Comparison of Incentive Policies for Renewable Energy in an Oligopolistic Market with Price-Responsive Demand

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APPENDIX A: MODELING OF RE POLICIES UNDER OLIGOPOLY

Base Model

$$
\begin{aligned}
Max \quad & q_i^c \cdot (p_i - c_i^c) + q_i^r \cdot (p_i - c_i^r) \\
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}
$$

Carbon Tax

$$
\begin{aligned}
Max \quad & q_i^c \cdot (p_i - c_i^c - \alpha^c \cdot \gamma_i^c) + q_i^r \cdot (p_i - c_i^r) \\
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}
$$

Feed - in Tariff

$$
\begin{aligned}
Max \quad & q_i^c \cdot (p_i - c_i^c) + q_i^r \cdot (p_i^{FIT} - c_i^r) \\
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}
$$

Premium Payments

$$Max \quad q_i^c \cdot (p_i - c_i^c) + q_i^r \cdot (p_i + PREM_i - c_i^r)$$

$$\begin{aligned}
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}$$

Quota Obligation

$$Max \; q_i^c \cdot (p_i - c_i^c) + q_i^r \cdot (p_i - c_i^r) - C^{penalty} \cdot q_i^{penalty}$$

$$\begin{aligned}
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& 0 \le q_i^{penalty} \\
& q_i^{penalty} \ge \left[\left(q_i^c + q_i^r \right) \cdot \beta - q_i^r \right] \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}$$

APPENDIX B: MODELING OF RE POLICIES UNDER PERFECT COMPETITION

Carbon Tax

$$Min \quad \sum_i \left[q_i^c \cdot (c_i^c + \alpha^c \cdot \gamma_i^c) + q_i^r \cdot c_i^r \right]$$

$$\begin{aligned}
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}$$

Feed - in Tariff

$$Min \quad \sum_i \left[q_i^c \cdot c_i^c + q_i^r \cdot (p_i^{FIT} - c_i^r) \right]$$

$$\begin{aligned}
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}$$

Premium Payments

$$Min \quad \sum_i \left[q_i^c \cdot c_i^c + q_i^r \cdot (PREM_i - c_i^r) \right]$$

$$\begin{aligned}
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}$$

Quota Obligation

$$Min \quad \sum_i \left[q_i^c \cdot c_i^c + q_i^r \cdot c_i^r + C^{penalty} \cdot q_i^{penalty} \right]$$

$$\begin{aligned}
s.t. \quad & y_1 + f = q_1^c + q_1^r \\
& y_2 - f = q_2^c + q_2^r \\
& p_1 + b_1 \cdot y_1 = a_1 \\
& p_2 + b_2 \cdot y_2 = a_2 \\
& 0 \le q_i^{penalty} \\
& q_i^{penalty} \ge \left[\left(q_i^c + q_i^r \right) \cdot \beta - q_i^r \right] \\
& p_1 - p_2 + \eta_1 - \eta_2 = 0 \\
& \eta_1 \cdot (f - K) = 0 \\
& \eta_2 \cdot (-f - K) = 0 \\
& f - K \le 0 \\
& -f - K \le 0 \\
& 0 \le q_1^c \le K_1^c \\
& 0 \le q_1^r \le K_1^r \\
& 0 \le q_2^c \le K_2^c \\
& 0 \le q_2^r \le K_2^r \\
& 0 \le p_1 \quad 0 \le y_1 \quad 0 \le \eta_1 \\
& 0 \le p_2 \quad 0 \le y_2 \quad 0 \le \eta_2
\end{aligned}$$

APPENDIX C: BEST-RESPONSE FUNCTION OF RE POLICIES

Figure 24: Best-Response Functions (Tax = $32/ton of CO_2) under the Carbon Tax Policy

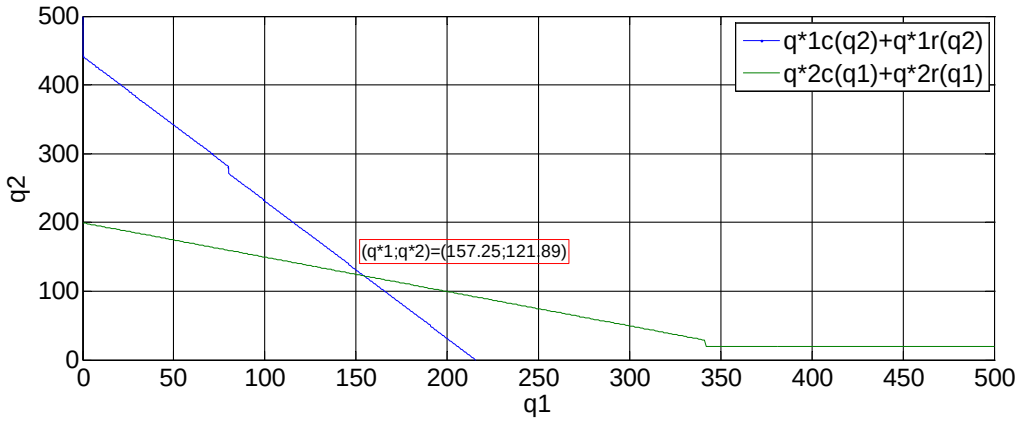

Figure 25: Best-Response Functions under the Feed-in Tariff Policy (FIT=$165/MWh)

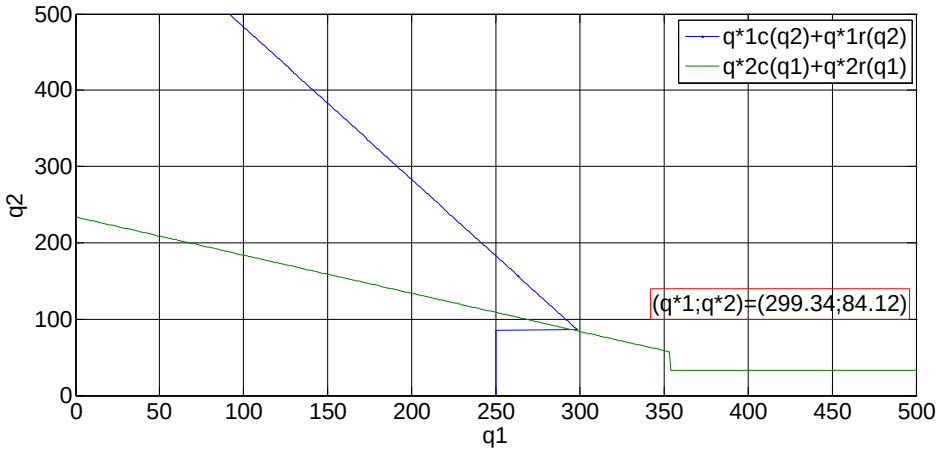

Figure 26: Best-Response Functions under the Premium Policy

(Premium=$32/MWh)

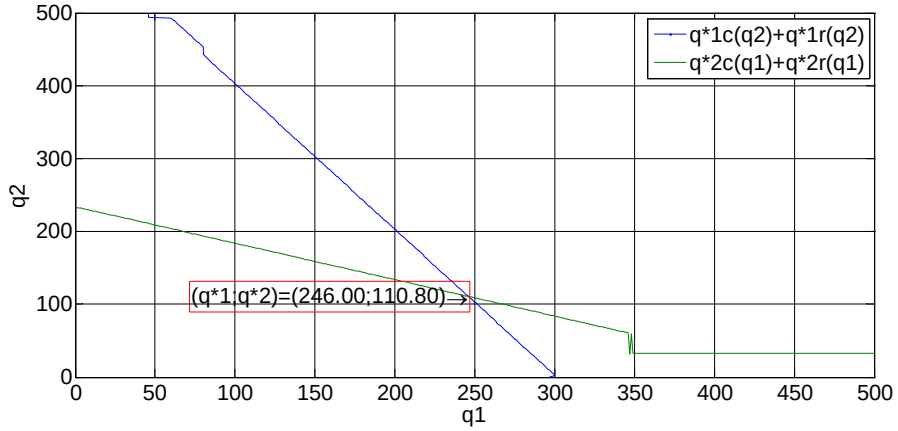

Figure 27: Best-Response Functions under the Quota Policy

(Fine $32/MWh)