

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

Miguel Pérez de Arce and Enzo Sauma

APPENDIX A: MODELING OF RE POLICIES UNDER OLIGOPOLY

Base Model

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

Carbon Tax

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

Feed-in Tariff

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

		<u>Quota Obligation</u>
<u>Premium Payments</u>		$\text{Max } q_i^c \cdot (p_i - c_i^c) + q_i^r \cdot (p_i - c_i^r) - C^{\text{penalty}} \cdot q_i^{\text{penalty}}$
Max	$q_i^c \cdot (p_i - c_i^c) + q_i^r \cdot (p_i + \text{PREM}_i - c_i^r)$	
$s.t.$		
	$y_1 + f = q_1^c + q_1^r$	
	$y_2 - f = q_2^c + q_2^r$	
	$p_1 + b_1 \cdot y_1 = a_1$	
	$p_2 + b_2 \cdot y_2 = a_2$	
	$0 \leq q_i^{\text{penalty}}$	
	$q_i^{\text{penalty}} \geq [(q_i^c + q_i^r) \cdot \beta - q_i^r]$	
	$p_1 - p_2 + \eta_1 - \eta_2 = 0$	
	$\eta_1 \cdot (f - K) = 0$	
	$\eta_2 \cdot (-f - K) = 0$	
	$f - K \leq 0$	
	$-f - K \leq 0$	
	$0 \leq q_1^c \leq K_1^c$	
	$0 \leq q_1^r \leq K_1^r$	
	$0 \leq q_2^c \leq K_2^c$	
	$0 \leq q_2^r \leq K_2^r$	
	$0 \leq p_1 \quad 0 \leq y_1 \quad 0 \leq \eta_1$	
	$0 \leq p_2 \quad 0 \leq y_2 \quad 0 \leq \eta_2$	
	$0 \leq p_1 \quad 0 \leq y_1 \quad 0 \leq \eta_1$	
	$0 \leq p_2 \quad 0 \leq y_2 \quad 0 \leq \eta_2$	

APPENDIX B: MODELING OF RE POLICIES UNDER PERFECT COMPETITION

<u>Carbon Tax</u>	<u>Feed - in Tariff</u>
$Min \quad \sum_i [q_i^c \cdot (c_i^c + \alpha^c \cdot \gamma_i^c) + q_i^r \cdot c_i^r]$	$Min \quad \sum_i [q_i^c \cdot c_i^c + q_i^r \cdot (p_i^{FT} - c_i^r)]$
<i>s.t.</i>	<i>s.t.</i>
$y_1 + f = q_1^c + q_1^r$	$y_1 + f = q_1^c + q_1^r$
$y_2 - f = q_2^c + q_2^r$	$y_2 - f = q_2^c + q_2^r$
$p_1 + b_1 \cdot y_1 = a_1$	$p_1 + b_1 \cdot y_1 = a_1$
$p_2 + b_2 \cdot y_2 = a_2$	$p_2 + b_2 \cdot y_2 = a_2$
$p_1 - p_2 + \eta_1 - \eta_2 = 0$	$p_1 - p_2 + \eta_1 - \eta_2 = 0$
$\eta_1 \cdot (f - K) = 0$	$\eta_1 \cdot (f - K) = 0$
$\eta_2 \cdot (-f - K) = 0$	$\eta_2 \cdot (-f - K) = 0$
$f - K \leq 0$	$f - K \leq 0$
$-f - K \leq 0$	$-f - K \leq 0$
$0 \leq q_1^c \leq K_1^c$	$0 \leq q_1^c \leq K_1^c$
$0 \leq q_1^r \leq K_1^r$	$0 \leq q_1^r \leq K_1^r$
$0 \leq q_2^c \leq K_2^c$	$0 \leq q_2^c \leq K_2^c$
$0 \leq q_2^r \leq K_2^r$	$0 \leq q_2^r \leq K_2^r$
$0 \leq p_1 \quad 0 \leq y_1 \quad 0 \leq \eta_1$	$0 \leq p_1 \quad 0 \leq y_1 \quad 0 \leq \eta_1$
$0 \leq p_2 \quad 0 \leq y_2 \quad 0 \leq \eta_2$	$0 \leq p_2 \quad 0 \leq y_2 \quad 0 \leq \eta_2$

<u>Premium Payments</u>		Quota Obligation
$Min \quad \sum_i [q_i^c \cdot c_i^c + q_i^r \cdot (PREM_i - c_i^r)]$		$Min \quad \sum_i [q_i^c \cdot c_i^c + q_i^r \cdot c_i^r + C^{penalty} \cdot q_i^{penalty}]$
$s.t.$		$s.t.$
$y_1 + f = q_1^c + q_1^r$		$y_1 + f = q_1^c + q_1^r$
$y_2 - f = q_2^c + q_2^r$		$y_2 - f = q_2^c + q_2^r$
$p_1 + b_1 \cdot y_1 = a_1$		$p_1 + b_1 \cdot y_1 = a_1$
$p_2 + b_2 \cdot y_2 = a_2$		$p_2 + b_2 \cdot y_2 = a_2$
$p_1 - p_2 + \eta_1 - \eta_2 = 0$		$0 \leq q_i^{penalty}$
$\eta_1 \cdot (f - K) = 0$		$q_i^{penalty} \geq [(q_i^c + q_i^r) \cdot \beta - q_i^r]$
$\eta_2 \cdot (-f - K) = 0$		$p_1 - p_2 + \eta_1 - \eta_2 = 0$
$f - K \leq 0$		$\eta_1 \cdot (f - K) = 0$
$-f - K \leq 0$		$\eta_2 \cdot (-f - K) = 0$
$0 \leq q_1^c \leq K_1^c$		$f - K \leq 0$
$0 \leq q_1^r \leq K_1^r$		$-f - K \leq 0$
$0 \leq q_2^c \leq K_2^c$		$0 \leq q_1^c \leq K_1^c$
$0 \leq q_2^r \leq K_2^r$		$0 \leq q_1^r \leq K_1^r$
$0 \leq p_1 \quad 0 \leq y_1 \quad 0 \leq \eta_1$		$0 \leq q_2^c \leq K_2^c$
$0 \leq p_2 \quad 0 \leq y_2 \quad 0 \leq \eta_2$		$0 \leq q_2^r \leq K_2^r$
		$0 \leq p_1 \quad 0 \leq y_1 \quad 0 \leq \eta_1$
		$0 \leq p_2 \quad 0 \leq y_2 \quad 0 \leq \eta_2$

APPENDIX C: BEST-RESPONSE FUNCTION OF RE POLICIES

Figure 24: Best-Response Functions (Tax = \$32/ton of CO₂) under the Carbon Tax Policy

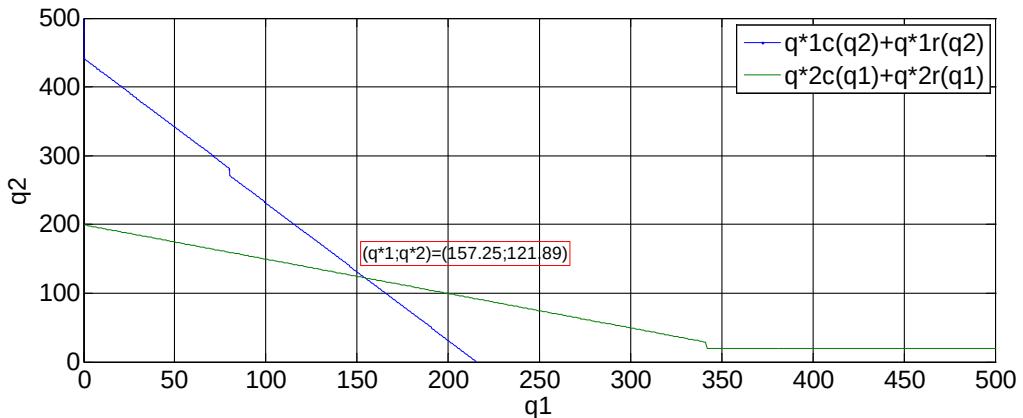


Figure 25: Best-Response Functions under the Feed-in Tariff Policy

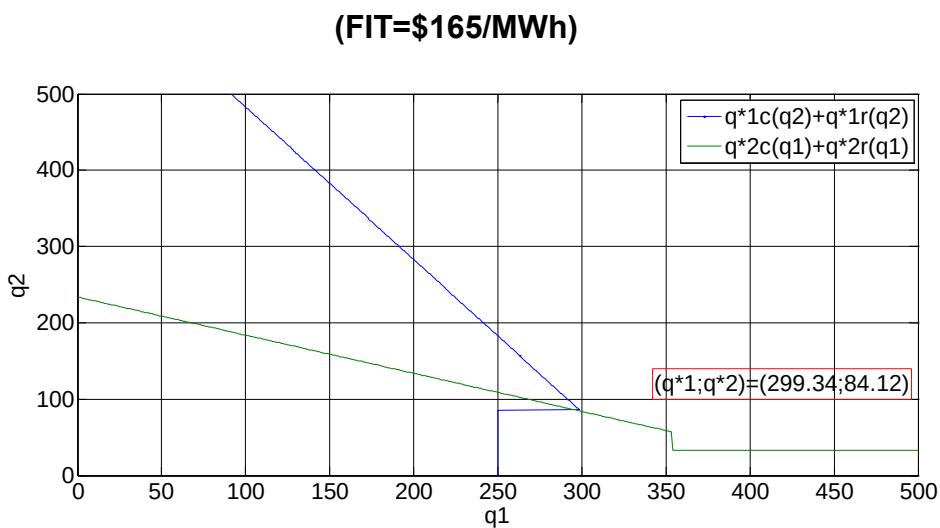


Figure 26: Best-Response Functions under the Premium Policy

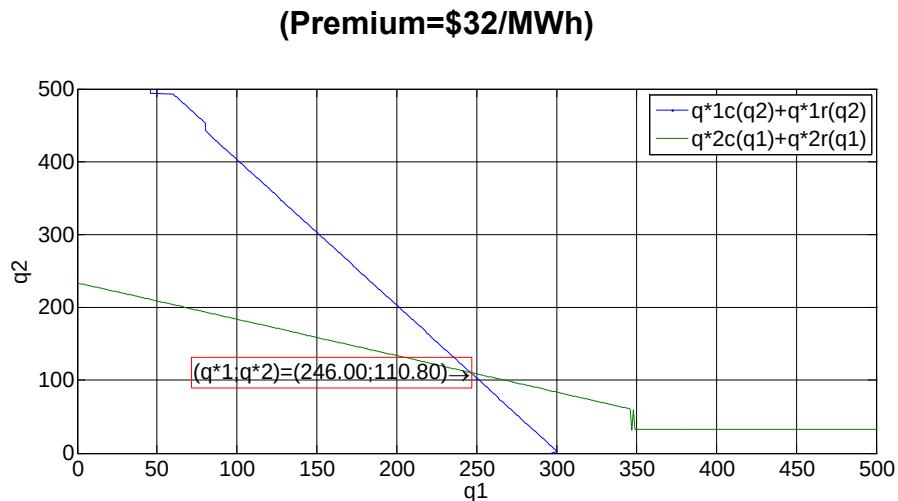


Figure 27: Best-Response Functions under the Quota Policy

