Regulatory Design and Incentives for Renewable Energy

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January 12, 2010

Abstract

Increasing electric power production from renewable energy sources is now widely perceived as a sensible goal for energy policy. In this paper, we analyze the most widely used regulatory mechanisms aimed at achieving this goal, i.e. feed-in tariffs and mandatory portfolio standards. We show without regulatory intervention there may indeed be a need for strong incentives because of high levels of "resource adequacy" associated to conventional technologies. The optimal feed-in tariff exceeds the marginal cost of the conventional technology if and only if there are significant economies of scale. In this case, an increase in the marginal cost of conventional technology (e.g. incorporation of social costs of GHG emissions) implies a *reduction* in the optimal feed-in tariff. The RPS standard that induces optimal investment in renewables further exacerbates under-investment in the conventional technology. A lower capacity margin in the conventional technology induces higher spot prices (on average) which serve to recoup the losses associated with socially optimal investment levels in the renewable technology. Given that regulators are generally averse to low excess capacity margins, an RPS standard is bound to co-exist with other regulatory interventions aimed at maintaining acceptable capacity margins (e.g. capacity market).

1 Introduction

Over the last few decades, rapidly growing energy demand and the potential for climate change have underscored the need to reduce greenhouse gas (GHG) emissions. Increasing electric power production from renewable energy sources is now widely perceived as a sensible goal for energy policy. In order to achieve this goal, various regulatory mechanisms (e.g. feed-in tariffs (FIT), renewable portfolio standards (RPS)) have been implemented. Under a feed-in tariff, the wholesale electricity market is forced to buy all renewable electricity at at fixed, pre-established price. Under RPS regime, utilities must invest so that their renewable capacity is always greater than a given fraction of their conventional capacity. Interestingly, the need for regulatory incentives seems to be a generally accepted fact as most of the literature on regulatory designs for increased renewable energy compares the relative effectiveness of various alternatives. For example, in [1] and [3], it is argued that the policies adopted by Germany for promoting wind energy (e.g. feed-in tariff) have been more effective than those adopted by the UK and US (e.g. renewable portfolio standard). Under such "conventional wisdom" one would expect that a situation of chronic under-investment in renewable technologies is to be expected unless incentives are put in place. Nonetheless, the healthy investment activity in small scale run-of-the-river hydro plants (also a base-load technology) in several electricity markets (without incentives) provides a counterexample of sorts (see [5]). It seems only prudent to take a closer look at the extent to which incentives are needed.

In this paper, we develop a model to analyze the need for incentives as well as the effectiveness of feed-in tariffs and renewable portfolio standards. Our analysis shows that incentives for increased investment in renewable technology may only be needed if there are significant economies of scale. Interestingly, the need for incentives for renewable energy is closely coupled with the "resource adequacy" of conventional fossil-fuel based generation capacity. Specifically, our analysis shows that the lower the ratio of conventional fossil-fuel based capacity to demand, the weaker the incentive needed to induce socially optimal renewable capacity. However, the increasing popularity of capacity markets throughout the world indicates that "resource adequacy" is an important concern for regulators. Hence, there may indeed exist a need for stronger incentives *precisely because* of high levels of "resource adequacy" associated to conventional technologies.

We show that the optimal feed-in tariff exceeds the marginal cost of the conventional technology *if and only if* the fixed costs of the renewable technology are relatively large. In the absence of significant economies of scale, feed-in tariffs exceeding the marginal cost of conventional technologies are inefficient. Under significant economies of scale, an increase in the marginal cost of conventional technology (e.g. incorporation of social cost of GHG emissions) implies a *reduction* in the optimal feed-in tariff. We also characterize the RPS standard that induces optimal investment in renewables. We show that this standard further exacerbates under-investment in the conventional technology. A lower capacity margin in the conventional technology induces higher spot prices that serve to recoup the losses associated with socially optimal investment levels in the renewable technology. Given the regulatory aversion to low excess capacity margins, an RPS standard is bound to co-exist with other regulatory interventions aimed at maintaining acceptable capacity margins (e.g. capacity market).

2 Framework

We now present a highly stylized two-stage model of investment. In the first stage of our model, investors decide how much capacity to install from two available technologies. A *conventional* (fossil fuel-based) with (constant) marginal cost of production c_T and (constant) marginal cost of investment κ. A *renewable* technology, with a potential for maximum instantaneous output W (which we assume to be a random variable with probability distribution F in a compact support), zero production cost and (constant) marginal cost of investment $\kappa + \delta$, where $\delta > 0$. In the second stage of our model, firms compete in prices to dispatch their production capacity. Let v denote the (constant) marginal surplus associated with electricity consumption. Instantaneous demand for electricity is equal to D provided electricity prices are less than or equal to v. We assume $W < D$ with probability one (i.e.

the maximum potential is less than instataneous demand).

Let K_T and K_W denote the aggregate levels of installed capacity in the market. Let $\bar{K}_W = \min\{D, K_W\}$. Instanstaneous electricity production from the renewable technology is $Q_W = \min\{W, \bar{K}_W\}$. The probability distribution of Q_W, say $\bar{F}(x)$, has support $[0, \bar{K}_W]$ and $\bar{F}(x) = F(x)$ when $x < \bar{K}_W$ and $\Pr(Q_W = \bar{K}_W) = 1 - F(\bar{K}_W)$. Also,

$$E[Q_W] = \int_0^{\bar{K}_W} udF(u) + \bar{K}_W(1 - F(\bar{K}_W)) = \int_0^{\bar{K}_W} (1 - F(u))du$$

and $\phi = \frac{E[Q_W]}{K_W}$ is the expected capacity utilization factor. Let $Q_T = \min\{D - Q_W, K_T\}$ denote the total instantaneous output from conventional fossil-fuel based technology. Expected social surplus can be written as:

$$\begin{aligned} E[S(K_T, K_W)] &= \int_0^{\infty} E[v(Q_W + Q_T) - c_T Q_T])e^{-\rho t}dt - \kappa K_T - (\kappa + \delta)K_W \\ &= \frac{vE[Q_W] + (v - c_T)E[Q_T]}{\rho} - \kappa K_T - (\kappa + \delta)K_W \end{aligned}$$

where $\rho > 0$ is the discount rate.

2.1 Socially Optimal Investment

Assuming $K_T + K_W > D$ (i.e. installed capacity is *nominally* enough to supply demand) we solve for (K_T^*, K_W^*) that maximize the expected social surplus. Since $K_W \le W$ and $W < D$, the conventional technology is always dispatched. We can write the expected output of the conventional technology as follows:

$$E[Q_T] = K_T F(D - K_T) + \int_{D-K_T}^{K_W} (D - u)dF(u) + (D - K_W)(1 - F(K_W))$$

Thus, the first order condition with respect to K_T is:

$$\frac{v - c_T}{\rho} F(D - K_T^*) = \kappa \tag{1}$$

As the conventional technology is the marginal technology, condition (1) characterizes the optimal capacity margin as the probability of outage $F(D - K_T^*)$ is set at the ratio of investment cost κ to consumption surplus $\frac{v-c_T}{\rho}$.

The first order condition with respect to K_W is:

$$\frac{c_T}{\rho}(1 - F(K_W^*)) = \kappa + \delta \tag{2}$$

The term on the left is the marginal production cost savings due to increased renewable-based power production. Note that if $\frac{c_T}{\rho} < \kappa + \delta$ (per unit, generation with conventional technology is cheaper than installing one unit of renewable capacity) it must be the case that $K_W^* = 0$. The condition $D - K_T^* < K_W^*$ (i.e. capacity is nominally enough to supply demand) holds provided $F(D - K_T^*) < F(K_W^*)$ or equivalently,

$$\frac{\rho\kappa}{v - c_T} < 1 - \frac{\rho(\kappa + \delta)}{c_T}$$

If this condition does not hold, rationing demand *with probability one* is optimal.

2.2 Equilibrium Investment without Intervention

In this section, we analyze equilibrium investment levels without any form of regulatory intervention. Assuming price-taking behavior, the price for electricity equals the marginal cost of the conventional fossil-fuel based technology if $D - Q_W \leq K_T$. Otherwise, when $D - Q_W > K_T$ the equilibrium price for electricity is the (constant) marginal surplus v. To summarize, the equilibrium spot price for electricity $\widetilde{p}$ can be expressed as follows:

$$\widetilde{p}(K_T, K_W) = \begin{cases} 0 & D - Q_W = 0 \\ c_T & D - Q_W \in (0, K_T] \\ v & D - Q_W > K_T \end{cases}$$

Aggregate expected producer surplus for both conventional and renewable technologies can be written as:

$$E[\Pi_T(K_T)] = \frac{E[(\widetilde{p} - c_T)Q_T]}{\rho} - \kappa K_T \quad \text{and} \quad E[\Pi_W(K_W)] = \frac{E[\widetilde{p}Q_W]}{\rho} - (\kappa + \delta)K_W$$

In a perfectly competitive equilibrium $(\hat{K}_T, \hat{K}_W)$ it must hold that

$$E[\Pi_T(\hat{K}_T)] = E[\Pi_W(\hat{K}_W)] = 0$$

Since $E[\Pi_T(K_T)] = [\frac{v-c_T}{\rho}F(D-K_T) - \kappa]K_T$, we have that in a perfectly competitive equilibrium, the generation capacity $\hat{K}_T$ of the conventional fossil-fuel technology must satisfy

$$\frac{v-c_T}{\rho}F(D-\hat{K}_T) = \kappa \tag{3}$$

Hence, we conclude from (1) and (3) that $\hat{K}_T = K_T^*$, that is, in a competitive equilibrium there is *optimal* investment in the conventional fossil-fuel technology.

Since the renewable technology is the "baseload" technology, (expected) average revenue exceeds marginal revenue. To see this, recall that for $D < K_T + K_W$ we have:

$$E[\widetilde{p}Q_W] = \frac{v}{\rho}\int_0^{D-K_T} udF(u) + \frac{c_T}{\rho}[\int_{D-K_T}^{K_W} udF(u) + K_W(1-F(K_W))]$$

Hence,

$$\frac{\partial E[\widetilde{p}Q_W]}{\partial K_W} = \frac{c_T}{\rho}(1-F(K_W)) < \frac{E[\widetilde{p}Q_W]}{K_W} \tag{4}$$

Note that the the renewable technology's (expected) revenue is strictly monotone decreasing in K_W. The equilibrium level of investment in renewable technology $\hat{K}_W$ is obtained by equating (expected) average revenue and cost:

$$E[\widetilde{p}Q_W]|_{K_W=\hat{K}_W} = (\kappa+\delta)\hat{K}_W$$

We claim $\hat{K}_W \geq K_W^*$, i.e. in a competitive equilibrium there is *excessive* investment in the renewable technology. By contradiction, assume $\hat{K}_W < K_W^*$. By monotonicity it follows that:

$$E[\widetilde{p}Q_W]|_{K_W=K_W^*} < E[\widetilde{p}Q_W]|_{K_W=\hat{K}_W} = (\kappa+\delta)\hat{K}_W < (\kappa+\delta)K_W^*$$

Thus, by (2) we have

$$\left.\frac{E[\widetilde{p}Q_W]}{K_W}\right|_{K_W=K_W^*} < \kappa+\delta = \left.\frac{\partial E[\widetilde{p}Q_W]}{\partial K_W}\right|_{K_W=K_W^*}$$

which is a contradition to (4).

2.3 Economies of Scale

Assume now the two available technologies have fixed costs. Let γ_T and γ_W denote the fixed costs associated with conventional and renewable technologies, respectively. For the conventional technology the condition that expected average revenue equals average cost (3) is rewritten as:

$$\frac{v - c_T}{\rho} F(D - \hat{K}_T) = \kappa + \frac{\gamma_T}{\hat{K}_T} \tag{5a}$$

Comparing (3) and (5a) we can infer that $\hat{K}_T < K_T^*$, as $F(D - \hat{K}_T) > F(D - K_T^*)$. In words, there is *under*-investment in the conventional technology. The equilibrium condition for renewable capacity is:

$$E[\widetilde{p}Q_W]|_{K_W = \hat{K}_W} = (\kappa + \delta)\hat{K}_W + \gamma_W \tag{5b}$$

Let $\gamma_W^* = E[\widetilde{p}Q_W]|_{K_W = K_W^*} - (\kappa + \delta)K_W^*$. It follows that whenever $\gamma_W > \gamma_W^*$ it holds that $\hat{K}_W \leq K_W^*$ (i.e. there will be *under*-investment in renewable capacity in a competitive equilibrium). To show this, assume by contradiction that $\hat{K}_W > K_W^*$. It follows that

$$E[\widetilde{p}Q_W]|_{K_W = \hat{K}_W} = (\kappa + \delta)\hat{K}_W + \gamma_W > (\kappa + \delta)K_W^* + \gamma_W^* = E[\widetilde{p}Q_W]|_{K_W = K_W^*}$$

which contradicts the fact that for the renewable technology expected revenue is (strictly) monotone decreasing in K_W. Conversely, when economies of scale are not significant, i.e. when $\gamma_W < \gamma_W^*$, there is *over*-investment in a competitive equilibrium i.e. $\hat{K}_W \geq K_W^*$. Note that γ_W^* is monotone increasing in $D - K_T^*$. The more "inadequate" the conventional resource (the higher the value of $D - K_T^*$) the more *likely* it is that $\gamma_W < \gamma_W^*$. In other words, high electricity prices (associated with a high value of $D - K_T^*$) may be enough to incentivize investment in the renewable technology (even with a fixed cost γ_W). However, the increasing popularity of capacity markets throughout the world indicates "resource adequacy" is an important concern for regulators. Hence, there may indeed be a need for incentives *because* of high levels of "resource adequacy" for conventional technologies. A capacity market (for both conventional and renewable technologies) addressing this disjunctive is proposed in [2].

3 Incentives via a Feed-in Tariff (FIT)

We shall now analyze the incentives induced by a feed-in tariff $p < v$ for all renewable output. To ease notational burden, we shall assume in the reminder of the paper that $\rho = 1$. Under this regulatory regime, the expected producer surplus for the renewable technology is:

$$\begin{aligned} E[\Pi_W(K_W)] &= pE[Q_W] - (\kappa+\delta)K_W - \gamma_W \\ &= p[\int_0^{K_W} udF(u) + K_W(1-F(K_W)] - (\kappa+\delta)K_W - \gamma_W \end{aligned}$$

In a perfectly competitive equilibrium with a feed-in tariff p, say $(\hat{K}_T(p), \hat{K}_W(p))$ we have $E[\Pi_W(\hat{K}_W(p)] = 0$, from which it follows that:

$$1 - F(\hat{K}_W(p)) = \frac{1}{p}\left[(\kappa+\delta) - \frac{(p\int_0^{K_W} udF(u) - \gamma_W)}{\hat{K}_W(p)}\right] \tag{6}$$

The feed-in tariff p^* that achieves socially optimal investment level in renewable technology is implicitly defined by the condition $\hat{K}_W(p^*) = K_W^*$. Recall that $Q_W^* = \min\{W, K_W^*\}$. After some algebraic manipulation (see Appendix), it can be shown that:

$$p^* = \frac{1}{\phi^*}[\kappa + \delta + \frac{\gamma_W}{K_W^*}] \tag{7a}$$

where $\phi^* \in (0,1)$ is the expected capacity utilization factor of the optimal renewable capacity level. Equation (7a) has a straightforward interpretation: when the expected capacity utilization factor of the optimal capacity is close to one (i.e. $\phi^* \simeq 1$), the optimal feed-in tariff is approximately equal to average cost. For decreasing expected capacity utilization factors, the optimal feed-in tariff provides an increasing mark-up over average cost. Using (2), equation (7a) can be rewritten as (see appendix for details):

$$p^* = c_T(1-\theta^*) + \frac{\gamma_W}{E[Q_W^*]} \tag{7b}$$

where

$$1 - \theta^* = \frac{1 - F(K_W^*)}{\phi^*} \quad \in (0,1)$$

Let $\gamma_W^* = c_T\theta^* E[Q_W^*]$. We conclude from (7*b*) that $p^* < c_T$ whenever $\gamma_W < \gamma_W^*$, i.e. for relatively low fixed costs the optimal feed-in tariff is *less* than the marginal cost of the conventional technology.

As we show in the appendix, $\frac{\partial\phi}{\partial K_W} < 0$ and $\frac{\partial\theta}{\partial K_W} > 0$ (provided the hazard rate is bounded below by 1, i.e. $\frac{f}{1-F} \geq 1$ and $K_W \geq 1$). These help establish the comparative statics of the optimal feed-in tariff. For example, as the marginal cost of renewable investment decreases (i.e. as δ decreases) because of say "learning by doing" effects, the optimal feed-in tariff must also decrease. To see this, note from (2) that as δ decreases, the socially optimal level of renewable capacity increases. By monotonicity of θ and (7b) it follows that p^* must also decrease.

Consider now an increase in the marginal cost of the conventional technology c_T. From (2) the socially optimal level of renewable capacity increases, that is $\frac{\partial K_W^*}{\partial c_T} > 0$ and in the appendix we show that

$$\frac{\partial p^*}{\partial K_W^*} = \frac{(\kappa + \delta)}{E[Q_W^*]c_T}(c_T - p^*) \tag{8}$$

Hence, when $p^* > c_T$, an increase in the marginal cost of conventional technology implies a *reduction* in the optimal feed-in tariff. Recall that $p^* > c_T$ whenever the fixed costs of the renewable technology are relatively large, i.e. $\gamma_W > \gamma_W^*$. An increase in the marginal cost of the conventional technology (say by the incorporation of the social costs of emissions via taxes or a cap & trade mechanism) implies an increase in the optimal scale of renewable technology. An increase in optimal scale implies (because of economies of scale) a reduction in the associated feed-in tariff.

4 Incentives via RPS

Under a renewable portfolio standard (RPS), renewable capacity must always equal a given fraction, say $\alpha \in (0,1)$, of conventional capacity. That is $\alpha = \frac{K_W}{K_T}$. Under this form of intervention, aggregate producer surplus is:

$$\Pi(\alpha, K_T) = \Pi_T(K_T) + \Pi_W(\alpha K_T)$$

The results in section (2.3) imply that $E[\Pi(\hat{\alpha}, \hat{K}_T)] = 0$ for $\hat{\alpha} = \frac{\hat{K}_W}{\hat{K}_T}$ since

$$E[\Pi_T(\hat{K}_T)] = E[\Pi_W(\hat{K}_W)] = 0$$

Thus, if the regulator sets the RPS standard at $\hat{\alpha}$, the investment levels induced are equal to those characterized in section 2.3, i.e. $(\hat{K}_T, \hat{K}_W)$. Let us assume $\hat{K}_W < K_W^*$, i.e. there is under-investment in renewable capacity without regulatory intervention. Suppose the regulator sets the RPS standard to $\alpha \neq \hat{\alpha}$. In a competitive equilibrium, we have:

$$E[\Pi(\alpha, K_T(\alpha))] = E[\Pi_T(K_T(\alpha))] + E[\Pi_W(\alpha K_T(\alpha))] = 0 \tag{9}$$

The optimal RPS standard is defined implicitly by $\alpha^* K_T(\alpha^*) = K_W^*$. By the under-investment assumption, we have that $E[\Pi_W(K_W^*)] < 0$, thus from (9) we conclude

$$E[\Pi_T(K_T(\alpha^*))] > 0$$

which in turn implies by monotonicity of expected revenues that $K_T(\alpha^*) < \hat{K}_T$. The RPS standard that induces optimal investment in renewables further exacerbates under-investment in the conventional technology. A lower capacity margin in the conventional technology induces higher spot prices that serve to recoup the losses associated with the socially optimal investment level in the renewable technology. Given the regulatory aversion to low excess capacity margins, an RPS standard is bound to co-exist with other regulatory interventions aimed at maintaining acceptable capacity margins (e.g. capacity market).

5 FIT vs RPS

In the context of a highly stylized model of investment we have characterized the feed-in tariff and the renewable portfolio standard needed to induce the socially optimal level of investments in renewable technology. In this section we discuss qualitative insights on the pros- and cons- of each regulatory instrument afforded by our model.

The determination of the optimal feed-in tariff requires the estimation of the cost structure of renewable technology as well as the expected capacity factor utilization. Recall that optimal renewable capacity is increasing in the ratio of renewable investment cost to marginal cost of conventional technology $\frac{\kappa+\delta}{c_T}$. There are widely divergent estimates of the social costs associated with GHG emissions (see Stern report [6] and differing views in [7]). A high value of c_T would justify a relatively high feed-in tariff (by way of high investment in renewable capacity and low expected capacity utilization). A low value of c_T would imply the opposite (more moderate investment in renewables with higher expected capacity utilization factor). Uncertainty is bound to create error. By the political nature of regulation, this error is bound to be one sided: regulatory capture implies that too high feed-in tariffs are more likely.

In principle, uncertainty in c_T is also bound to affect the determination of the optimal RPS standard. However, the optimal RPS is lower bounded by $\hat{\alpha}$ since

$$\hat{\alpha} = \frac{\hat{K}_W}{\hat{K}_T} < \frac{K_W^*}{\hat{K}_T} < \frac{K_W^*}{K_T(\alpha^*)} = \alpha^*$$

Note that $\hat{\alpha}$ could be approximated by the ratio of renewable to conventional capacity without regulatory intervention. In contrast to the optimal feed-in tariff (the value of which can vary significantly as a function of c_T while the optimal RPS is constrained in $(\hat{\alpha}, 1)$. These observations suggest that there maybe less room for error in an RPS scheme. Ultimately, the RPS scheme suffers from a major drawback as incentives for investment in conventional technologies are greatly reduced. An RPS scheme is likely to be implemented in conjunction with other forms of intervention aimed at guaranteeing adequate investment levels in conventional technology (e.g. capacity market). A feed-in tariff does not alter incentives for investment in conventional technology. It is therefore a "cleaner" form of regulatory intervention.

6 Conclusions

Feed-in tariffs and renewable portfolio standards are regulatory mechanisms used to foster investment in renewable power generation technologies. Though their use is widespread there are still important open questions regarding their efficacy. In this paper, we have developed a stylized model to analyze the need for incentives as well as the effectiveness of feed-in tariffs and renewable portfolio standards. Our analysis shows that incentives for increased investment in renewable technology may only be needed if there are significant economies of scale. Interestingly, the need for incentives for renewable energy is closely coupled with the "resource adequacy" of conventional fossil-fuel based generation capacity. Specifically, our analysis shows that the lower the ratio of conventional fossil-fuel based capacity to demand, the weaker the incentive needed to induce socially optimal renewable capacity. However, the increasing popularity of capacity markets throughout the world indicates that "resource adequacy" is an important concern for regulators. Hence, there may indeed exist a need for stronger incentives because of high levels of "resource adequacy" associated to conventional technologies.

We have shown that the optimal feed-in tariff exceeds the marginal cost of the conventional technology if and only if the fixed costs of the renewable technology are relatively large. In this case, an increase in the marginal cost of the conventional technology (say by the incorporation of the social costs of emissions via taxes or a cap & trade mechanism) implies an increase in the optimal scale of renewable technology. An increase in optimal scale implies (because of economies of scale) a reduction in the associated feed-in tariff.

The RPS standard that induces optimal investment in renewables further exacerbates under-investment in the conventional technology. A lower capacity margin in the conventional technology induces higher spot prices that serve to recoup the losses associated with socially optimal investment levels in the renewable technology. Given the regulatory aversion to low excess capacity margins, an RPS standard is bound to co-exist with other regulatory interventions aimed at maintaining acceptable capacity margins (e.g. capacity market).

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A Appendix

Derivation of (4)

$$E[\widetilde{p}Q_W] = \frac{v}{\rho}\int_0^{D-K_T} udF(u) + \frac{c_T}{\rho}[\int_{D-K_T}^{K_W} udF(u) + K_W(1-F(K_W))]$$

$$\frac{\partial}{\partial K_W}[\frac{E[\widetilde{p}Q_W]}{K_W}] = -\frac{1}{K_W^2}\frac{v}{\rho}\int_0^{D-K_T} udF(u) - \frac{c_T}{\rho}f(K_W) + \frac{c_T}{\rho}\frac{K_W^2 f(K_W)-}{K_W^2}$$

A.1 Derivation of $7a$ and $7b$

We require $\hat{K}_W(p^*) = K_W^*$. Substituting (2) in (6) we obtain:

$$\begin{aligned} 1 - F(\hat{K}_W(p^*)) &= 1 - F(K_W^*) \\ &= \frac{\kappa+\delta}{c_T} \\ &= \frac{1}{p^*}\left[(\kappa+\delta) - \frac{(p^*\int_0^{K_W^*} udF(u) - \gamma_W)}{K_W^*}\right] \end{aligned}$$

or equivalently,

$$p^*\left[\frac{\kappa+\delta}{c_T}K_W^* + \int_0^{K_W^*} udF(u)\right] = (\kappa+\delta)K_W^* + \gamma_W \qquad (*)$$

We use (2) to rewrite the expression in brackets as follows:

$$\begin{aligned} \frac{\kappa+\delta}{c_T}K_W^* + \int_0^{K_W^*} udF(u) &= (1 - F(K_W^*))K_W^* + \int_0^{K_W^*} udF(u) \\ &= E[Q_W^*] \end{aligned}$$

Substituting back into (*) we obtain:

$$p^* = \frac{\kappa+\delta}{\phi^*} + \frac{\gamma_W}{E[Q_W^*]} = \frac{1}{\phi^*}[\kappa+\delta+\frac{\gamma_W}{K_W^*}]$$

where $\phi^* = \frac{E[Q_W^*]}{K_W^*} \in (0,1)$ is the expected capacity utilization factor of the renewable technology. Using (2), this expression can be rewritten as follows:

$$\begin{aligned} p^* &= \frac{\kappa+\delta}{c_T}\frac{c_T}{\phi^*} + \frac{\gamma_W}{E[Q_W^*]} \\ &= c_T(\frac{1-F(K_W^*)}{\phi^*}) + \frac{\gamma_W}{E[Q_W^*]} \\ &= c_T(1-\theta^*) + \frac{\gamma_W}{E[Q_W^*]} \end{aligned}$$

where

$$1-\theta^* = \frac{1-F(K_W^*)}{\phi^*} = \frac{K_W^*(1-F(K_W^*))}{E[Q_W^*]} \in (0,1)$$

A.2 Derivation of $\frac{\partial \theta}{\partial K_W} > 0$ and $\frac{\partial \phi}{\partial K_W} < 0$

First, note that for $D > K_W$, we have:

$$\begin{aligned}
\frac{\partial \phi}{\partial K_W} &= \frac{K_W(1-F(K_W)) - E[Q_W]}{(K_W)^2} \\
&= \frac{-\int_0^{K_W} u dF(u)}{(K_W)^2} < 0
\end{aligned}$$

Recall that

$$\begin{aligned}
\theta &= 1 - \frac{1-F(K_W)}{\phi} \\
&= \frac{E[Q_W] - K_W(1-F(K_W))}{E[Q_W]} \\
&= \frac{\int_0^{K_W} u dF(u)}{\int_0^{K_W} u dF(u) + K_W(1-F(K_W))}
\end{aligned}$$

Hence,

$$\frac{\partial \theta}{\partial K_W} = \frac{\int_0^{K_W} u dF(u)[K_W f(K_W) - (1-F(K_W))] + K_W f(K_W)(1-F(K_W))}{\left[\int_0^{K_W} u dF(u) + K_W(1-F(K_W))\right]^2}$$

From which it follows that $\frac{\partial \theta}{\partial K_W} > 0$ if $K_W > 1$ and

$$\frac{f(K_W)}{1-F(K_W)} \geq 1$$

A.3 Derivation of (8)

Note that (7a) can be rewritten as:

$$p^* = \frac{K_W^*(\kappa+\delta) + \gamma_W}{E[Q_W^*]}$$

Thus,

$$\frac{\partial p^*}{\partial K_W^*} = \frac{(\kappa+\delta)E[Q_W^*] - (1-F(K_W^*))(K_W^*(\kappa+\delta)+\gamma_W)}{E[Q_W^*]^2}$$

Substituting (2) into this last equation we obtain:

$$\begin{aligned}\frac{\partial p^*}{\partial K_W^*} &= \frac{(\kappa+\delta)}{E[Q_W^*]^2}(E[Q_W^*] - \frac{K_W^*(\kappa+\delta)+\gamma_W}{c_T}) \\ &= \frac{(\kappa+\delta)}{E[Q_W^*]c_T}(c_T - p^*)\end{aligned}$$