0 e^{tx} \tau0}{2(a4p - \tau1)} + \frac{a2p \tau0}{2(a4p - \tau1)} + \frac{a5Kp \tau0}{2(a4p - \tau1)} + \frac{Bc0 e^{tx} t \tau0}{2(a4p - \tau1)} - \\ & \frac{c0 e^{tx} tx\lambda \tau0}{2B(a4p - \tau1)} + \frac{\sigma f \tau0}{2(a4p - \tau1)} - \frac{\tau0^2}{4(a4p - \tau1)} - \frac{a0p \tau1}{a4p - \tau1} - \frac{a1Kp \tau1}{a4p - \tau1} - \frac{a3K^2 p \tau1}{a4p - \tau1} \end{aligned}$$

% /. { $e^{2tx} x^2 \rightarrow B^2 A (A + 1) (1 - 2Bt)^{-(A+2)}$, $e^{2tx} x \rightarrow BA (1 - 2Bt)^{-(A+1)}$,
 $e^{tx} x \rightarrow BA (1 - Bt)^{-(A+1)}$, $e^{2tx} \rightarrow (1 - 2Bt)^{-A}$, $e^{tx} \rightarrow (1 - Bt)^{-A}$ }

$$\begin{aligned} & -\frac{a2^2 p^2}{4(a4p - \tau1)} + \frac{a0a4 p^2}{a4p - \tau1} + \frac{a1a4 Kp^2}{a4p - \tau1} - \frac{a2a5 Kp^2}{2(a4p - \tau1)} + \frac{a3a4 K^2 p^2}{a4p - \tau1} - \frac{a5^2 K^2 p^2}{4(a4p - \tau1)} - \\ & \frac{c0^2}{4(1 - 2Bt)(a4p - \tau1)} + \frac{Bc0^2 t}{2(1 - 2Bt)(a4p - \tau1)} - \frac{B^2 c0^2 t^2}{4(1 - 2Bt)(a4p - \tau1)} + \\ & \frac{a2c0 p}{2(1 - Bt)(a4p - \tau1)} + \frac{a5c0 Kp}{2(1 - Bt)(a4p - \tau1)} - \frac{a2Bc0 pt}{2(1 - Bt)(a4p - \tau1)} - \frac{a5Bc0 Kpt}{2(1 - Bt)(a4p - \tau1)} - \\ & \frac{c0^2 t \lambda}{2(1 - 2Bt)^2 (a4p - \tau1)} + \frac{Bc0^2 t^2 \lambda}{2(1 - 2Bt)^2 (a4p - \tau1)} + \frac{a2c0 p t \lambda}{2(1 - Bt)^2 (a4p - \tau1)} + \\ & \frac{a5c0 Kp t \lambda}{2(1 - Bt)^2 (a4p - \tau1)} - \frac{c0^2 t^2 \lambda^2}{2(1 - 2Bt)^3 (a4p - \tau1)} - \frac{a2p \sigma f}{2(a4p - \tau1)} - \frac{a5Kp \sigma f}{2(a4p - \tau1)} + \\ & \frac{c0 \sigma f}{2(1 - Bt)(a4p - \tau1)} - \frac{Bc0 t \sigma f}{2(1 - Bt)(a4p - \tau1)} + \frac{c0 t \lambda \sigma f}{2(1 - Bt)^2 (a4p - \tau1)} - \frac{\sigma f^2}{4(a4p - \tau1)} + \\ & \frac{a2p \tau0}{2(a4p - \tau1)} + \frac{a5Kp \tau0}{2(a4p - \tau1)} - \frac{c0 \tau0}{2(1 - Bt)(a4p - \tau1)} + \frac{Bc0 t \tau0}{2(1 - Bt)(a4p - \tau1)} - \\ & \frac{c0 t \lambda \tau0}{2(1 - Bt)^2 (a4p - \tau1)} + \frac{\sigma f \tau0}{2(a4p - \tau1)} - \frac{\tau0^2}{4(a4p - \tau1)} - \frac{a0p \tau1}{a4p - \tau1} - \frac{a1Kp \tau1}{a4p - \tau1} - \frac{a3K^2 p \tau1}{a4p - \tau1} \end{aligned}$$

$$\begin{aligned}
x\pi[\mathbf{K}, \mathbf{B}, \lambda] := & -\frac{a^2 p^2}{4(a^4 p - \tau 1)} + \frac{a_0 a^4 p^2}{a^4 p - \tau 1} + \frac{a_1 a^4 K p^2}{a^4 p - \tau 1} - \frac{a_2 a^5 K p^2}{2(a^4 p - \tau 1)} + \\
& \frac{a_3 a^4 K^2 p^2}{a^4 p - \tau 1} - \frac{a_5^2 K^2 p^2}{4(a^4 p - \tau 1)} - \frac{c_0^2}{4(1 - 2B t)(a^4 p - \tau 1)} + \frac{B c_0^2 t}{2(1 - 2B t)(a^4 p - \tau 1)} - \\
& \frac{B^2 c_0^2 t^2}{4(1 - 2B t)(a^4 p - \tau 1)} + \frac{a_2 c_0 p}{2(1 - B t)(a^4 p - \tau 1)} + \frac{a_5 c_0 K p}{2(1 - B t)(a^4 p - \tau 1)} - \\
& \frac{a_2 B c_0 p t}{2(1 - B t)(a^4 p - \tau 1)} - \frac{a_5 B c_0 K p t}{2(1 - B t)(a^4 p - \tau 1)} - \frac{c_0^2 t \lambda}{2(1 - 2B t)^2(a^4 p - \tau 1)} + \\
& \frac{B c_0^2 t^2 \lambda}{2(1 - 2B t)^2(a^4 p - \tau 1)} + \frac{a_2 c_0 p t \lambda}{2(1 - B t)^2(a^4 p - \tau 1)} + \frac{a_5 c_0 K p t \lambda}{2(1 - B t)^2(a^4 p - \tau 1)} - \\
& \frac{c_0^2 t^2 \lambda^2}{2(1 - 2B t)^3(a^4 p - \tau 1)} - \frac{a_2 p \sigma f}{2(a^4 p - \tau 1)} - \frac{a_5 K p \sigma f}{2(a^4 p - \tau 1)} + \frac{c_0 \sigma f}{2(1 - B t)(a^4 p - \tau 1)} - \\
& \frac{B c_0 t \sigma f}{2(1 - B t)(a^4 p - \tau 1)} + \frac{c_0 t \lambda \sigma f}{2(1 - B t)^2(a^4 p - \tau 1)} - \frac{\sigma f^2}{4(a^4 p - \tau 1)} + \frac{a_2 p \tau_0}{2(a^4 p - \tau 1)} + \\
& \frac{a_5 K p \tau_0}{2(a^4 p - \tau 1)} - \frac{c_0 \tau_0}{2(1 - B t)(a^4 p - \tau 1)} + \frac{B c_0 t \tau_0}{2(1 - B t)(a^4 p - \tau 1)} - \frac{c_0 t \lambda \tau_0}{2(1 - B t)^2(a^4 p - \tau 1)} + \\
& \frac{\sigma f \tau_0}{2(a^4 p - \tau 1)} - \frac{\tau_0^2}{4(a^4 p - \tau 1)} - \frac{a_0 p \tau 1}{a^4 p - \tau 1} - \frac{a_1 K p \tau 1}{a^4 p - \tau 1} - \frac{a_3 K^2 p \tau 1}{a^4 p - \tau 1} - R[\mathbf{K}] + \sigma \mathbf{K}
\end{aligned}$$

Expected Costs of Feedstock Production, Expected Reduction in Costs

$$\begin{aligned}
\text{EC}[\mathbf{K}, \mathbf{B}, \lambda] := & \text{Expand}[\text{Cunc}[\mathbf{Q}[\mathbf{K}, \mathbf{B}, \lambda, \mathbf{x}], \mathbf{x}]] /. \\
& \{e^{2tx} x^2 \rightarrow B^2 A (A + 1) (1 - 2B t)^{-(A+2)}, e^{2tx} x \rightarrow B A (1 - 2B t)^{-(A+1)}, \\
& e^{tx} x \rightarrow B A (1 - B t)^{-(A+1)}, e^{2tx} \rightarrow (1 - 2B t)^{-A}, e^{tx} \rightarrow (1 - B t)^{-A}\} \\
\text{ER}[\mathbf{B}] := & 1/(1 - B t)
\end{aligned}$$

Processor Lagrangian

$$L1[\mathbf{K}, \mathbf{B}, \lambda] := x\pi[\mathbf{K}, \mathbf{B}, \lambda] - \lambda t (\mathbf{B} + 1)$$

Solve for Co-state Variable using First-Order Condition

$$\begin{aligned}
\lambda\text{hat} = & \text{Solve}[\text{D}[L1[\mathbf{K}, \mathbf{B}, \lambda], \lambda] == 0, \lambda][[1]]; \\
\Lambda[\mathbf{K}, \mathbf{B}] := & (1 /. \lambda\text{hat}) /. \{\mathbf{K} \rightarrow \mathbf{K}, \mathbf{B} \rightarrow \mathbf{B}\}
\end{aligned}$$

$\Lambda[\mathbf{K}, \mathbf{B}]$

$$\begin{aligned}
& -\frac{1}{c_0^2 t^2} \\
& \left((1 - 2B t)^3 \left((1 + B) t + \frac{c_0^2 t}{2(1 - 2B t)^2(a^4 p - \tau 1)} - \frac{B c_0^2 t^2}{2(1 - 2B t)^2(a^4 p - \tau 1)} - \frac{a_2 c_0 p t}{2(1 - B t)^2(a^4 p - \tau 1)} - \right. \right. \\
& \left. \left. \frac{a_5 c_0 K p t}{2(1 - B t)^2(a^4 p - \tau 1)} - \frac{c_0 t \sigma f}{2(1 - B t)^2(a^4 p - \tau 1)} + \frac{c_0 t \tau_0}{2(1 - B t)^2(a^4 p - \tau 1)} \right) (a^4 p - \tau 1) \right)
\end{aligned}$$

Learning Rent and Total and Average Payment to Grower

Integrate[-C2[Q[K, B, Λ[K, B], ξ], ξ], {ξ, 0, x}] // Simplify

$$\frac{1}{16 B t^2 (-1 + B t)^2 (a4 p - \tau 1)} \left(-c0^2 t (-1 + B t)^3 (1 + 2 B t) + c0 t (-1 - 2 B t + 4 B^2 t^2) (a2 p + a5 K p + \sigma f - \tau 0) + e^{t x} (c0^2 e^{t x} t (-1 + B t)^3 (1 - 2 t x + 2 B t (1 + 2 t x)) + c0 t (8 B t (-1 + B t)^2 + e^{t x} (-1 + 2 B t)^3 (-1 + 2 t x)) (a2 p + a5 K p + \sigma f - \tau 0) + 2 (1 + B) e^{t x} (-1 + B t)^2 (-1 + 2 B t)^3 (1 - 2 t x) \iota (a4 p - \tau 1)) - 2 (1 + B) (-1 + B t)^2 (-1 + 2 B t)^3 \iota (a4 p - \tau 1) \right)$$

$$\text{Bonus}[K_ , B_ , x_] := \frac{1}{16 B t^2 (-1 + B t)^2 (a4 p - \tau 1)} \left(-c0^2 t (-1 + B t)^3 (1 + 2 B t) + c0 t (-1 - 2 B t + 4 B^2 t^2) (a2 p + a5 K p + \sigma f - \tau 0) + e^{t x} (c0^2 e^{t x} t (-1 + B t)^3 (1 - 2 t x + 2 B t (1 + 2 t x)) + c0 t (8 B t (-1 + B t)^2 + e^{t x} (-1 + 2 B t)^3 (-1 + 2 t x)) (a2 p + a5 K p + \sigma f - \tau 0) + 2 (1 + B) e^{t x} (-1 + B t)^2 (-1 + 2 B t)^3 (1 - 2 t x) \iota (a4 p - \tau 1)) - 2 (1 + B) (-1 + B t)^2 (-1 + 2 B t)^3 \iota (a4 p - \tau 1) \right)$$

$$w[K_ , B_ , x_] := \text{Cunc}[Q[K, B, \Lambda[K, B], x], x] + \text{Bonus}[K, B, x]$$

$$aw[K_ , B_ , x_] := w[K, B, x] / Q[K, B, \Lambda[K, B], x]$$

Expected Electricity Generation: Using Moment-generating function

$$\text{Ef}[K_ , B_] := \text{Expand}[f[K, Q[K, B, \Lambda[K, B], x]] / \{ e^{2 t x} x^2 \rightarrow B^2 A (A + 1) (1 - 2 B t)^{-(A+2)}, e^{2 t x} x \rightarrow B A (1 - 2 B t)^{-(A+1)}, e^{t x} x \rightarrow B A (1 - B t)^{-(A+1)}, e^{2 t x} \rightarrow (1 - 2 B t)^{-A}, e^{t x} \rightarrow (1 - B t)^{-A} \}$$

Objective Function

$$L[K_ , B_] := L1[K, B, \Lambda[K, B]]$$

Parameters

(* Parameters of COST and PRODUCTION Functions *)

a0 = 0;
a1 = 4.655357384276914⁶;
a2 = 815.7420662122216⁶;
a3 = -35757.06436566231⁶;
a4 = -0.0015212658313828406⁶;
a5 = 14.686413993115751⁶;
c0 = 65.04;

(* Parameters of TRANSPORT and CAPITAL Costs *)

r0 = 1848191.14 * 0.101;
r1 = -4026.1237 * 0.101;
r2 = 7.969360393 * 0.101;
τ0 = 7.1664;
τ1 = 2.19426⁻⁰⁷;

(* Parameters for REPI, Feedstock, and Capital subsidies *)

REPI = 0;
σf = 0;
σK = 0;

Baseline Viability

Solution determined through search of price that achieves profit at or near zero with an operation and maintenance charge = 0.008 c/kWh.

t = 2000; t = -0.003; p = 0.063640637 - 0.008; NMaximize[{L[K, B], K ≥ 0 && B ≥ 50}, {K, B}]
{0.604764, {B → 62.0101, K → 211.581}}

■ Expected Cost Reduction

(1 - ER[62.01011523996824⁶]) c0
10.2016

■ Expected Feedstock Production

EQ[211.58108850997047⁶, 62.01011523996824⁶, Λ[211.58108850997047⁶, 62.01011523996824⁶]]
863434.

- Expected Price Paid for Feedstock

`aw[211.58108850997047, 62.01011523996824, 62.01011523996824]`

64.5305

Appendix C. Verifying Second-Order Conditions

Define Bordered Hessian

C2[Q[K, B, λ, x], x] * Ge[x, B] // Expand

$$\begin{aligned} & -\frac{c0^2 e^{-\frac{x}{B}+2tx} t x}{2 B^2 (a4 p - \tau 1)} + \frac{a2 c0 e^{-\frac{x}{B}+tx} p t x}{2 B^2 (a4 p - \tau 1)} + \frac{a5 c0 e^{-\frac{x}{B}+tx} K p t x}{2 B^2 (a4 p - \tau 1)} + \\ & \frac{c0^2 e^{-\frac{x}{B}+2tx} t^2 x}{2 B (a4 p - \tau 1)} - \frac{c0^2 e^{-\frac{x}{B}+2tx} t^2 x^2 \lambda}{2 B^3 (a4 p - \tau 1)} + \frac{c0 e^{-\frac{x}{B}+tx} t x \sigma f}{2 B^2 (a4 p - \tau 1)} - \frac{c0 e^{-\frac{x}{B}+tx} t x \tau 0}{2 B^2 (a4 p - \tau 1)} \end{aligned}$$

$$\% /. \left\{ e^{-\frac{x}{B}+2tx} x \rightarrow \frac{1}{\left(\frac{1}{B} - 2t\right)^2}, e^{-\frac{x}{B}+2tx} x^2 \rightarrow \frac{1}{\left(\frac{1}{B} - 2t\right)^3}, e^{-\frac{x}{B}+tx} x \rightarrow \frac{1}{\left(\frac{1}{B} - t\right)^2} \right\}$$

$$\begin{aligned} & -\frac{c0^2 t}{2 B^2 \left(\frac{1}{B} - 2t\right)^2 (a4 p - \tau 1)} + \frac{a2 c0 p t}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} + \\ & \frac{a5 c0 K p t}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} + \frac{c0^2 t^2}{2 B \left(\frac{1}{B} - 2t\right)^2 (a4 p - \tau 1)} - \\ & \frac{c0^2 t^2 \lambda}{2 B^3 \left(\frac{1}{B} - 2t\right)^3 (a4 p - \tau 1)} + \frac{c0 t \sigma f}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} - \frac{c0 t \tau 0}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} \end{aligned}$$

$$\begin{aligned} h[K_, B_, \lambda_] := & -\frac{c0^2 t}{2 B^2 \left(\frac{1}{B} - 2t\right)^2 (a4 p - \tau 1)} + \frac{a2 c0 p t}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} + \\ & \frac{a5 c0 K p t}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} + \frac{c0^2 t^2}{2 B \left(\frac{1}{B} - 2t\right)^2 (a4 p - \tau 1)} - \frac{c0^2 t^2 \lambda}{2 B^3 \left(\frac{1}{B} - 2t\right)^3 (a4 p - \tau 1)} + \\ & \frac{c0 t \sigma f}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} - \frac{c0 t \tau 0}{2 B^2 \left(\frac{1}{B} - t\right)^2 (a4 p - \tau 1)} - t (B + 1) \end{aligned}$$

$$h1[K_, B_, \lambda_] := D[h[K, B, λ], K] /. {K → K, B → B, λ → λ}$$

$$h2[K_, B_, \lambda_] := D[h[K, B, λ], B] /. {K → K, B → B, λ → λ}$$

$$L11[K_, B_, \lambda_] := D[D[L1[K, B, λ], K], K] /. {K → K, B → B, λ → λ}$$

$$L22[K_, B_, \lambda_] := D[D[L1[K, B, λ], B], B] /. {K → K, B → B, λ → λ}$$

$$L12[K_, B_, \lambda_] := D[D[L1[K, B, λ], B], K] /. {K → K, B → B, λ → λ}$$

$$H[K_, B_] := -h1[K, B, λ[K, B]]$$

$$\begin{aligned} & (h1[K, B, λ[K, B]] * L22[K, B, λ[K, B]] - h2[K, B, λ[K, B]] * L12[K, B, λ[K, B]]) + h2[K, B, \\ & λ[K, B]] (h1[K, B, λ[K, B]] * L12[K, B, λ[K, B]] - h2[K, B, λ[K, B]] * L11[K, B, λ[K, B]]) \end{aligned}$$

Parameters

(* Parameters of COST and PRODUCTION Functions *)

a0 = 0;

a1 = 4.655357384276914⁶;

a2 = 815.7420662122216⁶;

a3 = -35757.06436566231⁶;

a4 = -0.0015212658313828406⁶;

a5 = 14.686413993115751⁶;

(* W/ Storage = \$11/ton and 2 % storage losses*)

c0 = 65.04;

(* Parameters of TRANSPORT and CAPITAL Costs *)

r0 = 1848191.14 * 0.101;

r1 = -4026.1237 * 0.101;

r2 = 7.969360393 * 0.101;

A = 1;

$\tau_0 = 7.1664;$

$\tau_1 = 2.19426 \times 10^{-7};$

REPI = 0.0185 * 7.3601 * 0.0726;

■ Feedstock Subsidy needed to match REPI break-even price

$\sigma_f = 18.46; \sigma_K = 0; \iota = 2000; t = -0.003; p = 0.063640637 - 0.008 - \text{REPI};$

NMaximize[{L[K, B], K ≥ 150 && B ≥ 30}, {K, B}]

{5458.25, {B → 69.6791, K → 231.511}}

H[231.5112478824459⁶, 69.67914104686508⁶]

2.40719×10^9

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