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Abstract

This paper extends Salop’s model of localized competition by introducing the consumers’ willingness to pay (WTP) for clean products and allows an individual firm to choose between a clean or a dirty technology. We assume that a clean technology is relatively costly to adopt. The consumer is willing to pay more for a product produced with clean technology and the model can also be interpreted as a world economy model where each firm represents a country. There exists a critical value of \( m \) (proportion of firms adopting the clean technology), \( m^* \), such that if \( m < m^* \) then no country adopts the clean technology, all countries adopt the clean technology only if \( m > m^* \) while some countries will adopt the clean technology and some will not adopt the clean technology if \( m = m^* \). Our results also identify an example of coordination failure. Since symmetric technology adoption delivers the same level of profits as non-adoption, global coordination will be necessary to achieve the clean technology adoption outcome. Finally, we demonstrate that the private and public (social planner) incentives to adopt clean technology differ.

**JEL Classifications:** C72, D43, D60, F12

**Keywords:** clean technology, willingness to pay, coordination failure

1. Introduction

The issue of the adoption of clean technology in production has important implications for the world environment and world trade and much has been written on technology adoption across countries, the race to the bottom and pollution havens (Copeland and Taylor, 2004). This paper emphasizes the relationship between the consumers’ willingness to pay (WTP) for a product produced with clean technology and the strategic interaction among countries (firms) in competing for market share. Studies by Wustenhagen, Markard and Truffer (2003) in Switzerland and Moon, Florkowski,
Bruckner and Schonhof (2002) in Germany demonstrate that consumers are willing to pay a premium for environmentally benign production techniques.¹

Our paper extends the analysis of Salop’s (1979) model of localized or regional competition. Thus, this would capture trade between China and Australia, or China (or Australia) and the Asia Pacific. It is shown that, with a positive WTP, some firms adopt the clean technology while others do not (asymmetric adoption). If all countries adopt clean technology (symmetric adoption), each firm will face a symmetric market size with intense competition, forcing them to charge the same price. This may result in the firms earning less profit. On the other hand, if some firms adopt and others do not, then each firm will face an asymmetric market size with price differentials and may earn a higher profit. This result is driven by the fraction \((m)\) of total firms that adopt, \(\theta\) which captures the consumers’ WTP and the marginal cost of production \(c\).

Our results also identify an example of coordination failure. Although symmetric technology adoption delivers the same level of profits, global co-ordination may be necessary to achieve the clean technology adoption outcome.

Finally, we show that the private and public (social planner) incentive to adopt clean technology differs and that given the World Trade Organization (WTO) policies, a solution to reducing emissions is to educate/inform the consumer in order to increase their WTP.

2. Model

2.1 Firms

We consider an N-country and N-variety world economy model.² Each country \(C_i\) consists of one individual firm \(i\) which produces brand \(i\) good and competes in the global market, where \(i = \{1,2,3,... N\}\). Since each country \(C_i\) consists of only one firm \(i\), each firm represents its own country and vice versa. We assume that these are equidistant countries located on the unit-circumference of a circle. This also implies that there are \(N\) equidistant firms located on unit-circumference of a circle, where \(N > 1\).

The location of the firm is denoted by the sequence of integers³:

\[
\mathcal{L} = \left\{ \bar{L}(N) = \frac{1 - N}{2}, \frac{1 - N}{2} + 1, \ldots, 0, 1, \ldots, \bar{L}(N) = \frac{N - 1}{2} \right\}
\]

We assume that \(\{g\}\) is the approximation of \(g\) to its larger integer. For example, if \(N = 4\) then this implies that \(\bar{L}(4) = -1, \bar{L}(4) = 2\) and those firms are located on the following sequence of integers: \{-1, 0, 1, 2\}. Furthermore, we assume that \(N\) is given,

¹Moon et al. (2002) found the “majority of respondents were willing to pay a premium of various sizes for environmentally benign techniques”. This “provides a solid incentive for farmers to consider converting to environmentally friendly practices”. The issue of whether this also led to an increase in total market size was not discussed and their results are more in line with the circular city approach.

²Like Gandel and Shy (2001), although our analysis differs from theirs.

³We follow the sequence, which is mentioned in Alderighi and Piga (2008).
i.e., the number of total independent countries will remain constant. Following the assumption of Alderighi and Piga (2008), we denote \( h \in \Lambda \) as the number of locations separating any two firms. For firm \( n \), \( h < 0 \) identifies the firm which is its \( h \)-step clockwise neighbor, while \( h > 0 \) refers to the firm \( n \)'s \( h \)-step counter-clockwise neighbor (Alderighi and Piga, 2008).\(^4\) For given technology \( T \), each firm \( i \) is producing output \( q_i \) and engaging in Bertrand price competition.

2.1.1 Technology

Assume that each firm faces a constant marginal cost of production \( \gamma \) to produce one unit of output. Without loss of generality, we normalize \( \gamma \) to zero. Two technologies are available and these are \( T = \{ T_E, T_C \} \), where \( T_E \) is an existing technology, which is not environmentally friendly, and \( T_C \) is a clean technology, which is environmentally friendly. In addition, technology \( T_C \) incurs constant marginal cost \( c \), whereas \( T_E \) incurs no extra cost. If \( X_T \), for a given technology \( T \), is the measure of pollution emission per unit of output then we assume the following:

\[
X_T = \begin{cases} 
0 & \text{if an individual firm adopts technology } T_E, \\
\hat{s} > 0 & \text{if an individual firm adopts technology } T_C.
\end{cases}
\]  

(1)

where \( \hat{s} \) is the emission per unit of output. This implies that \( T_C \) is a clean technology and the adoption of clean technology is costly, as \( c > 0 \).

An individual firm \( i \), which is located on the \( n \)th location of the unit-circumference of a circle, will face two close neighborhood competitive firms who are located on the \((n + 1)\)th and \((n - 1)\)th location respectively. Ex-ante, given technology \( T \), an individual firm located at the \( n \)th location will anticipate three possible scenarios regarding the adoption of clean technology for its close neighborhood firm. These possible scenarios are: (i) both firms adopt the clean technology, (ii) both firms do not adopt the clean technology or (iii) one will adopt the clean technology and the other firm will not.

\(^4\) For more details, please see Alderighi and Piga (2008), page 5 and Figure 1.
Figure 1 illustrates the ex-ante three scenarios:

**Figure 1 Ex-ante Three Possible Scenarios**

Firm located on n\textsuperscript{th} location (for given technology T)

- distance 1 / N

Firm located on (n – 1)\textsuperscript{th} location
Firm either adopts clean technology or not.

Firm located on (n + 1)\textsuperscript{th} location
Firm either adopts clean technology or not.

2.1.2 Probability of the Adoption of Clean Technology

The ex-ante probability of the adoption of clean technology by the neighborhood firm is denoted \( m \). An individual firm does not know the exact value of \( m \) but it knows that \( m \) is distributed over an interval \([0,1]\). Without loss of generality, we can also interpret \( m \) as the fraction of total firms that adopt the clean technology.

We make the following assumptions.

**Assumption 1:**

A. Since \( m \) is a probability; it must lie between zero and one i.e. \( 0 \leq m \leq 1 \).

B. We assume that \( m \) is normally distributed over an interval \([0,1]\) with mean \( \mu_m \) and variance \( \sigma_m^2 \) i.e. \( \varphi(m) \sim N(\mu_m, \sigma_m^2) \).

Assumption 1 tells us that \( m \) is normally distributed over an Interval \([0,1]\). Each individual firm \( i \) will maximize the following objective function:

\[
\Pi_i = \begin{cases} 
(P_i^c - c)D_{ir}^c \left( P_i^c, P_j \right) & \text{(If firm } i \text{ adopts the clean technology)} \\
D_{ir}^d \left( P_i^d, P_j \right) & \text{(Otherwise)}
\end{cases}
\]

Here \( P_i^c \) and \( P_i^d \) are the prices charged by an individual firm \( i \) when it adopts the clean technology or existing technology, respectively. \( P_j \) is the price charged by neighborhood
firm \( j \) (where \( i, j = \{1, 2\} \) and \( i \neq j \)) and \( D'_{it}(P_i, P_j) \) is the expected quantity demand for firm \( i \) for a given technology \( T \).

2.2 Consumers

Consumers are assumed to be uniformly distributed on the unit-circumference of a circle. Each consumer obtains utility \( k \) from the good that he or she consumes. In addition, each consumer is characterized by a parameter \( \theta \in [0,1] \) where \( \theta \) is interpreted as his or her utility level for a product produced by using the clean technology only\(^5\). Let \( f(\theta|m) \) be the conditional probability density function of \( \theta \) given \( m \) distributed over interval \([0,1] \). The following properties are assumed to hold for \( f(\theta|m) \):

**Assumption 2**

Assume a bivariate normal distribution with the following properties:\(^6\)

A. \( f(\theta|m) \) has normal density for each value of \( m \in [0,1] \).
B. \( f_m(m) \sim N(\mu_m, \sigma_m^2) \), i.e., the marginal probability density function of \( m \) is normally distributed over an interval \([0,1] \).
C. Conditional variance of \( \theta \) for given \( m \), i.e., \( \sigma_{\theta|m}^2 \) is independent.
D. If the above assumptions i.e. A, B and C hold, then it implies that \( E(\theta|m) \) is linear in \( m \), i.e., \( E(\theta|m) = \tau + \xi m \), where \( \tau = \mu_{\theta} - \rho \frac{\sigma_{\theta}}{\sigma_m} \mu_m \) and \( \xi = \rho \frac{\sigma_{\theta}}{\sigma_m} \).

Here, \( \rho \), \( \sigma_{\theta} \) and \( \sigma_m \) are the correlation coefficient (for \( \theta \) and \( m \)), standard deviations of \( \theta \) and \( m \) respectively. Furthermore, \( \mu_{\theta} \) and \( \mu_m \) are the mean values of \( \theta \) and \( m \) respectively.

We denote \( t \) as the consumer’s transportation cost per unit of distance from her place \( x \) to her nearest firm’s location \( n \). An individual consumer \( \chi \) faces an inelastic demand and purchases one unit of good that minimizes the sum of the price and the transportation cost. Therefore, his or her net utility denoted by \( V_{\chi} \) is as follows\(^7\):

\[
V_{\chi} = \left\{ \begin{array}{ll}
 k + \theta - P_i - t | n - x | & \text{If she purchases a good using clean technology} \\
 k - P_i - t | n - x | & \text{Otherwise}
\end{array} \right.
\]

Suppose, firm \( i \), which does not adopt the clean technology, is located at \( n = 0 \) and its nearest two firms are located at \( n - 1 = -1 \) and \( n + 1 = +1 \) respectively. Since they are equidistant firms, the distance between each firm will be \( \frac{1}{N} \). Denote \( \hat{x} \) as the location of a consumer who is indifferent between buying goods from firm \( i \) and its neighborhood firm \( j \).

If its neighborhood firm \( j \) adopts the clean technology \( \hat{x} \) will be calculated as follows:

\(^5\) See also Economides (1993).
\(^6\) These are standard properties; for more details see Ghahramani (2004), page 449.
\(^7\) We assume that \( k \) is sufficiently large so that \( V_{\chi} > 0 \).
If its neighborhood firm \( j \) does not adopt the clean technology \( \hat{x} \) will be calculated as follows:

\[
k - P_i^d - tx = k - P_j - t \left( \frac{1}{N} - x \right) \Rightarrow \hat{x} = \left\{ \frac{1}{2t} \left[ P_j - P_i^d - \theta \right] + \frac{1}{2N} \right\} = \hat{x}_i
\]

Since firm \( i \) has customers on its left and right side, it will calculate its \textit{ex-ante} expected demand for the three possible scenarios. Though firm \( i \) knows its own preference regarding its technology adoption choice, \textit{ex-ante}, it does not know the preference of its rival firm \( j \) for the same. However, firm \( i \) assigns the probability \( m \) that firm \( j \) will adopt the clean technology and the probability \( (1 - m) \) that firm \( j \) does not adopt the clean technology. This also needs to be justified in the presence of three \textit{ex-ante} possible scenarios (as mentioned previously). Figure 2 illustrates the game tree where the end nodes specify the adoption and non-adoption options:

**Figure 2 Game Tree of Technology Adoption**

Firm \( i \) either adopts the clean technology (c) or does not adopt (d)

\[ \downarrow \]

Neighborhood two firms, each firm denoted as \( j \)

\[ \downarrow \]

Scenario 1 \quad \text{Scenario 2} \quad \text{Scenario 3}

\begin{align*}
\text{Scenario 1} & : m \quad m \quad (1 - m) \\
\text{Scenario 2} & : (1 - m) \quad (1 - m) \quad m \\
\text{Scenario 3} & : (1 - m) \quad m \quad (1 - m)
\end{align*}

Firm \( i \)’s \textit{ex-ante} expected demand will be as follows:

\[
D_{ix}^e (P_i^d, P_j) = m^2 \left[ \int_0^1 2 \int_0^t dx dF(\theta \mid m) \right] + (1 - m)^2 \left[ \int_0^1 2 \int_0^t dx dF(\theta \mid m) \right] \\
+ m(1 - m) \left\{ \left[ \int_0^1 \int_0^t dx dF(\theta \mid m) \right] + \left[ \int_0^1 \int_0^t dx dF(\theta \mid m) \right] \right\}
\]
By simplifying equation (4), it can be written as follows:

$$D_{iTE}^{e}(P_i^e, P_j) = a \left[ \frac{1}{2t} (P_j - P_i^e) - E(\theta | m) + \frac{1}{2N} \right] + b \left[ \frac{1}{2t} (P_j - P_i^e) + \frac{1}{2N} \right]$$ (5)

Here, $a = 2m^2 + m(1 - m)$ and $b = 2(1 - m)^2 + m(1 - m)$. By using a similar calculation, we can derive the expected demand for firm $i$ when it adopts the clean technology $T_c$ as:

$$D_{iTC}^{e}(P_i^c, P_j) = a \left[ \frac{1}{2t} (P_j - P_i^c) + \frac{1}{2N} \right] + b \left[ \frac{1}{2t} (P_j - P_i^c) + E(\theta | m) + \frac{1}{2N} \right]$$ (6)

Because of symmetry, firm $i$’s neighborhood firm $j$ which is located either at -1 (i.e. on right hand side of firm $i$’s position on the circle) or +1 (i.e. on left hand side of firm $i$’s position on the circle) will calculate its own expected demand. Let $D_{jTE}^{e}(P_i^e, P_j)$ and $D_{jTC}^{e}(P_i^d, P_j)$ denote firm $j$’s ex-ante expected demand when it does not adopt the clean technology and when it does adopt clean technology, respectively. Therefore, firm $j$’s ex-ante expected demand is as follows:

$$D_{jTE}^{e}(P_i^e, P_j) = a \left[ \frac{1}{2t} (P_i^e - P_j) - E(\theta | m) + \frac{1}{2N} \right] + \left[ \frac{1}{2t} (P_i^e - P_j) + \frac{1}{2N} \right]$$ (7)

$$D_{jTC}^{e}(P_i^d, P_j) = a \left[ \frac{1}{2t} (P_i^d - P_j) + \frac{1}{2N} \right] + b \left[ \frac{1}{2t} (P_i^d - P_j) + E(\theta | m) + \frac{1}{2N} \right]$$ (7)

### 2.3 Firm’s Profit Maximization Problem

Firm $i$’s profit maximization problem will be as follows:

$$\Pi_i = \begin{cases} (P_i^e - c) D_{iTC}^{e}(P_i^e, P_j) & \text{(If firm } i \text{ adopts the clean technology)} \\ P_i^d D_{iTC}^{e}(P_i^d, P_j) & \text{(Otherwise)} \end{cases}$$ (8)

Firm $i$ is anticipating that firm $j$’s ex-ante profit maximization problem will be as follows:

$$\Pi_j = m[(P_j - c) D_{jTC}^{e}(P_i^e, P_j)] + (1 - m)[P_j D_{jTC}^{e}(P_i^d, P_j)]$$ (9)

This game is similar to the incomplete information game and to solve this game we need to find out the Nash Equilibrium. In order to do so, we consider firm $i$ when it does not adopt the clean technology, as a separate player. Therefore, we need to derive the reaction functions for these three players and determine the strategy profile that solves
them simultaneously. The reaction functions are derived by evaluating the following first order conditions:

\[
\frac{\partial \Pi_i}{\partial P_i^c} = 0, \quad \frac{\partial \Pi_i}{\partial P_i^d} = 0, \quad \text{and} \quad \frac{\partial \Pi_j}{\partial P_j} = 0
\]

This yields the following reaction functions \( R_k \) where \( k = \{i, j\} \):

\[
R_i^c(P_j) = \frac{1}{2} \left[ P_j + \frac{t}{N} + c + \frac{b}{(a+b)} E(\theta | m) \right]
\]

\[
R_i^d(P_j) = \frac{1}{2} \left[ P_j + \frac{t}{N} - \frac{a}{(a+b)} E(\theta | m) \right]
\]

\[
R_j^c(P_i^c, P_i^d) = \frac{1}{2} \left[ P_i^c + m(P_i^c - P_i^d) + \frac{t}{N} + mc + \frac{E(\theta | m)}{(a+b)} (a - m(a+b)) \right]
\]

(10)

Here, \( R_i^c(P_j) \), \( R_i^d(P_j) \) are the reaction functions of firm \( i \) when it adopts clean technology and when it does not, respectively. \( R_j^c(P_i^c, P_i^d) \) is the reaction function of firm \( j \).

By solving the above system of equations, we obtain the following:

\[
P_i^{c*} = \frac{1}{2} (1 + m)c + \frac{t}{N} + \frac{1}{2} E(\theta | m) \left[ m - \frac{a-b}{a+b} \right]
\]

\[
P_i^{d*} = \frac{1}{2} mc + \frac{t}{N} + E(\theta | m) \left[ \frac{m}{2} - \frac{a}{a+b} \right]
\]

\[
P_j^{*} = mc + \frac{t}{N} + E(\theta | m) \left[ m - \frac{a}{a+b} \right]
\]

(11)

From the above equations we obtain the following Lemma:

**Lemma 1:** For any given \( m \) such that \( 0 < m < 1 \), \( E(\theta | m) > 0 \) and \( c > 0 \), the following will be true: \( P_i^{c*} > P_j^{*} > P_i^{d*} \).

**Proof:**

By using the equations in (11), we can calculate the following:

(i) \( P_i^{c*} - P_j^{*} = \frac{(1-m)}{2} \left[ c + E(\theta | m) \right] > 0 \Rightarrow P_i^{c*} > P_j^{*} \);

(ii) \( P_j^{*} - P_i^{d*} = \frac{m}{2} (c + E(\theta | m)) > 0 \Rightarrow P_j^{*} > P_i^{d*} \).

These imply that \( P_i^{c*} > P_j^{*} > P_i^{d*} \).
The intuition of the above lemma is similar to Bayesian Nash Equilibrium. Here, firm $i$ knows whether it adopts the clean technology, but it does not know whether its rival firms will do the same. As a result, it considers the expected outcome of its rival firms - there is $m$ probability that its rival firm adopts the clean technology and $(1 - m)$ probability it does not. Therefore, the expected cost of adoption of clean technology of its rival firm is $mc + (1 - m)0 = mc$. If firm $i$ adopts the clean technology its cost is $c$ and if it does not adopt the clean technology then its adoption cost will be zero. Note that since $\forall m \in (0,1)$, $c > mc > 0$. This implies that if firm $i$ adopts the clean technology, it will face a higher cost than that of its rival firm and, as a result, firm $i$ will charge a price higher than its rival firm’s price. Similarly, one can also explain why firm $i$ charges a lower price than its rival firm when it does not adopt the clean technology.

The above discussion leads to the following proposition:

**Proposition 1:**

A. When no one adopts the clean technology (i.e. $m = 0$), $P_i^* = P_j^* = \frac{t}{N}$, which is a standard result in Salop’s circular model.

B. When everyone adopts the clean technology (i.e. $m = 1$), $P_i^* = P_j^* = \frac{t}{N} + c$

**Proof:**

The proof of Proposition 1 (A) follows from the fact that if no one adopts the clean technology $c = E(\theta | m) = 0$ and by substituting these values in the relevant equations in (11) i.e. equations $P_i^{d*}$ and $P_j^*$, we obtain $P_i^* = P_j^* = \frac{t}{N}$. For the proof of Proposition 1 (B), calculate the value of $a$ and $b$ when everyone adopts the clean technology ($m = 1$). Given that $m = 1 \Rightarrow a = 2m^2 + m(1 - m) = 2$ and $b = 2(1 - m)^2 + m(1 - m) = 0$. By substituting these values in the relevant equations in (11) i.e. $P_i^{c*}$ and $P_j^*$, we obtain $P_i^* = P_j^* = \frac{t}{N} + c$. This completes our proof.

2.3.1 Firm’s Decision Regarding the Adoption of Clean Technology

By using equations (8)-(10), firm $i$’s profit level at Nash Equilibrium will be as follows:

$$\Pi_i = \begin{cases} \frac{(a + b)}{2t} (P_i^{c*} - c)^2 & \text{(If firm } i\text{ adopts the clean technology)} \\ \frac{(a + b)}{2t} [P_i^{d*}]^2 & \text{(Otherwise)} \end{cases}$$

(12)

An individual firm $i$ has an incentive to adopt the clean technology if, and only if, the following condition is satisfied:
\[
\frac{(a + b)}{2t} (P_i^* - c)^2 \geq \frac{(a + b)}{2t} [P_i^{d*}]^2
\]
\[
\Rightarrow P_i^* - P_i^{d*} \geq c
\]
\[
\Rightarrow \frac{1}{2} [E(\theta | m) + c] \geq c
\]
\[
\Rightarrow E(\theta | m) \geq c
\]  

(13)

where the values of \(P_i^*\) and \(P_i^{d*}\) are substituted from equation (11). Since \(m\) is the fraction of total firms that adopt the clean technology, we can solve for \(m\) by replacing the weak inequality sign with equality in equation (13). Therefore, we obtain the following (assuming that an interior solution exists):

\[
E(\theta | m) = c \iff m^* \text{ (where } m^* \text{ is a critical threshold)}
\]  

(14)

**Proposition 2:** For any given \(m\), such that if \(m < m^*\), then no one adopts the clean technology and if \(m < m^*\) then everyone adopts the clean technology. However, if \(m = m^*\) then some firms will adopt the clean technology and some firms will not adopt the same.

**Proof:** The proof follows from our conditions (13) and (14).

Figure 3 illustrates this proposition. From Assumption 2 (D) \(E(\theta | m)\) is linear in \(m\). Since both \(c\) and \(m\) lie over an interval \([0,1]\), we can plot the two curves \(E(\theta | m)\) and \(c\). Assumption 2 (D) in equation (14), can be used to define $m^*$ explicitly as follows:

\[
\mu_o - \rho \frac{\sigma_o}{\sigma_m} m = c,(\text{by Assumption 2 (D)})
\]
\[
m^* = \mu_m + \rho \frac{\sigma_m}{\sigma_o} (c - \mu_o)
\]  

(15)

Since both \(m \in [0,1]\) and \(\theta \in [0,1]\), for feasibility we require that: \(0 \leq E(\theta | m) \leq 1\) and \(c \in [0,1]\).
Figure 3 illustrates the case that for any given \( m \) such that \( m < m^* \), no one adopts the clean technology, while for \( m > m^* \), every one adopts the clean technology. At the interaction point of \( E(\theta|m) \) and \( c \) curves, some firms adopt the clean technology and some firms do not adopt the same technology. Note that if \( m = 0 \) then \( \mu_m = 0 \), therefore, \( E(\theta|m) = \tau = \mu_0 > 0 \) as long as \( \theta > 0 \) (from Assumption 2 (D)).

### 2.4 Decomposition of \( m^* \) & Risk Adjustment Factor

In condition (15) \( m^* \) is decomposed into two parts, (i) the expected value of \( m \) i.e. \( \mu_m \) and (ii) \( \rho \frac{\sigma_m}{\sigma_\theta} (c - \mu_\theta) \), let us call this term a risk adjustment factor. For given values of \( \rho > 0 \), \( \sigma_\theta > 0 \) and \( \sigma_m > 0 \), this risk adjustment factor depends on (i) the consumers’ expected willingness to pay (WTP) \( \mu_0 \) and (ii) the unit cost/marginal cost of clean technology adoption. Indeed, the risk adjustment factor explains why an individual firm deviates from \( \mu_m \). For example, if \( c > \mu_\theta \) then it raises the critical value of \( m^* \) (follows from equation (15)). This implies that an individual firm has relatively less incentive to adopt the clean technology (follows from the Proposition 2). If the firm’s cost of clean technology adoption goes up, the adoption of clean technology becomes less
likely. However, the reverse will be true if $c < \mu_\theta$. In this case, $m^*$ will decrease and an individual firm has a relatively higher incentive to adopt the clean technology as it involves less risk. Note that if $c = \mu_\theta$ then the critical $m^*$ will converge to its mean value $\mu_m$. This observation leads to following proposition:

**Proposition 3:** For given parameters’ values such that $\rho > 0$, $\sigma_\theta > 0$ and $\sigma_m > 0$, the following will be true:

A. $m^*$ is increasing in $c$ but decreasing in $\mu_\theta$.

B. If $c > \mu_\theta$ then $m^* > \mu_m$ and if $\mu_\theta > c$ then $m^* < \mu_m$.

C. If $c = \mu_\theta$ then $m^*$ will converge to its expected value $m^* = \mu_m$.

**Proof:** By differentiating equation (14) with respect to $c$ and $\mu_\theta$, we obtain

$$\frac{\partial m^*}{\partial c} = \frac{\sigma_m}{\rho \sigma_\theta} > 0$$

and

$$\frac{\partial m^*}{\partial \mu_\theta} = -\frac{\sigma_m}{\rho \sigma_\theta} < 0$$

respectively. Proposition 3(B) and Proposition 3(C) follow from equation (14).

One of the important aspects of the above analysis is that the solution for critical $m^*$ does not depend on transport cost $t$. The reason is that, since an individual consumer has to bear the transport cost, a firm always tries to identify the indifferent consumer to determine its market size irrespective of whether it adopts a clean technology or not. Furthermore, if one examines the reaction function of each individual firm in equation (10) then it is easy to see that a change in $t$ will lead to a level shift of each reaction function without altering the outcome of the Nash Equilibrium.

### 2.5 Coordination Failure

From Proposition 2, if $m < m^*$ then no one adopts the clean technology, while if $m > m^*$ then everyone adopts the clean technology. Furthermore, Proposition 1 defines the Nash prices for all firms that adopt or do not adopt the clean technology. It is interesting to see what happens to the profit level of each firm when all the firms behave in the same manner. This leads to the following Lemma:

**Lemma 2:** The profit earned by an individual firm when no firm adopts the clean technology will be the same profit level for an individual firm when all the firms adopt the clean technology.

**Proof:** If all the firms are of the same type and adopt clean technology or not, each will face a symmetric market size (follows from the intuition of equation (3)). Therefore, profit earned by an individual firm (when all adopt the clean technology) will be

$$\Pi^*_c = \frac{1}{t} \left[ \frac{t}{N} + c - c \right]^2 = \left[ \frac{t}{N^2} \right]$$

(follows from Proposition 1 and equation (8)). Similarly, the profit earned by an individual firm when no one adopts the clean technology

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8 If we were to change the model and assumed delivered pricing where firms would bear transport costs then their marginal costs will increase. Qualitatively our results will still hold.
will be $\Pi_{c}^{*} = \frac{1}{t} \left[ \frac{t}{N} \right]^{2}$ (follows from Proposition 1 and equation (8). This implies that

$$
\Pi_{c}^{*} = \left[ \frac{t}{N^{2}} \right].
$$

Lemma 2 tells us when there is symmetric technology adoption (irrespective of whether all firms adopt the technology or not) each individual firm will earn the same level of profit. This implies that when $m < m^*$ no firm adopts the clean technology and, in such a scenario, the profit level earned by each individual firm will be the same as that earned when each firm adopts a clean technology. This latter case is possible, if and only if, all the firms cooperate to adopt the same clean technology at the same time. This implies that we need a global coordinator to establish an outcome where everyone adopts the clean technology even though $m < m^*$.

3. Welfare Analysis

This section investigates the optimal level of $m$ and compares this optimal level to the outcome of the free market economy. Assume that the social planner of each country is only concerned about the damage arising from the total world volume of pollution emissions and he or she is willing to cooperate to reduce this volume. In order to do so, a social planner will calculate the economy’s loss function, which consists of the total volume of pollution emissions that cause damage to our environment, and also the total cost of adoption of clean technology. Assume that the damage function is linear in total volume of pollution emissions. Note that, unlike Salop’s model, we are not calculating total transport costs as there are $N$ independent countries and each country’s social planner will not be concerned about minimizing the transport cost of the firms of other countries. Assume that $m$ of total firms have adopted the clean technology, therefore, $1 - m$ of total firms have not adopted the clean technology. In our model this will occur when $m = m^*$ (follows from Proposition 2). Therefore, the damage function arising from the total volume of pollution emissions will be as follows:

$$
X = (1 - m) \hat{s} N q^{d}. \tag{16}
$$

This follows from our assumption of linearity and the condition (1). The variable $q^d$ is the total demand for those goods, which are produced by existing technology. For simplicity, we assume that each firm is located in the following sequence on the unit circumference of a circle:

$$
\{d_{0}, d_{1}, d_{2}, \ldots, d_{k - 1}, c_{k}, c_{k + 1}, \ldots, c_{-2}, c_{-1}, d_{0}\}. \tag{10}
$$

9 Also see Oz Shy (1995), page 156.

10 Various scenarios and, therefore, sequences are possible; we are assuming this sequence to keep our analysis simple.
$d_i$ represents an individual firm, which is located at $i$ and does not adopt a clean technology, and $c_j$ an individual firm which is located at $j$ and has adopted a clean technology. In other words, most of the firms that do not adopt the clean technology have neighborhood firms, which also have not adopted the clean technology and vice versa. The important aspect is that a border firm such as $d_0$ and $d_{k-1}$ will face a neighborhood firm that adopts the clean technology. By using equations (2) and (3), we can calculate, $q^d$ for the $N$ firm case which is as follows:

\[
q^d = [(1 - m)N - 1]2x^{(d,d)} + 2x^{(d,c)}
\]

\[
= [(1 - m)N - 1] \frac{1}{N} + \frac{1}{t}(\theta + c) + \frac{1}{N}
\]

\[
= (1 - m) + \frac{1}{t}(\theta + c)
\]  

(17)

Here, $2x^{(d,d)}$ is the demand for the goods of a firm that does not adopt the technology, as well as its neighborhood firms, which also do not adopt the clean technology, and $2x^{(d,c)}$ is the demands for the goods of a firm that does not adopt the technology but its neighborhood firms do adopt the clean technology. Without loss of generality, we can replace $\theta$ with its conditional expected value $E(\theta|m)$. Therefore, the above equation can be written as follows:

\[
q^d = (1 - m) + \frac{1}{t}(E(\theta|m) + c)
\]  

(18)

The total cost of adoption of clean technology will be $mNc$. Therefore, the loss function denoted by $\mathcal{L}$ will be as follows:

\[
\min_{m} \mathcal{L} = X + mNc
\]

\[
= (1 - m)\hat{s}N \left[ (1 - m) + \frac{1}{t}(E(\theta|m) + c) \right] + mNc
\]

\[
= (1 - m)\hat{s}N \left[ (1 - m) + \frac{1}{t}(\tau + \xi m + c) \right] + mNc
\]  

(19)

Note that $E(\theta|m) = \tau + \xi m$ (follows from Assumption 2). The first order condition is $\frac{\partial \mathcal{L}}{\partial m} = 0$. By solving this with respect to $m$, we obtain the social desired level of $m$, $m^*_s$, which is as follows:

\[
m^*_s = 1/2 \left( \frac{2\hat{s}t + \hat{s}\tau + \hat{s}c - \hat{s}\xi - ct}{\hat{s}(t - \xi)} \right)
\]  

(20)
Here, \( \tau = \mu_\theta - \rho \frac{\sigma_\theta}{\sigma_m} \mu_m \) and \( \xi = \rho \frac{\sigma_\theta}{\sigma_m} \). We normalize \( t = 1 \) and \( \frac{\sigma_\theta}{\sigma_m} = 1 \) and re-write the above equation as follows:

\[
m_\sigma^* = \left( -(-2 + 2 \rho)^{-1} + 1/2 \frac{1}{(-1 + \rho)\hat{s}} \right) c - 1/2 \frac{\mu_\theta - \rho \mu_m}{-1 + \rho} - 1/2 \frac{2 - \rho}{-1 + \rho}
\]

(21)

For feasibility, \( m_\sigma^* \) must lie in interval \([0,1]\). Equation (21) leads to the following Lemma:

**Lemma 3:** For given \( \rho \in [0,1], \hat{s} \in [0,1] \), the following will be true:

A. \( m_\sigma^* \) is increasing in \( \mu_\theta \) i.e. \( \frac{\partial m_\sigma^*}{\partial \mu_\theta} = \frac{1}{2(1-\rho)} > 0 \).

B. \( m_\sigma^* \) is decreasing in \( c \) i.e. \( \frac{\partial m_\sigma^*}{\partial c} = \frac{1}{2(1-\rho)} \left( 1 - \frac{1}{\hat{s}} \right) \leq 0 \).

C. \( m_\sigma^* \) is increasing in \( \hat{s} \) i.e. \( \frac{\partial m_\sigma^*}{\partial \hat{s}} = \frac{c}{2(1-\rho)\hat{s}^2} > 0 \).

The important feature to note is that \( m_\sigma^* \) is positively related to \( \hat{s} \). As pollution increases, a social planner wants more firms to adopt the clean technology whereas an individual firm may not adopt the clean technology as its profit maximization problem fails to incorporate the effect of \( \hat{s} \). Furthermore, \( m_\sigma^* \) (from equation (15)) decreases with respect to \( \mu_\theta \) but increases with respect to \( c \), however, the opposite relationship holds for \( m_\sigma^* \) for the same variables. This may increase the conflict of interest between a social planner and a profit-maximizing firm. For example, when \( m < m_\sigma^* \), no individual firm will adopt the clean technology (follows from Proposition 2) but in that scenario the social planner’s \( m_\sigma^* > 0 \). The following figure 4 illustrates this:
Note that, here $m^*$ is a private threshold level (whether an individual firm will adopt the clean technology) and $m^*_s$ is a socially desirable level for the fraction of total firms who adopt the clean technology. We calculate both $m^*$ and $m^*_s$ for the parameter values $c = \frac{1}{8}$, $\rho = \frac{1}{2}$, $\mu = \frac{3}{10}$ and $s = \frac{1}{10}$ (also by using the equations (15) and (21) respectively). For $\mu_\theta \in [0,1]$, if any $m$ is such that $m^*_s \leq m < m^*$ then no individual firm will adopt the clean technology but the socially desirable level of $m$ will be $m^*_s > 0$.  

3.1 Policy Implication

Since the WTO encourages countries to reduce trade barriers by lowering tariffs and reducing subsidies, we need to look at alternative policies to encourage firms to adopt clean technology. This model suggests that, by educating consumers, we can achieve...
that. As consumers receive more information regarding environmental degradation, their willingness to pay for clean technology will increase. This implies that $\mu_\theta$ in equation (15) will increase, which will also reduce the critical $m^*$, therefore, more firms are likely to adopt the clean technology (follows from Proposition 3 and equation (15)).

4. Conclusion

This paper extends Salop’s model of localized competition by allowing firms the choice of clean or dirty technology and introducing the consumers’ willingness to pay (WTP) for clean products. That is, the consumer is willing to pay more for a product produced with clean technology. The model can also be interpreted as a world economy model where each firm represents a country. Given the cost of adopting new technology, and in the presence of incomplete information, we find that there exists a critical value of $m$ (an individual firm’s belief regarding clean technology adoption) $m^*$. If $m < m^*$, then no country adopts the clean technology. While, if the WTP increases, some countries find it profitable to adopt the clean technology, if and only if, $m > m^*$. Finally, some countries will adopt the clean technology and some of them will not adopt the same clean technology if $m = m^*$. Furthermore, the WTP plays a crucial role in determining risk factor. The higher the expected value of $\theta$ i.e. $\mu_\theta$, the lower the value of $m^*$; hence, more firms are likely to adopt the clean technology.

This paper also identifies the problem of coordination failure. Although symmetric technology adoption (irrespective of whether an individual firm adopts clean technology) gives the same level of profit for each firm, the outcome of clean technology adoption will be achieved if, and only if, all the firms cooperate. This implies that a global coordinator may be necessary to achieve such an outcome.

Finally, we demonstrate that the private and public (social planner) incentives to adopt clean technology differ and that, given the policies of the World Trade Organization (WTO), a solution to reducing emissions is to educate/inform the consumer in order to increase their WTP.

References


