Optimal Unilateral Carbon Policy

David Weisbach, Samuel Kortum, and Michael Wang

Excellent research assistance by Bella Yao and
comments from Michael Barresi

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Need for Unilateral Policy

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- Hard to solve the global externality of carbon emissions without a broad coalition adopting a policy
  - Nordhaus (2015) explores how to sustain such a coalition, advocating international trade policy as leverage
- Broader is better, but unlikely to get all countries on board
- **We take the coalition as given** and ask how to optimize a unilateral carbon policy
  - to minimize the cost of achieving a given reduction in global emissions

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  - via so called “carbon leakage”
- Or can trade strengthen a coalition’s unilateral policy?
  - by expanding its reach
- **Analysis here implies coalition can exploit trade to make its unilateral policy more efficient than in autarky**

Preview of Results

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- Home country's optimal unilateral policy:

    1. tax energy extraction and energy used in goods production; the two sum to marginal damages

    2. mix of taxes reduces leakage and improves terms of trade

    3. Full border adjustment on energy content of imports

    4. Tax is not removed on energy content of goods exports

    5. Home subsidizes marginal exporters, per unit exported

    6. The set of goods Home exports expands relative to BAU

Modeling Ingredients

- Two-country trade model (Home acts unilaterally)
- Markusen (1975) suitable for modeling energy extraction, externalities, and policy
- Combine with Dornbusch, Fischer, Samuelson (1977) to get trade in manufactured goods using energy as an input
- Primal method for deriving optimal policy, Dixit (1985)
  - applied to DFS by Costinot, Donaldson, Vogel, and Werning (2015)
- Stylized, but key elements mimic a big CGE model

Carbon in the Model

1. Carbon is pulled from the earth by fossil fuel extraction

2. It’s then embodied in energy trade

3. Released into the atmosphere through combustion

    - by manufacturers producing goods (or utilities generating electricity for them)

4. Carbon is implicitly embodied in these manufactured goods, traded prior to being consumed

5. Carbon can therefore be tracked to where manufactured goods are consumed

Outline

1. Model setup
2. Competitive equilibrium
3. Planner's problem (a gargantuan Lagrangian!)
    1. Autarky
    2. Trade in energy and services
    3. Trade in energy, services, and manufactured goods
4. Implement solution in a decentralized economy
5. Insights for policy

Model Setup

- **Countries:** Home and Foreign (*)
- **Endowments:** L (labor) and E (energy deposits)
- **Sectors:** services (uses labor), manufactured goods (uses energy and labor), energy (uses labor and energy deposits)
- Full labor mobility across sectors
- Services are the numeraire when we decentralize
  - unit labor requirement for services pins down wage of 1
  - … assume services are produced in each country

Preferences

- Home

Social Cost of Carbon

$$U = C_s + \alpha^{1/\sigma} \frac{C_g^{(\sigma-1)/\sigma}}{(\sigma - 1)/\sigma} - \varphi Q_e^W$$

$$C_g = \left(\int_0^1 c_j^{(\sigma-1)/\sigma} dj \right)^{\sigma/(\sigma-1)}$$

- Note the linearity across goods!

- Foreign parameters may differ (*), but for today's talk many are assumed to be the same for simplicity

Technology

- Energy extraction

$$Q_e = \left(L_e/\beta\right)^{\beta} E^{1-\beta}$$

- Production of manufactured good $j \in [0,1]$

$$q_j = \frac{1}{a_j}\left(l_j/\gamma\right)^{\gamma}\left(e_j/(1-\gamma)\right)^{1-\gamma}$$

- Relative efficiency Home continuous, strictly decreasing

$$\frac{a_j^*}{a_j} = F(j)$$

- Iceberg trade costs τ for manufactured goods

Competitive Equilibrium

Business as Usual (BAU)

Overview

1. Given an energy price, calculate energy intensity of production
2. Comparative advantage and trade costs determine which goods are imported and exported
3. Calculate supply and demand for each good
4. Aggregate to obtain demand for energy
5. Energy extraction sector determines supply
6. Energy price clears the global energy market

Energy in Production

- Energy intensity $z_j = e_j / l_j$
  - equalized across countries and goods in BAU

$$z = z(p_e) = \frac{1-\gamma}{\gamma p_e}$$

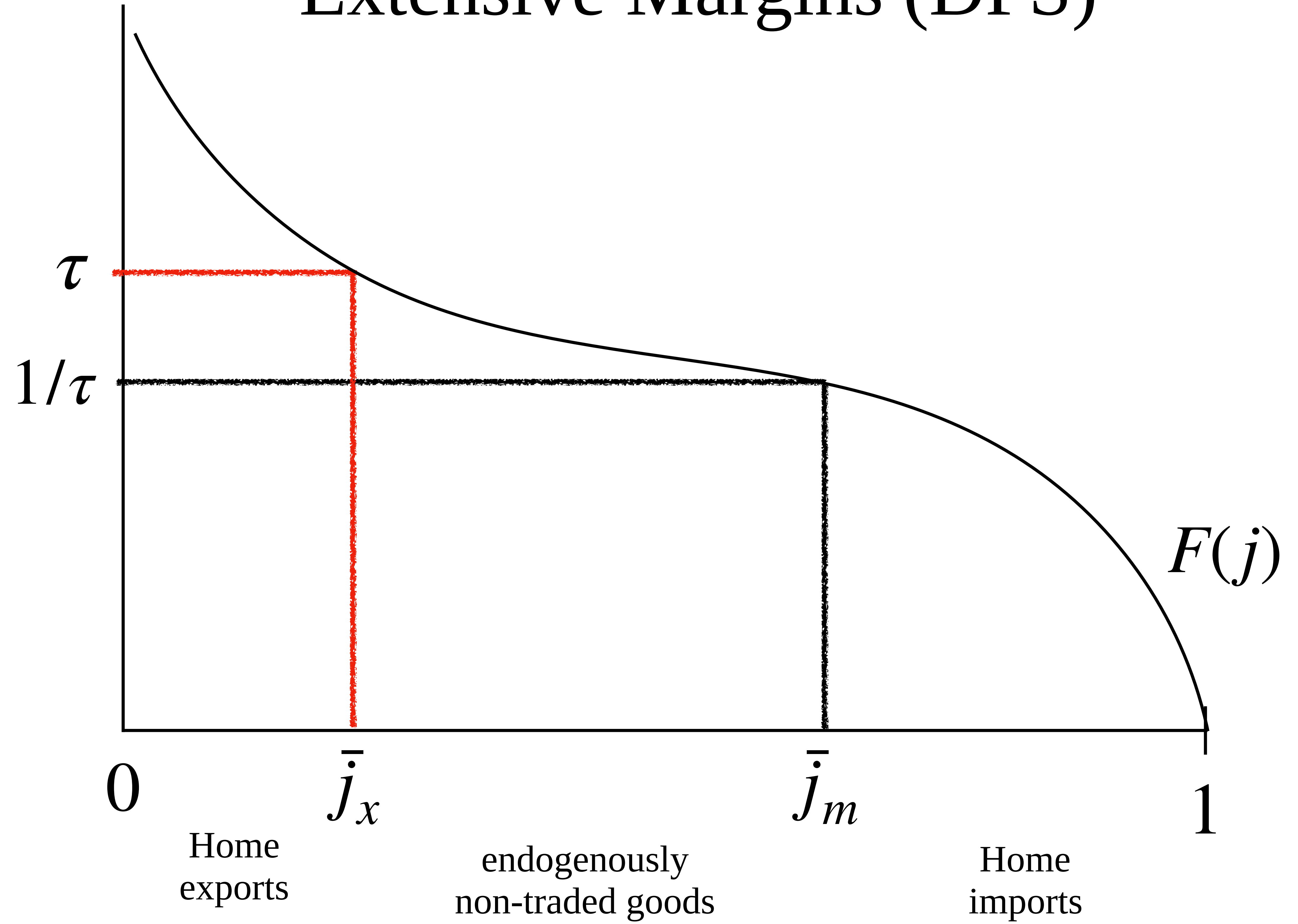
- Home's unit energy requirement

$$a_j^e = a_j^e(z) = (1-\gamma) a_j p_e^{-\gamma}$$

- Unit cost to produce good j in Home

$$a_j^l + p_e a_j^e = a_j p_e^{1-\gamma}$$

Extensive Margins (DFS)



Intensive Margin

- Need to consider

$$q_j = y_j + x_j$$

$$q_j^* = y_j^* + m_j$$

- If Home doesn't import good j it consumes

$$c_j = y_j = \alpha(a_j p_e^{1-\gamma})^{-\sigma}$$

- similar reasoning for the other 3 terms …

Demand for Energy

- Energy demand by Home's manufacturers to serve domestic consumers

$$C_e^{HH} = \int_0^{\bar{j}_m} a_j^e y_j dj$$

- Demand elasticity:

$$\gamma + (1-\gamma)\sigma$$

- Carbon flow matrix

$$\begin{array}{cc|c} C_e^{HH} & C_e^{HF} & C_e \\ C_e^{FH} & C_e^{FF} & C_e^* \\ \hline M_e & M_e^* & C_e^W \end{array}$$

Equilibrium Energy Price

- Home's energy supply curve (recall the wage is 1)

$$Q_e = Ep_e^{\beta/(1-\beta)}$$

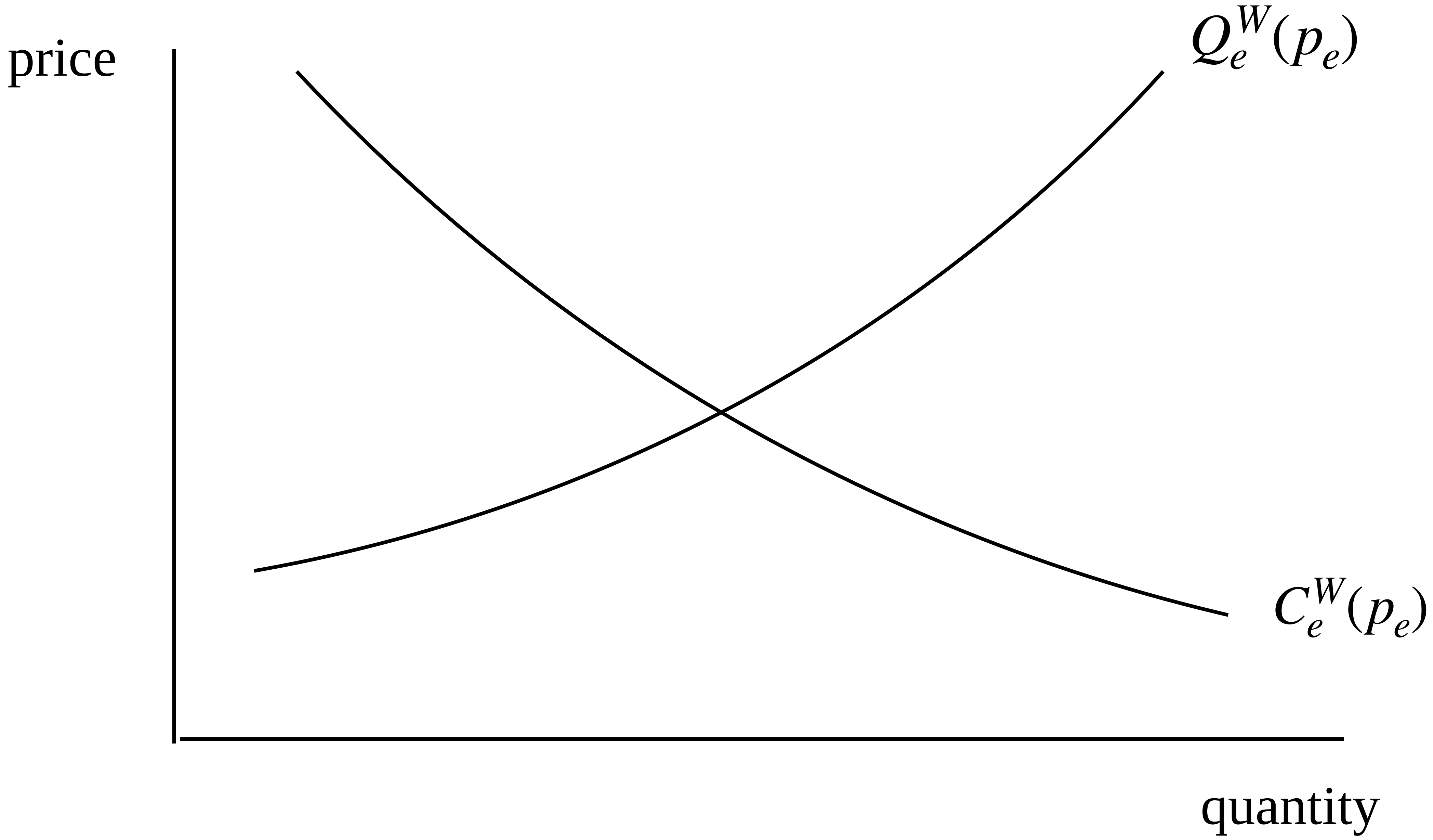
- World energy price solves

$$Q_e(p_e) + Q_e^*(p_e) = C_e(p_e) + C_e^*(p_e)$$

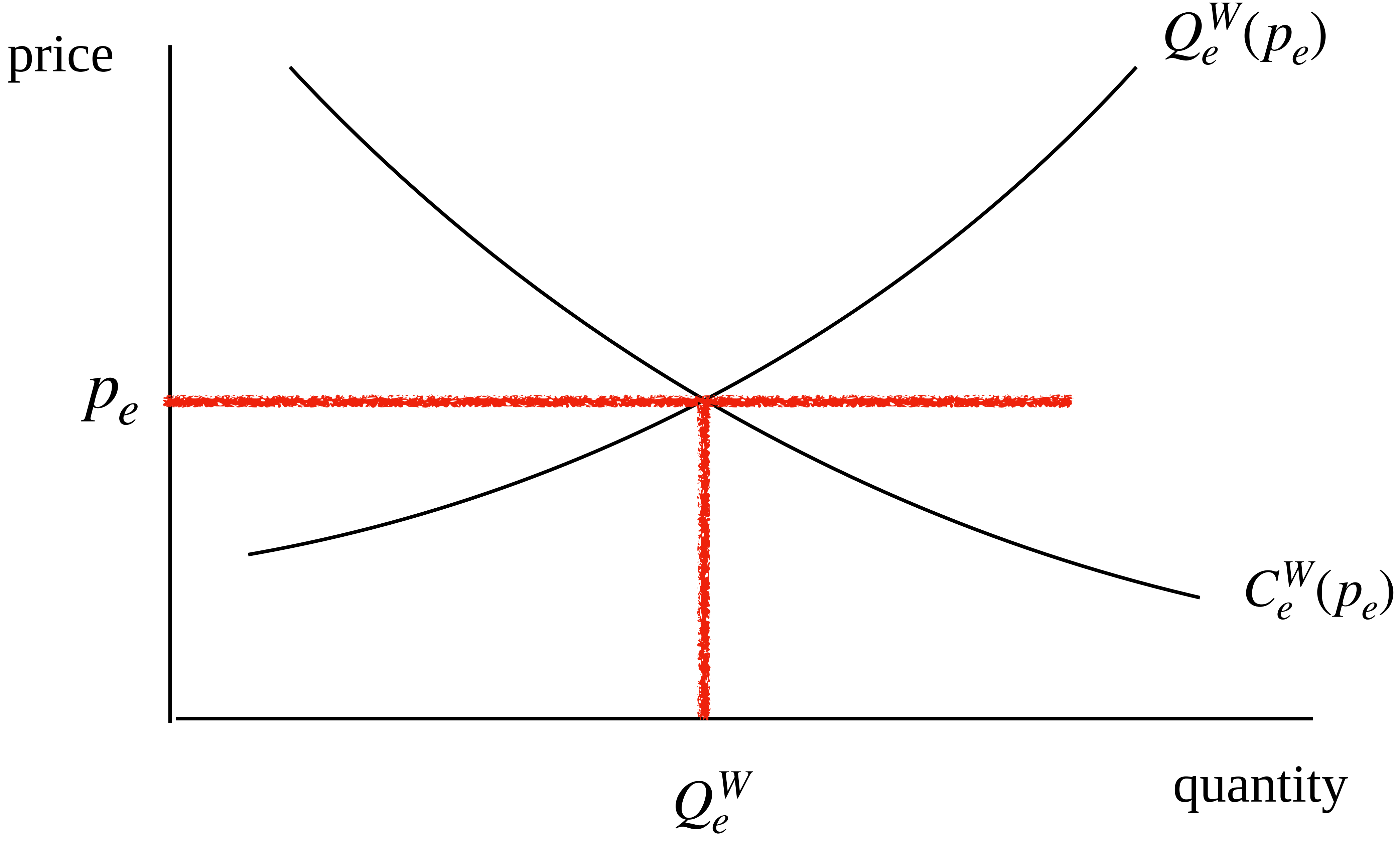
- Global emissions

$$Q_e^W(p_e) = C_e^W(p_e)$$

Global Energy Market



Global Energy Market



Planner’s Problem

Overview

- In BAU agents simply ignore the climate externality
- We now turn to a planner’s problem
    - the Home country does internalize the externality
    - while Foreign remains a price taker
    - no taxes or subsidies in the planner’s problem
        - they appear only when we decentralize it
        - no need to figure out which to include

Three Cases

1. Autarky
   - trivial but sets the stage
2. Trade in services and energy only
   - similar to Markusen (1975)
3. Trade in services, energy, and manufactured goods
   - extending Costinot, Donaldson, Vogel, and Werning (2015)

1. Autarky

Case I: Autarky

- **Planner's choices**
  - energy intensity of production for each good j
  - quantity produced of each good
  - quantity of energy to extract
- **Planner's constraints**
  - labor used constrained by L
  - energy used in production constrained by Q_e
- Substitute out the labor constraint using $C_s = Q_s$

Case I: Planner's Lagrangian

$$\mathscr{L} = \frac{\alpha^{1/\sigma}}{1 - 1/\sigma} \int_0^1 q_j^{1-1/\sigma} dj - \varphi Q_e$$

Home's welfare

$$-\beta E^{-(1-\beta)/\beta} Q_e^{1/\beta} - \int_0^1 a_j^l(z_j) q_j dj$$

Home's labor constraint

$$-\lambda_e \left(\int_0^1 a_j^e(z_j) q_j dj - Q_e \right)$$

Home's energy constraint

Optimality Conditions

- **Micro level** (good j)
  - energy intensity $z_j = z$
  - quantity of good j $c_j = q_j = \alpha \left(a_j \lambda_e^{1-\gamma} \right)^{-\sigma}$
- **Macro level**
  - energy extraction $\left(Q_e / E \right)^{(1-\beta)/\beta} = \lambda_e - \varphi$
  - like BAU energy supply curve, but "price" $\lambda_e - \varphi$
    - potential for a corner solution with $Q_e = 0$

Interpret as Decentralized Economy

- Try implementing planner's solution with specific unit taxes on extraction of energy and on use of energy

- Want a Pigouvian wedge φ between price that

  - extractors receive for energy $p_e - t_e$

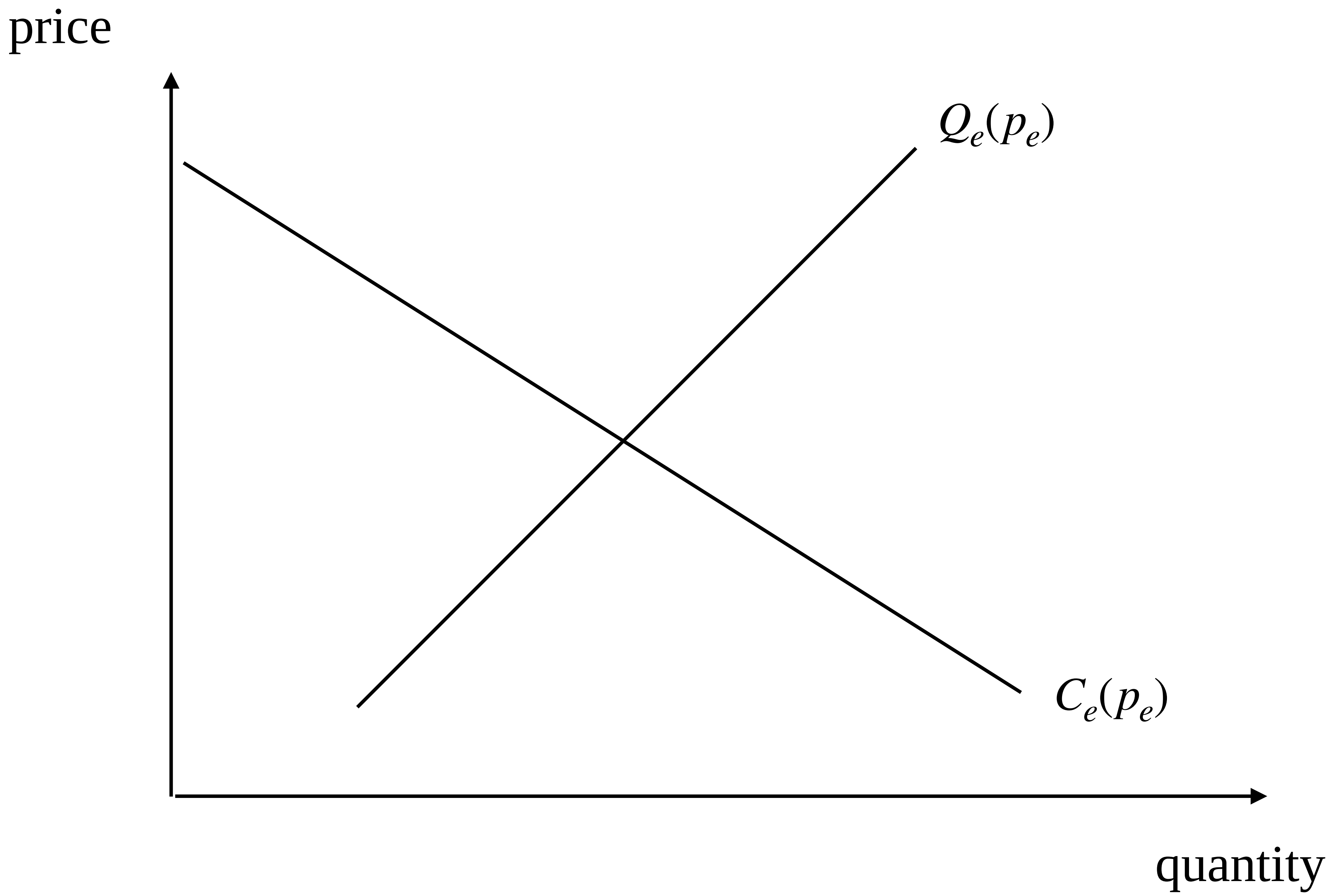
  - and price that manufacturers pay for it $p_e + t_p$

- Any combination will do if it satisfies

$$t_p + t_e = \varphi$$

  - this indeterminacy will vanish in an open economy

Home in Autarky



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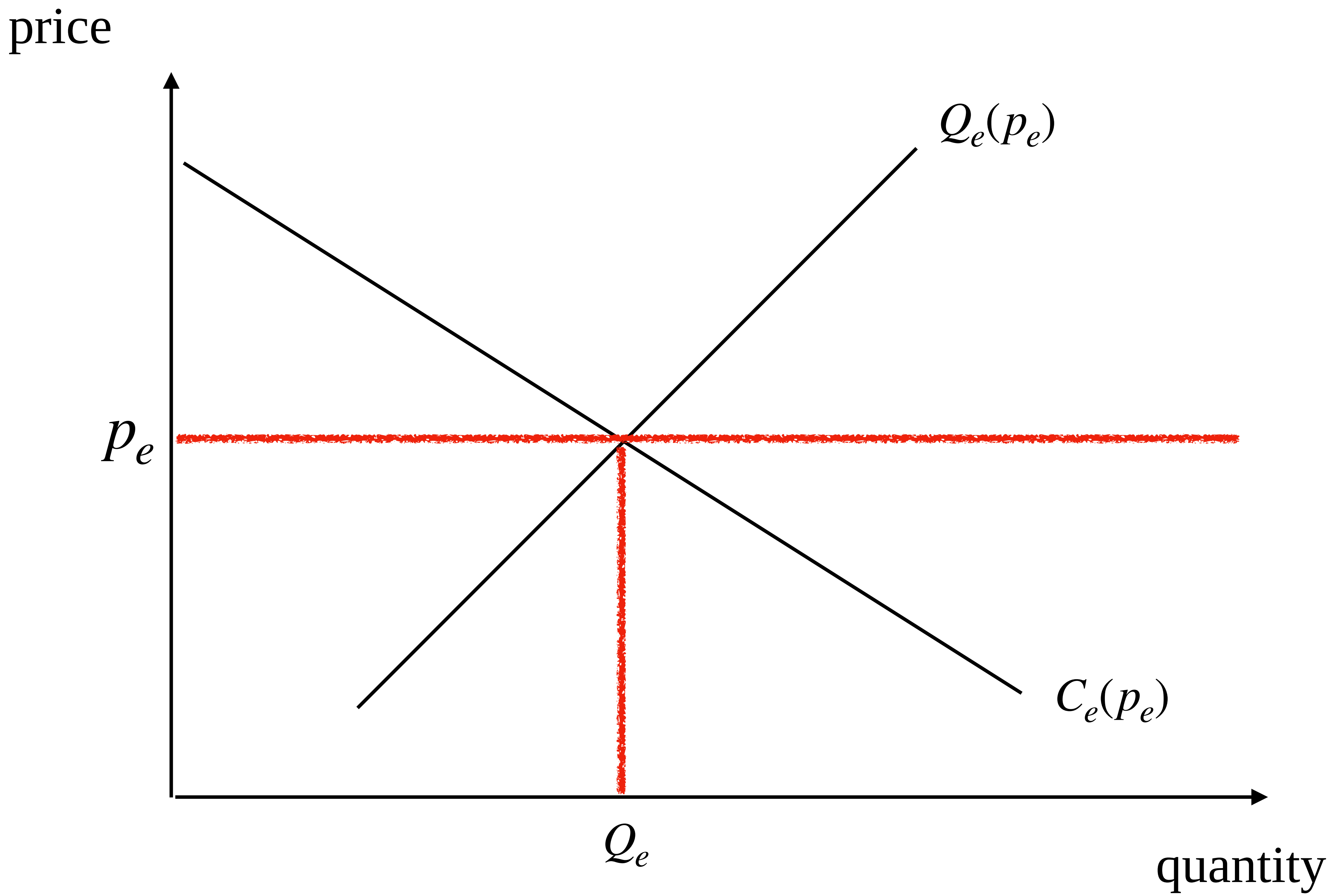

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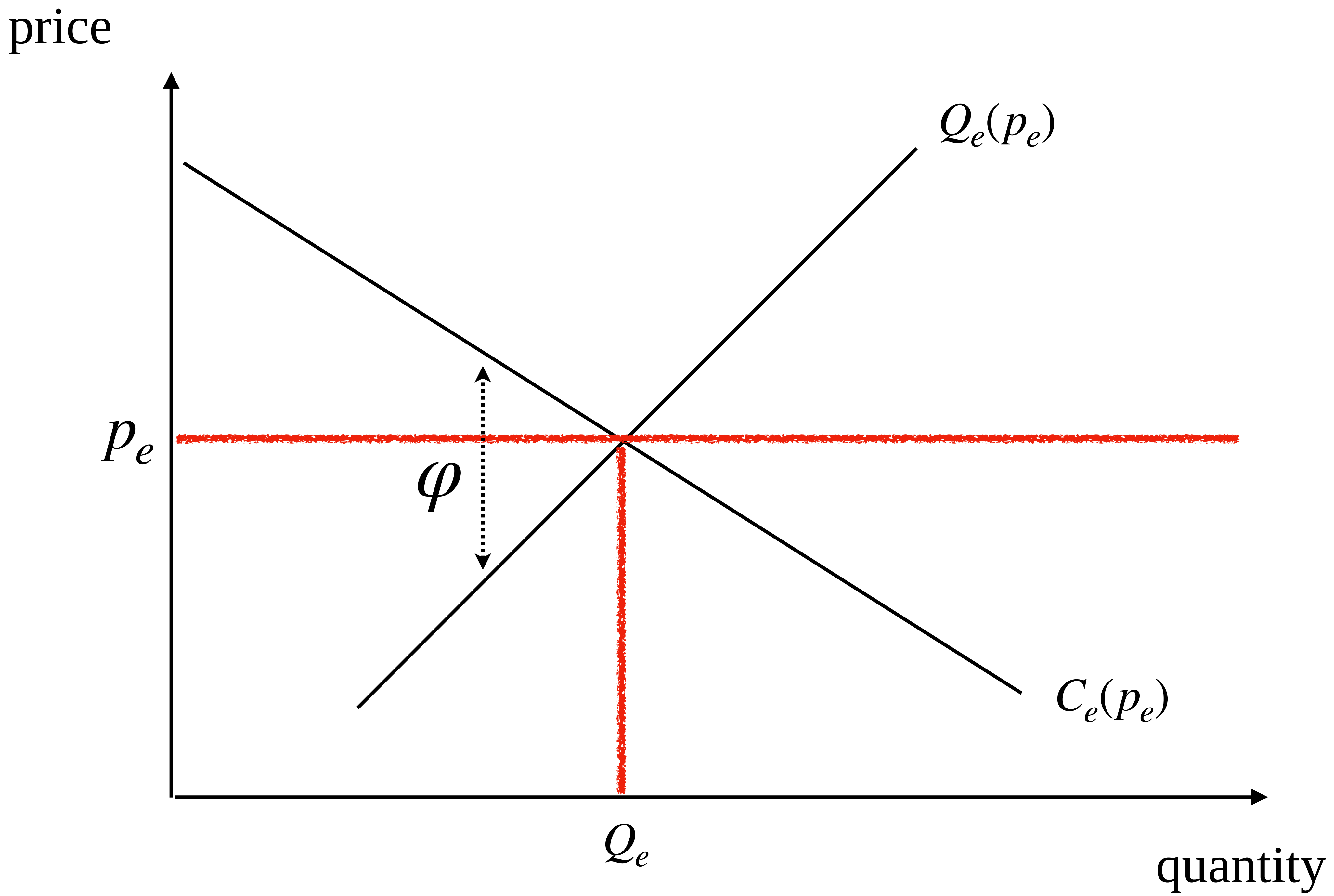

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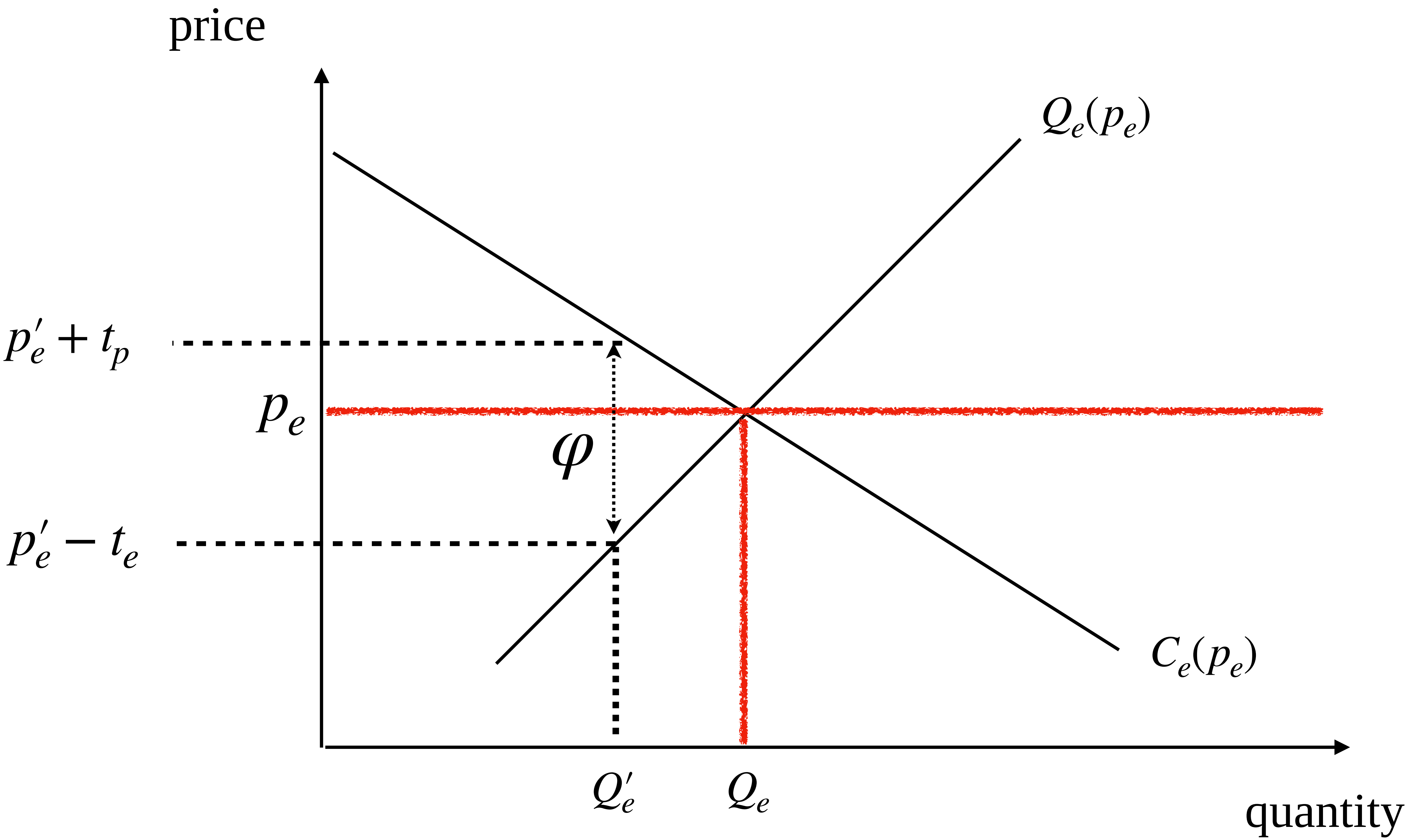

2. Trade in Services and Energy

Case II: Trade in Services and Energy

- **Planner's additional choices**
  - energy exports
  - energy price
- **Planner's additional constraints**
  - trade balance (exports X, may be negative) $X_s + p_e X_e = 0$
  - energy use in Foreign constrained by $Q_e^* + X_e$
- Substitute out trade balance constraint using $C_s = Q_s - X_s$

Treatment of Foreign

- Foreign chooses energy extraction, energy intensity, and quantities of each good j as in BAU

$$Q_e^*(p_e) = E^* p_e^{\beta/(1-\beta)}$$

$$z^*(p_e) = \frac{1-\gamma}{\gamma p_e}$$

$$q_j^*(p_e) = \alpha^*(a_j^* p_e^{1-\gamma})^{-\sigma}$$

- Home gets to choose the price of energy, to its advantage

Case II: Planner's Lagrangian

$$\mathscr{L} = \frac{\alpha^{1/\sigma}}{1-1/\sigma}\int_0^1 q_j^{1-1/\sigma}dj - \varphi\left(Q_e + Q_e^*(\downarrow p_e)\right)$$

Home's welfare

$$-\beta E^{-(1-\beta)/\beta}Q_e^{1/\beta} - \int_0^1 a_j^l(z_j)q_j dj$$

Home's labor constraint

$$+p_e X_e$$

trade balance constraint

$$-\lambda_e\left(\int_0^1 a_j^e(z_j)q_j dj - Q_e + X_e\right)$$

Home's energy constraint

$$-\lambda_e^*\left(\int_0^1 a_j^{e*}(z^*(\downarrow p_e))q_j^*(\downarrow p_e)dj - Q_e^*(\downarrow p_e) - X_e\right)$$

Foreign's energy constraint

Optimality Conditions

- Those from Case I plus:

  - First order condition for energy exports

$$\lambda_e = p_e + \lambda_e^*$$

  - First order condition for energy price

$$\lambda_e^* = \varphi \frac{\partial Q_e^* / \partial p_e}{\partial X_e^* / \partial p_e} + \frac{X_e^*}{\partial X_e^* / \partial p_e}$$

    - where $X_e^* = -X_e$ is Foreign's energy exports

Interpret as Decentralized Economy

- Production tax

$$t_p = \lambda_e^*$$

- Extraction tax

$$t_e = \varphi - t_p$$

- New: optimal production tax (resolves indeterminacy)

$$t_p = \varphi \frac{\partial Q_e^* / \partial p_e}{\partial X_e^* / \partial p_e} + \frac{X_e^*}{\partial X_e^* / \partial p_e}$$

Green is due to environmental externality

Red is classical optimal tariff

+

+ if Home imports
- if Home exports

Interpretation of New Condition

- As if Home's objective, given Pigouvian tax, is **minimize**

$$\min_{p_e} \left\{ t_e Q_e^*(p_e) + t_p C_e^*(p_e) + \int_0^{p_e} X_e^*(p)dp \right\}$$

carbon leakage terms — market power term

- If Home is an **energy importer**, rewrite as **maximizing**

$$\max_{p_e} \left\{ t_p X_e^*(p_e) - \varphi Q_e^*(p_e) - \int_0^{p_e} X_e^*(p)dp \right\}$$

import tariff revenue — externality — monopsony power

- If Home is an **energy exporter**, rewrite as **maximizing**

$$\max_{p_e} \left\{ -t_e X_e^*(p_e) - \varphi C_e^*(p_e) - \int_0^{p_e} X_e^*(p)dp \right\}$$

export tax revenue — externality — monopoly power

Examples for Illustration

- If **demand is totally inelastic**, the condition simplifies to

$$t_p = \varphi + \frac{X_e^*}{\partial Q_e^* / \partial p_e}$$

  - or

$$t_e = \frac{-X_e^*}{\partial Q_e^* / \partial p_e}$$

- If **supply is totally inelastic**, condition simplifies to

$$t_p = \frac{X_e^*}{-\partial C_e^* / \partial p_e}$$

  - recall that

$$-\partial C_e^* / \partial p_e > 0$$

Case II: Inelastic Foreign Demand

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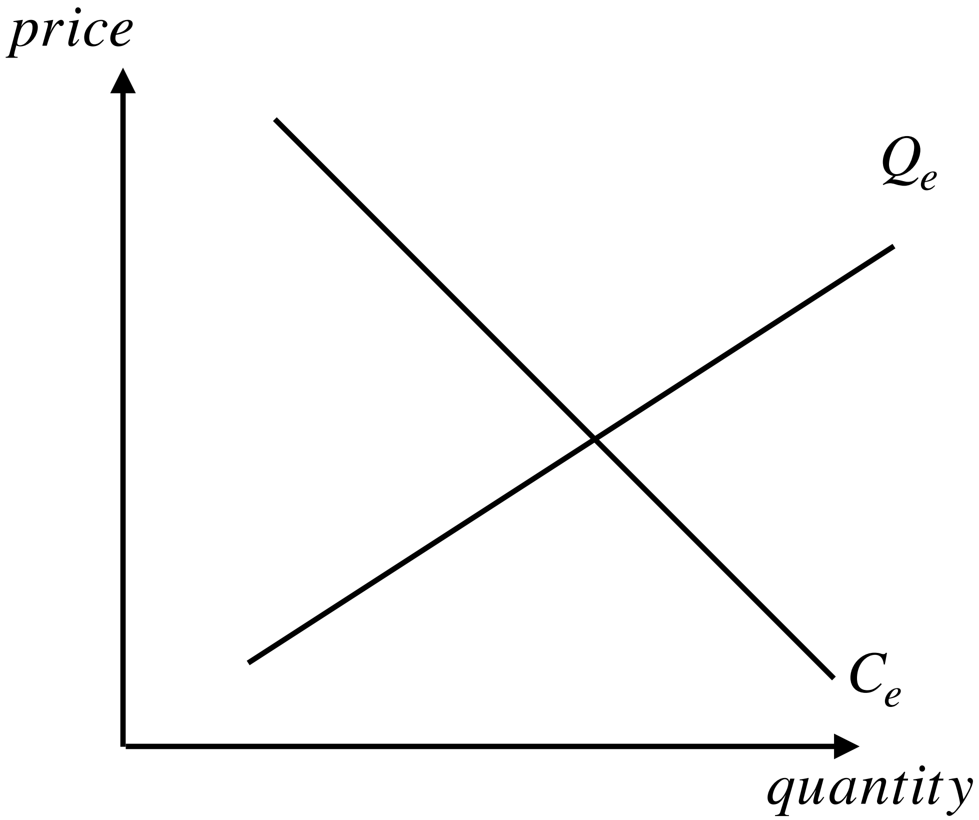
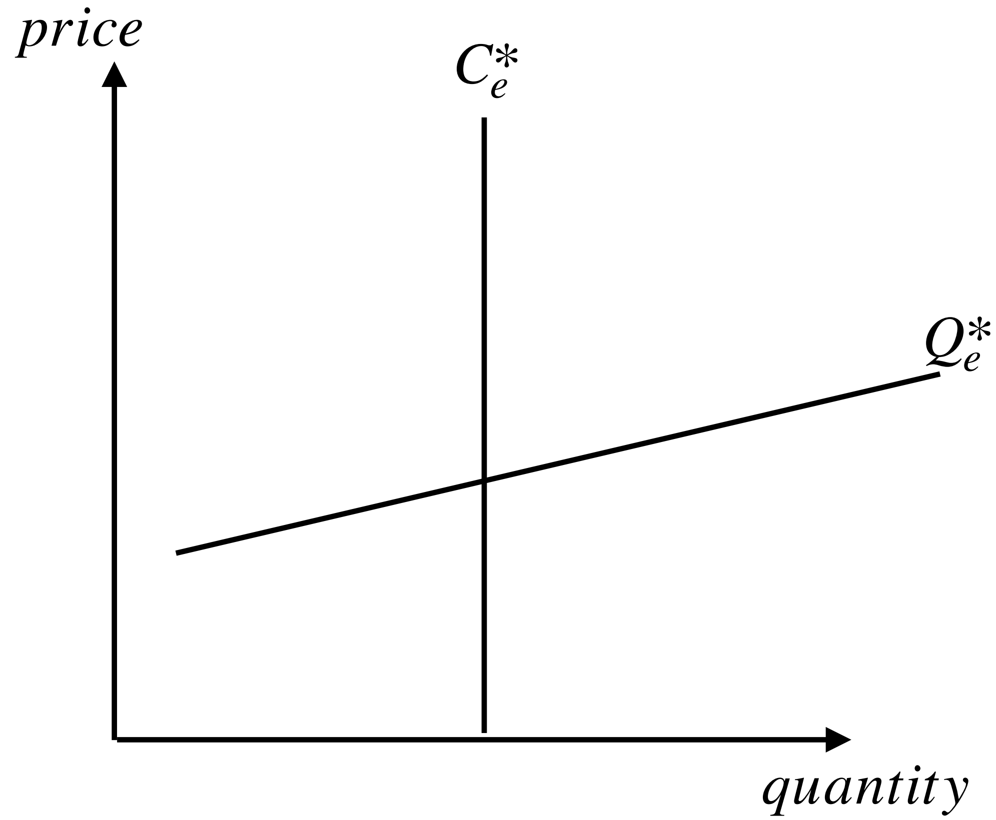
Home



Foreign



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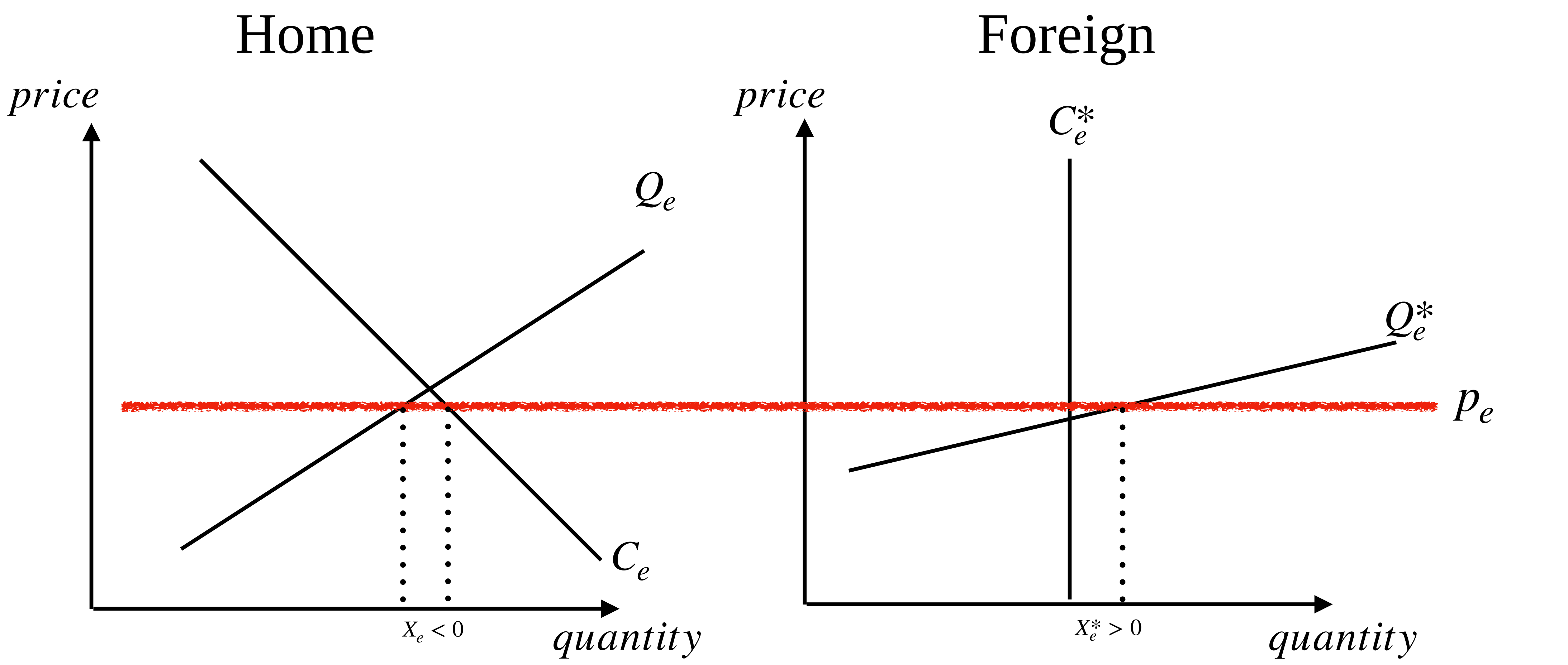

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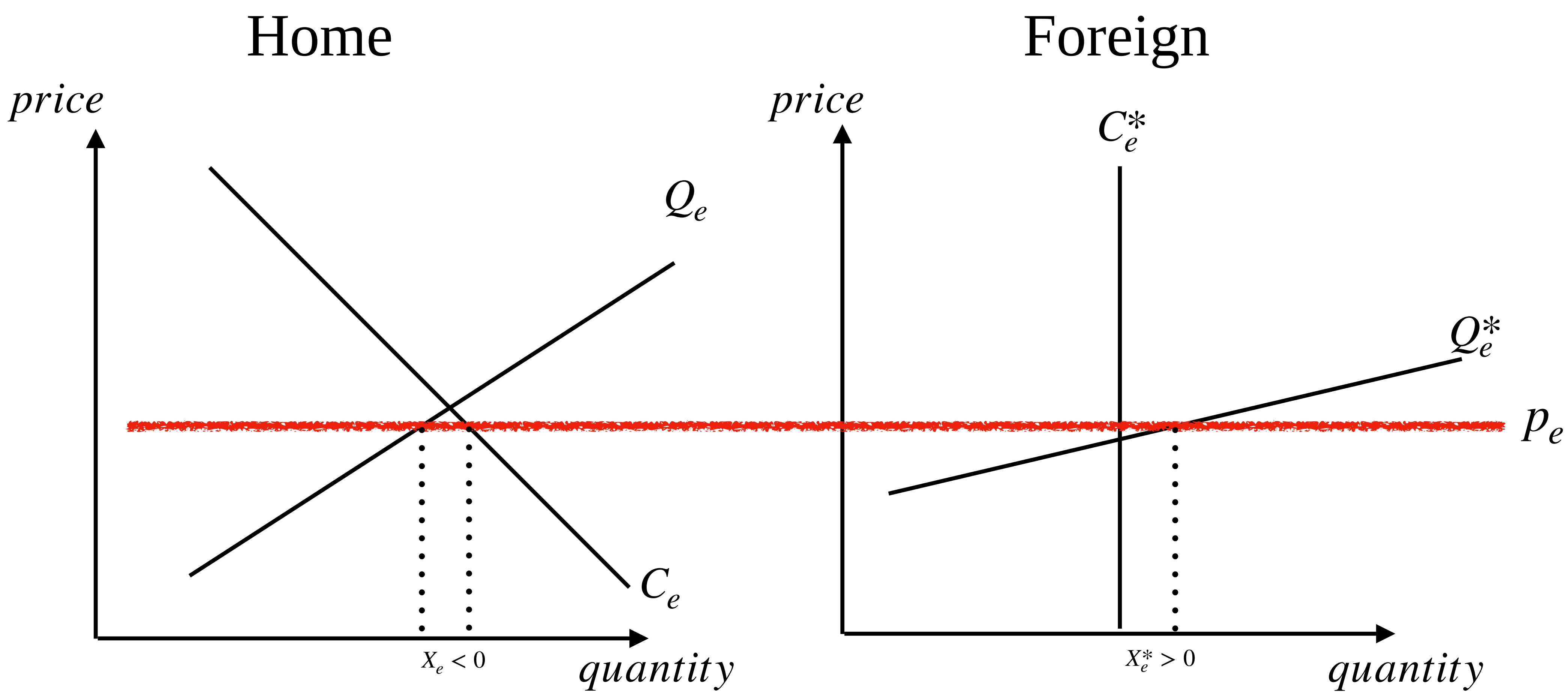

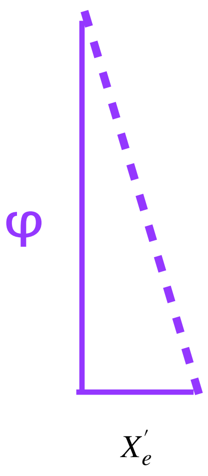

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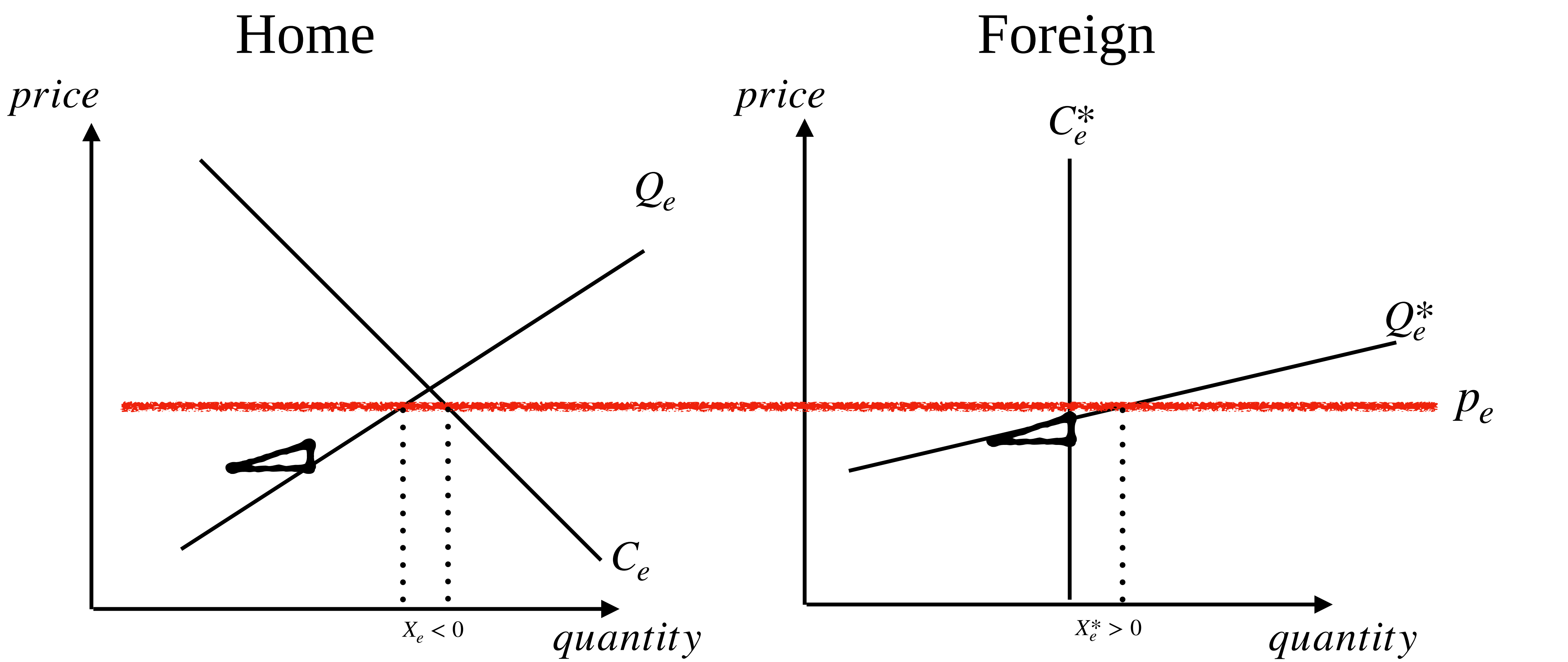

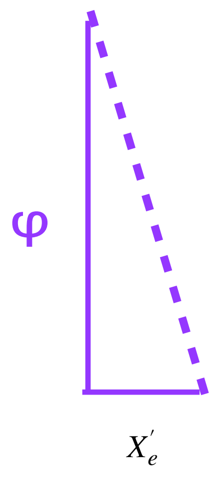

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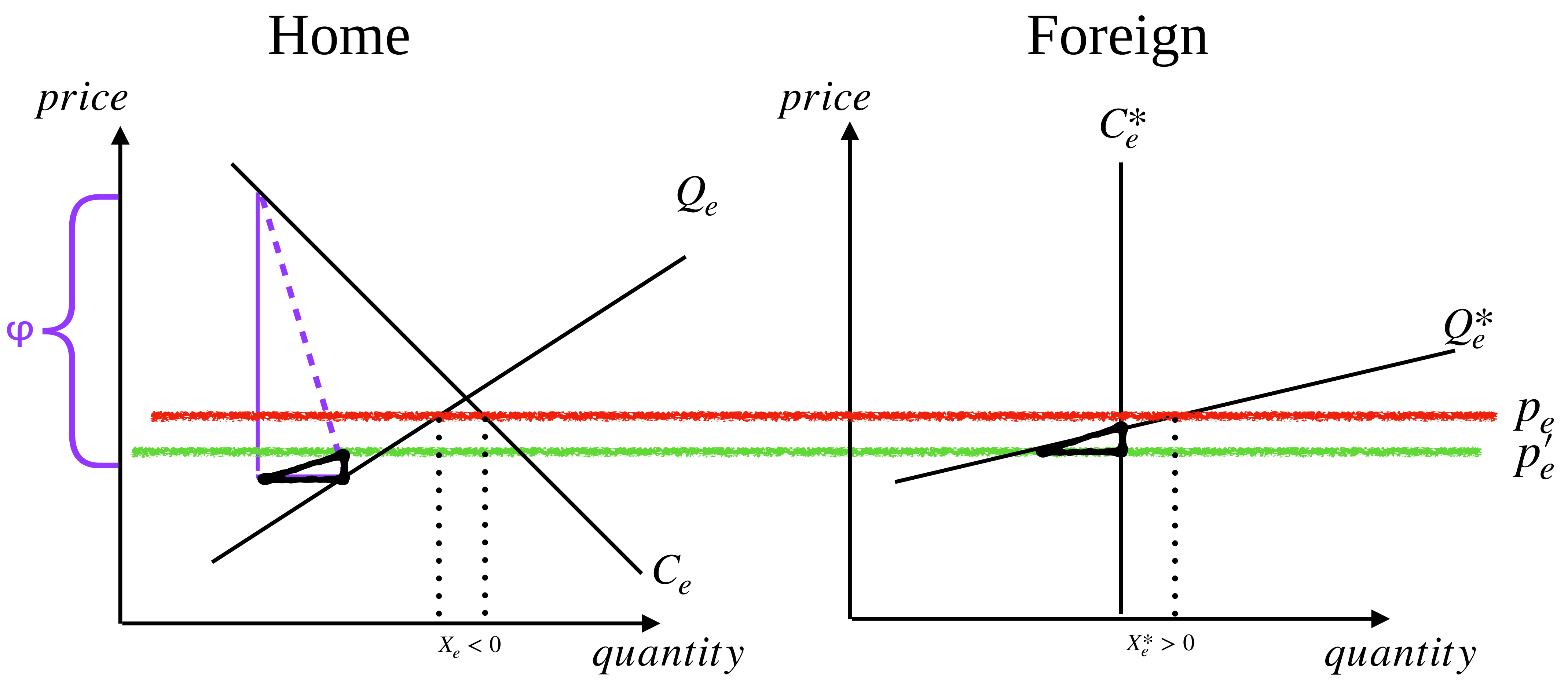

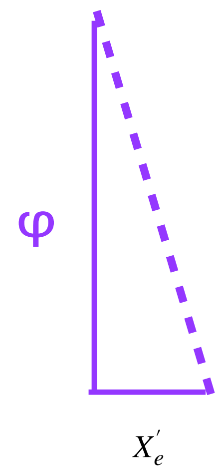

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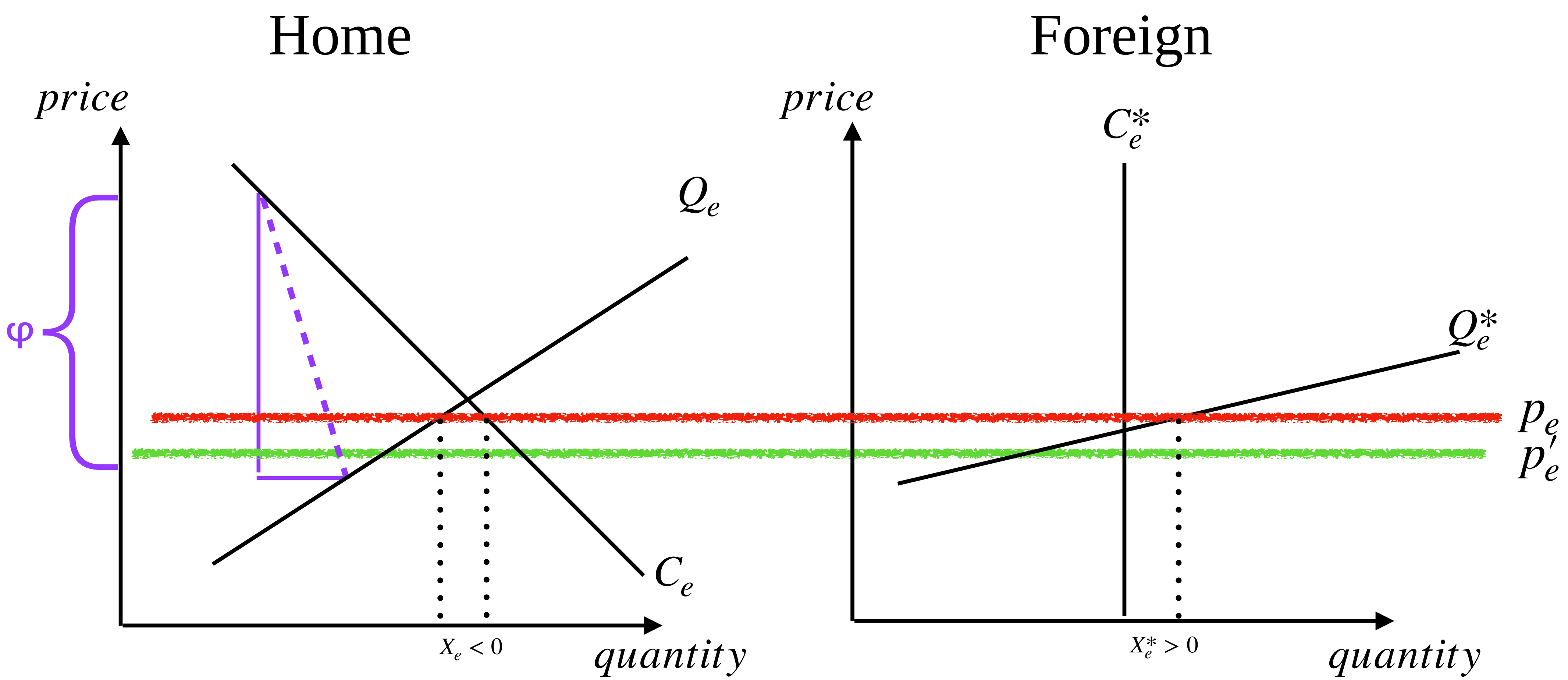

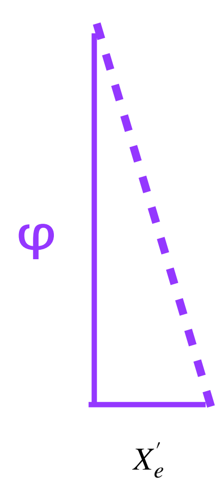

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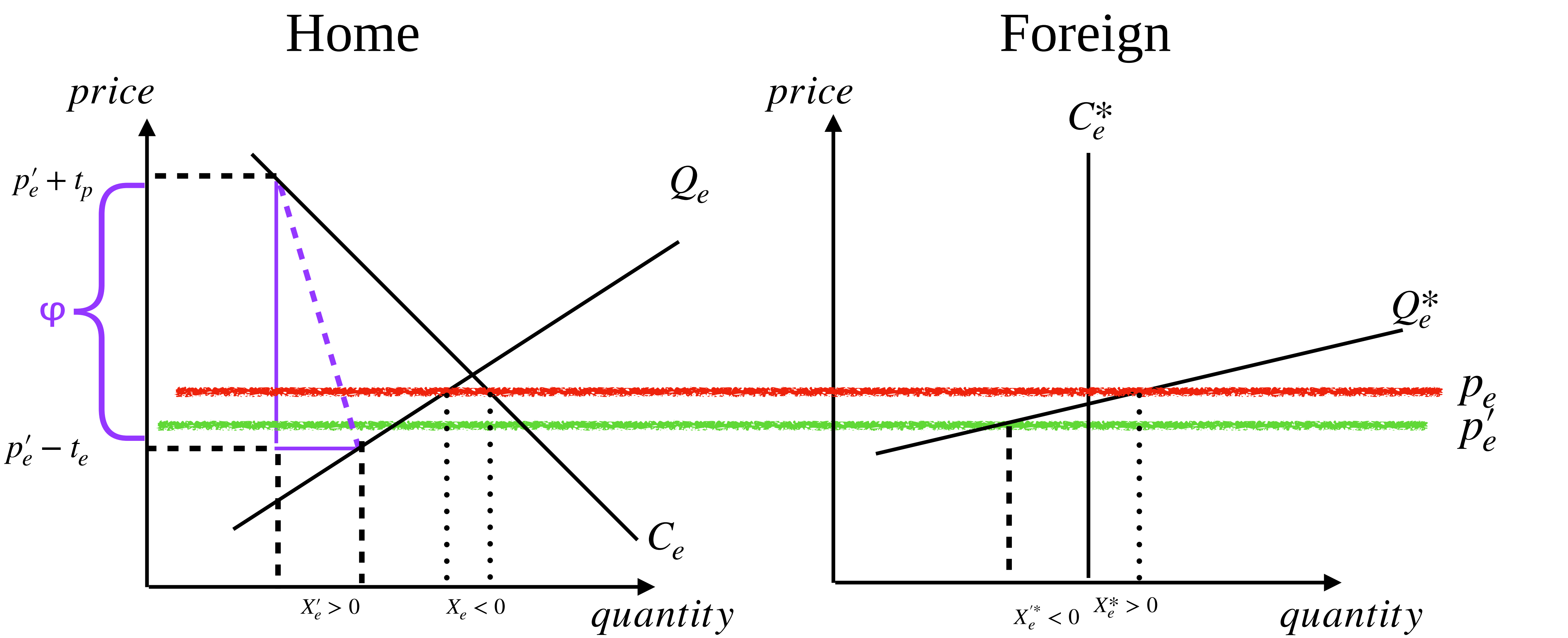

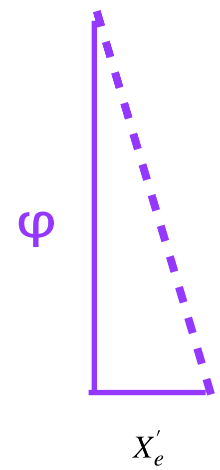

Case II: Inelastic Foreign Supply

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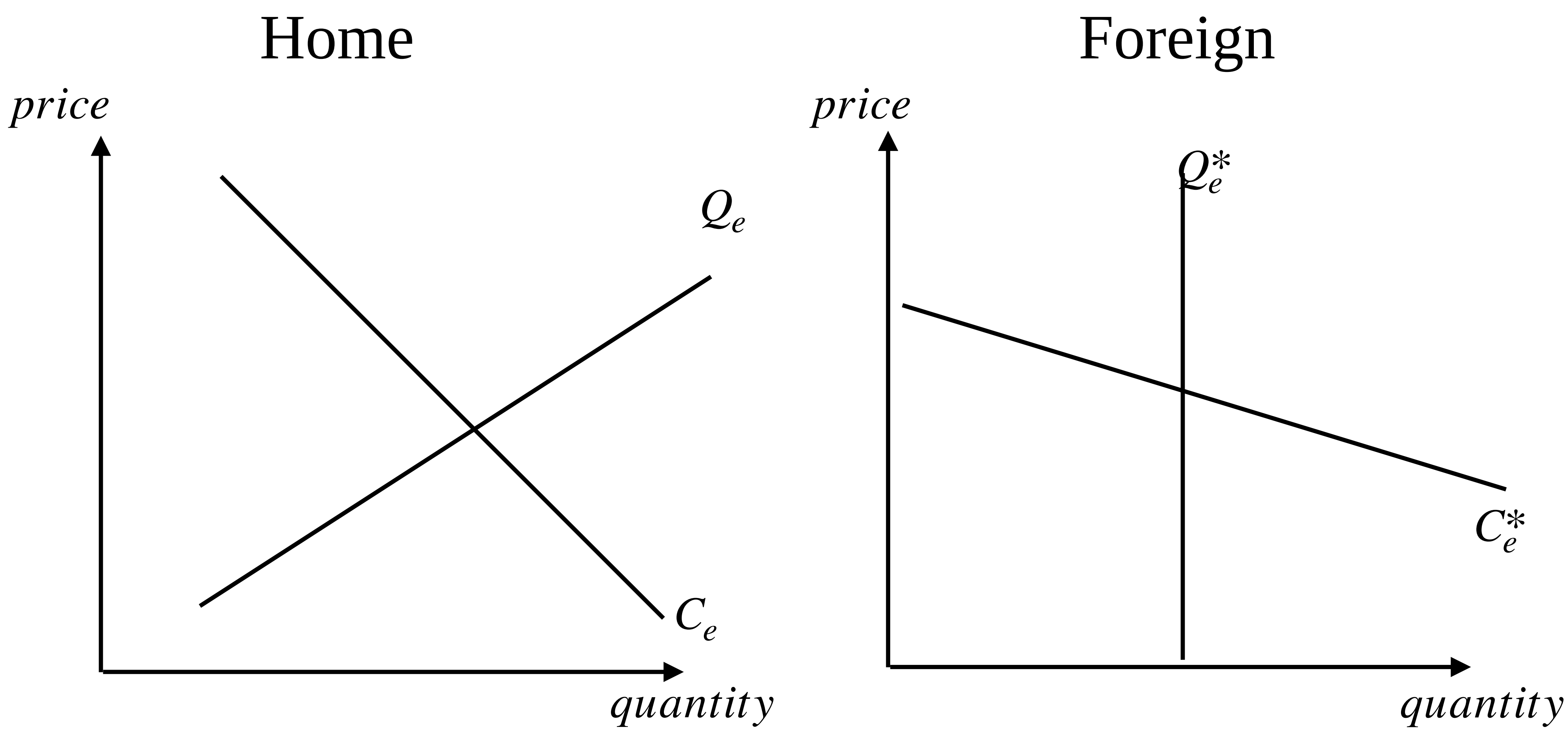

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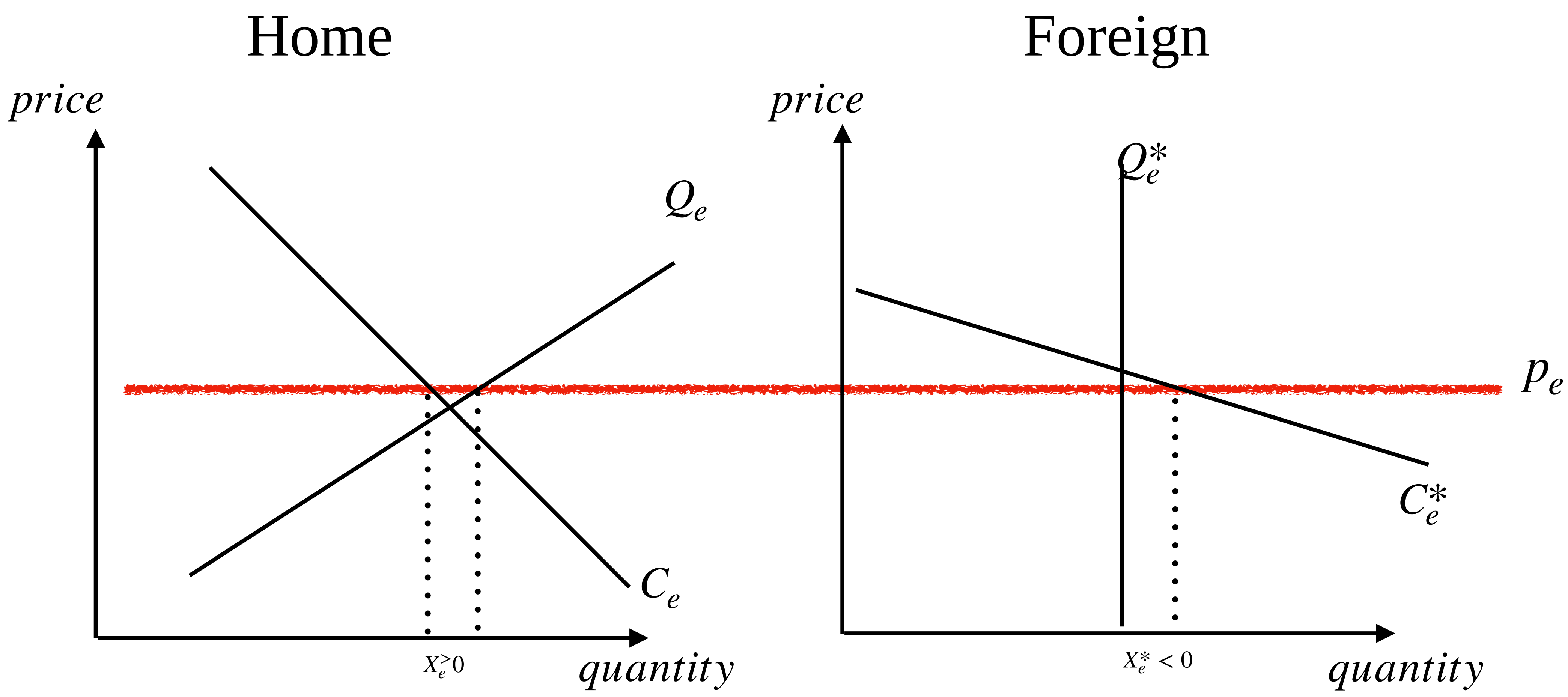

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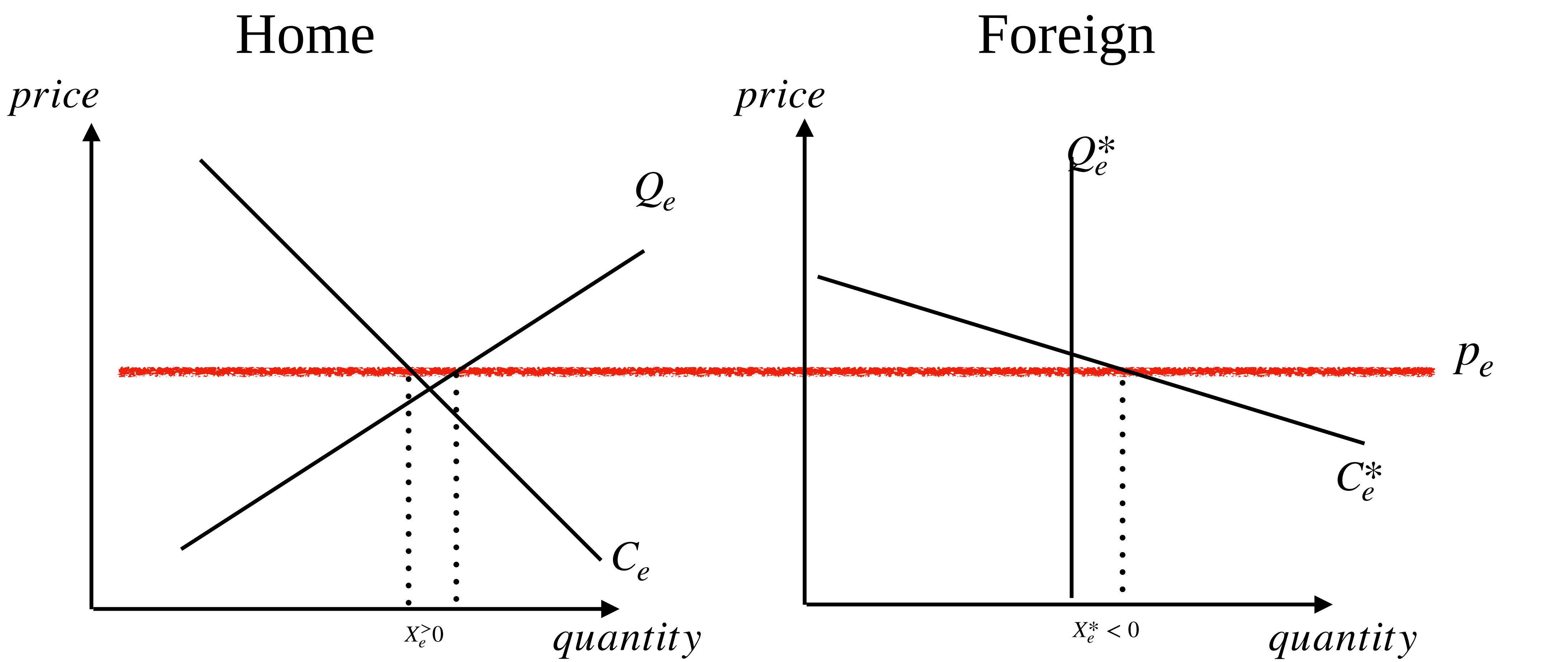

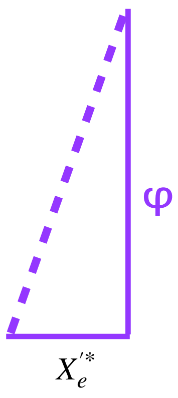

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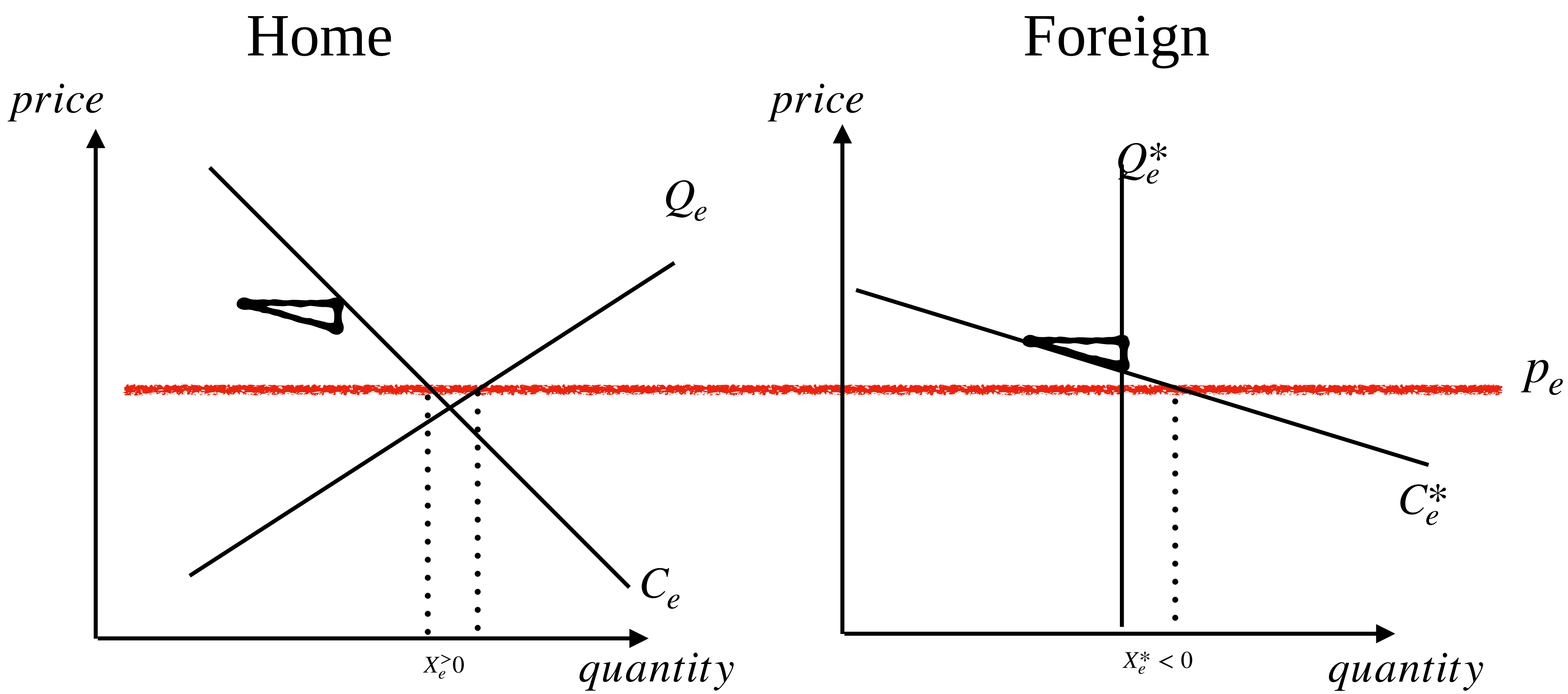

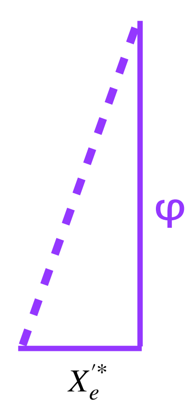

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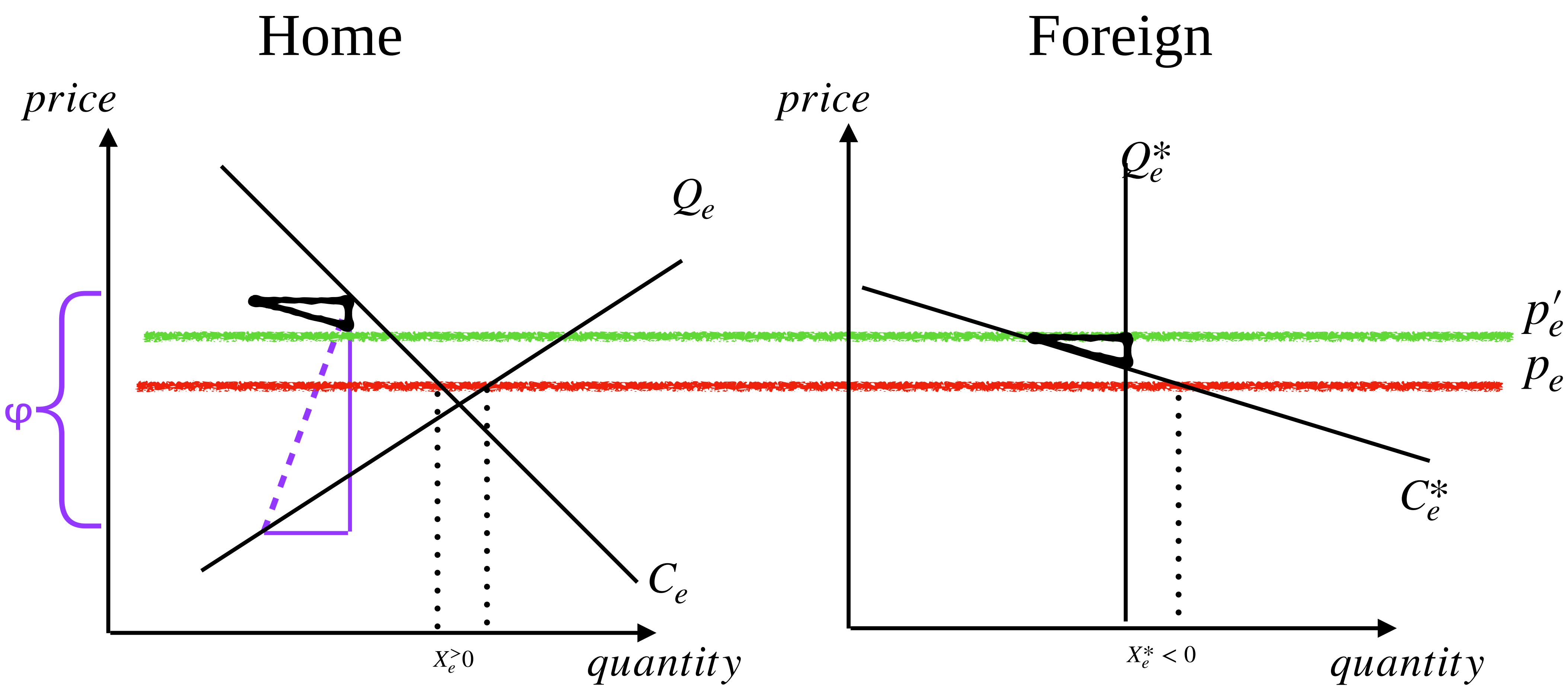
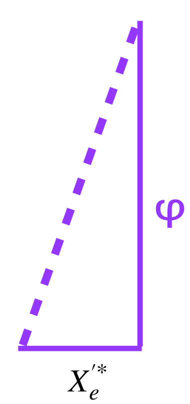
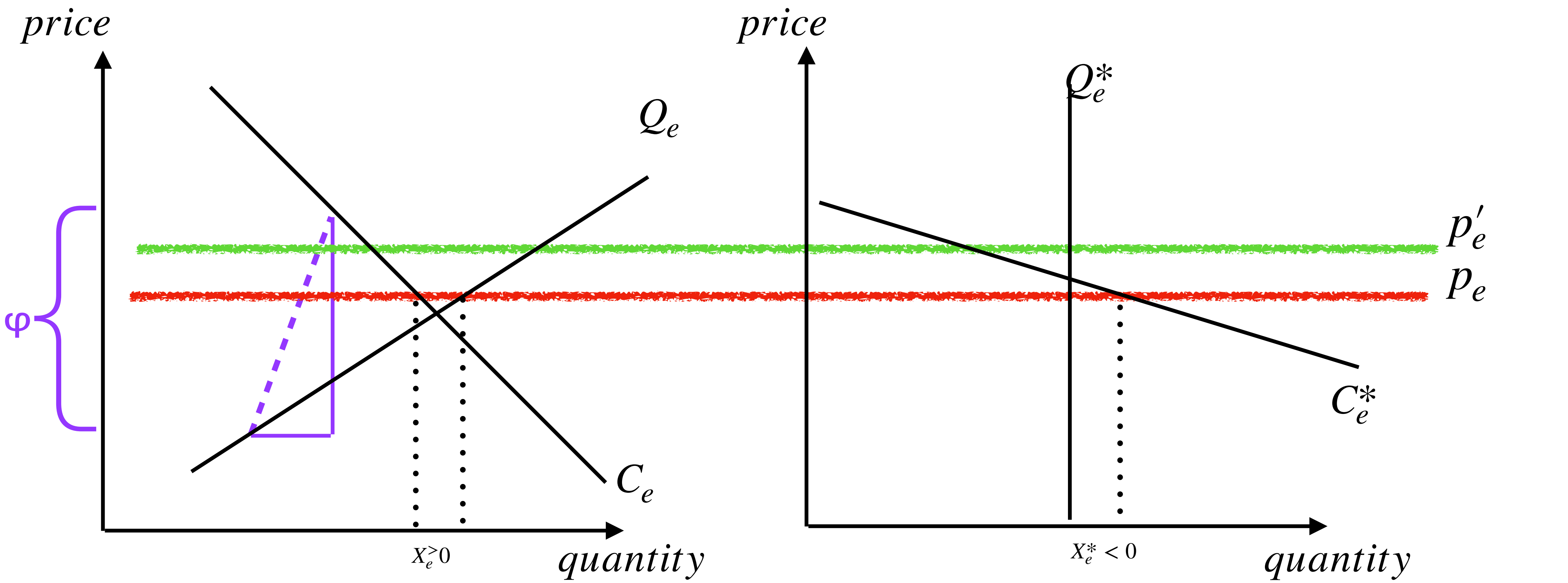
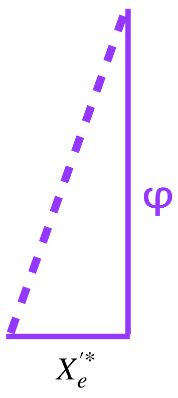




Case II: Inelastic Foreign Supply

Home　　　　Foreign





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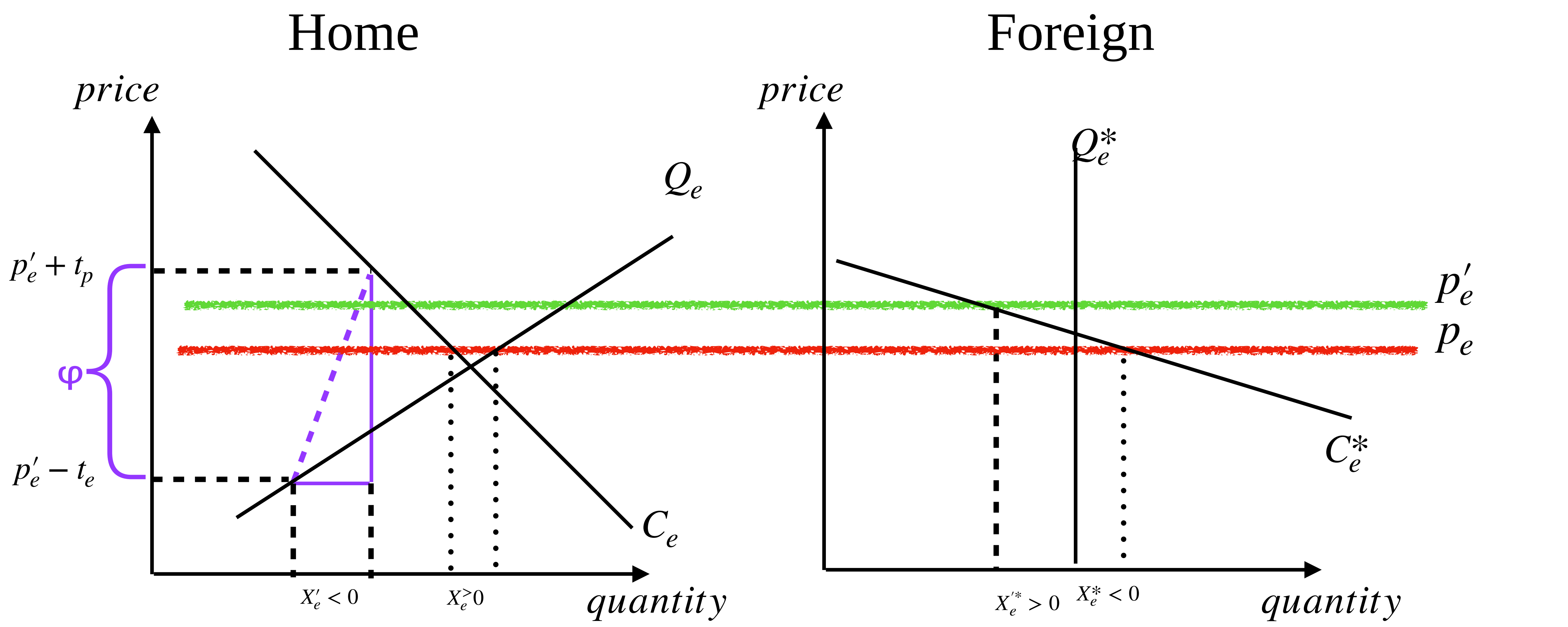
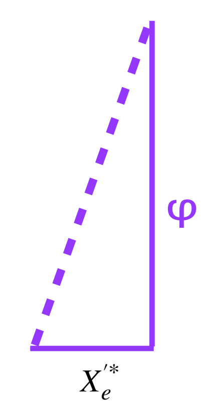




3. Trade in All Goods

Case III: Trade in All Goods

- **Planner's additional choices**
  - energy intensity for imports and exports of each manufacture good j
  - set of goods to import and to export
  - quantity of imports and exports
- **Planner's additional constraints**
  - none except for constraints on pricing …

Prices of Manufactured Goods

- When Foreign produces for itself, BAU results hold

$$z^*(p_e) = \frac{1-\gamma}{\gamma p_e} \qquad p_j^*(p_e) = a_j^* p_e^{1-\gamma}$$

- Home optimizes by limit pricing of exports (we simplify this part by assuming $\sigma \leq 1$)

$$p_j^x(p_e) = p_j^*(p_e)$$

- When Home imports, it must cover Foreign's costs

$$p_j^m(p_e) = \tau\left(a_j^{l*}(z_j^m) + p_e a_j^{e*}(z_j^m)\right)$$

Case III: Planner's Lagrangian

$$\mathscr{L} = \frac{\alpha^{1/\sigma}}{1 - 1/\sigma} \int_0^1 \left(y_j + m_j\right)^{1-1/\sigma} dj - \varphi\left(Q_e + Q_e^*(p_e)\right)$$

Home's welfare

$$-\beta E^{-(1-\beta)/\beta} Q_e^{1/\beta} - \int_0^1 \left(a_j^l(z_j^y)y_j + \tau a_j^l(z_j^x)x_j\right) dj$$

Home's labor constraint

$$-\int_0^1 \tau\left(a_j^{l*}(z_j^m) + p_e a_j^{e*}(z_j^m)\right) m_j dj + \int_0^1 p_j^x(p_e)x_j dj + p_e X_e$$

trade balance constraint

$$-\lambda_e\left(\int_0^1 \left(a_j^e(z_j^y)y_j + \tau a_j^e(z_j^x)x_j\right) dj - Q_e + X_e\right)$$

Home's energy constraint

$$-\lambda_e^*\left(\int_0^1 \left(a_j^{e*}(z^*(p_e))y_j^*(p_e) + \tau a_j^{e*}(z_j^m)m_j\right) dj - Q_e^*(p_e) - X_e\right)$$

Foreign's energy constraint

Solution

1. energy intensity $$z_j^y = z_j^x = z_j^m = z = \frac{1-\gamma}{\gamma\lambda_e}$$
2. Home domestic $$y_j = \alpha\left(a_j\lambda_e^{1-\gamma}\right)^{-\sigma} \qquad j < \bar{j}_m$$
3. imports $$m_j = \alpha\left(\tau a_j^*\lambda_e^{1-\gamma}\right)^{-\sigma} \qquad j > \bar{j}_m$$
4. import cutoff $$F(\bar{j}_m) = 1/\tau$$
5. exports $$x_j(p_e) = \alpha^*\left(a_j^* p_e^{1-\gamma}\right)^{-\sigma} \qquad j < \bar{j}_x$$
6. Foreign domestic $$y_j^*(p_e) = \alpha^*\left(a_j^* p_e^{1-\gamma}\right)^{-\sigma} \qquad j > \bar{j}_x$$
7. export cutoff $$F(\bar{j}_x) = \frac{\tau(\lambda_e/p_e)^{1-\gamma}}{1+(1-\gamma)\lambda_e^*/p_e}$$
8. optimal price $$\lambda_e^* = \varphi\frac{\partial Q_e^*/\partial p_e}{\partial X_e^*/\partial p_e} + \frac{X_e^* - \partial V_g/\partial p_e - \lambda_e\sigma^* C_e^{FH}/p_e}{\partial X_e^*/\partial p_e}$$

Properties of Optimal Policy

- Home equates all energy intensities that it controls

- Extensive margin of imports is same as in BAU

- Home sets export quantity based on Foreign's cost, ignoring its cost of producing them (given extensive margin of exports)

- Extensive margin of exports expands relative to BAU

  - Leads to cross-hauling if iceberg costs are low

- Home's strategy involves expanding its control of energy use in manufacturing

Interpret as Decentralized Economy

- As in Case II, production tax on energy $t_p = \lambda_e^*$
- Also, **border tax** on energy content of imports $t_b = \lambda_e^*$
- As in Case II, extraction tax $t_e = \varphi - t_p$
- Optimal production tax

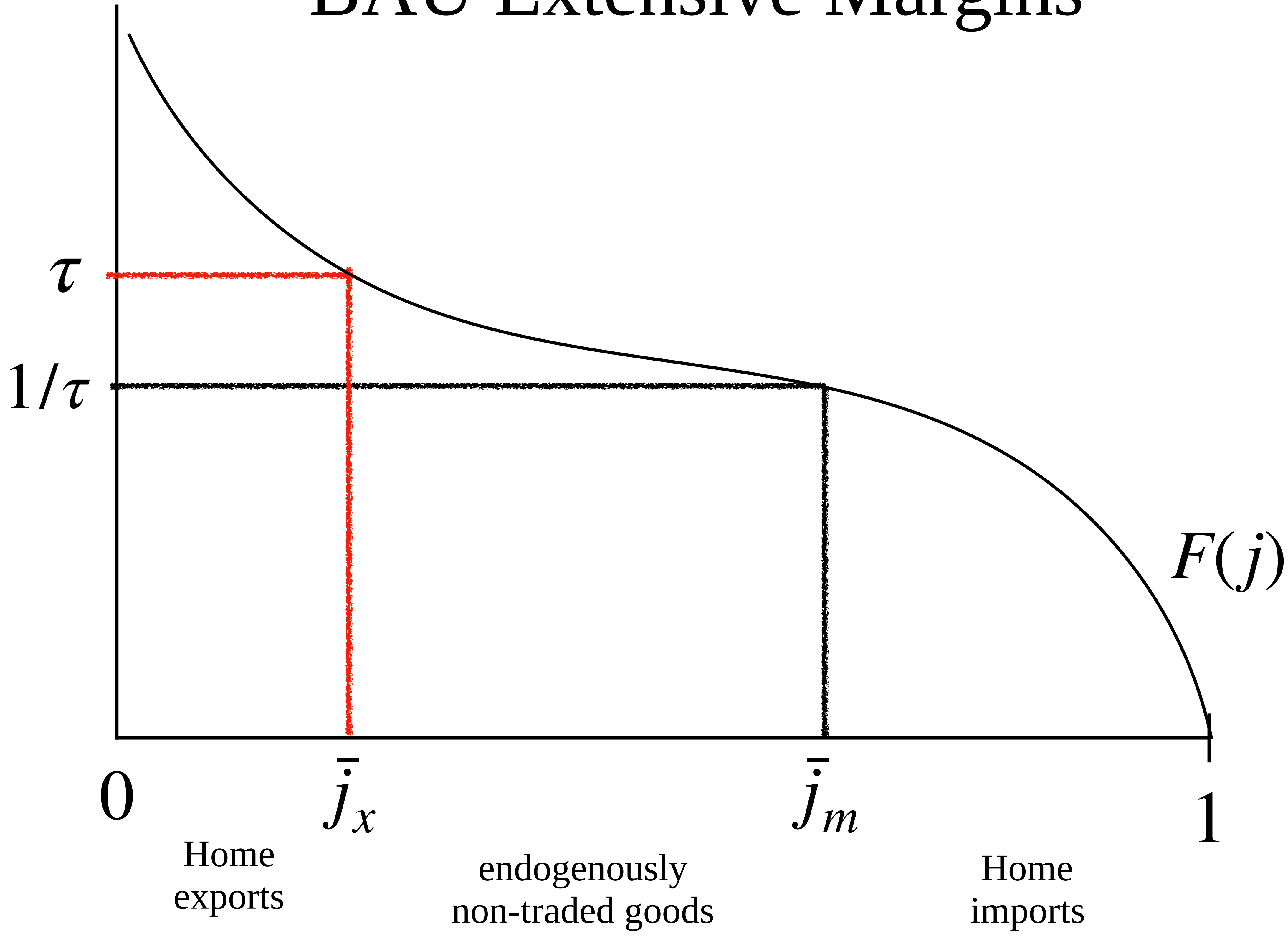
$$t_p = \varphi \frac{\partial Q_e^* / \partial p_e}{\partial X_e^* / \partial p_e} + \frac{X_e^* - \partial V_g / \partial p_e - (1 + t_p / p_e) \sigma^* C_e^{FH}}{\partial X_e^* / \partial p_e}$$

- Subsidize marginal exporters, per unit exported
  - ***not*** the same as a rebate of the production tax on exports
- Home taxes its best exporters to implement limit pricing

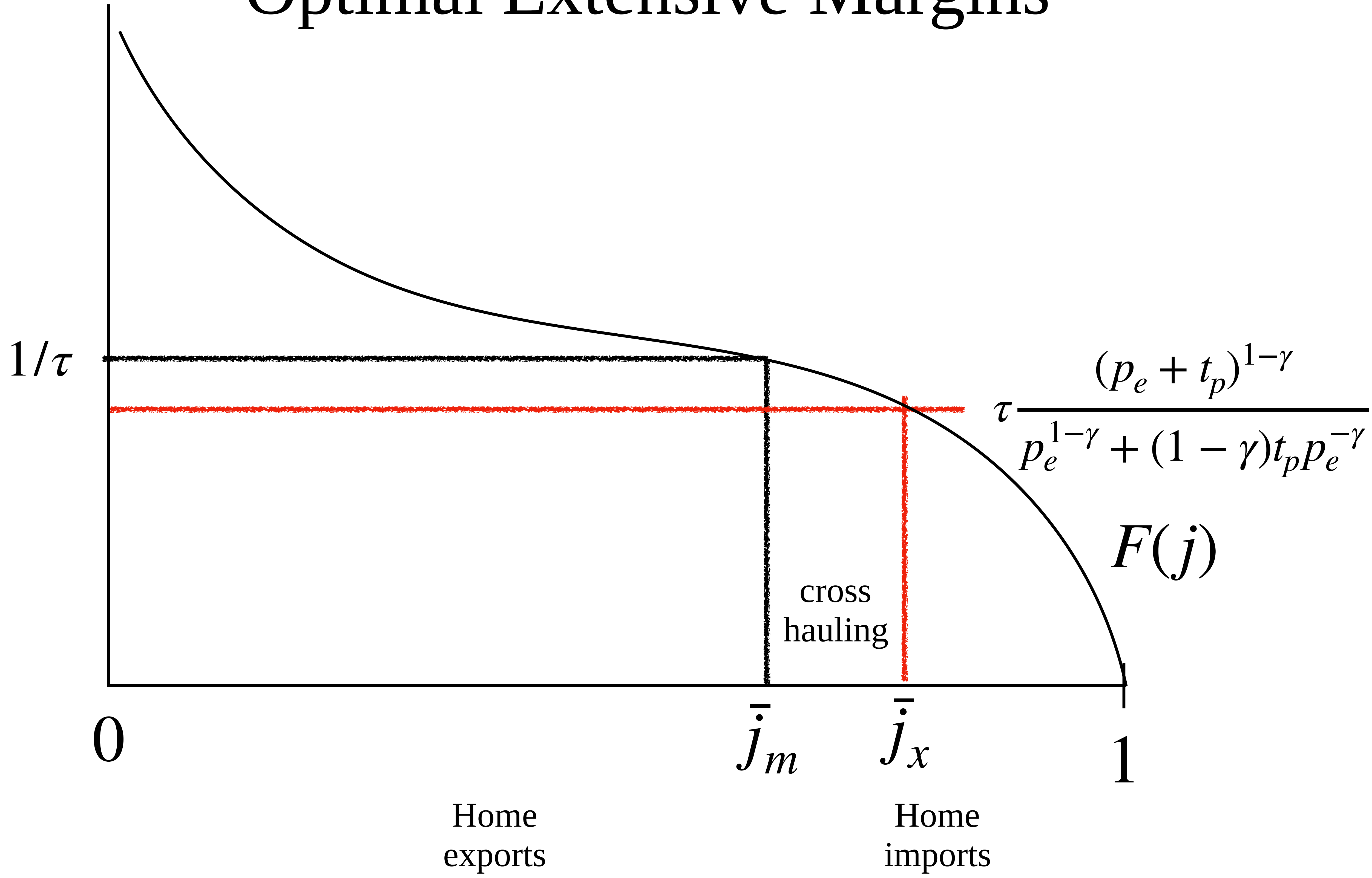
Exporter Policy

- Import side: full border adjustment on energy content of goods imports turns production tax into a consumption tax …
  - … except production tax on energy content is not removed on goods exports
- **Fischer and Fox reasoning:** keep the tax on energy content of exports, but provide rebates per unit exported
- **Costinot et. al. reasoning:** per-unit subsidies to marginal exporters, per unit taxes on the "best" exporters (actually goods)
- **New reasoning:** per-unit subsidies apply even to goods Home doesn't export in BAU, to expand the reach of policy

BAU Extensive Margins



Optimal Extensive Margins



Quantification

Calibration

- Impose functional form for comparative advantage, consistent with EK (2002)
- Calibrate to world with no carbon policy
- Fit to 2 by 2 matrix of carbon flows between Kyoto Protocol countries (Annex B) and all others in 2020
    - … from Elliott et. al. (2010)
- Could fit to GDP’s as well, but wouldn’t matter
    - … since services absorb all excess labor

Parameter Values

Symbol	Definition	Value
α	Importance of energy in Home's preferences	21.8
α^*	Importance of energy in Foreign's preferences	20.5
β	Share of labor in extraction	0.7
γ	Share of labor in manufacturing goods	0.7
θ	Scope of comparative advantages	4
σ	Demand elasticity for manufactured goods	0.75
φ	Marginal damages from carbon emission	0.5
E , E^*	Energy deposits in Home and Foreign	250 , 500
L, L^*	Labor endowments in Home and Foreign	big enough
A , A^*	Absolute advantage of Home and Foreign	1.5 , 1.7
τ, τ*	Iceberg trade costs of Home and Foreign	1.8 , 1.6

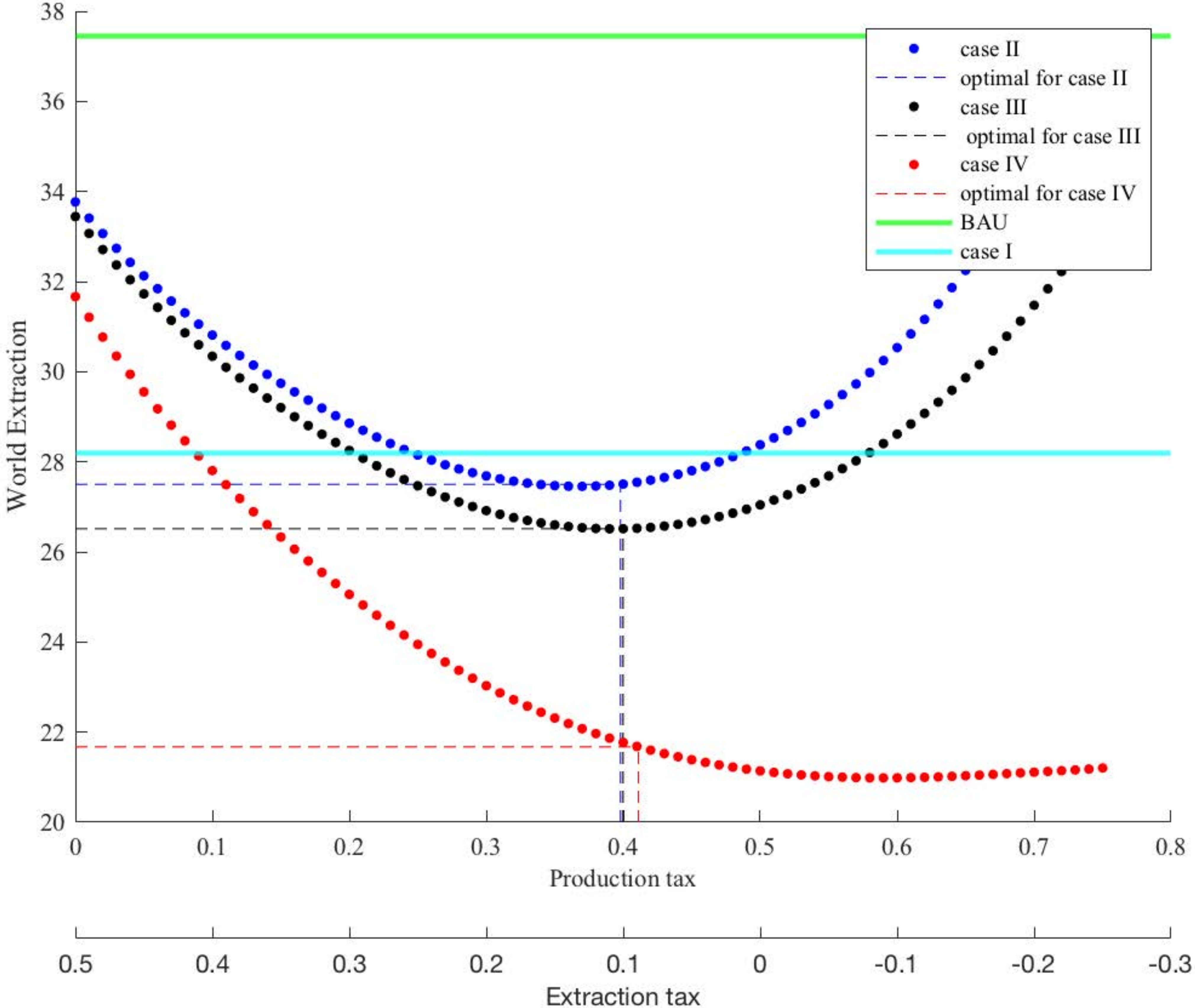
Computational Strategy

1. Guess a production tax rate (perhaps 0)
2. Solve for energy price that clears world energy market
3. Use the optimal tax formula to update production tax rate
4. Update extraction tax rate so that the two sum to φ
5. Return to step 2, continuing to iterate until tax rates converge

Result I

- Set damage parameter $\varphi = 0.5$
- Thus specific tax rates satisfy $t_e + t_p = 0.5$
- Show consequence of optimizing over t_p and hence t_e
  - **Case I**: autarky
  - **Case II**: no trade in manufactures
  - **Case III**: trade in all goods (model calibration)
  - **Case IV**: frictionless trade $\tau = 1$
  - **BAU**: competitive equilibrium (model calibration)

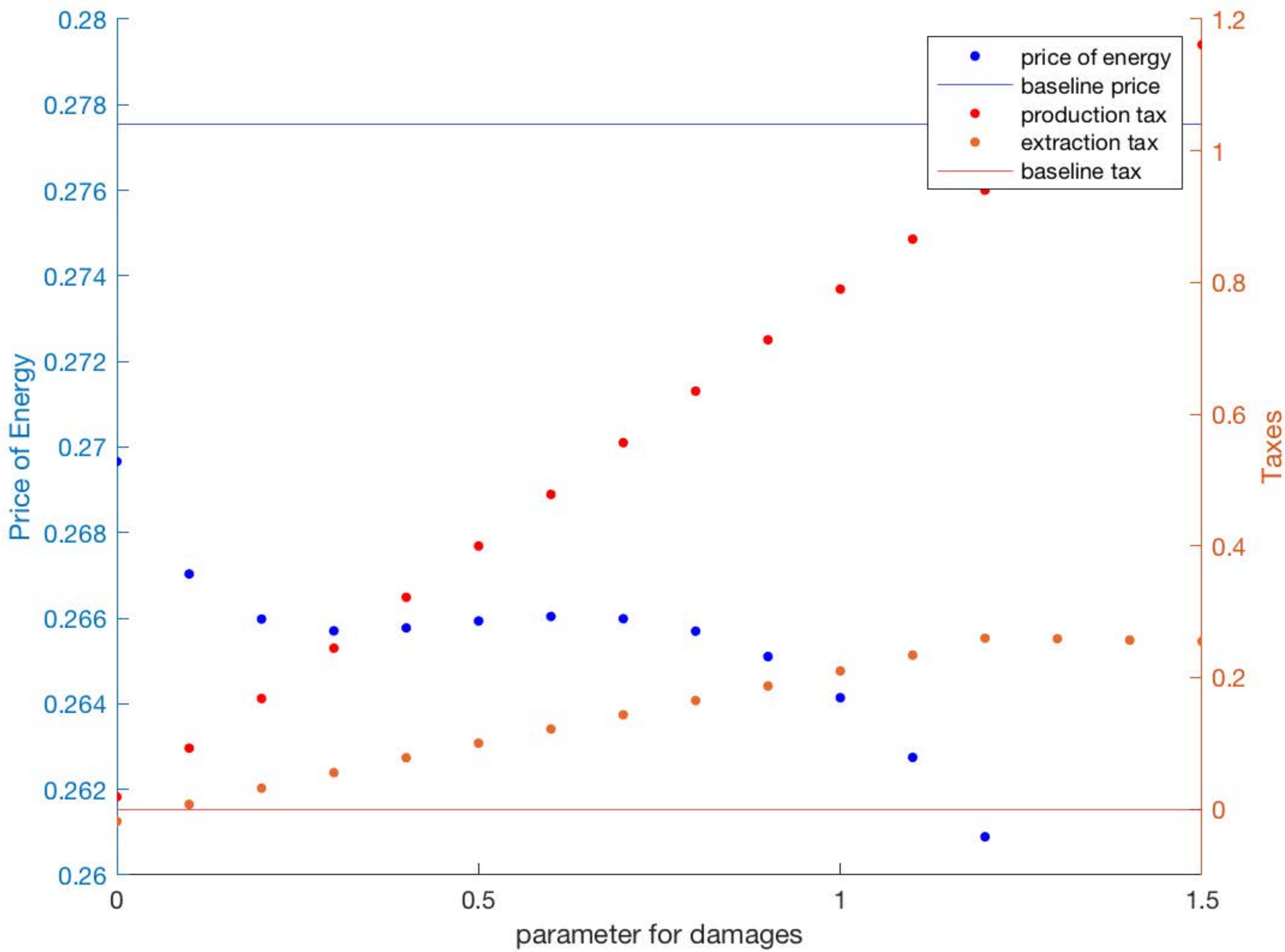
Global Emissions (Case I - IV)



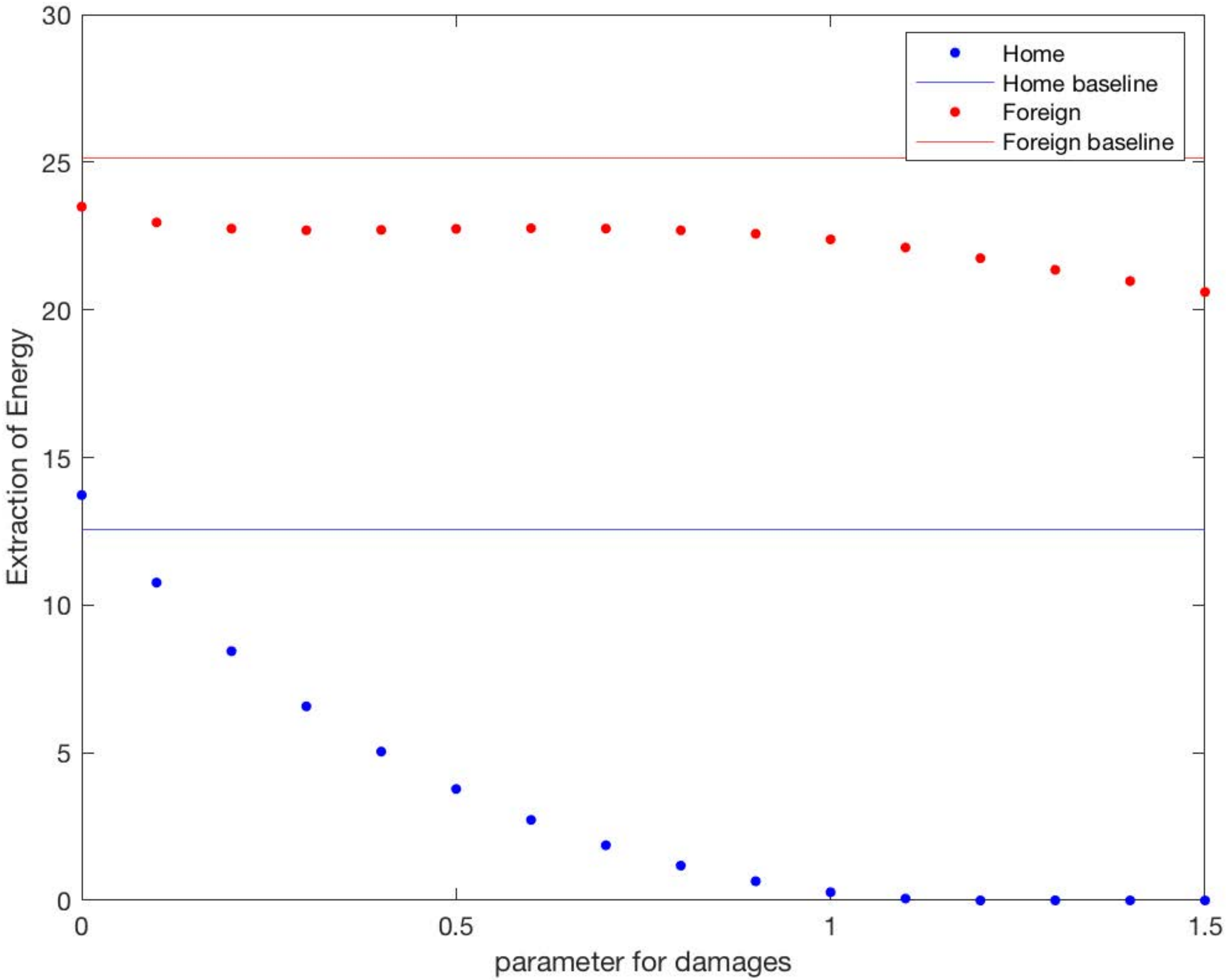
Result II

- Now consider **optimal policies** over a range of φ
  - including some very extreme values
- Specific tax rates satisfy $t_e + t_p = \varphi$
- Case III only

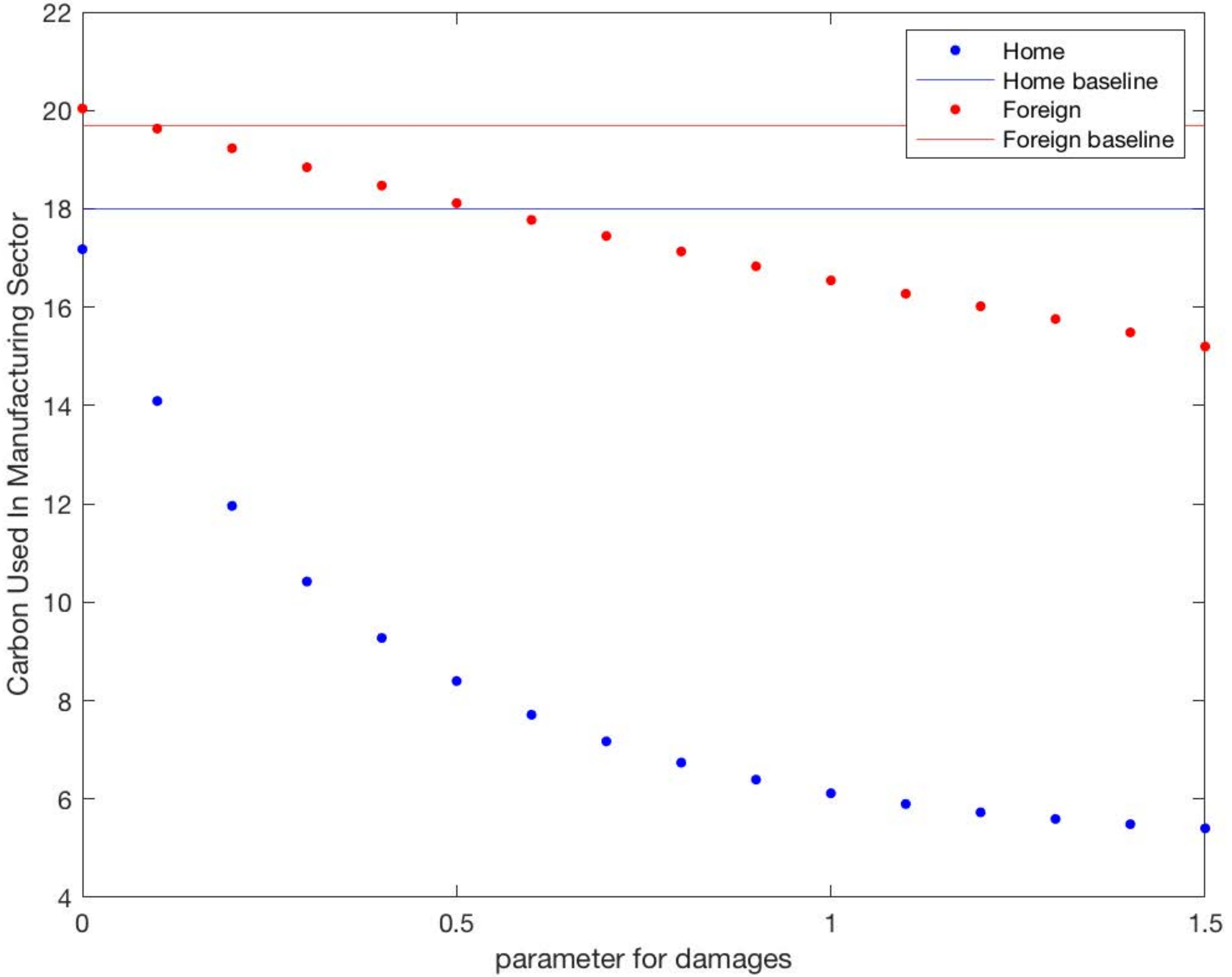
Energy Prices and Taxes



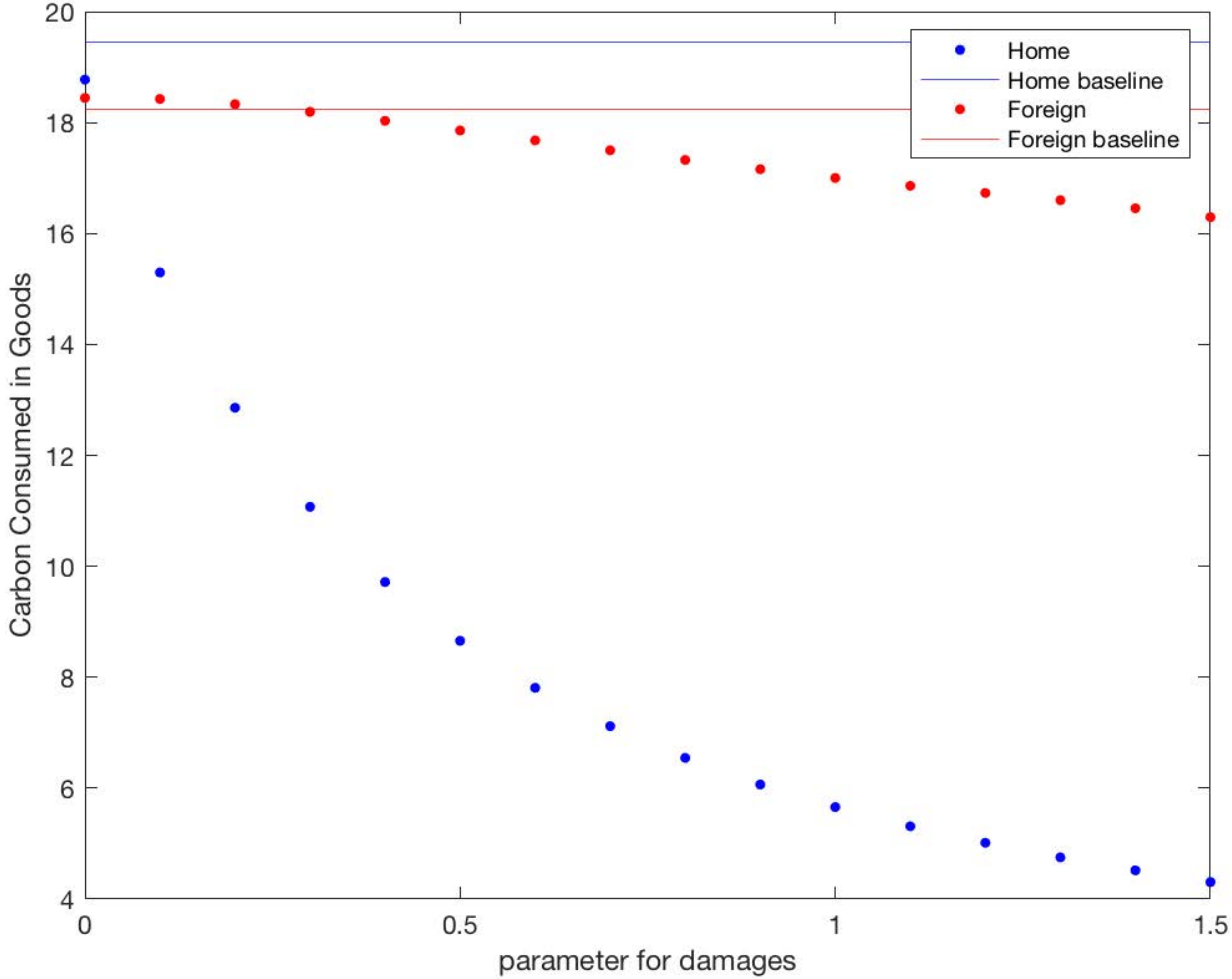
Energy Extraction



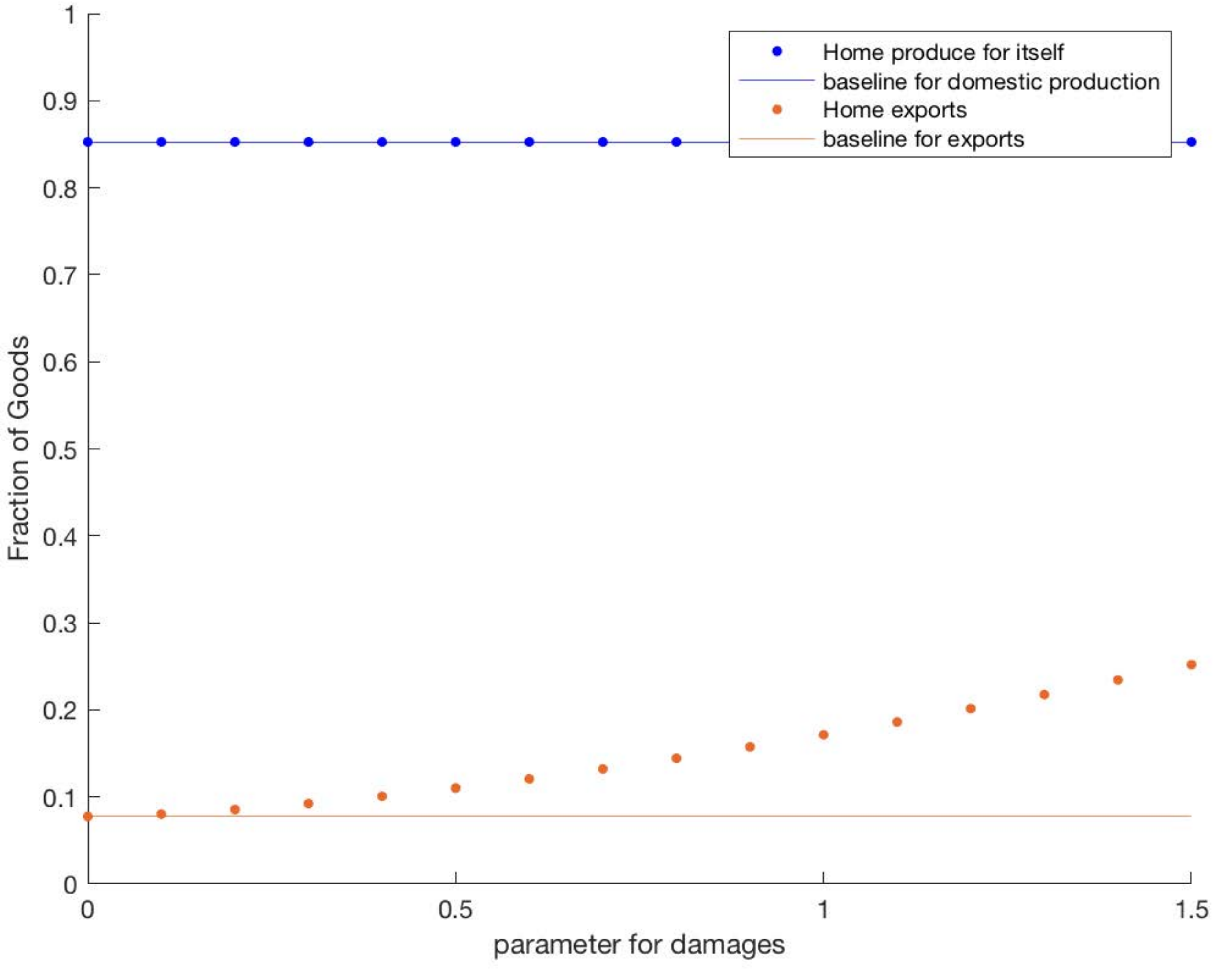
Energy Demand by Manufacturers



Energy Embodied in Consumption



Extensive Margin of Trade



Conclusion

- Theory reveals basic logic of optimal unilateral policy
    - key insight: use international trade to expand the reach of carbon policy
- To advance, we need to move in a quantitative direction
    - Potential for scaling up to many countries using EK (2002)
    - Potential for making it dynamic using Golosov, Hassler, Krusell, and Tsyvinsky (2014)
- Need to incorporate other key elements, such as “green energy”