APPENDICES

Appendix I

Proof for $\dfrac{\partial V_2^L\left(a_2^L, a_2^F\right)}{\partial a_2} \le 0$,

From the objective equation of Leader in second period,

$$V_2^L\left(a_2,\alpha\right) = \min_{p_{a_2}}\left\{p_{a_2}\left(e_2^L - a_2^L - q_2^L\right) + C^L\left(q_2^L,\theta\right)\right\} \tag{A1}$$

where $0 \le \alpha \le 1$ is the fraction of permits granted to Leader: $a_t^L = \alpha a_t$ and $a_t^F = \left(1-\alpha\right)a_t$.

By $a_t^L = \alpha a_t$, equation (A1) can be,

$$V_2^L\left(a_2,\alpha\right) = \min_{p_{a_2}}\left\{p_{a_2}\left(e_2^L - \alpha a_2 - q_2^L\right) + C^L\left(q_2^L,\theta\right)\right\} \tag{A2}$$

Differentiate this equation with respect to a_2,

$$\frac{\partial V_2^L\left(a_2,\alpha\right)}{\partial a_2} = -\alpha p_{a_2} - p_{a_2}\frac{\partial q_2^L}{\partial a_2} + \frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2} \tag{A3}$$

By market clearing, $e_t^L + e_t^F - \left(q_t^L + q_t^F\left(p_{a_t}\right)\right) = a_t^L + a_t^F$, and $a_t^F = \left(1-\alpha\right)a_t$, equation (A2) can be,

$$V_2^L\left(a_2,\alpha\right) = \min_{p_{a_2}}\left\{p_{a_2}\left(\left(1-\alpha\right)a_2 - e_2^F + q_2^F(p_{a_2})\right) + C^L\left(q_2^L,\theta\right)\right\} \tag{A4}$$

Differentiate this equation with respect to a_2,

$$\frac{\partial V_2^L\left(a_2,\alpha\right)}{\partial a_2} = \left(1-\alpha\right)p_{a_2} + p_{a_2}\frac{\partial q_2^F\left(p_{a_2}\right)}{\partial a_2} + \frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2} \tag{A5}$$

Equations (A3) and (A5) are equal,

$$-\alpha p_{a_2} - p_{a_2}\frac{\partial q_2^L}{\partial a_2} + \frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2} = \left(1-\alpha\right)p_{a_2} + p_{a_2}\frac{\partial q_2^F\left(p_{a_2}\right)}{\partial a_2} + \frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2}$$

$$-\alpha p_{a_2} - p_{a_2}\frac{\partial q_2^L}{\partial a_2} = \left(1-\alpha\right) p_{a_2} + p_{a_2}\frac{\partial q_2^F\left(p_{a_2}\right)}{\partial a_2}$$

$$-\frac{\partial q_2^L}{\partial a_2} = 1 + \frac{\partial q_2^F\left(p_{a_2}\right)}{\partial a_2}$$

$$\frac{\partial q_2^L}{\partial a_2} + \frac{\partial q_2^F\left(p_{a_2}\right)}{\partial a_2} = -1 \qquad \text{(A6)}$$

From the first order condition of Leader in second period, equation (10),

$$\left[\hat{p}_{a_2} - \hat{C}_q{}^L\left(\hat{q}_2^L,\theta\right)\right]\frac{\partial \hat{q}_2^F(\hat{p}_{a_2})}{\partial p_{a_2}} = e_2^F - a_2^F - \hat{q}_2^F(\hat{p}_{a_2})$$

which by market clearing, $\left[\hat{p}_{a_2} - \hat{C}_q{}^L\left(\hat{q}_2^L,\theta\right)\right]\frac{\partial \hat{q}_2^F(\hat{p}_{a_2})}{\partial p_{a_2}} = \alpha a_2 + \hat{q}_2^L - e_2^L$ (A7)

Differentiate this equation with respect to a_2,

$$\left[\frac{\partial \hat{p}_{a_2}}{\partial a_2} - \frac{\partial \hat{C}_q^L\left(\hat{q}_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial \hat{q}_2^L}{\partial a_2}\right]\cdot\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}} = \alpha + \frac{\partial \hat{q}_2^L}{\partial a_2}$$

Assume that $\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}}$ is stable with respect to a_2, then rearrange this equation,

$$\frac{\partial \hat{q}_2^L}{\partial a_2} = \frac{\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial a_2} - \alpha}{1 + \hat{C}_{qq}^L\left(\hat{q}_2^L,\theta\right)\cdot\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}}}$$

(A8)

From equation (A6) and (A8), $\frac{\partial \hat{q}_2^L}{\partial a_2} = \frac{-1 - \frac{\partial \hat{q}_2^L}{\partial a_2} - \alpha}{1 + \hat{C}_{qq}^L\left(\hat{q}_2^L,\theta\right)\cdot\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}}}$

$$\left(1 + \hat{C}_{qq}^L\left(\hat{q}_2^L,\theta\right)\cdot\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}}\right)\cdot\frac{\partial \hat{q}_2^L}{\partial a_2} + \frac{\partial \hat{q}_2^L}{\partial a_2} = -1 - \alpha$$

$$\frac{\partial \hat{q}_2^L}{\partial a_2} = \frac{-1-\alpha}{2+\hat{C}_{qq}^L\left(\hat{q}_2^L,\theta\right)\cdot\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}}} \qquad \text{(A9)}$$

Because $2+\hat{C}_{qq}^L\left(\hat{q}_2^L,\theta\right)\cdot\frac{\partial \hat{q}_2^F\left(\hat{p}_{a_2}\right)}{\partial p_{a_2}} > 0$ and $-1-\alpha<0$, so $\frac{\partial \hat{q}_2^L}{\partial a_2}<0$ (A10)

Again from the first order condition of Leader in second period, equation (10),

$$\left[\hat{p}_{a_2}-\hat{C}_q{}^L\left(\hat{q}_2^L,\theta\right)\right]\frac{\partial \hat{q}_2^F(\hat{p}_{a_2})}{\partial p_{a_2}} = e_2^F - a_2^F - \hat{q}_2^F(\hat{p}_{a_2})$$

we concern in two cases, Monopoly market and Monopsony market.

1) **Monopoly market**, Leader is seller of permit and Follower is buyer.
   Follower is buyer, $e_2^F - a_2^F - \hat{q}_2^F(\hat{p}_{a_2}) \geq 0$ then $\hat{p}_{a_2}-\hat{C}_q{}^L\left(\hat{q}_2^L,\theta\right)\geq 0$.

From (A3),

$$\frac{\partial V_2^L\left(a_2,\alpha\right)}{\partial a_2} = -\alpha p_{a_2} - p_{a_2}\frac{\partial q_2^L}{\partial a_2} + \frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2}$$

$$\frac{\partial V_2^L\left(a_2,\alpha\right)}{\partial a_2} = \left(-\alpha-\frac{\partial q_2^L}{\partial a_2}\right)\cdot p_{a_2} + \frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2} \qquad \text{(A11)}$$

We separate equation (A11) to, $\frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2}$ and $\left(-\alpha-\frac{\partial q_2^L}{\partial a_2}\right)\cdot p_{a_2}$.

By equation (A10) and marginal abatement cost is positive,

then $\frac{\partial C^L\left(q_2^L,\theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2}<0$. (A12)

For term $\left(-\alpha-\frac{\partial q_2^L}{\partial a_2}\right)\cdot p_{a_2}$,

1.1) If $-\alpha-\frac{\partial q_2^L}{\partial a_2}\leq 0$ or $\frac{\partial q_2^L}{\partial a_2}\geq -\alpha$, mean if regulator allow more permit for 1 unit then Leader will reduce abatement level less than permit received. That is Leader sell some permits or Leader will be seller.

1.2) If $-\alpha-\frac{\partial q_2^L}{\partial a_2}\geq 0$ or $\frac{\partial q_2^L}{\partial a_2}\leq -\alpha$, mean if regulator allow more permit for 1 unit then Leader will reduce abatement level more than permit received. That is

Leader buy some permits or Leader will be buyer. Therefore, if $-\alpha - \frac{\partial q_2^L}{\partial a_2} \geq 0$ Leader is buyer and Follower is seller, which is is monopsony market. Hence, $-\alpha - \frac{\partial q_2^L}{\partial a_2} \geq 0$ is impossible in monopoly market case.

From 1.1) and 1.2), $\left(-\alpha - \frac{\partial q_2^L}{\partial a_2}\right) \cdot p_{a_2} \leq 0$ (A13)

Therefore, from (A11) – (A13) in monopoly market, $\frac{\partial V_2^L\left(a_2^L, a_2^F\right)}{\partial a_2} \leq 0$.

2) Monopsony market, Leader is buyer of permit and Follower is seller.

Follower is seller, $e_2^F - a_2^F - \hat{q}_2^F(\hat{p}_{a_2}) \leq 0$ then $\hat{p}_{a_2} - \hat{C}_q{}^L\left(\hat{q}_2^L, \theta\right) \leq 0$.

From (A3),

$$\begin{aligned}
\frac{\partial V_2^L\left(a_2, \alpha\right)}{\partial a_2} &= -\alpha\, p_{a_2} - p_{a_2}\frac{\partial q_2^L}{\partial a_2} + \frac{\partial C^L\left(q_2^L, \theta\right)}{\partial q_2^L} \cdot \frac{\partial q_2^L}{\partial a_2} \\
&= -\alpha\, p_{a_2} - \left(p_{a_2} - \frac{\partial C^L\left(q_2^L, \theta\right)}{\partial q_2^L}\right) \cdot \frac{\partial q_2^L}{\partial a_2} \\
&= -\alpha\, p_{a_2} - \left(p_{a_2} - C_q^L\left(q_2^L, \theta\right)\right) \cdot \frac{\partial q_2^L}{\partial a_2} \qquad \text{(A14)}
\end{aligned}$$

By $\hat{p}_{a_2} - \hat{C}_q{}^L\left(\hat{q}_2^L, \theta\right) \leq 0$ and equation (A10), $-\alpha\, p_{a_2} - \left(p_{a_2} - C_q^L\left(q_2^L, \theta\right)\right) \cdot \frac{\partial q_2^L}{\partial a_2} \leq 0$

Therefore, in monopsony market, $\frac{\partial V_2^L\left(a_2^L, a_2^F\right)}{\partial a_2} \leq 0$.

Hence, from both monopoly and monopsony market, $\frac{\partial V_2^L\left(a_2^L, a_2^F\right)}{\partial a_2} \leq 0$.

Appendix II

Proof for $\frac{\partial V_2^L\left(T_2, a_2, \alpha\right)}{\partial a_2} = -\alpha T_2 \le 0$,

From the objective equation of Leader in second period,

$$V_2^L\left(T_2, a_2, \alpha\right) = \underset{q_2^L}{Min}\left\{T_2\left(e_2^L - a_2^L - q_2^L\right) + C^L\left(q_2^L, \theta\right)\right\} \tag{A15}$$

where $0 \le \alpha \le 1$ is the fraction of permits granted to Leader: $a_t^L = \alpha a_t$ and $a_t^F = \left(1-\alpha\right)a_t$.

By $a_t^L = \alpha a_t$, equation (A15) turn out to be,

$$V_2^L\left(T_2, a_2, \alpha\right) = \underset{q_2^L}{Min}\left\{T_2\left(e_2^L - \alpha a_2 - q_2^L\right) + C^L\left(q_2^L, \theta\right)\right\} \tag{A16}$$

Differentiate this equation with respect to a_2,

$$\begin{aligned}\frac{\partial V_2^L\left(T_2, a_2, \alpha\right)}{\partial a_2} &= -\alpha T_2 - T_2\frac{\partial q_2^L}{\partial a_2} + \frac{\partial C^L\left(q_2^L, \theta\right)}{\partial q_2^L}\cdot\frac{\partial q_2^L}{\partial a_2} \\ &= -\alpha T_2 - \left(T_2 - \frac{\partial C^L\left(q_2^L, \theta\right)}{\partial q_2^L}\right)\cdot\frac{\partial q_2^L}{\partial a_2}\end{aligned} \tag{A17}$$

From the first order condition of Leader in second period,

$\hat{T}_2 = \hat{C}_q^{\,L}\left(\hat{q}_2^L, \theta\right) = \frac{\partial C^L\left(q_2^L, \theta\right)}{\partial q_2^L}$,

equation (A17) turn out to be, $\frac{\partial V_2^L\left(T_2, a_2, \alpha\right)}{\partial a_2} = -\alpha T_2 < 0$

Appendix III

Proof for $\dfrac{\partial V_2^F\left(T_2, a_2, \alpha\right)}{\partial a_2} \leq 0$,

From the objective equation of Follower in second period,

$$V_2^F\left(T_2, a_2, \alpha\right) = \underset{q_2^F}{Min}\left\{T_2\left(e_2^F - a_2^F - q_2^F\right) + C^F\left(q_2^F, \theta\right)\right\} \tag{A15}$$

where $0 \leq \alpha \leq 1$ is the fraction of permits granted to Leader: $a_t^L = \alpha a_t$ and $a_t^F = (1-\alpha)a_t$.

By $a_t^F = (1-\alpha)a_t$, equation (A15) turn out to be,

$$V_2^F\left(T_2, a_2, \alpha\right) = \underset{q_2^F}{Min}\left\{T_2\left(e_2^F - (1-\alpha)a_2 - q_2^F\right) + C^F\left(q_2^F, \theta\right)\right\} \tag{A16}$$

Differentiate this equation with respect to a_2,

$$\begin{aligned}\frac{\partial V_2^F\left(T_2, a_2, \alpha\right)}{\partial a_2} &= -(1-\alpha)T_2 - T_2\frac{\partial q_2^F}{\partial a_2} + \frac{\partial C^F\left(q_2^F, \theta\right)}{\partial q_2^F}\cdot\frac{\partial q_2^F}{\partial a_2} \\ &= -(1-\alpha)T_2 - \left(T_2 - \frac{\partial C^F\left(q_2^F, \theta\right)}{\partial q_2^F}\right)\cdot\frac{\partial q_2^F}{\partial a_2}\end{aligned} \tag{A17}$$

From the first order condition of Follower in second period,

$\hat{T}_2 = \hat{C}_q^F\left(\hat{q}_2^F, \theta\right) = \dfrac{\partial C^F\left(q_2^F, \theta\right)}{\partial q_2^F}$,

equation (A17) turn out to be, $\dfrac{\partial V_2^F\left(T_2, a_2, \alpha\right)}{\partial a_2} = -(1-\alpha)T_2 < 0$

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