# Contract Structure, Learning-by-Doing and the Viability of New Agricultural Industries

Conrad J. Choinière
University of Maryland

To be presented at the
American Agricultural Economics Association Annual Meeting 2002

Abstract: The paper examines contracts in new agricultural industries that exhibit learning-by-doing. A dynamic model analyzes a contract's effect on production decisions, as well as investments in processing capacity and learning. The results of the model are applied qualitatively to the biomass electricity industry.

Submitted by:
Conrad J. Choinière
Dept. of Agricultural and Resource Economics
University of Maryland
2200 Symons Hall
College Park, MD 20742
Tel: (301) 405-0104
Fax: (301) 314-9091
cchoiniere@arec.umd.edu

## Introduction

Biobased 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. Limitations in the contractual arrangements between growers and processors, however, may prohibit industries from realizing the full economic benefits accrued through learning. In particular, the lack of alternative markets for growers, the need for specific investments and uncertainty in the extent of cost reductions possible through learning-by-doing limit the efficiency of contractual arrangements between agents. 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 paper examines the nature and extent of this potential problem using a multiple period model of investment and production in a new industry involved with biobased products and energy in which agents make specific investments before production occurs 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 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 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 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 (Rosen, Fudenberg, Spence, Brueckner and Raymon.) These models have been extended to include strategic behavior to address the issue of learning with spillovers within an industry and the effect that may have on competitive markets. (Ghemawat and Spence, Fudenberg, Petrakis.) However, 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.

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 are also private information of the grower. As a result, the processor faces a contracting environment characterized by both moral hazard (in investment) and adverse selection (in production.) Uncertainty about the future costs of producing the new crop further constrains the contracting environment. In unfavorable scenarios, cost reductions may not be achieved and the grower will have an incentive to breach contract terms. The processor, in order to protect his capital investment, is thus limited in to a set of contracts that limit the liability of the grower. In general, a first-best solution is unachievable under these conditions. (Laffont and Tirole, Sappington.)

The paper constructs a two-period model to analyze a 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. In general, the analysis reveals that the principal (the processor with a large capital investment) is unable to appropriate any of the gains from learning-by-doing. This results from the hidden information problem. In order to elicit information from the agent about the amount of learning that has occurred the principal must make the agent the residual claimant on any of the learning-induced cost reductions due to his efforts. The payment of rents to growers with high levels of learning induces overall overproduction of the crop and over-investment in learning. Processors also over-invest, resulting in an industry that is too large and potentially unprofitable. Analysis of the model is followed by a discussion of the results and the implications for one new agricultural industry in particular, the biomass for electricity industry.

## New Agricultural Industry: Biomass for Electricity Generation

It is useful to place the analysis in the context of a specific industry: the use of closed-loop biomass for electricity generation. This industry 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 et al.). 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 et al., 1995).

There are several defining characteristics of the investment and production decisions for biomass electricity generation that will influence the optimal governance structure for a biomass electricity firm and sector. The lack of developed markets and the presence of relationship-specific investments suggest that vertical integration or a form of contracting will be preferred over the 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 and that the industry may need to rely on limited liability contracts in the early stages of formation.

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 pose as challenges to the formation of contracts that are capable of inducing efficient investments in technology, production capacity and learning. Relationship-specific assets are those that have little or no value outside of an economic relationship. The existence of specific assets lock agents into a relationship, thereby increasing the likelihood of opportunism on the part of an agent whereby one of the agents may hold-up a relationship in order to appropriate a larger share of the production surplus. Within biomass electricity generation, these assets may be characterized as site-specific assets, physical assets, and dedicated assets. The idiosyncratic nature of the assets is likely to have some influence on the organization of a bioenergy system as certain governance structures, i.e. allocations of asset ownership or contractual arrangements, will more effectively mitigate the potential for hold-up than others.

Investments are *site specific* when agents must locate near each other for the purposes of minimizing inventory or transportation costs. 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 and limits 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 generator and growers are engaged in a so-called cheek-by-jowl arrangement and the generating facility must be located in close proximity to the growers of energy crops. As in many electricity-generating technologies, production exhibits a certain degree of increasing returns to scale. In the case of biomass, however, increasing the scale of a plant requires increasing the transportation distance of biomass. A trade-off exists between economies of scale in production and diseconomies of scale in transportation.

In addition to site specificity, the generators are also susceptible to hold-up due to 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.

The industry also has *dedicated assets.* Indeed mostly all of the investments necessary for the industry to take shape may be characterized as dedicated. 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 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.

Temporal considerations are also important characteristics in the industry. As discussed above, the agreement to generate electricity via biomass must be made years before actual production commences in order to assure adequate supply of feedstock. Yet the relationship may be needed for a much longer period of time. 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. Long-term contracting is uncommon in United States agriculture, and in those sectors where it does exist long-term is defined in terms of four to seven years. On the part of the grower, energy crop production exists in cycles of seven years (switchgrasses) to fifteen years (poplars and willows.) At the end of each of these cycles the growers must replant the crops and again allow for a period for crop maturity.

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. Learning curve theory generally states that costs of production decline over time as experience with a technology or technique accumulates. 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 2020[1]. 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).

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 Initiative[2]. 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 and bioenergy in the United States by 2010, with the goal of expanding economic and trade opportunities for agricultural producers.

---

[1] All monetary values expressed in 2001 U.S. dollars.

[2] 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.

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.

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. The following theoretical model illustrates the difficulties inherent in contracting for an industry with the characteristics of biomass for electricity generation.

## The Model

A processor (the principal) wishes to enter a contractual relationship with a grower or a cooperative acting on behalf of a group of growers (the agent) for the production of 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. The timeline of the model is as follows. The processor offers a contract to the grower in the first period. The contract consists of a menu of production and payment options from which the grower will choose at a later date. Both parties make investments in the second period. The processor invests in physical capital, such as a processing facility, that requires feedstock from the grower. The grower undertakes investments in this period as well, however her decisions are unobservable and unverifiable. These investments have a direct impact on the grower's learning curve; however the ultimate impact they have on future costs is unknown. 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. Learning investments, therefore, only increase the probability that costs will be reduced at a future date. The grower observes the resulting costs and chooses a production level and corresponding payment from the contract menu in the third period.

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 place the processor in risk of opportunism on the part of the grower. A contract must be written that satisfies the grower in all states of nature and that leaves no incentive for contract breach. Therefore, the processor offers a "renegotiation-proof" contract to the grower, 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.

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, $\theta$. The investment made by the grower, $e$, may be viewed as the quality of prior experience growers have 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, $\Omega(q,\theta)$, 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: $\Omega_1(q,\theta)>0$, $\Omega_{11}(q,\theta)>0$, $\Omega_2(q,\theta)<0$, $\Omega_{22}(q,\theta)>0$. Marginal cost of production also decreases in favorable states of nature, $\Omega_{12}(Q,\theta)<0$. The state of nature may take any value in the support, $\theta \in [\underline{\theta},\overline{\theta}]$, where $\underline{\theta}$ is the worst state of nature. The cumulative distribution, $G(\theta|e)$, and probability density, $g(\theta|e)$, of $\theta$ are conditional on investment where

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

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

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

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, $f_1(\cdot)>0$, $f_{11}(\cdot)<0$, $f_2(\cdot)>0$, $f_{22}(\cdot)<0$, and the inputs are complementary, $f_{12}(\cdot)>0$. The cost of physical capital is represented as a rate of return, $r$, on the monetary value of the investment. The processor faces an output price, $p$, for the final good.

As a benchmark for the analysis, consider the first-best levels of production and investment. Ex post, i.e. after the resolution of uncertainty over the state of nature, a benevolent social planner chooses production that maximizes total surplus.

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

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

$$\frac{\partial U^{FB}}{\partial q}=pf_2(K,q)-\Omega_1(q,\theta)=0 \quad \forall\,\theta \tag{1}$$

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,

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

The first order conditions for the ex ante maximization, after application of the envelope theorem and integration by parts, are

$$\begin{aligned}\frac{\partial U^{FB}}{\partial K}&=\int_{\underline{\theta}}^{\overline{\theta}}\left[pf_1(K,q(K,\theta))+(pf_2(K,q(K,\theta))-\Omega_1(q(K,\theta),\theta))q_\theta\right]dG(\theta|e)-r\\&=\int_{\underline{\theta}}^{\overline{\theta}}pf_1(K,q(K,\theta))dG(\theta|e)-r=0\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{\partial U^{FB}}{\partial e}&=\int_{\underline{\theta}}^{\overline{\theta}}\left[pf(K,q(K,\theta))-\Omega(q(K,\theta),\theta)\right]dG_e(\theta|e)-1\\&=\int_{\underline{\theta}}^{\overline{\theta}}\Omega_2(q(\theta),\theta)G_e(\theta|e)d\theta-1=0\end{aligned} \tag{3}$$

Equations (1)-(3) will be used later in the analysis to compare with levels obtained in a contractual environment.

The contractual environment described above 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. Although the grower is risk neutral, the optimal level of investment may not be achievable due to the threat of contract breach and renegotiation. With zero conversion costs, the grower may at any time choose to leave the joint project and grow another commodity of fixed value. This threat 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. This reduces the overall power of the contract, reducing incentives to invest in learning. Ex post, the principal wishes to elicit optimal production levels given the level of learning that has occurred. However, 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. information rents. The following model is similar to one presented by Laffont and Tirole (?), however 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 of a variable portion, *w* that depends on the level of production and a fixed portion, *T*. The mechanism is such that for the payment, (*w*,*T*), and output level, *q*, for the "announced" state of nature, $\hat{\theta}$, an agent of type $\theta$ will find that her best response is to announce the true state of nature. The utility (ex post) of an agent (grower) of type $\theta$ that has announced, through her choice of contract option, that she is type $\hat{\theta}$ is

$$U^G(\hat{\theta},\theta) = w(\hat{\theta}) + T - \Omega(q(\hat{\theta}),\theta).$$

Therefore the following must hold,

$$\frac{\partial U^G(\hat{\theta},\theta)}{\partial \hat{\theta}} = w_\theta(\hat{\theta}) - \Omega_1(q(\hat{\theta}),\theta)q_\theta(\hat{\theta}) = 0 \qquad (4)$$

$$\left.\begin{array}{l} w(\theta)+T-\Omega(q(\theta),\theta)\geq w(\theta')+T-\Omega(q(\theta'),\theta) \\ w(\theta')+T-\Omega(q(\theta'),\theta')\geq w(\theta)+T-\Omega(q(\theta),\theta') \end{array}\right\}\forall\ \theta\neq\theta'$$

The other crop commodity that may be grown by the agent has no value to the principal but determines the grower's reservation utility, Π. The grower is assumed to be completely risk-neutral above this level of utility. This implies that the contract must satisfy (ex ante) the following condition,

$$U^G(\theta)=w(\theta)+T-\Omega(q(\theta),\theta)-e\geq\Pi\quad\forall\theta \tag{5}$$

By the revelation principle, the contract mechanism elicits truthful information from the agent. However, truthful revelation under limited liability comes at a cost to the principal. These "information" rents may be found by deriving an expression for the variable portion of the payment scheme. Differentiation of the grower's utility function over type and application of the envelope theorem yields,

$$\frac{\partial U^G(\theta,\theta)}{\partial\theta}=w_\theta(\theta)-\Omega_1(q(\theta),\theta)q_\theta(\theta)-\Omega_2(q(\theta),\theta)=-\Omega_2(q(\theta),\theta)$$

(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 (5) holds at equality in the worst state of nature.

$$U^G(\underline{\theta},\underline{\theta})=w(\underline{\theta})+T-\Omega(q(\underline{\theta}),\underline{\theta})-e=\Pi \tag{7}$$

An expression for $w(\theta)$ may be found by integrating equation (4) over types and substituting equations (6) and (7) to find,

$$w(\theta)=\Pi-T+e+\Omega(q(\theta),\theta)-\int_{\underline{\theta}}^{\theta}\Omega_2(q(z),z)dz \tag{8}$$

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 costs of investment and production plus an additional amount to induce higher levels of production in more favorable states of nature.

Optimal ex ante investment by the grower is represented by

$$e = \arg\max_{a} \int_{\underline{\theta}}^{\bar{\theta}} [w(\theta) + T - \Omega(q(\theta),\theta)] dG(\theta|a) - a \,,$$

which implies that equation (3), the first-order condition for grower investment in the social optimum, must hold in the contractual environment:

$$\int_{\underline{\theta}}^{\bar{\theta}} \Omega_2(q(\theta),\theta) G_e(\theta|e) d\theta - 1 = 0$$

When solving for optimal level of production, the processor must take into account this condition – the moral hazard in investment constraint. This is equivalent to allowing the processor to choose the optimal level of grower investment in his optimization problem, where the grower investment constraint appears in the processor's Lagrangian. The processor problem, therefore, is

$$U^P = \max_{K,e,q(\theta)} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} [pf(K,q(\theta)) - w(\theta) - T] dG(\theta|e) - rK \right\} \text{ s.t. } \int_{\underline{\theta}}^{\bar{\theta}} \Omega_2(q(\theta),\theta) G_e(\theta|e) d\theta - 1 = 0$$

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

$$\mathsf{L} = \max_{K,e,q(\theta)} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} \left[ pf(K,q(\theta)) - \Omega(q(\theta),\theta) + \int_{\underline{\theta}}^{\theta} \Omega_2(q(\theta),\theta) d\theta \right] dG(\theta|e) + \lambda \left[ \int_{\underline{\theta}}^{\bar{\theta}} \Omega_2(q(\theta),\theta) G_e d\theta - 1 \right] - \Pi - rK - e \right\} \cdot$$

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

$$\mathsf{L} = \max_{K,e,q(\theta)} \left\{ \int_{\underline{\theta}}^{\bar{\theta}} \left[ pf(K,q(\theta)) - \Omega(q(\theta),\theta) - \Omega_2(q(\theta),\theta)\frac{1-G(\theta|e)}{g(\theta|e)} \right] dG(\theta|e) + \lambda \left[ \int_{\underline{\theta}}^{\bar{\theta}} \Omega_2(q(\theta),\theta) G_e \, d\theta \right] - \lambda - \Pi - rK - e \right\} ,$$

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

$$\begin{aligned} \frac{\partial \mathsf{L}}{\partial q(\theta)} &= pf_2(K,q(\theta)) - \Omega_1(q(\theta),\theta) - \Omega_{21}(q(\theta),\theta)\frac{1-G(\theta|e)}{g(\theta|e)} + \lambda\Omega_{21}(q(\theta),\theta)\frac{G_e(\theta|e)}{g(\theta|e)} \\ &= 0 \;\; \forall\, \theta \end{aligned} \tag{9}$$

$$\begin{aligned} \frac{\partial \mathsf{L}}{\partial e} &= \int_{\underline{\theta}}^{\bar{\theta}} \left[ pf(K,q(\theta)) - \Omega(q(\theta),\theta) - \Omega_2(q(\theta),\theta)\frac{1-G(\theta|e)}{g(\theta|e)} \right] dG_e(\theta|e) \\ &\quad + \int_{\underline{\theta}}^{\bar{\theta}} \left[ -\Omega_2(q(\theta),\theta)\frac{\partial}{\partial e}\left( \frac{1-G(\theta|e)}{g(\theta|e)} \right) \right] dG(\theta|e) + \lambda \left[ \int_{\underline{\theta}}^{\bar{\theta}} \Omega_2(q(\theta),\theta) G_{ee} \, d\theta \right] - 1 = 0 \end{aligned} \tag{10}$$

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

$$\frac{\partial \mathsf{L}}{\partial \lambda} = \int_{\underline{\theta}}^{\bar{\theta}} \Omega_2(q(\theta),\theta) G_e(\theta|e) d\theta - 1 = 0 \tag{12}$$

Rearrangement of equation (9) facilitates comparison with the first-best level of production of the crop. The optimal contract will elicit production of $q$ for each $\theta$ such that the following holds:

$$\frac{\partial \mathsf{L}}{\partial q(\theta)} = \left( pf_2(K,q(\theta)) - \Omega_1(q(\theta),\theta) \right) + \Phi(\theta,e) = 0 \;\; \forall\, \theta$$

where,

$$\Phi(\theta,e) = -\Omega_{21}(q(\theta),\theta)\frac{1-G(\theta|e)}{g(\theta|e)} + \lambda\Omega_{21}(q(\theta),\theta)\frac{G_e(\theta|e)}{g(\theta|e)}$$

Assumptions on the cost function and the distribution of θ allow us to sign the expression, $\Phi(\theta,e)$, defined above. When the shadow value of the grower investment is positive, this expression is strictly positive at all values of $\theta$, with exception with the best state of nature, $\bar{\theta}$, where it is equal to zero. This implies that the optimal contract will elicit overproduction of $q$ in all realized states of nature except the most favorable.

Now consider the grower investment decision. A qualitative analysis of the level of investment as compared to the first-best may be done via inspection of equation (12) or the moral hazard of investment constraint. Differentiating the constraint by $q(\theta)$ and also by $e$ one finds that,

$$\frac{\partial}{\partial q(\theta)}\left(\int_{\underline{\theta}}^{\bar{\theta}}\Omega_2(q(\theta),\theta)G_e(\theta|e)d\theta-1\right)=\int_{\underline{\theta}}^{\bar{\theta}}\Omega_{21}(q(\theta),\theta)G_e(\theta|e)d\theta>0$$

$$\frac{\partial}{\partial e}\left(\int_{\underline{\theta}}^{\bar{\theta}}\Omega_2(q(\theta),\theta)G_e(\theta|e)d\theta-1\right)=\int_{\underline{\theta}}^{\bar{\theta}}\Omega_2(q(\theta),\theta)G_{ee}(\theta|e)d\theta<0$$

Together these two conditions imply that, in order for the constraint to hold with equality, an increase in production must be accompanied by a corresponding increase in investment in learning. As the optimal contract elicits overproduction (relative to the first best) in nearly all states of nature, then the contract also elicits corresponding level of investment in learning that is greater than that of the first-best.

The first-order condition for investment in capital on the part of the processor states that $K$ will be chosen such that the expected marginal value of capital equals the marginal cost of capital, $r$. Due to the expected overproduction of $q$ in the third period, the expected marginal value of capital is greater under contractual arrangements than that of the first-best. As a result, the principal will over-invest in processing capacity relative to the social optimum.

Intuitively, the problem of over investment in the industry occurs because the processor must overcompensate the grower for production of the intermediate good. The overcompensation results from the need to pay information rents that elicit truthful revelation from the growers about the state of nature. As the information rents of this particular problem increase in the level of learning, then growers have a greater incentive to invest in learning. The expected level of learning will be higher than the first best and therefore the expected level of production of the crop will also be higher than the first best. The processor anticipates the overproduction and invests in capital accordingly.

## Implications for Policy and Extensions to the Model

Let us reconsider the case of biomass for electricity generation. In general, current energy crop cost estimates have been too high for generators and utilities to consider investing in large scale biomass electricity technology. However, if investors were able to plan on lower crop costs in the future as a result of learning, they may find it worthwhile to make large investments in the new technologies. This is contingent on the investor's ability to reap some of the gains from learning in the form of reduced feedstock (fuel) costs for electricity generation.

The model suggests that when the learning investments are unobservable, and therefore noncontractible, and when the resulting cost reductions are unverifiable, the processor will be unable to realize any of the benefit from learning. In order to encourage investments that spur learning and elicit truthful revelation through efficient production, the processor (principal) must make the grower (agent) the residual claimant of the learning. As a result, the contract mechanism elicits over-investment in learning and over-production of feedstock. The expected surplus of feedstock induces the generator to invest in capital at a level greater than the first-best.

Although the optimal size of the industry in this contracting environment is larger than the first-best, it is not necessarily a profitable industry. If in fact, the processor is reluctant to invest when fuel (energy crop) costs without any learning effect are high relative to another fuel (coal) then it is unlikely that a generator would invest in the technology. The grower appropriates all of the rents from learning and so the generator sees no overall reduction in the cost of fuel. In this case, the return that the generator realizes on his investment in the industry is likely to be less than the return on an equivalent investment in a conventional technology. In essence, a participation constraint on the generator is not met and so the optimal investment for the generator in biomass is zero.

Despite the lack of profitability to the generator, it is possible that overall welfare to society would be improved by the existence of a biomass electricity industry. Growers may enjoy a profitable new agricultural enterprise and society may benefit from improved environmental conditions or reduced reliance on exhaustible resources. In this case, the government may find it worthwhile to subsidize the industry. The model suggests that the appropriate subsidy in this case would be granted to the processor in order to meet his participation constraint. The form of contracts that are likely to arise within the industry would ensure that growers are compensated adequately for learning investments and are properly insured for risk.

After the industry has been established, there may be potential for the generator to extract some of the rents from learning. Crop rotation schedules are shorter than the planning horizon of an electricity generator. As such, there may be several contracting periods over the lifespan of a generation facility. Generators 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 generator to extract learning rents from the less efficient growers. The generator may then no longer require a subsidy beyond the initial establishment phase. Although the generator could now enjoy lower costs of production at a future date without the need for a subsidy, the industry would still be inefficient as a result of the initial over-investment.

Alternatively, the government could pursue a policy of encouraging vertical integration within the industry. 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 biomass electricity, diseconomies of backward vertical integration (generator acquiring grower) may occur due to geographical reasons. As an example, consider a 100 mega-watt (MW) generating facility using gasification technology. Calculations using published estimates of switchgrass yields (Turhollow 1994) and technical efficiencies (Larson and Marrison 1997) suggest that 20,000 to 60,000 hectares (ha) of energy crops would likely be needed to supply a power plant with sufficient biomass feedstock. The management problem would require a generator to hire 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 generator will need to offer a wage contract identical to that under contracting, resulting in an inefficient industry. The problem cannot be solved by backward integration.

A more likely scenario may be forward vertical integration where a cooperative of growers invests in generation 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. When the expected profitability of the industry is greater than the grower's outside option, a first-best solution may be achievable. Problems may arise, however, when industry profits turn out to be lower than expected;

particularly if growers demand a government bailout from the biomass project. A possible extension to the model could include a risk averse grower cooperative.

Finally, the model could be extended to include learning on the generation side of technology. Research has shown that learning-by-doing has played an important role in reducing costs for renewable energy technologies (McDonald and Schrattenholzer.) This may be especially true for new biomass gasification technologies. If learning is one-sided, the results are likely to be similar to the ones presented here where one-sided learning occurs on the grower side. However, if the learning is two-sided then both agents will require information rents to elicit optimal investment decisions. A processor may not be able to offer a contract to the agent that allows him to realize the full gain on his investment in learning. As a result, there may be underinvestment in generation technology learning and overinvestment in grower learning. A situation of two-sided learning is most probable, and should prove challenging for investors, growers and policy-makers alike.

## References

Bransby, D. I., S. B. Mclaughlin, and D. J. Parrish. 1998. "A Review of Carbon and Nitrogen Balances in Switchgrass Grown for Energy." *Biomass and Bioenergy* 14(4):379-84.

Brown, Marilyn A., Mark D. Levine, Joseph P. Romm, Arthur H. Rosenfeld, and Jonathon G. Koomey. 1998. "Engineering-Economic Studies of Energy Technologies to Reduce Greenhouse Gas Emissions: Opportunities and Challenges." *Annual Review of Energy and the Environment* 23:287-385.

Brueckner, J. K. and N. Raymon. 1983. "Optimal Production With Learning by Doing." *Journal of Economic Dynamics & Control* 6(1-2):127-35.

Costello, Raymond and Janine Finnell. 1998. "Institutional Opportunities and Constraints to Biomass Development." *Biomass and Bioenergy* 15(3):201-4.

Energy Information Administration. 2001. *Natural Gas Monthly October 2001*. Report DOE/EIA-0130(2001/10). Available at http://www.eia.doe.gov/oil_gas/natural gas/data_publications/natural_gas_monthly/ngm.html [viewed December 2001.]

Fudenberg, D. and J. Tirole. 1983. "Learning-by-Doing and Market Performance." *Bell Journal of Economics* 14(2):522-30.

Ghemawat, P. and A. M. Spence. 1985. "Learning-Curve Spillovers and Market Performance." *Quarterly Journal of Economics* 100:839-52.

Graham, Robin L., Erik Lichtenberg, Vernon O. Roningen, Hossein Shapouri, and Marie E. Walsh. 1995. "The Economics of Biomass Production in the United States." *Second Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry*. Available at http://bioenergy.ornl.gov/papers/bioam95/graham3.html [viewed December 2001.]

Joskow, Paul L. 1985. "Vertical Integration and Long-Term Contracts: The Case of Coal-Burning Electric Generating Plants." *Journal of Law, Economics, and Organization* 1(1):33-80.

Joskow, P. L. 1990. "The Performance of Long-Term-Contracts - Further Evidence From Coal Markets." *Rand Journal of Economics* 21(2):251-74.

Laffont, Jean-Jacques and Jean Tirole. 1993. *A Theory of Incentives in Procurement and Regulation.* Cambridge, Massachusetts: The MIT Press.

Larson, Eric D. and Christopher I. Marrison. 1997. "Economic Scales for First-Generation Biomass-Gasifier/Gas Turbine Combined Cycles Fueled From Energy Plantations." *Journal of Engineering for Gas Turbines and Power - Transactions of the ASME* 119(2):285-90.

Marrison, Christopher I. and Eric D. Larson. 1995. "Cost Versus Scale for Advanced Plantation-Based Biomass Energy Systems in the U.S." *U.S. EPA Symposium on Greenhouse Gas Emissions and Mitigation Research* (Washington, D.C., Jun).

Mcdonald, A. and L. Schrattenholzer. 2001. "Learning Rates for Energy Technologies." *Energy Policy* 29(4):255-61.

McKenna, J. R. and D. D. Wolf. 1990. "No-Till Switchgrass Establishment As Affected by Lime, Phosphorus, and Carbofuran." *Journal of Production Agriculture* 3(4):475-78.

Petrakis, E., E. Rasmusen, and S. Roy. 1997. "The Learning Curve in a Competitive Industry." *Rand Journal of Economics* 28(2):248-68.

Roos, Anders, Robin L. Graham, Bo Hektor, and Christian Rakos. 1999. "Critical Factors to Bioenergy Implementation." *Biomass and Bioenergy* 17(2):113-26.

Rösch, Christine and Martin Kaltschmitt. 1999. "Energy From Biomass - Do Non-Technical Barriers Prevent an Increased Use?" *Biomass and Bioenergy* 16(5):347-56.

Rosen, S. 1972. "Learning by Experience As Joint Production." *Quarterly Journal of Economics* 83(3):366-82.

Sappington, David. 1983. "Limited liability contracts between principal and agent." *Journal of Economic Theory* 29 (1): 1-21.

Spence, A. M. 1981. "The Learning-Curve and Competition." *Bell Journal of Economics* 12(1):49-70.

Turhollow, Anthony. 1994. "The Economics of Energy Crop Production." *Biomass and Bioenergy* 6(3):229-41.

Williamson, Oliver E. 1971. "The Vertical Integration of Production: Market Failure Considerations." *American Economic Review* 61(2):112-23.

———. 1989. "Transaction Cost Economics." Pp. 135-82 in *Handbook of Industrial Organization. Volume 1. Handbooks in Economics*, edited by Richard Schmalensee and Robert D. Willig. New York: Elsevier Science Publishers.

Wolak, Frank A. 1996. "Why Do Firms Simultaneously Purchase in Spot and Contract Markets? Evidence From the United States Steam Coal Market." Pp. 109-68 in *Agricultural Markets: Mechanisms, Failures and Regulations*, vol. 234 of Contributions to Economic Analysis, edited by D. Martimort. New York: Elsevier, North-Holland.