Strategic Interactions in the Solar PV Module Supply Chain: An EPEC Framework for Economic and Geopolitical Analysis

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Abstract

Keywords— Nomenclature

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Sets:	$r, i, e \in R$	
Parameters:	$a_i > 0,\ b_i > 0$	Inverse demand in i : $P_i(x_i) = a$
	$D_i^{max} > 0$	Demand/installation cap in i
	c_r^{man}	Manufacturing cost in r
	c_{ri}^{ship}	Shipping cost from r to i
	Q_r^{cap}	Existing capacity in r
	$\overline{\tau}_{ir}^{imp} \geq 0$	Upper bound on import tariff (i
	$\overline{\tau}_{ri}^{exp} \geq 0$	Upper bound on export tax (r to
	$\rho_r^{imp}, \rho_r^{exp} \geq 0$	**Linear penalty weights**
	$\kappa_r \geq 0$	Linear penalty on offered capacit
	$w_r \geq 0$	Weight on consumer surplus in w
	$\varepsilon_x \geq 0$	Flow regularization parameter
	$\varepsilon_{comp} \geq 0$	Complementarity relaxation toler
Strategic (ULP) variables:	$Q_r^{offer} \in [0, Q_r^{cap}]$	Offered capacity in r
	$\tau_{ir}^{imp} \in [0, \overline{\tau}_{ir}^{imp}]$	Import tariff set by i on r
	$\tau_{ri}^{exp} \in [0, \overline{\tau}_{ri}^{exp}]$	Export tax set by r on i
	$\tau_{ii}^{imp} = 0,\ \tau_{ii}^{exp} = 0$	$\forall i$
LLP primal variables:	$x_{ri} \geq 0$	Shipment $r \to i$
	$x_i^{dem} \in [0, D_i^{max}]$	Consumption in i
LLP dual variables:	$\lambda_i \in \mathbb{R}$	Dual of node balance in i
	$\mu_r \geq 0$	Dual of exporter capacity in r
	$\gamma_{ri} \geq 0$	Dual of $x_{ri} \geq 0$
	$\beta_i \geq 0$	Dual of $x_i^{dem} \leq D_i^{max}$
	$\psi_i \geq 0$	Dual of $x_i^{dem} \geq 0$
Implemented price bounds (numerical stabilization):	$0 \leq \lambda_i \leq a_i$	$\forall i$

Utility: $U_i(x) = a_i x_i^{dem} - \frac{1}{2} b_i (x_i^{dem})^2$

Delivered wedge: $k_{ri} := c_r^{man} + c_{ri}^{ship} + \tau_{ri}^{exp} + \tau_{ir}^{imp}$

LLP (system clearing):

$$
\begin{aligned}
\min_{x,\, x^{dem}} \quad & \sum_{r,i\in R} \left(c_r^{man} + c_{ri}^{ship} + \tau_{ri}^{exp} + \tau_{ir}^{imp}\right) x_{ri} + \frac{\varepsilon_x}{2} \sum_{r,i\in R} x_{ri}^2 - \sum_{i\in R} \Big(a_i x_i^{dem} - \tfrac{1}{2} b_i (x_i^{dem}) \\
\text{s.t.} \quad & \sum_{r\in R} x_{ri} - x_i^{dem} = 0 \quad (\lambda_i) \\
& Q_r^{offer} - \sum_{i\in R} x_{ri} \geq 0 \quad (\mu_r) \\
& x_{ri} \geq 0 \quad (\gamma_{ri}) \\
& D_i^{max} - x_i^{dem} \geq 0 \quad (\beta_i) \\
& x_i^{dem} \geq 0 \quad (\psi_i)
\end{aligned}
$$

Stationarity (KKT):

$$
\begin{aligned}
& k_{ri} + \varepsilon_x x_{ri} - \lambda_i + \mu_r - \gamma_{ri} = 0 && \forall r, i \in R \\
& -\left(a_i - b_i x_i^{dem}\right) + \lambda_i + \beta_i - \psi_i = 0 && \forall i \in R
\end{aligned}
$$

Complementarity (relaxed):

$$
\begin{aligned}
& \mu_r \cdot \left(Q_r^{offer} - \sum_{i\in R} x_{ri}\right) \leq \varepsilon_{comp} && \forall r \in R \\
& \gamma_{ri} \cdot x_{ri} \leq \varepsilon_{comp} && \forall r, i \in R \\
& \beta_i \cdot \left(D_i^{max} - x_i^{dem}\right) \leq \varepsilon_{comp} && \forall i \in R \\
& \psi_i \cdot x_i^{dem} \leq \varepsilon_{comp} && \forall i \in R
\end{aligned}
$$

ULP (welfare player r):

$$
\begin{aligned}
\max_{Q_r^{offer},\, \tau_{r\cdot}^{imp},\, \tau_{r\cdot}^{exp}} \quad & w_r \left[\left(a_r x_r^{dem} - \tfrac{1}{2} b_r (x_r^{dem})^2\right) - \lambda_r x_r^{dem}\right] \\
& + \sum_{j\in R} \tau_{rj}^{imp}\, x_{jr} + \sum_{j\in R} \tau_{rj}^{exp}\, x_{rj} \\
& + \sum_{j\in R} \left(\lambda_j - c_r^{man} - c_{rj}^{ship} - \tau_{jr}^{imp}\right) x_{rj} \\
& - \rho_r^{imp} \sum_{e\in R} \tau_{re}^{imp} - \rho_r^{exp} \sum_{i\in R} \tau_{ri}^{exp} - \kappa_r Q_r^{offer} \\
\text{s.t.} \quad & 0 \leq Q_r^{offer} \leq Q_r^{cap} \\
& 0 \leq \tau_{re}^{imp} \leq \overline{\tau}_{re}^{imp} \\
& 0 \leq \tau_{ri}^{exp} \leq \overline{\tau}_{ri}^{exp} \\
& \text{LLP KKT conditions hold.}
\end{aligned}
$$