The Economics of Combining CO_2-EOR with Storage

Klaas van 't Veld

University of Wyoming

Department of Economics & Finance



Center for Energy Economics and Public Policy

Outline

Outline

- Engineering-economics studies

Outline

- Engineering-economics studies
- Economic study

Outline

- Engineering-economics studies
- Economic study
- Effect of oil prices and CO_2-storage subsidies

Outline

- Engineering-economics studies
- Economic study
- Effect of oil prices and CO_2-storage subsidies
- Common misconception

Outline

- Engineering-economics studies
- Economic study
- Effect of oil prices and CO_2-storage subsidies
- Common misconception
- Optimal policy

Engineering-Economics Studies

- Ashgari, K., A. Al-Dliwe (2004) "Optimization of carbon dioxide sequestration and improved oil recovery in oil reservoirs," *GHGT-7 Proceedings*
- Babadagli, T. (2006) "Optimization of CO_2 injection for sequestrationenhanced oil recovery and current status in Canada," In Lombardi et al., eds. *Advances in the Geological Storage of Carbon Dioxide*
- Forooghi, A., Hamouda, A.A. (2009) "Co-optimization of CO_2 EOR and sequestration in a North Sea chalk reservoir," *SPE 125550*
- Ghomian, Y. et al. (2010) "Efficient investigation of uncertainties in flood design parameters for coupled CO_2 sequestration and enhanced oil recovery," *SPE 139738*
- Jahangiri, H.R., Zhang, D. (2011) "Optimization of the net present value of carbon dioxide sequestration and enhanced oil recovery," *OTC 21985*
- Jessen, K. et al. (2005) "Increasing CO_2 storage in oil recovery," *Energy Conversion and Management* 46: 293–311
- Kovscek, A.R., Cakici, M.D. (2005) "Geologic storage of carbon dioxide and enhanced oil recovery. II. Cooptimization of storage and recovery," *Energy Conversion and Management* 46: 1941–1956
- Pamuçku, Y.Z., Gumrah, F. (2009) "A numerical simulation study of carbon-dioxide sequestration into a depleted oil reservoir," *Energy Sources, Part A* 31: 1348–1367

Engineering-Economics Studies

- Ashgari, K., A. Al-Dliwe (2004) "Optimization of carbon dioxide sequestration and improved oil recovery in oil reservoirs," *GHGT-7 Proceedings*
- Babadagli, T. (2006) "Optimization of CO_2 injection for sequestrationenhanced oil recovery and current status in Canada," In Lombardi et al., eds. *Advances in the Geological Storage of Carbon Dioxide*
- Forooghi, A., Hamouda, A.A. (2009) "Co-optimization of CO_2 EOR and sequestration in a North Sea chalk reservoir," *SPE 125550*
- Ghomian, Y. et al. (2010) "Efficient investigation of uncertainties in flood design parameters for coupled CO_2 sequestration and enhanced oil recovery," *SPE 139738*
- Jahangiri, H.R., Zhang, D. (2011) "Optimization of the net present value of carbon dioxide sequestration and enhanced oil recovery," *OTC 21985*
- Jessen, K. et al. (2005) "Increasing CO_2 storage in oil recovery," *Energy Conversion and Management* 46: 293–311
- Kovscek, A.R., Cakici, M.D. (2005) "Geologic storage of carbon dioxide and enhanced oil recovery. II. Cooptimization of storage and recovery," *Energy Conversion and Management* 46: 1941–1956
- Pamuçku, Y.Z., Gumrah, F. (2009) "A numerical simulation study of carbon-dioxide sequestration into a depleted oil reservoir," *Energy Sources, Part A* 31: 1348–1367

Problem: ad hoc economic assumption

Problem: ad hoc economic assumption

Assumption: The producer's goal, or "objective function," is a weighted sum of oil production and CO_2 storage

Problem: ad hoc economic assumption

Assumption: The producer's goal, or "objective function," is a weighted sum of oil production and CO_2 storage

E.g., Kovscek and Cakici (2005):

$$w_1 \times \underbrace{\frac{N_p^*}{\mathrm{OIP}}}_{\substack{\text{Net oil} \\ \text{production}}} + w_2 \times \underbrace{\frac{V_{\mathrm{CO}_2}^R}{V^R}}_{\substack{\mathrm{CO}_2 \\ \text{storage}}}$$

with weights $w_1 = w_2 = 0.5$.

Problem: ad hoc economic assumption

Assumption: The producer's goal, or "objective function," is a weighted sum of oil production and CO_2 storage

E.g., Kovscek and Cakici (2005):

$$w_1 \times \underbrace{\frac{N_p^*}{\mathrm{OIP}}}_{\substack{\text{Net oil} \\ \text{production}}} + w_2 \times \underbrace{\frac{V_{\mathrm{CO}_2}^R}{V^R}}_{\substack{\mathrm{CO}_2 \\ \text{storage}}}$$

with weights $w_1 = w_2 = 0.5$.

Problem: ad hoc economic assumption

Assumption: The producer's goal, or "objective function," is a weighted sum of oil production and CO_2 storage

E.g., Kovscek and Cakici (2005):

$$w_1 \times \underbrace{\frac{N_p^*}{\mathrm{OIP}}}_{\substack{\text{Net oil} \\ \text{production}}} + w_2 \times \underbrace{\frac{V_{\mathrm{CO}_2}^R}{V^R}}_{\substack{\mathrm{CO}_2 \\ \text{storage}}}$$

with weights $w_1 = w_2 = 0.5$.

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} - \underbrace{p_{CO_2} q_{CO_2}^{\text{pur}}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{rec}}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}\, q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} - \underbrace{p_{CO_2}\, q^{\text{pur}}_{CO_2}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}}\, q^{\text{rec}}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} - \underbrace{p_{CO_2} q_{CO_2}^{\text{pur}}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{rec}}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} - \underbrace{p_{CO_2} q_{CO_2}^{\text{pur}}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{rec}}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} - \underbrace{p_{CO_2} q_{CO_2}^{\text{pur}}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{rec}}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} - \underbrace{p_{CO_2} q_{CO_2}^{\text{pur}}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{rec}}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{s_{CO_2} q_{CO_2}^{seq}}_{\text{CO}_2\text{ sequestration subsidies}} - \underbrace{p_{CO_2} q_{CO_2}^{pur}}_{\text{CO}_2\text{ purchase costs}} - \underbrace{c^{rec} q_{CO_2}^{rec}}_{\text{CO}_2\text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{s_{CO_2} q^{\text{seq}}_{CO_2}}_{\substack{CO_2 \\ \text{sequestration} \\ \text{subsidies}}} - \underbrace{p_{CO_2} q^{\text{pur}}_{CO_2}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}} q^{\text{rec}}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$q^{pur}_{CO_2} = q^{seq}_{CO_2}$$

$$\downarrow$$

$$profit = \underbrace{p_{oil}\, q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{s_{CO_2}\, q^{seq}_{CO_2}}_{\substack{CO_2 \\ \text{sequestration} \\ \text{subsidies}}} - \underbrace{p_{CO_2}\, q^{pur}_{CO_2}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{rec}\, q^{rec}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$q^{pur}_{CO_2} = q^{seq}_{CO_2}$$

$$\downarrow$$

$$profit = \underbrace{p_{oil}\, q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{s_{CO_2}\, q^{seq}_{CO_2}}_{\substack{CO_2 \\ \text{sequestration} \\ \text{subsidies}}} - \underbrace{p_{CO_2}\, q^{pur}_{CO_2}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{rec}\, q^{rec}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$q^{pur}_{CO_2} = q^{seq}_{CO_2}$$

$$\downarrow$$

$$profit = \underbrace{p_{oil}\, q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{s_{CO_2}\, q^{seq}_{CO_2}}_{\substack{CO_2 \\ \text{sequestration} \\ \text{subsidies}}} - \underbrace{p_{CO_2}\, q^{seq}_{CO_2}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{rec}\, q^{rec}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}\, q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{s_{CO_2}\, q^{\text{seq}}_{CO_2}}_{\substack{CO_2 \\ \text{sequestration} \\ \text{subsidies}}} - \underbrace{p_{CO_2}\, q^{\text{seq}}_{CO_2}}_{\substack{CO_2 \\ \text{purchase} \\ \text{costs}}} - \underbrace{c^{\text{rec}}\, q^{\text{rec}}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2}) q_{CO_2}^{seq}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q_{CO_2}^{rec}}_{CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{rec}}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$q^{\text{rec}}_{CO_2} = q^{\text{inj}}_{CO_2} - q^{\text{seq}}_{CO_2}$$

$$\downarrow$$

$$\textit{profit} = \underbrace{p_{\text{oil}} q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2}) q^{\text{seq}}_{CO_2}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q^{\text{rec}}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$q^{\text{rec}}_{CO_2} = q^{\text{inj}}_{CO_2} - q^{\text{seq}}_{CO_2}$$

$$\downarrow$$

$$\textit{profit} = \underbrace{p_{\text{oil}} q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2}) q^{\text{seq}}_{CO_2}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q^{\text{rec}}_{CO_2}}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$q^{\text{rec}}_{CO_2} = q^{\text{inj}}_{CO_2} - q^{\text{seq}}_{CO_2}$$

$$\downarrow$$

$$\textit{profit} = \underbrace{p_{\text{oil}} q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2}) q^{\text{seq}}_{CO_2}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}}(q^{\text{inj}}_{CO_2} - q^{\text{seq}}_{CO_2})}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}}(q_{CO_2}^{\text{inj}} - q_{CO_2}^{\text{seq}})}_{\substack{CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2}) q_{CO_2}^{seq}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec}(q_{CO_2}^{inj} - q_{CO_2}^{seq})}_{CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2}) q^{seq}_{CO_2}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec}(q^{inj}_{CO_2} - q^{seq}_{CO_2})}_{CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q^{\text{prd}}_{\text{oil}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q^{\text{seq}}_{CO_2}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q^{\text{inj}}_{CO_2}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec}) q_{CO_2}^{seq}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q_{CO_2}^{inj}}_{\text{gross } CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec}) q_{CO_2}^{seq}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q_{CO_2}^{inj}}_{\text{gross } CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec}) q^{seq}_{CO_2}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q^{inj}_{CO_2}}_{\text{gross } CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}} q_{\text{oil}}^{\text{prd}}}_{\substack{\text{oil} \\ \text{revenues}}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

constant?

$$profit = \underbrace{p_{oil} q_{oil}^{prd}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec}) q_{CO_2}^{seq}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q_{CO_2}^{inj}}_{\text{gross } CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

constant?

$$profit = \underbrace{p_{oil} q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec}) q^{seq}_{CO_2}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q^{inj}_{CO_2}}_{\text{gross } CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

Profit objective function

$$profit = \underbrace{p_{oil} q^{prd}_{oil}}_{\text{oil revenues}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec}) q^{seq}_{CO_2}}_{\text{net } CO_2 \text{ sequestration revenues}} - \underbrace{c^{rec} q^{inj}_{CO_2}}_{\text{gross } CO_2 \text{ recycling costs}} - \underbrace{c^{oth}}_{\text{other costs}}$$

constant?

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight} \\ \text{on oil} \\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}}) q_{CO_2}^{\text{seq}}}_{\substack{\text{net } CO_2 \\ \text{sequestration} \\ \text{revenues}}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2 \\ \text{recycling} \\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other} \\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$\mathit{Profit} = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q^{\text{prd}}_{\text{oil}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q^{\text{seq}}_{CO_2} - \underbrace{c^{\text{rec}} Q^{\text{inj}}_{CO_2}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$Profit = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q^{prd}_{oil} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q^{seq}_{CO_2} - \underbrace{c^{rec} Q^{inj}_{CO_2}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{C^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

$$Profit = profit_1 + profit_2 + profit_3 + \ldots + profit_T$$

$$Q^{prd}_{oil} = q^{prd}_{oil,1} + q^{prd}_{oil,2} + q^{prd}_{oil,3} + \ldots + q^{prd}_{oil,T}$$

$$Q^{seq}_{CO_2} = q^{seq}_{CO_2,1} + q^{seq}_{CO_2,2} + q^{seq}_{CO_2,3} + \ldots + q^{seq}_{CO_2,T}$$

etc.

Profit objective function

$$\mathit{Profit} = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q^{\text{prd}}_{\text{oil}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q^{\text{seq}}_{CO_2} - \underbrace{c^{\text{rec}} Q^{\text{inj}}_{CO_2}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

constant?

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

fall over time

constant?

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

Benefits of CO_2 injection fall over time

constant?

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

Benefits of CO_2 injection fall over time

Costs constant?

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}} q_{CO_2}^{\text{inj}}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

Benefits of CO_2 injection fall over time

Costs must fall over time

$$profit = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{seq} - \underbrace{c^{rec} q_{CO_2}^{inj}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

Benefits of CO_2 injection fall over time

Costs must fall over time

$$profit = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{seq} - \underbrace{c^{rec} q_{CO_2}^{inj}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q^{\text{prd}}_{\text{oil}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q^{\text{seq}}_{CO_2} - \underbrace{c^{\text{rec}} q^{\text{inj}}_{CO_2}}_{\substack{\text{gross } CO_2\\ \text{recycling}\\ \text{costs}}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} q_{CO_2}^{\text{inj}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} q_{CO_2}^{\text{inj}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

$$Profit = profit_1 + profit_2 + profit_3 + \ldots + profit_T$$

$$Q_{\text{oil}}^{\text{prd}} = q_{\text{oil},1}^{\text{prd}} + q_{\text{oil},2}^{\text{prd}} + q_{\text{oil},3}^{\text{prd}} + \ldots + q_{\text{oil},T}^{\text{prd}}$$

$$Q_{CO_2}^{\text{seq}} = q_{CO_2,1}^{\text{seq}} + q_{CO_2,2}^{\text{seq}} + q_{CO_2,3}^{\text{seq}} + \ldots + q_{CO_2,T}^{\text{seq}}$$

etc.

Profit objective function

$$profit = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} q_{CO_2}^{inj} - \underbrace{c^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

$$Profit = profit_1 + \delta profit_2 + \delta^2 profit_3 + \ldots + \delta^T profit_T$$

$$Q_{oil}^{prd} = q_{oil,1}^{prd} + q_{oil,2}^{prd} + q_{oil,3}^{prd} + \ldots + q_{oil,T}^{prd}$$

$$Q_{CO_2}^{seq} = q_{CO_2,1}^{seq} + q_{CO_2,2}^{seq} + q_{CO_2,3}^{seq} + \ldots + q_{CO_2,T}^{seq}$$

etc.

Profit objective function

$$profit = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} q_{CO_2}^{\text{inj}} - \underbrace{c^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

$$NPV = profit_1 + \delta profit_2 + \delta^2 profit_3 + \ldots + \delta^T profit_T$$

$$Q_{\text{oil}}^{\text{prd}} = q_{\text{oil},1}^{\text{prd}} + q_{\text{oil},2}^{\text{prd}} + q_{\text{oil},3}^{\text{prd}} + \ldots + q_{\text{oil},T}^{\text{prd}}$$

$$Q_{CO_2}^{\text{seq}} = q_{CO_2,1}^{\text{seq}} + q_{CO_2,2}^{\text{seq}} + q_{CO_2,3}^{\text{seq}} + \ldots + q_{CO_2,T}^{\text{seq}}$$

etc.

Profit objective function

$$profit = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} q_{CO_2}^{inj} - \underbrace{c^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

$$NPV = profit_1 + \delta profit_2 + \delta^2 profit_3 + \ldots + \delta^T profit_T$$

$$Q_{oil}^{prd} = q_{oil,1}^{prd} + \delta q_{oil,2}^{prd} + \delta^2 q_{oil,3}^{prd} + \ldots + \delta^T q_{oil,T}^{prd}$$

$$Q_{CO_2}^{seq} = q_{CO_2,1}^{seq} + \delta q_{CO_2,2}^{seq} + \delta^2 q_{CO_2,3}^{seq} + \ldots + \delta^T q_{CO_2,T}^{seq}$$

etc.

Profit objective function

$$NPV = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q^{\text{prd}}_{\text{oil}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q^{\text{seq}}_{CO_2} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q^{\text{inj}}_{CO_2} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

$$NPV = profit_1 + \delta profit_2 + \delta^2 profit_3 + \ldots + \delta^T profit_T$$

$$Q^{\text{prd}}_{\text{oil}} = q^{\text{prd}}_{\text{oil},1} + \delta q^{\text{prd}}_{\text{oil},2} + \delta^2 q^{\text{prd}}_{\text{oil},3} + \ldots + \delta^T q^{\text{prd}}_{\text{oil},T}$$

$$Q^{\text{seq}}_{CO_2} = q^{\text{seq}}_{CO_2,1} + \delta q^{\text{seq}}_{CO_2,2} + \delta^2 q^{\text{seq}}_{CO_2,3} + \ldots + \delta^T q^{\text{seq}}_{CO_2,T}$$

etc.

Profit objective function

$$NPV = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

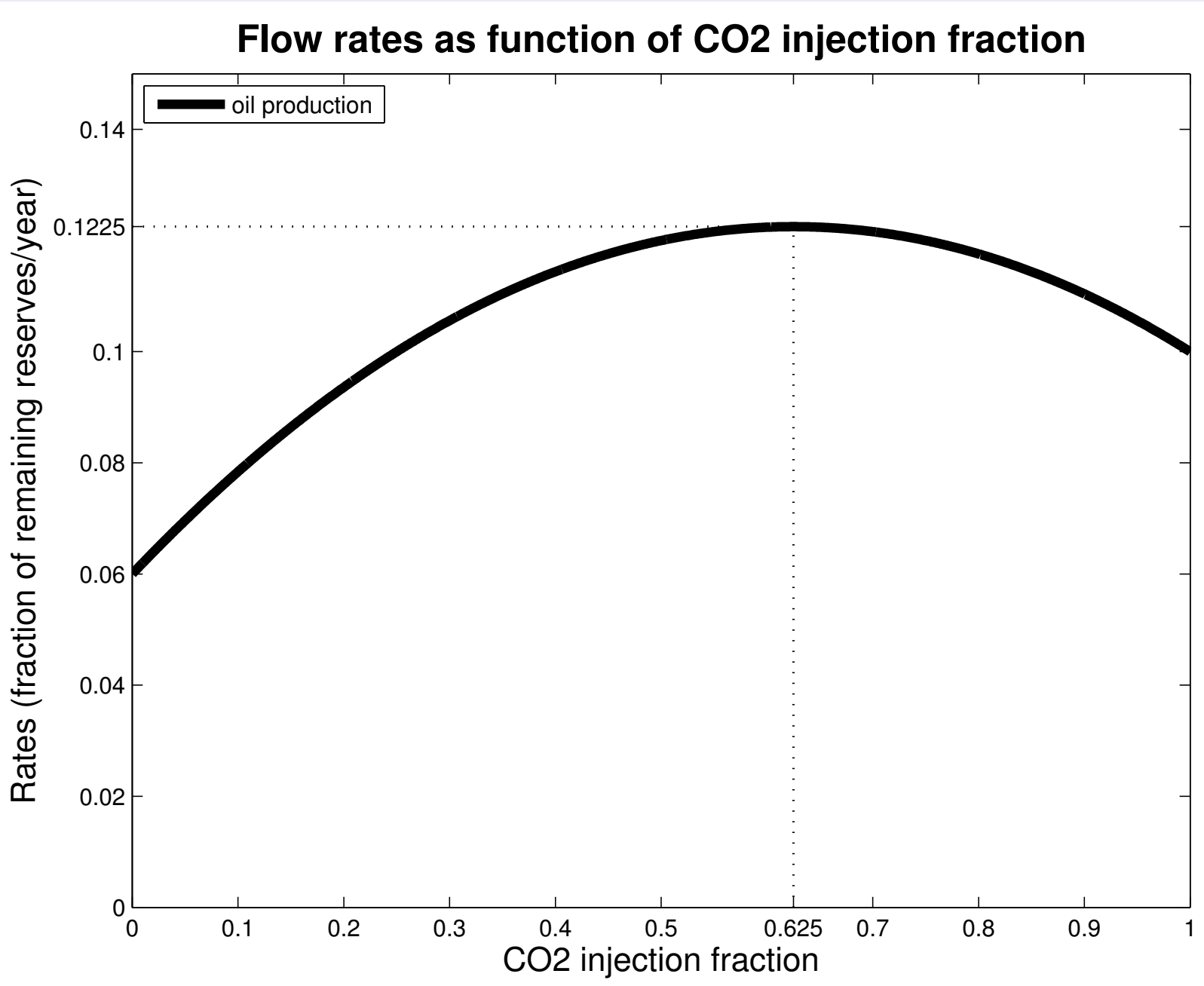
Economic Study

Leach, A., Mason, C.F., van 't Veld, K. (2011) "Co-optimization of enhanced oil recovery and carbon sequestration," *Resource and Energy Economics* 33: 893–912

Problem: ad hoc engineering assumptions

Problem: ad hoc engineering assumptions

Assumption 1: Oil production is an inverse U-shaped function of the CO_2 injection fraction $q^{\text{inj}}_{CO_2}/(q^{\text{inj}}_{CO_2} + q^{\text{inj}}_{\text{wat}})$.


Flow rates as function of CO2 injection fraction
oil production
Rates (fraction of remaining reserves/year)
0.14
0.1225
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.625
0.7
0.8
0.9
1
CO2 injection fraction

Problem: ad hoc engineering assumptions

Assumption 1: Oil production is an inverse U-shaped function of the CO_2 injection fraction $q^{\text{inj}}_{CO_2}/(q^{\text{inj}}_{CO_2} + q^{\text{inj}}_{\text{wat}})$.

Problem: ad hoc engineering assumptions

Assumption 1: Oil production is an inverse U-shaped function of the CO_2 injection fraction $q^{\text{inj}}_{CO_2}/(q^{\text{inj}}_{CO_2} + q^{\text{inj}}_{\text{wat}})$.

Assumption 2: CO_2 sequestration is the product of the CO_2 injection fraction and oil production:

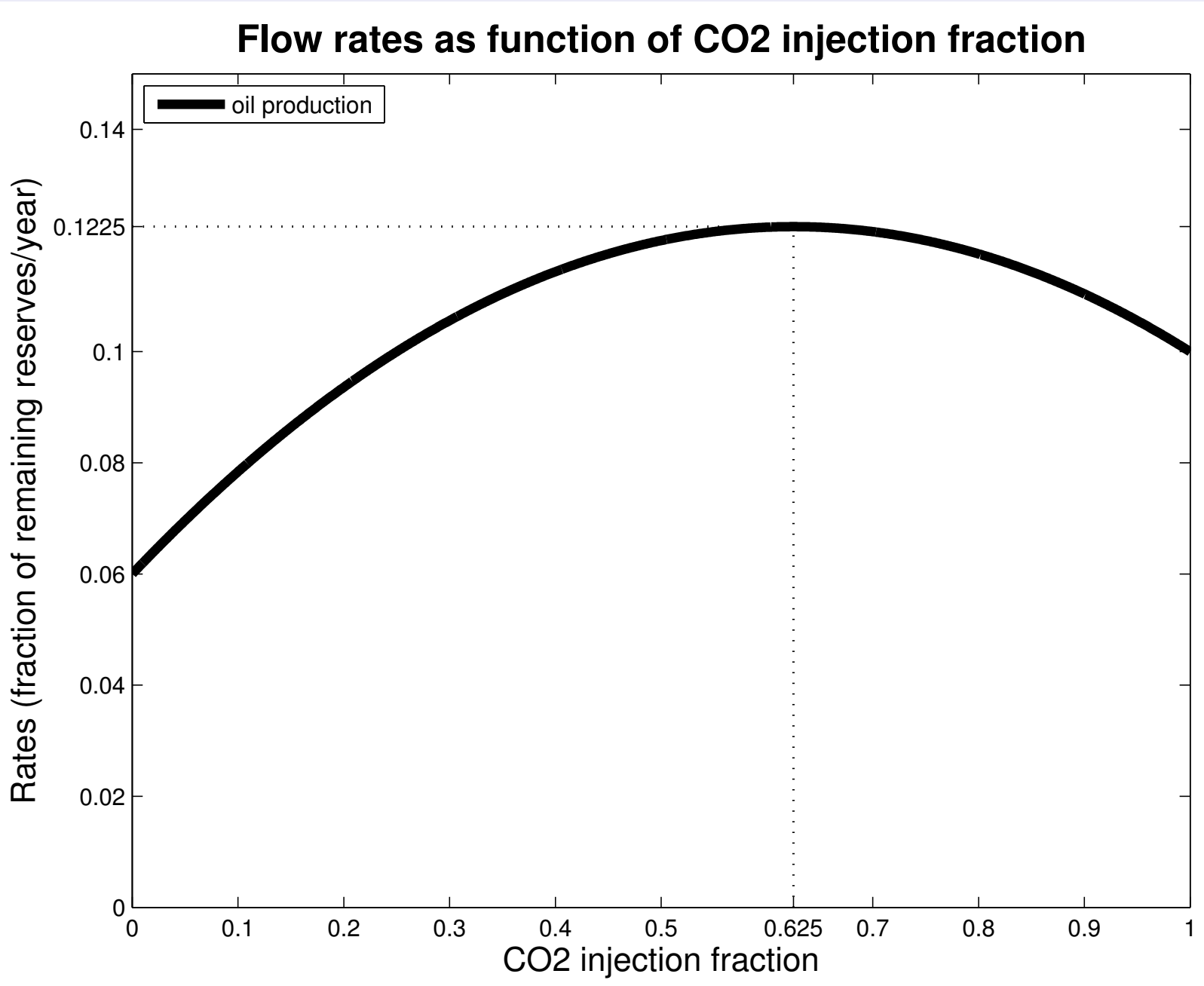
$$q^{\text{seq}}_{CO_2} = \frac{q^{\text{inj}}_{CO_2}}{q^{\text{inj}}_{CO_2} + q^{\text{inj}}_{\text{wat}}} \times q^{\text{prd}}_{\text{oil}}$$

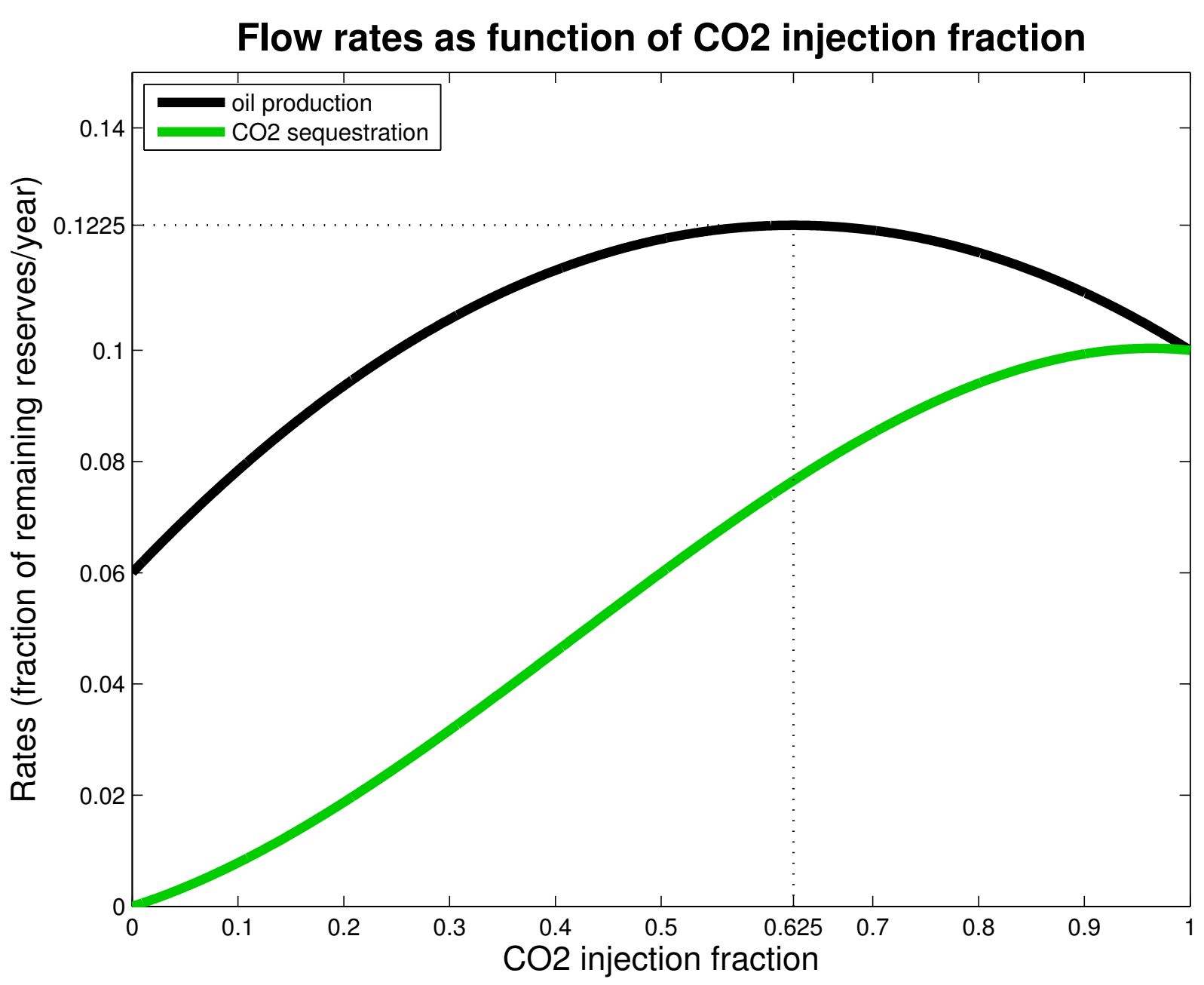
Problem: ad hoc engineering assumptions

Assumption 1: Oil production is an inverse U-shaped function of the CO_2 injection fraction $q^{\text{inj}}_{CO_2}/(q^{\text{inj}}_{CO_2} + q^{\text{inj}}_{\text{wat}})$.

Assumption 2: CO_2 sequestration is the product of the CO_2 injection fraction and oil production:

$$q^{\text{seq}}_{CO_2} = \underbrace{\frac{q^{\text{inj}}_{CO_2}}{q^{\text{inj}}_{CO_2} + q^{\text{inj}}_{\text{wat}}}}_{0.5} \times q^{\text{prd}}_{\text{oil}}$$


Flow rates as function of CO2 injection fraction
oil production
Rates (fraction of remaining reserves/year)
0.14
0.1225
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.625
0.7
0.8
0.9
1
CO2 injection fraction

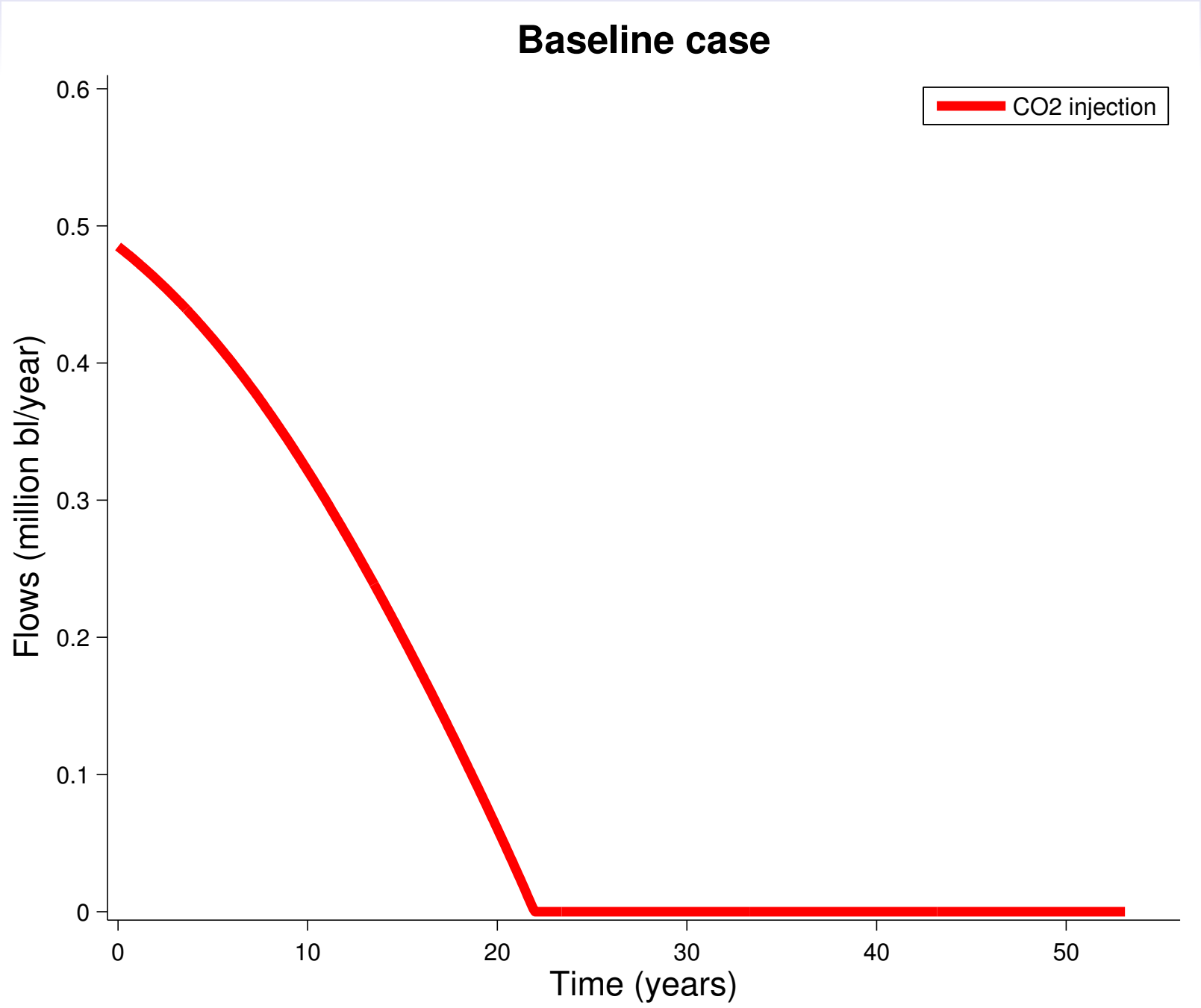

Flow rates as function of CO2 injection fraction
oil production
CO2 sequestration
Rates (fraction of remaining reserves/year)
0.14
0.1225
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.625
0.7
0.8
0.9
1
CO2 injection fraction

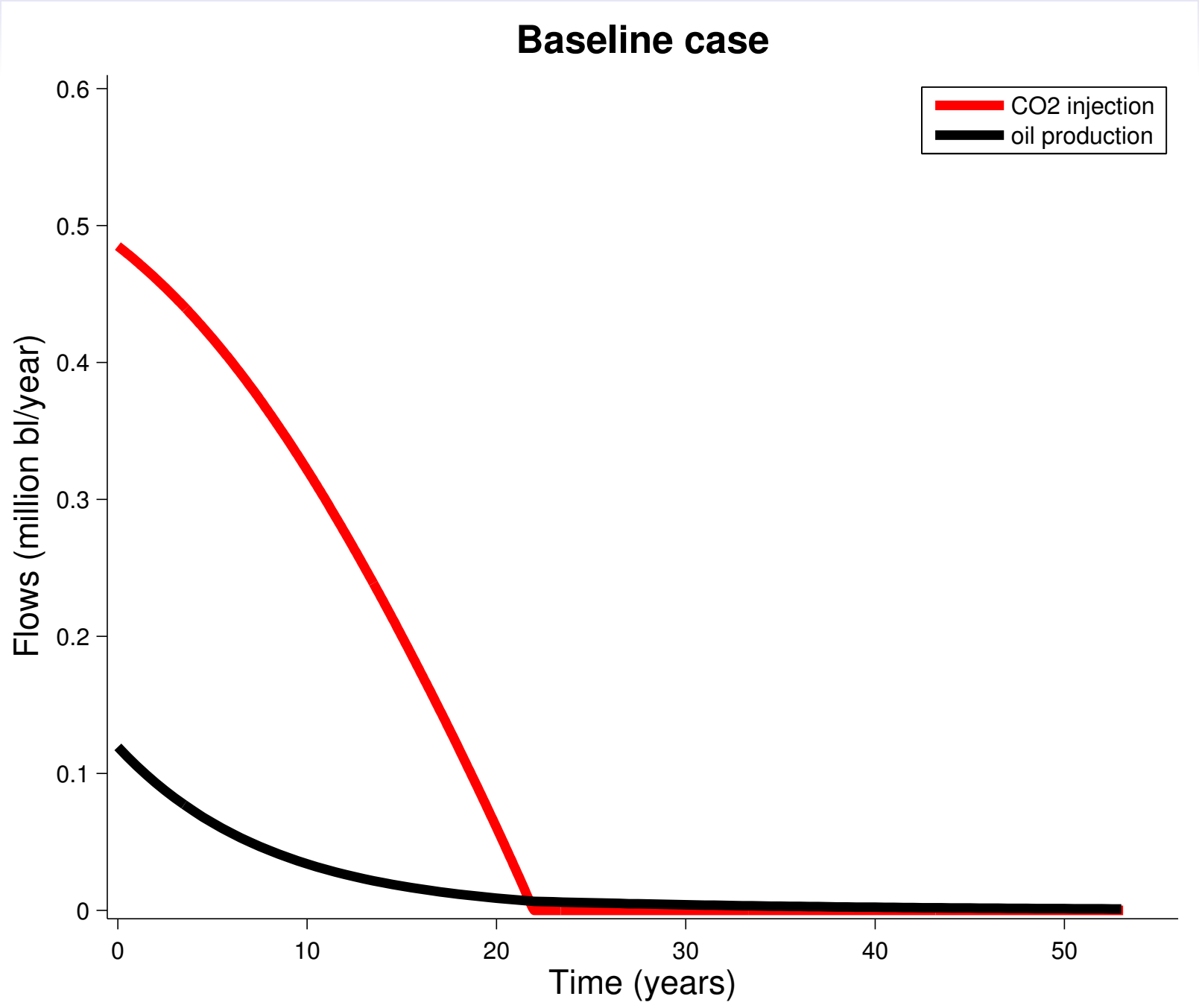
Profit objective function

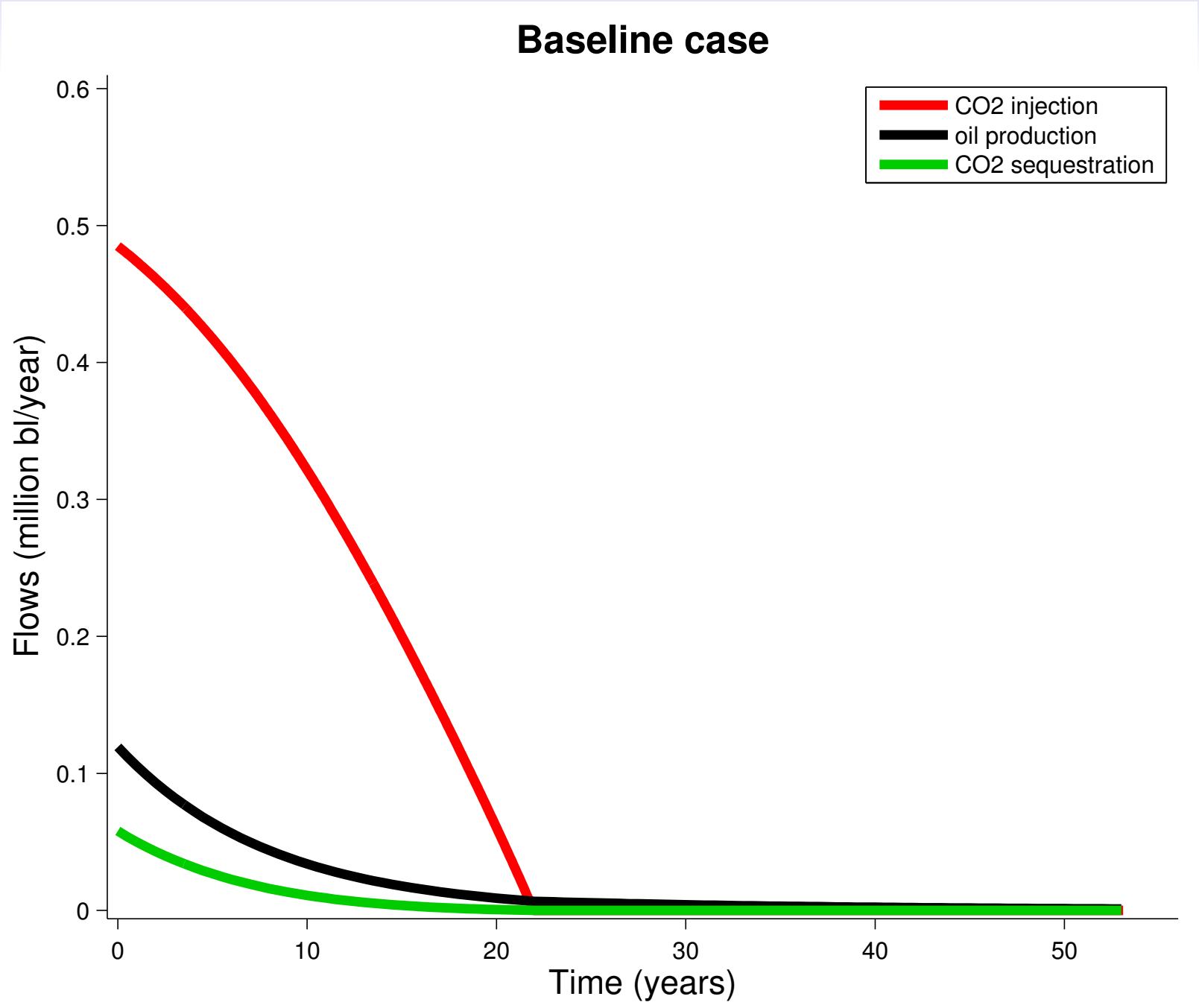
Benefits of CO_2 injection fall over time

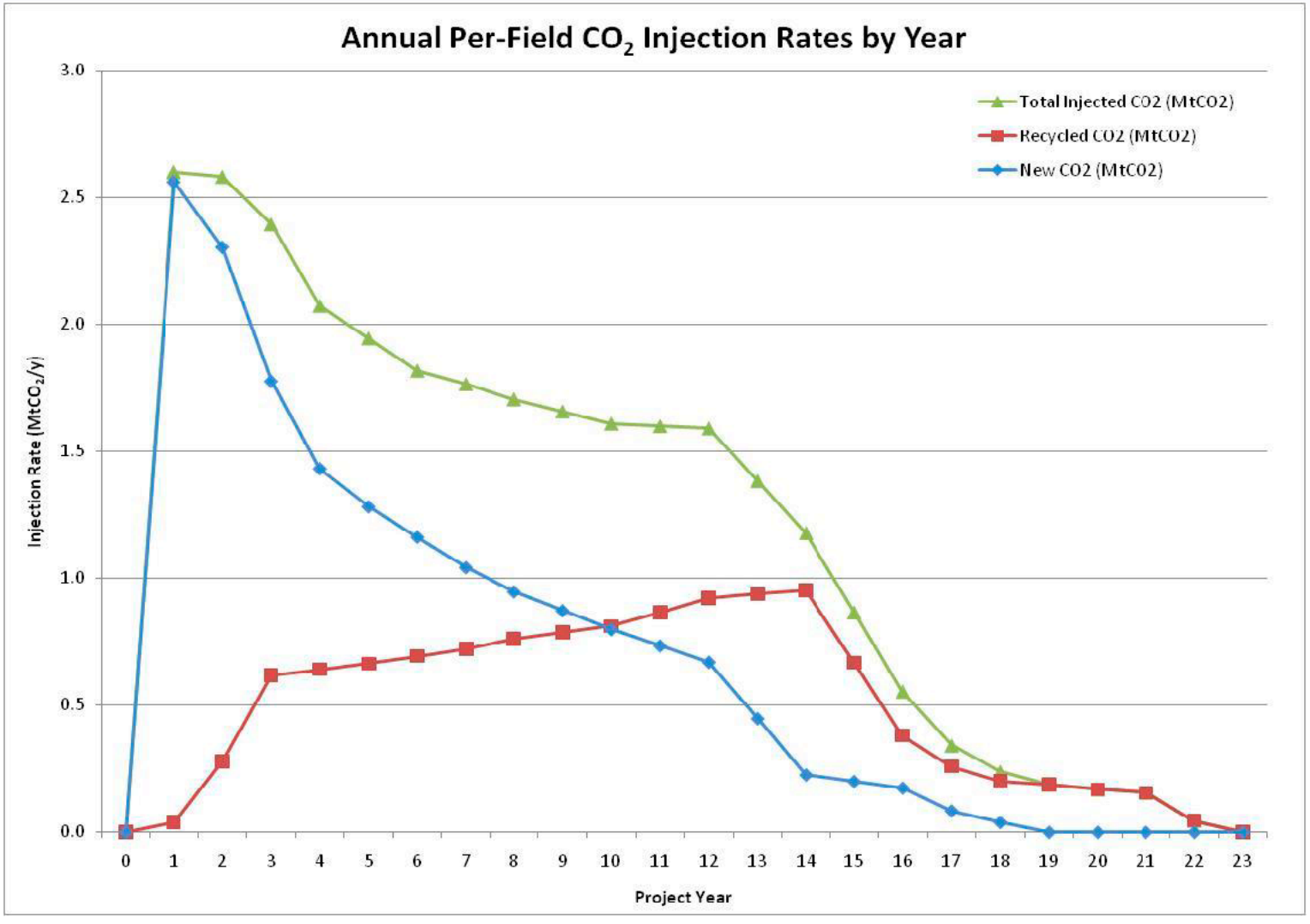
Costs must fall over time

$$profit = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} q_{CO_2}^{inj} - \underbrace{c^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$


Baseline case
CO2 injection
Flows (million bl/year)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
Time (years)


Baseline case
CO2 injection
oil production
Flows (million bl/year)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
Time (years)

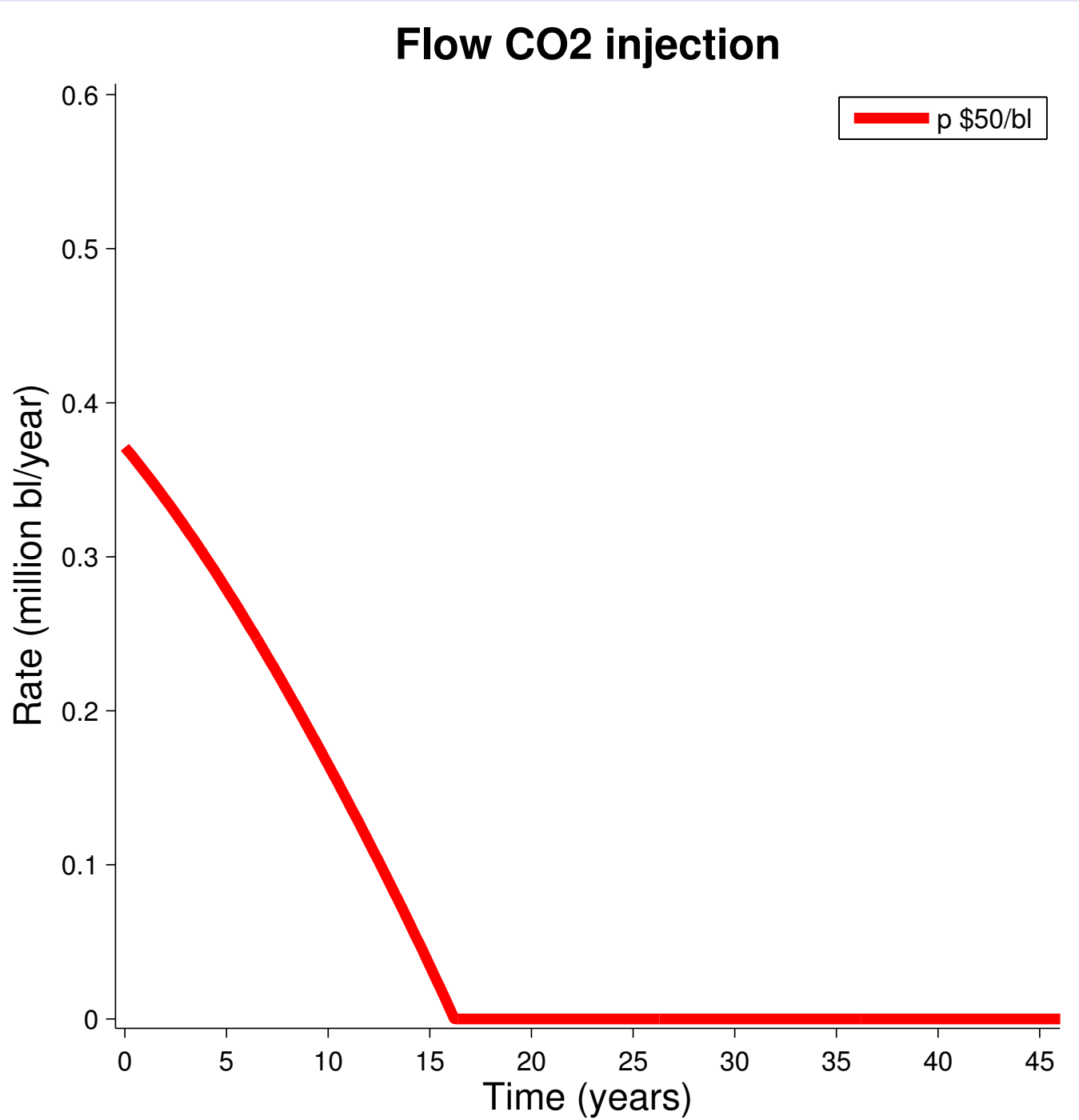

Baseline case
CO2 injection
oil production
CO2 sequestration
Flows (million bl/year)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
Time (years)

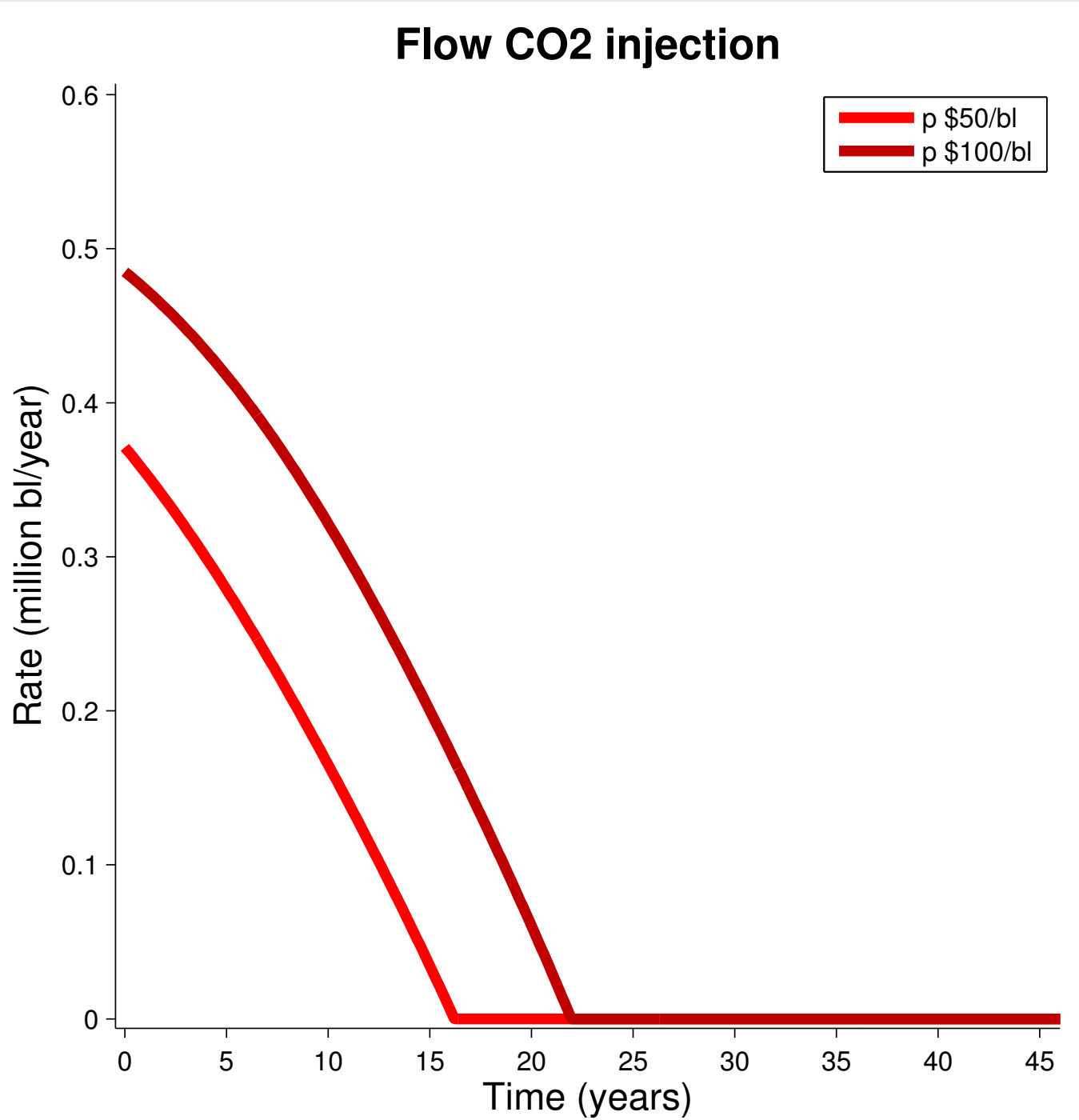


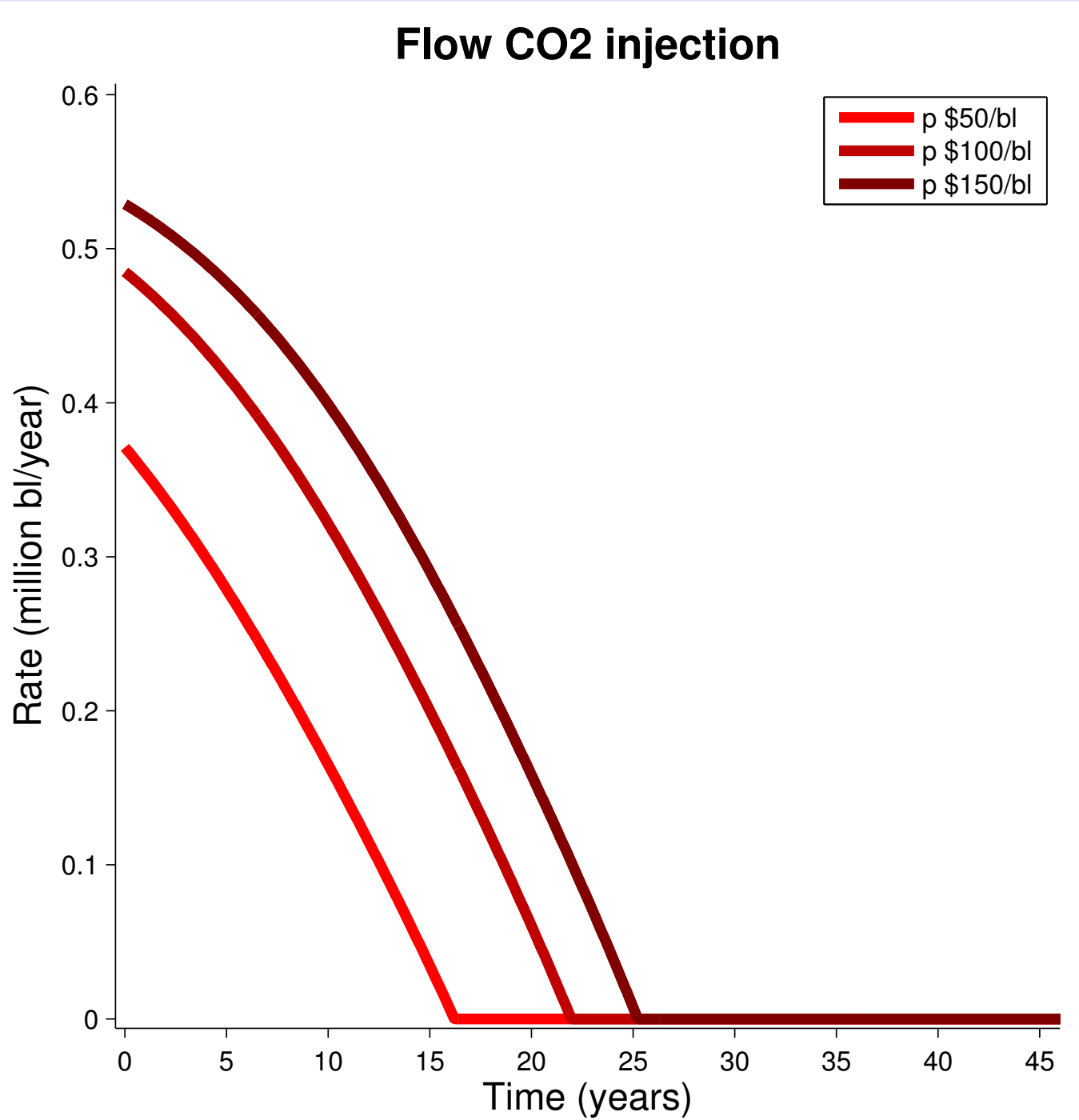
Source: Davidson, C.L. et al. (2011) "A quantitative comparison of the cost of employing EOR-coupled CCS supplemented with secondary DSF storage for two large CO_2 point sources," *Energy Procedia* 4: 2361–2368

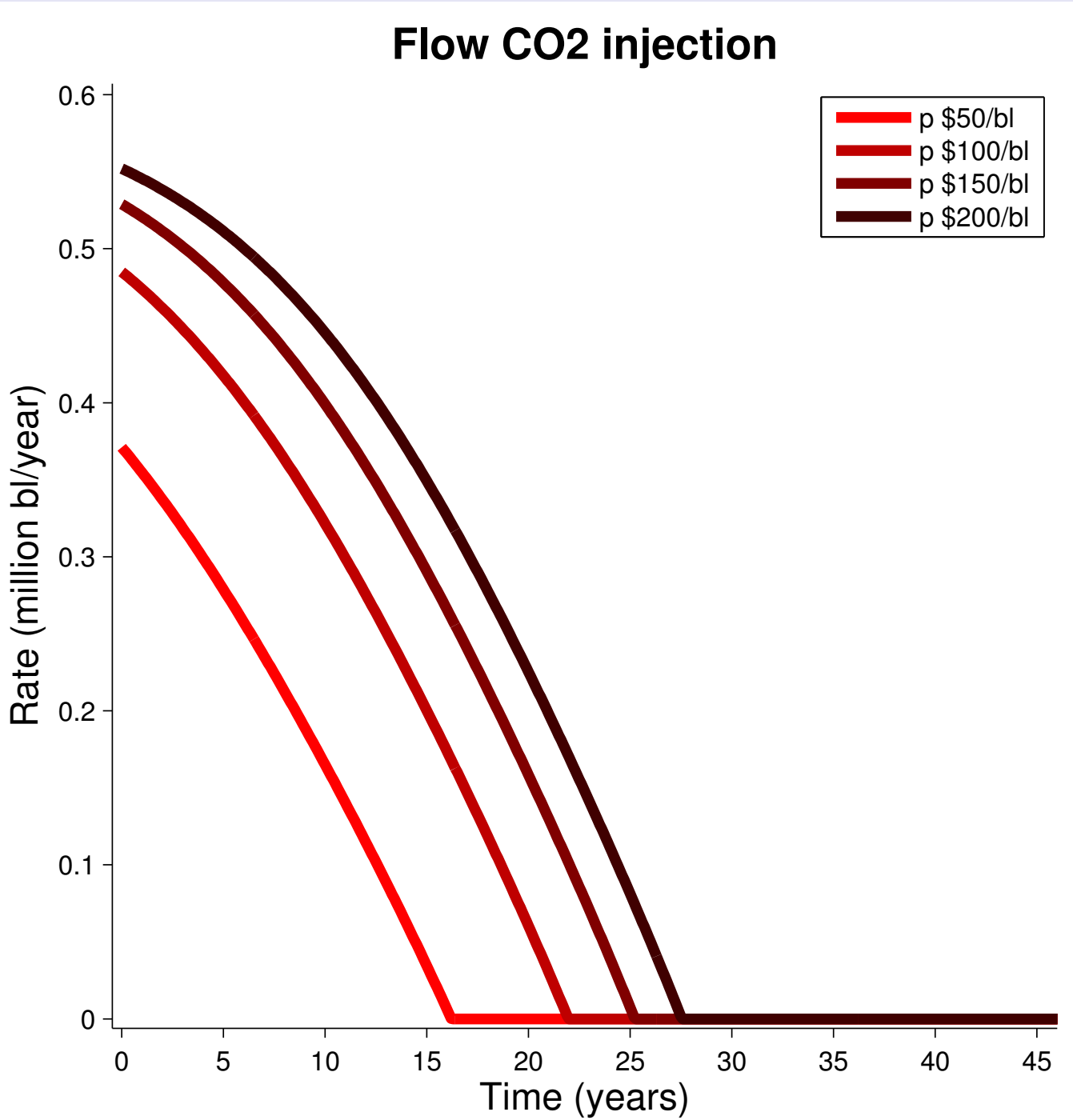
CO_2-EOR profits

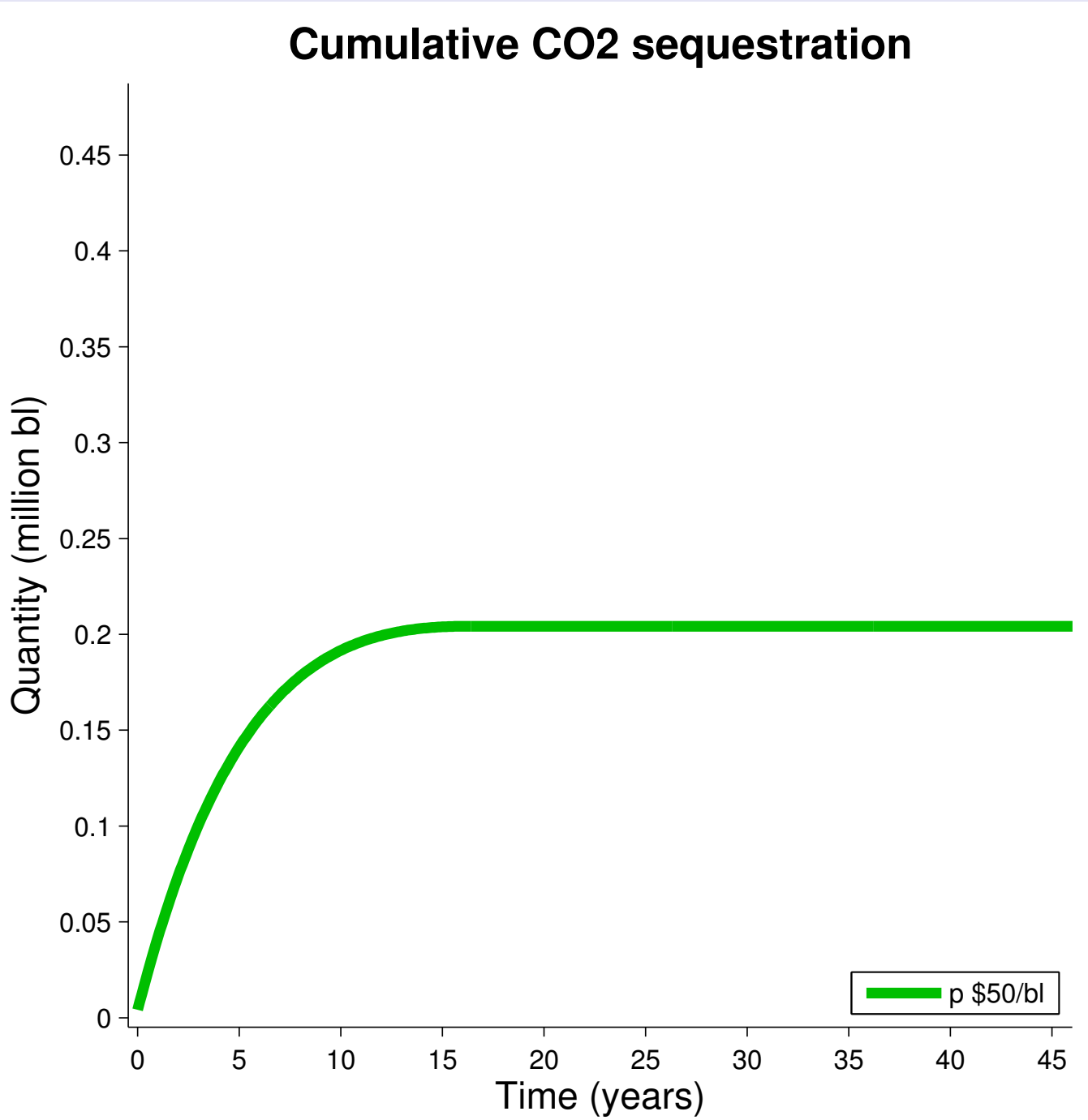
$$NPV = \underbrace{p_{oil}}_{\substack{\text{weight} \\ \text{on oil} \\ \text{production}}} Q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

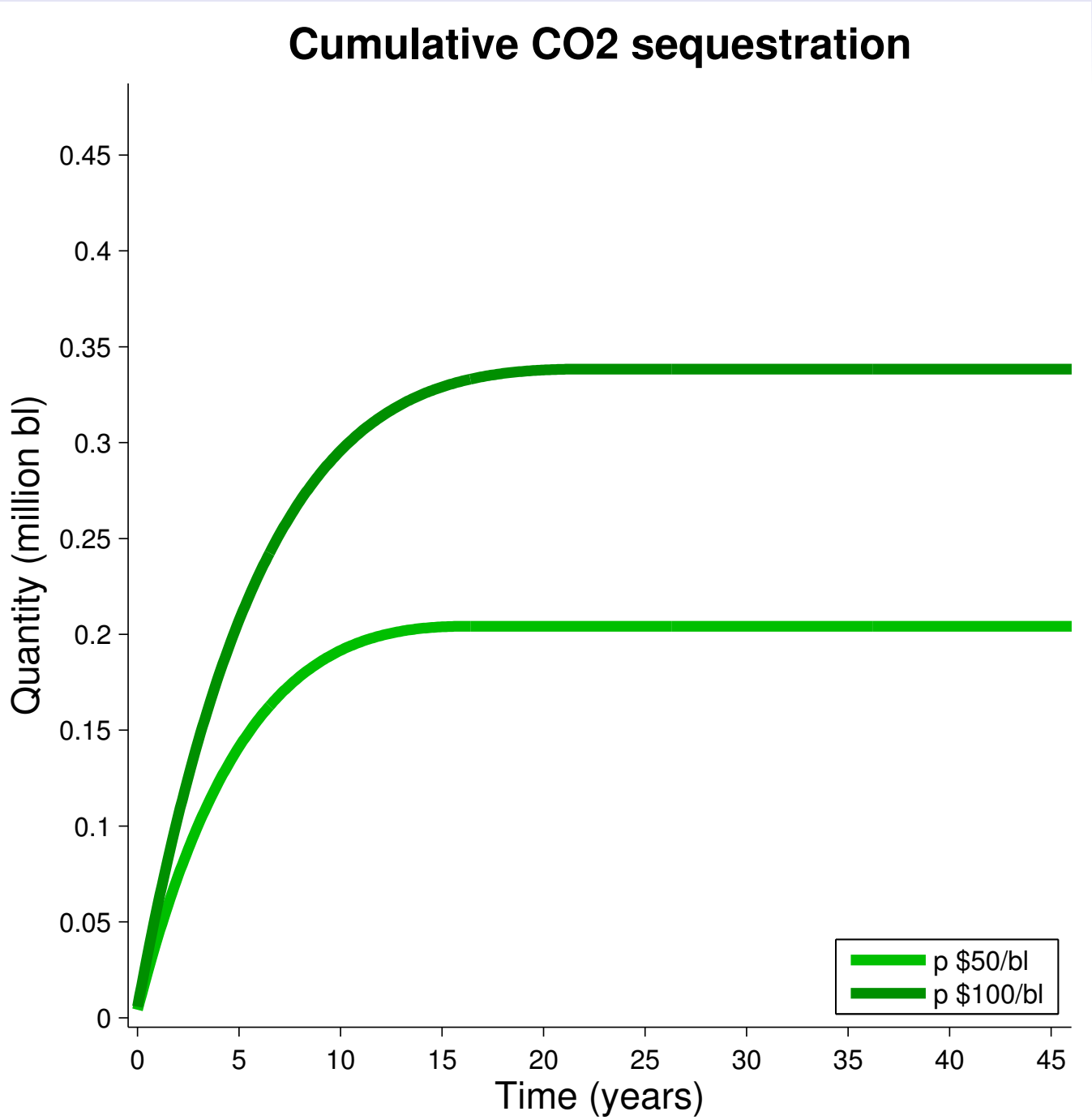

Flow CO2 injection
p $50/bl
Rate (million bl/year)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
Time (years)

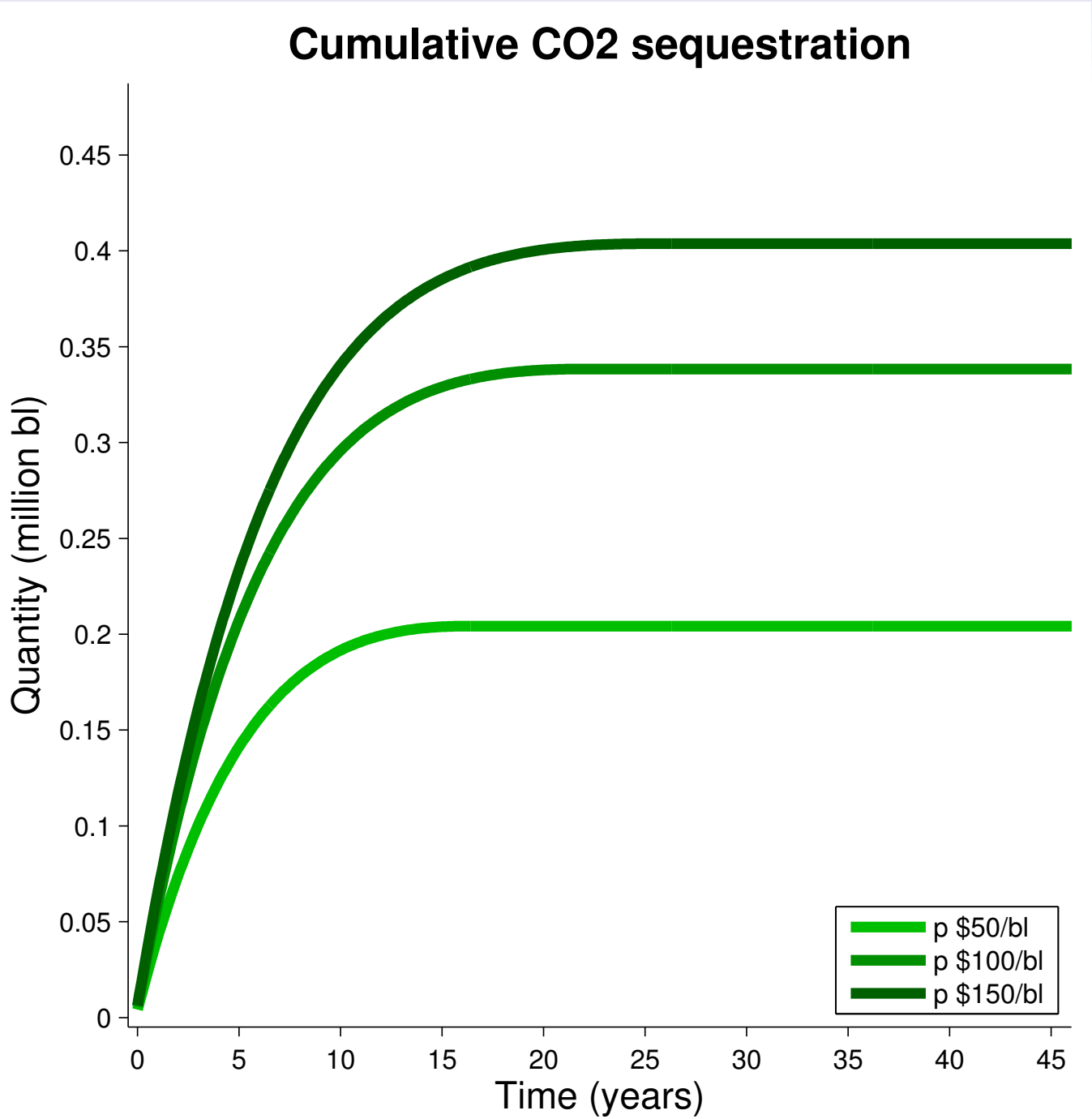

Flow CO2 injection
p $50/bl
p $100/bl
Rate (million bl/year)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
Time (years)

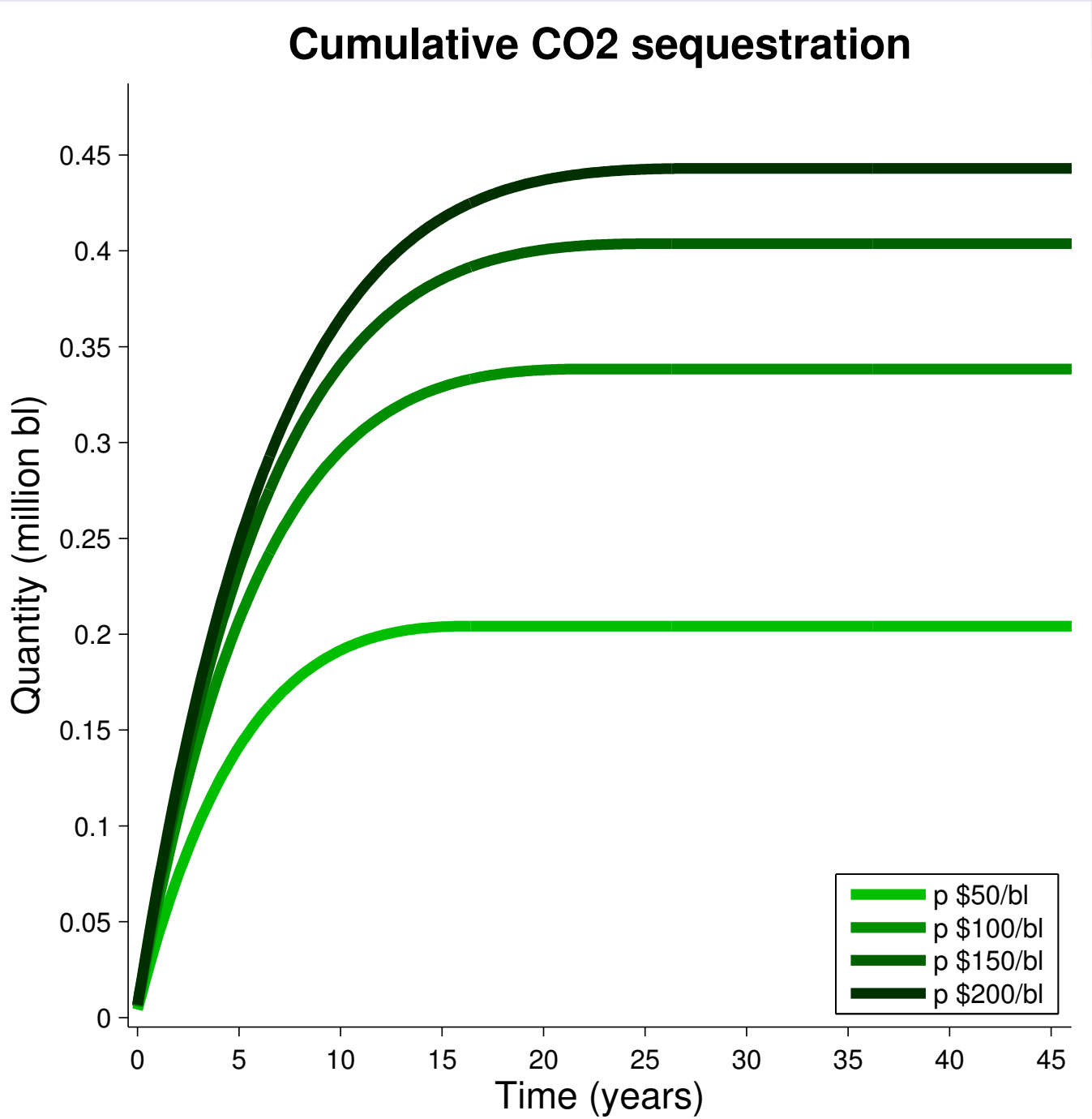

Flow CO2 injection
p $50/bl
p $100/bl
p $150/bl
Rate (million bl/year)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
35
40
45
Time (years)

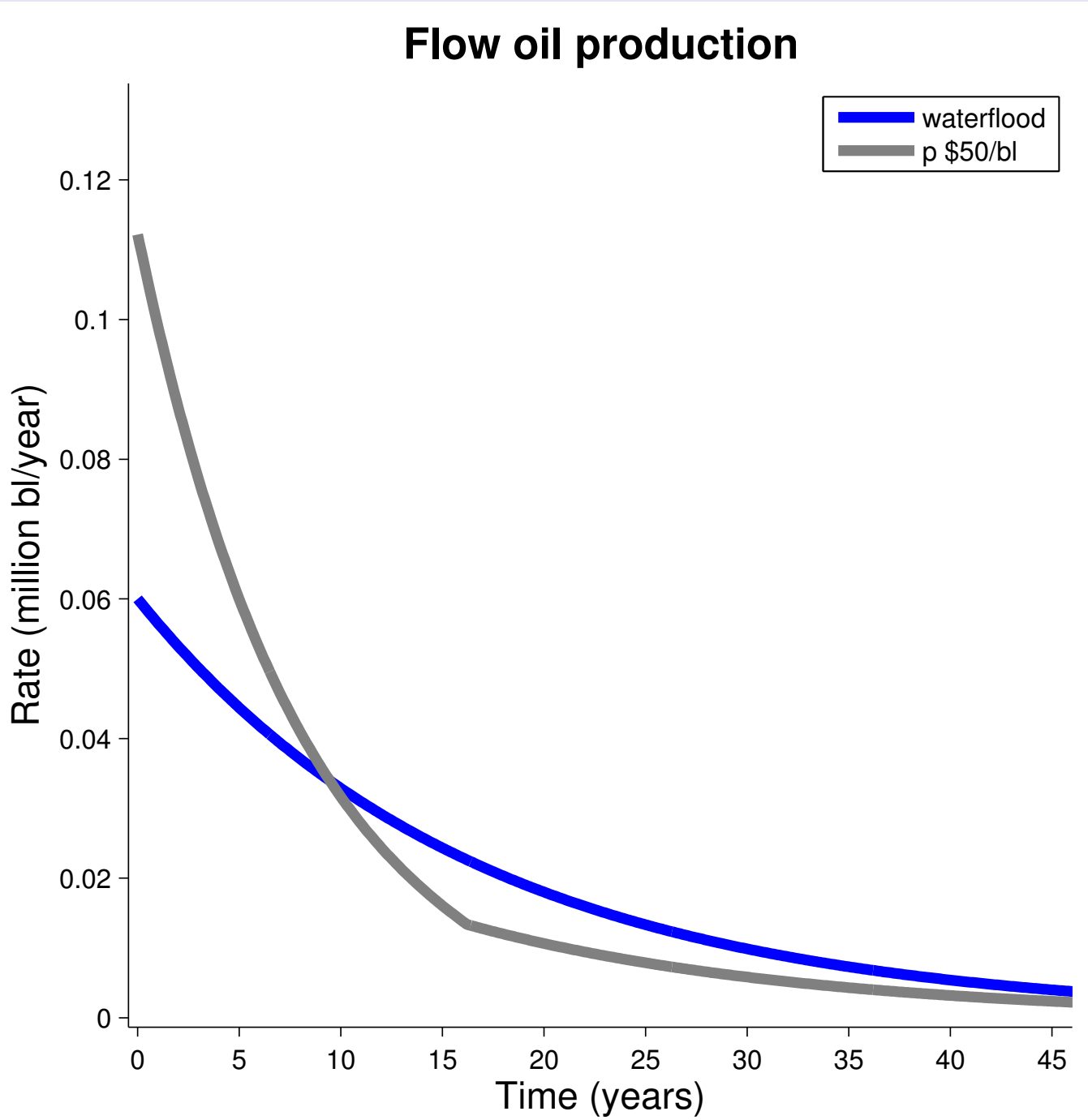

Flow CO2 injection
p $50/bl
p $100/bl
p $150/bl
p $200/bl
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)

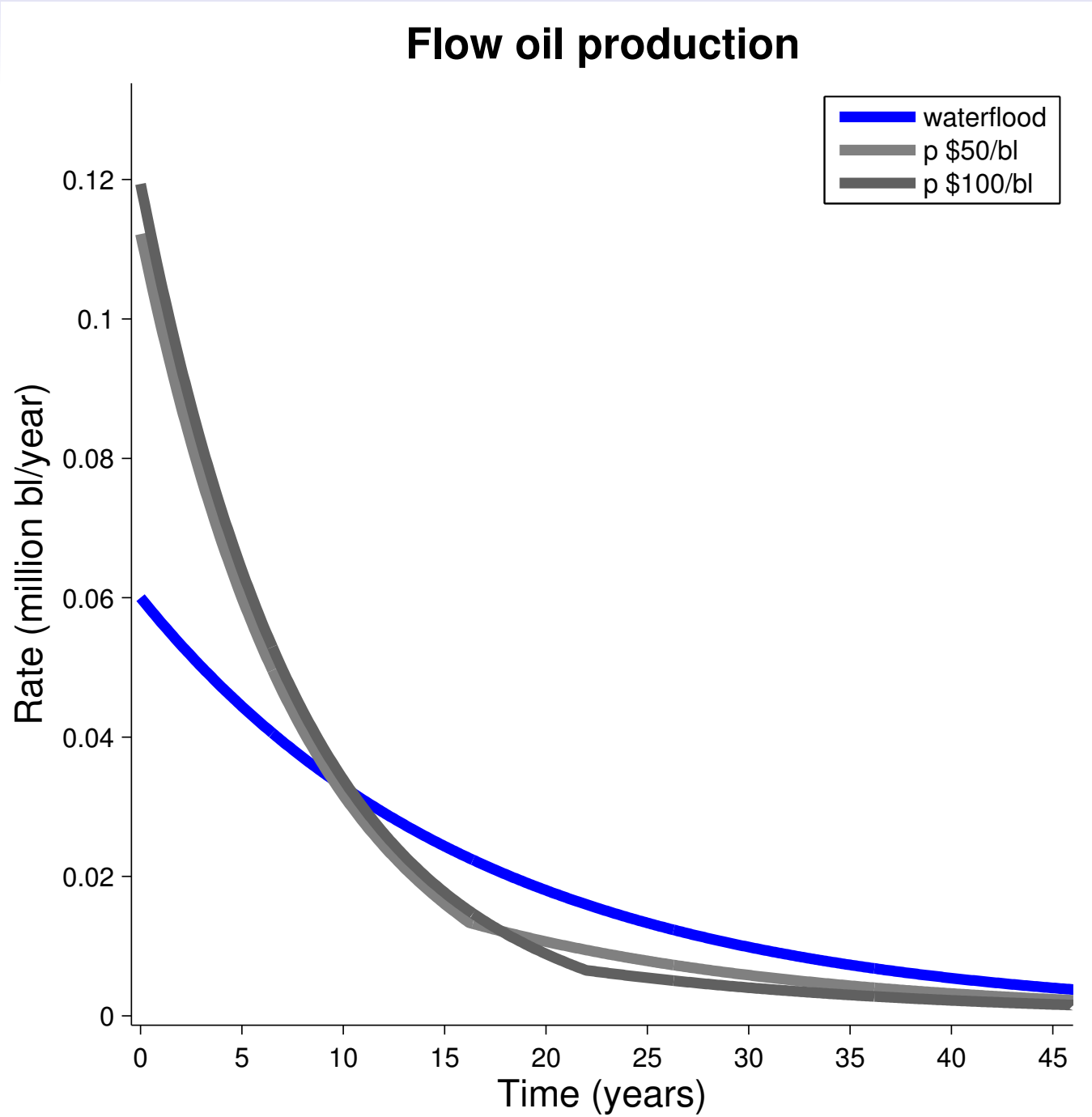

Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45
Time (years)
p $50/bl

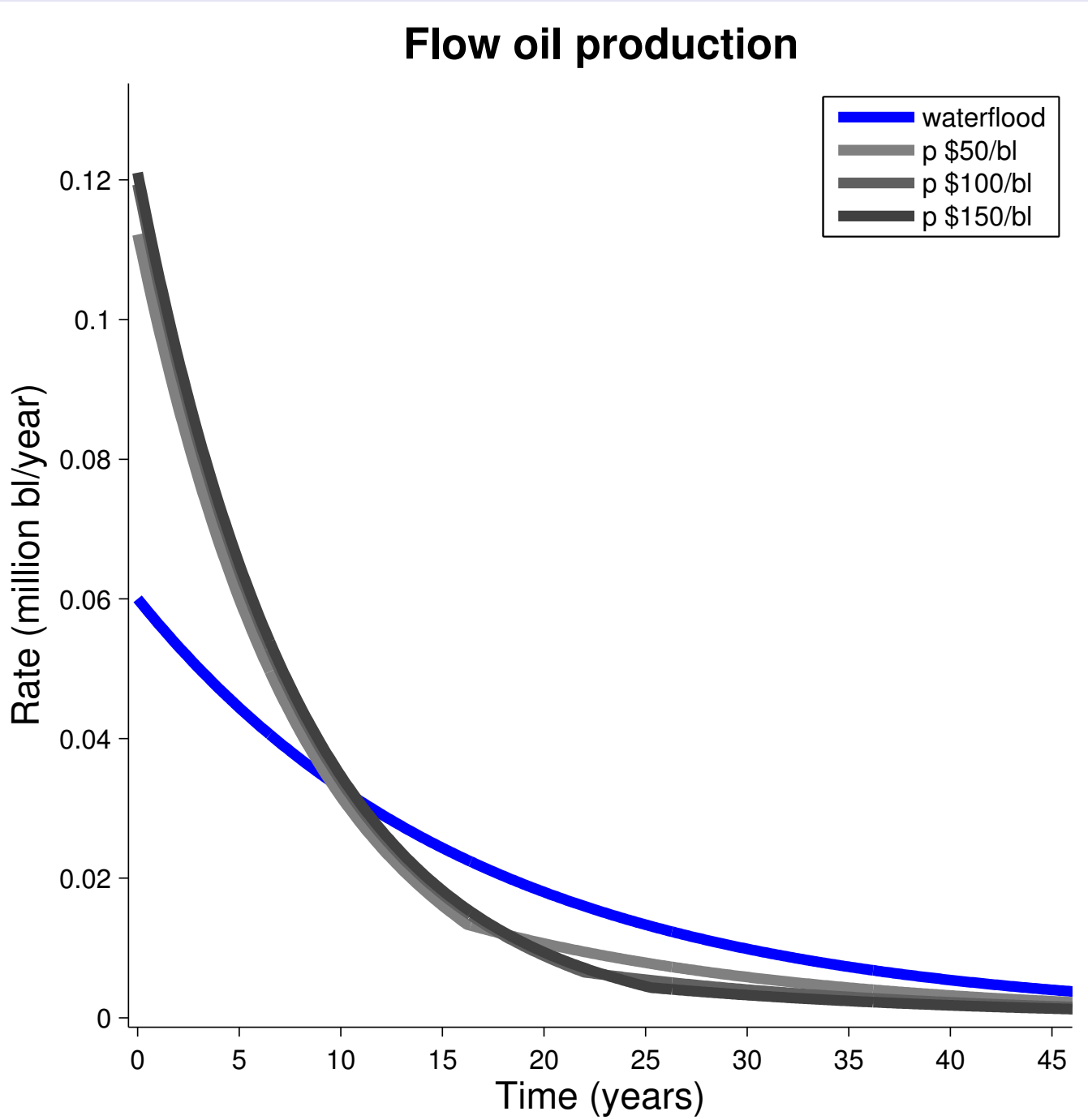

Cumulative CO2 sequestration
Quantity (million bl)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
Time (years)
p $50/bl
p $100/bl

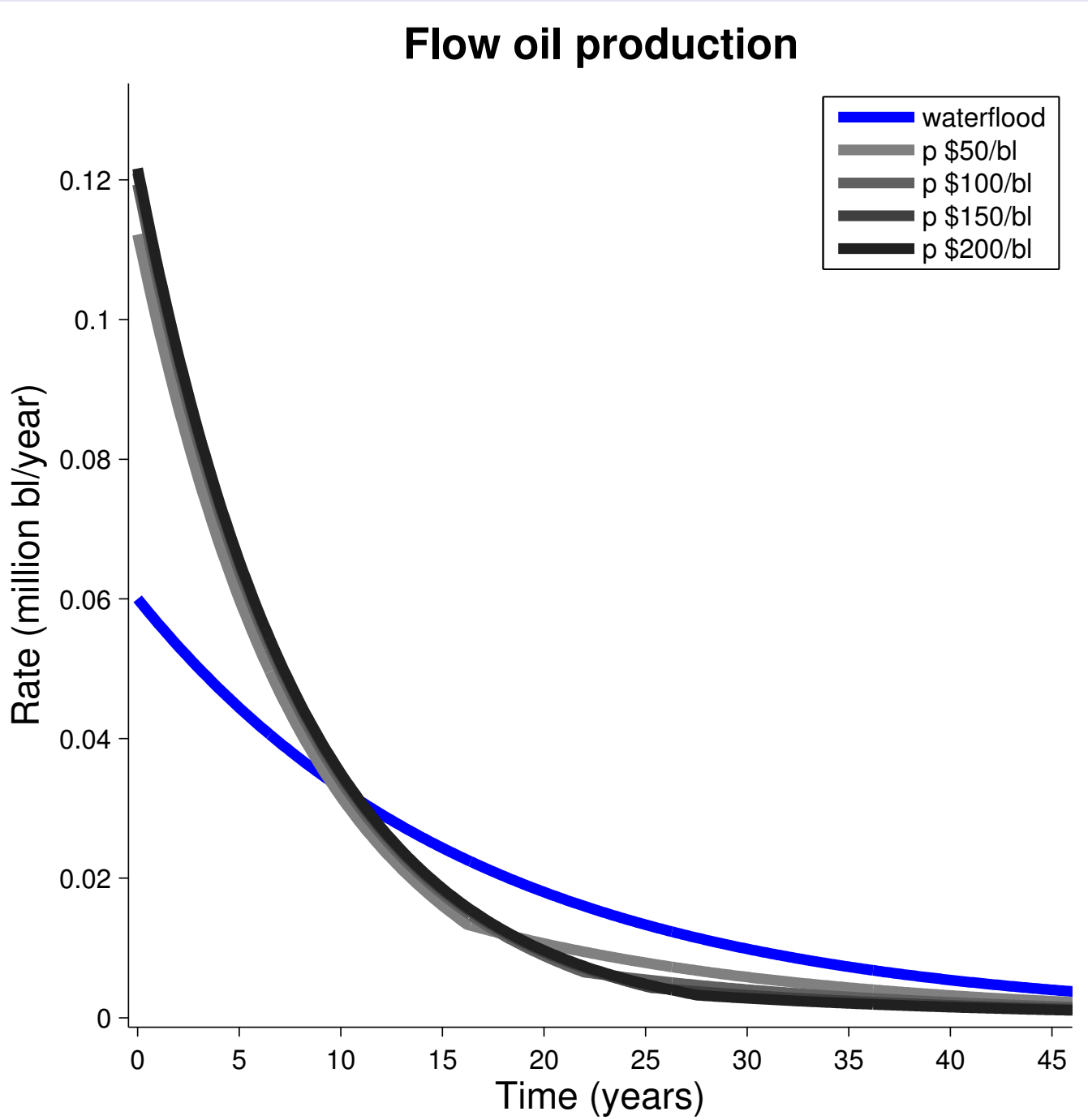

Cumulative CO2 sequestration
Quantity (million bl)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
Time (years)
p $50/bl
p $100/bl
p $150/bl

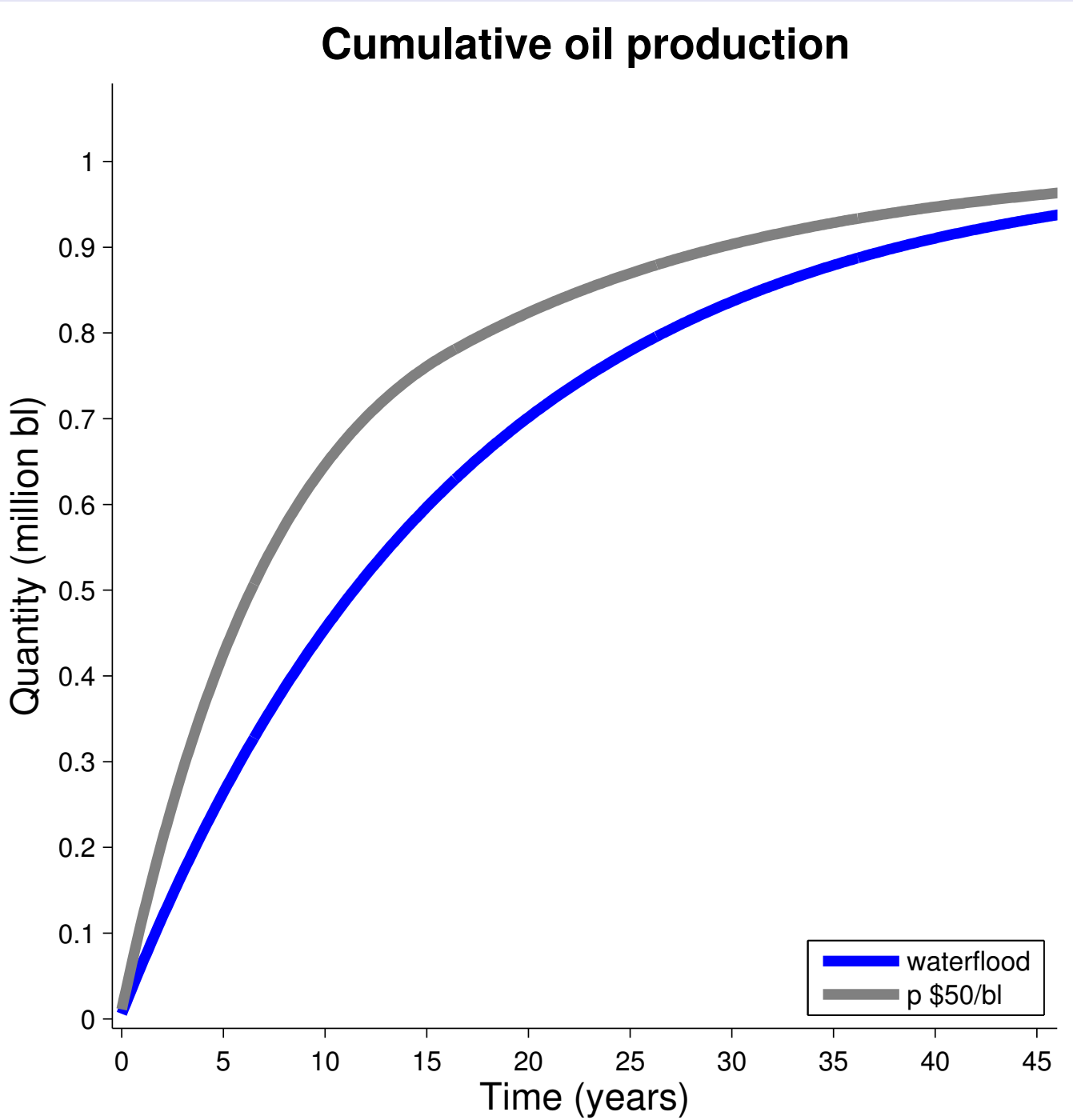

Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45
Time (years)
p $50/bl
p $100/bl
p $150/bl
p $200/bl

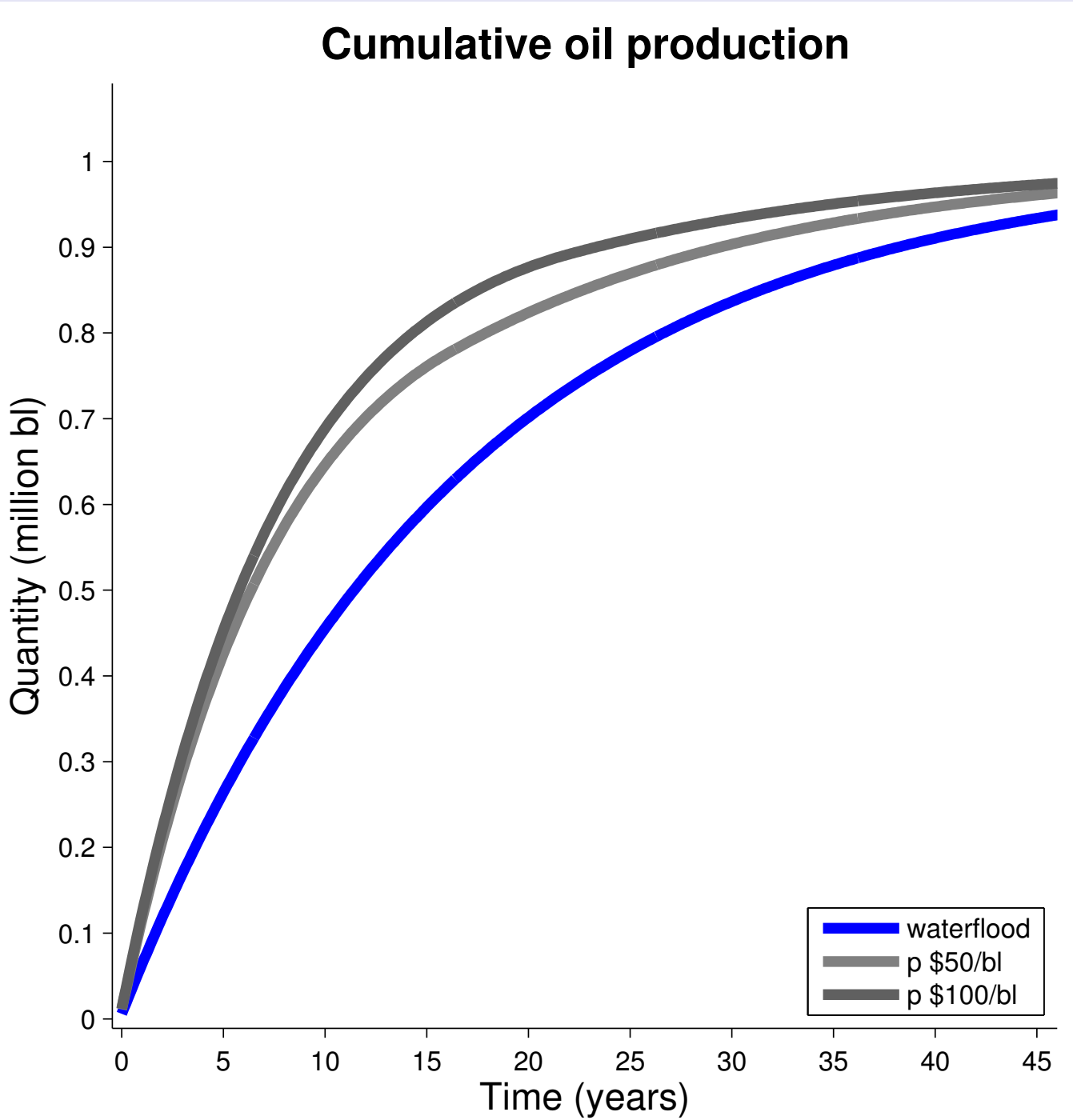

Flow oil production
waterflood
p $50/bl
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)

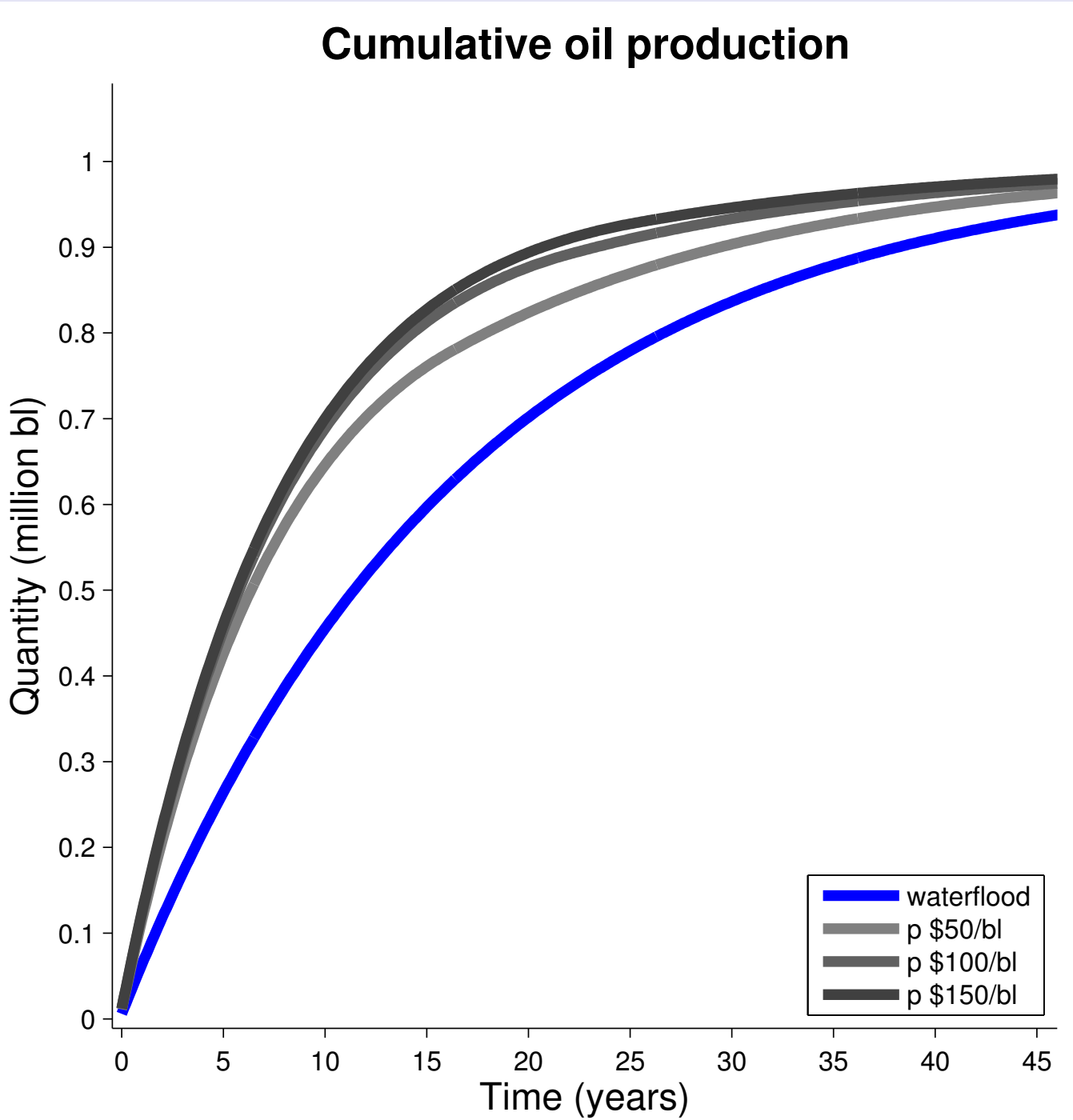

Flow oil production
waterflood
p $50/bl
p $100/bl
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)

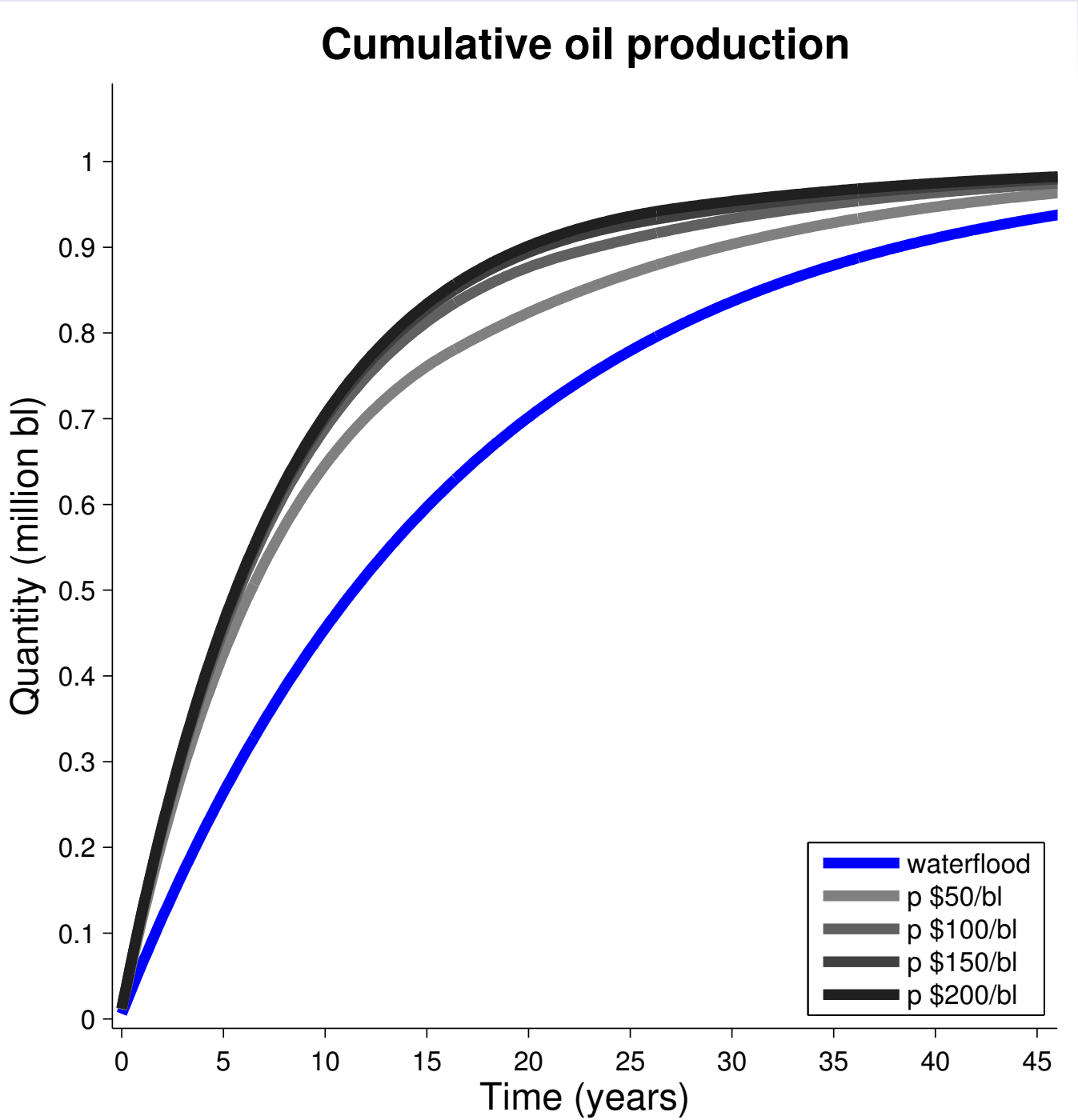

Flow oil production
waterflood
p $50/bl
p $100/bl
p $150/bl
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)

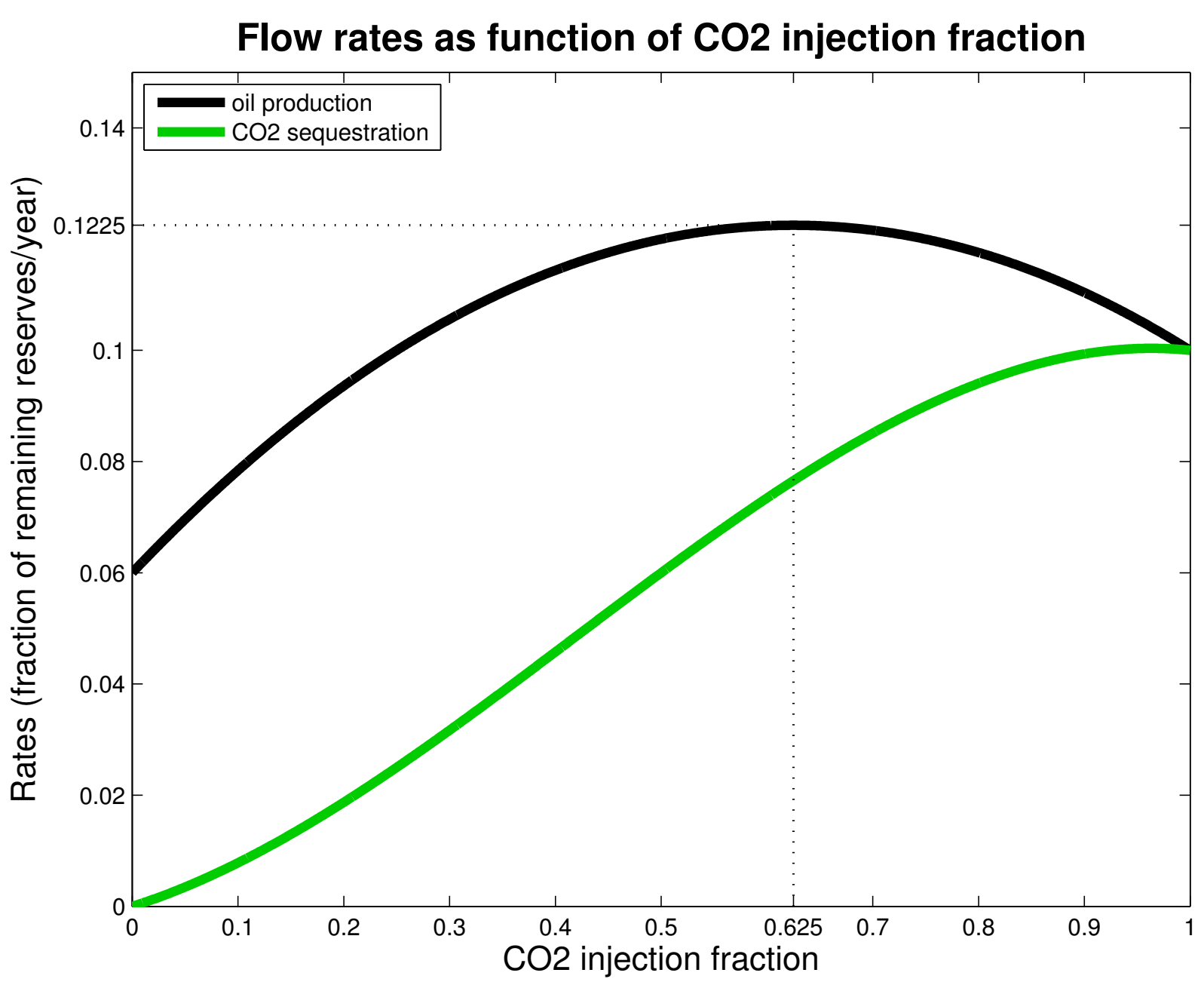

Flow oil production
waterflood
p $50/bl
p $100/bl
p $150/bl
p $200/bl
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)

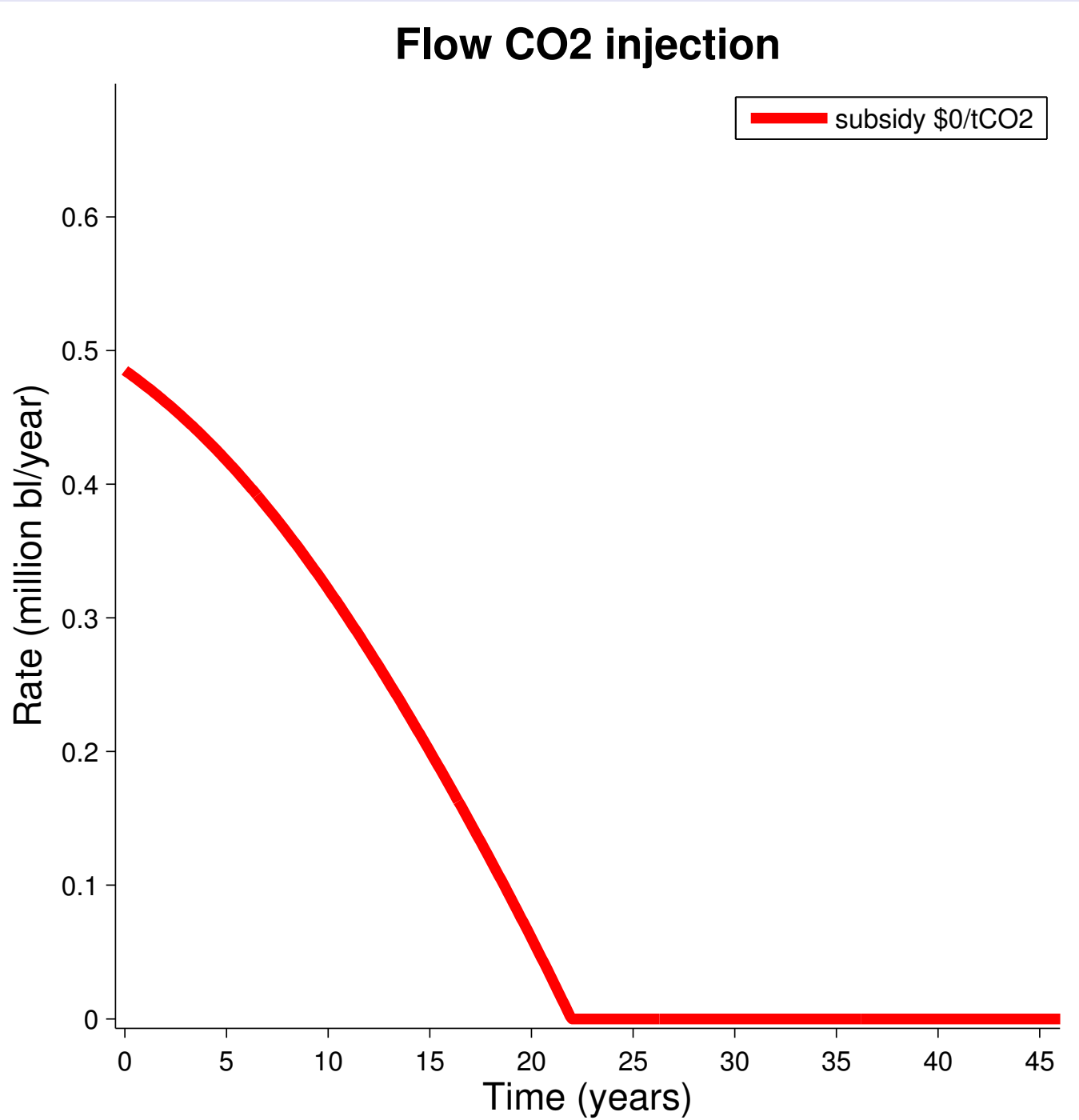

Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
p $50/bl

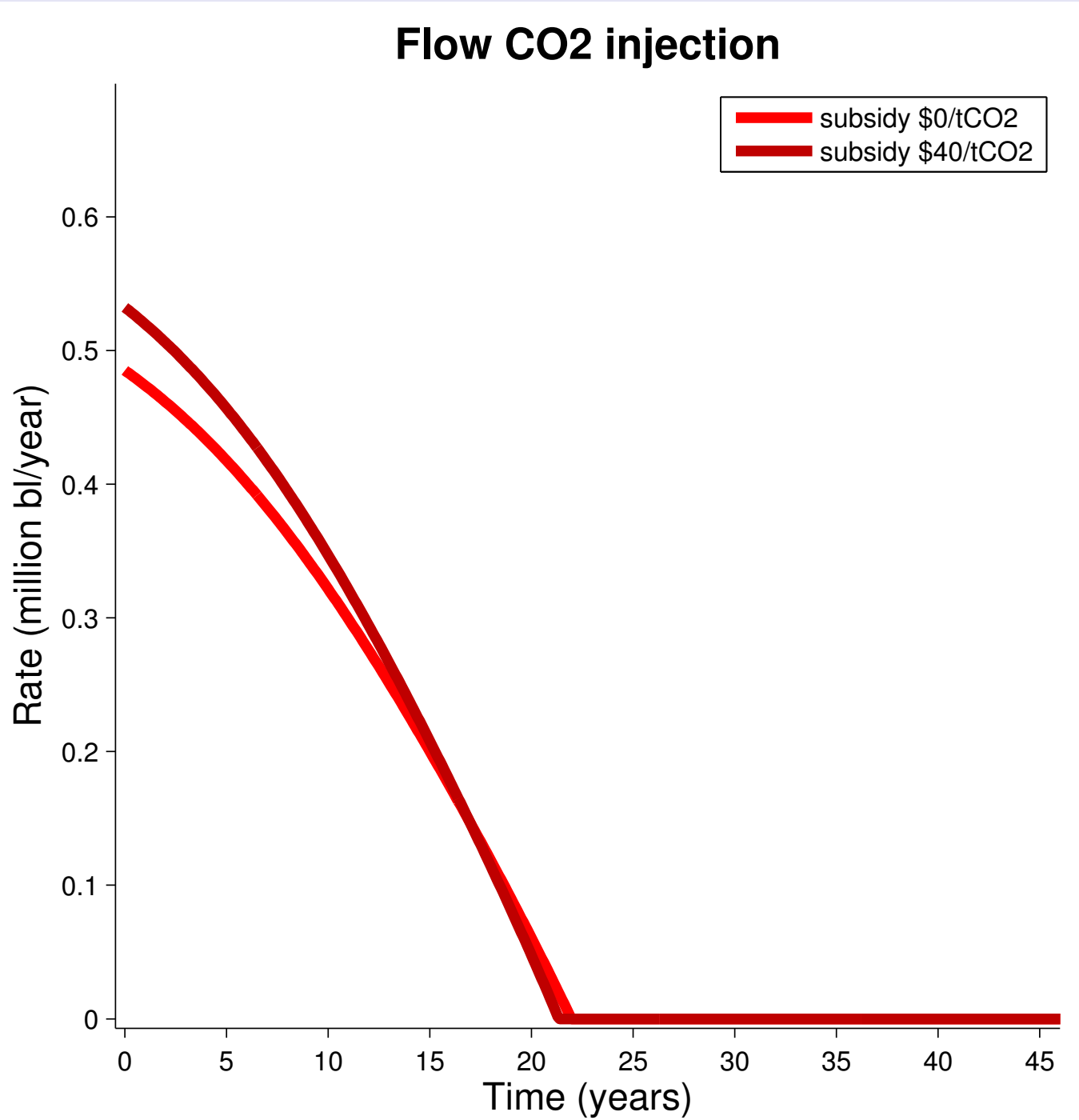

Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
p $50/bl
p $100/bl

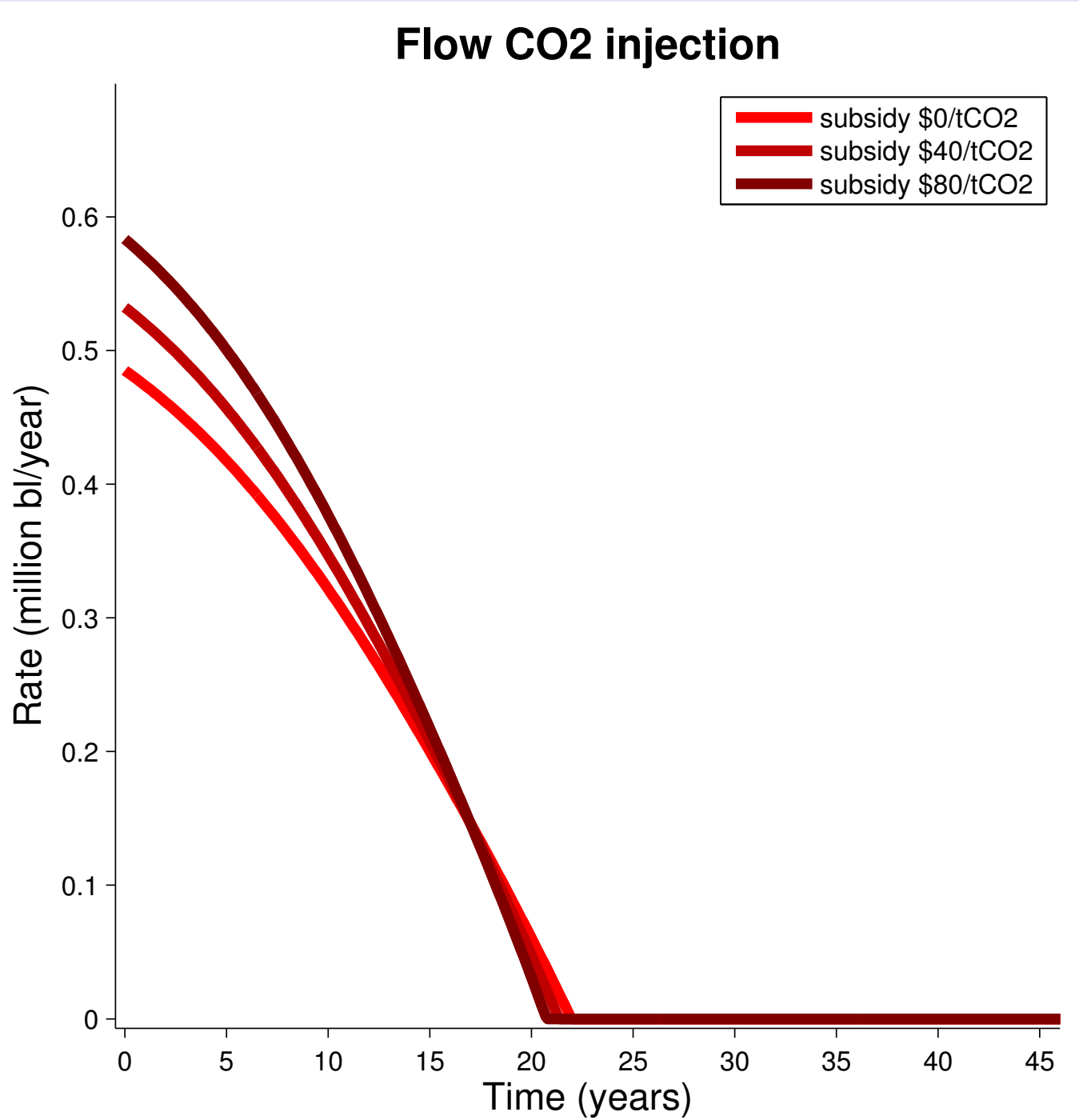

Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
p $50/bl
p $100/bl
p $150/bl

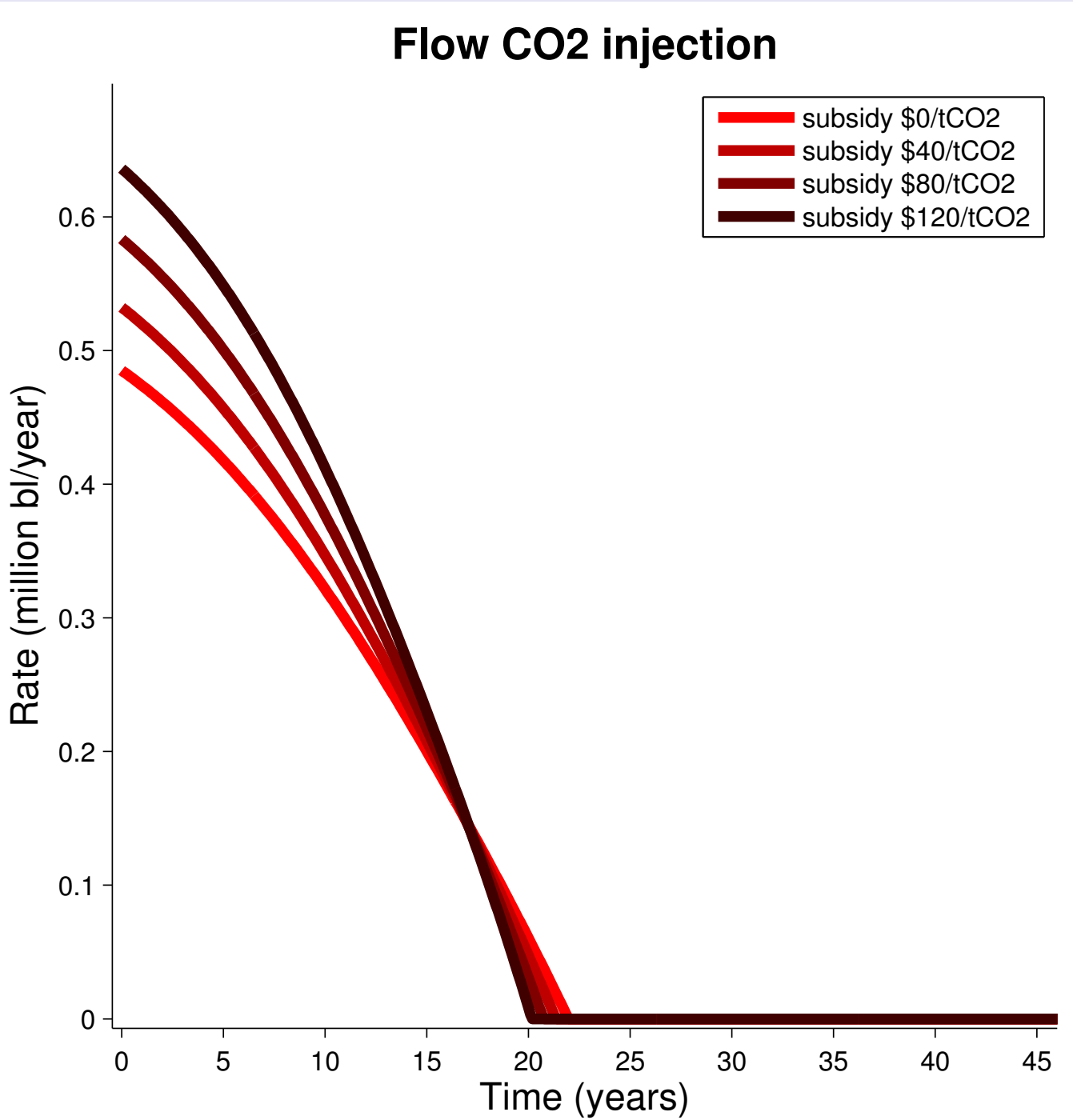

Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
p $50/bl
p $100/bl
p $150/bl
p $200/bl

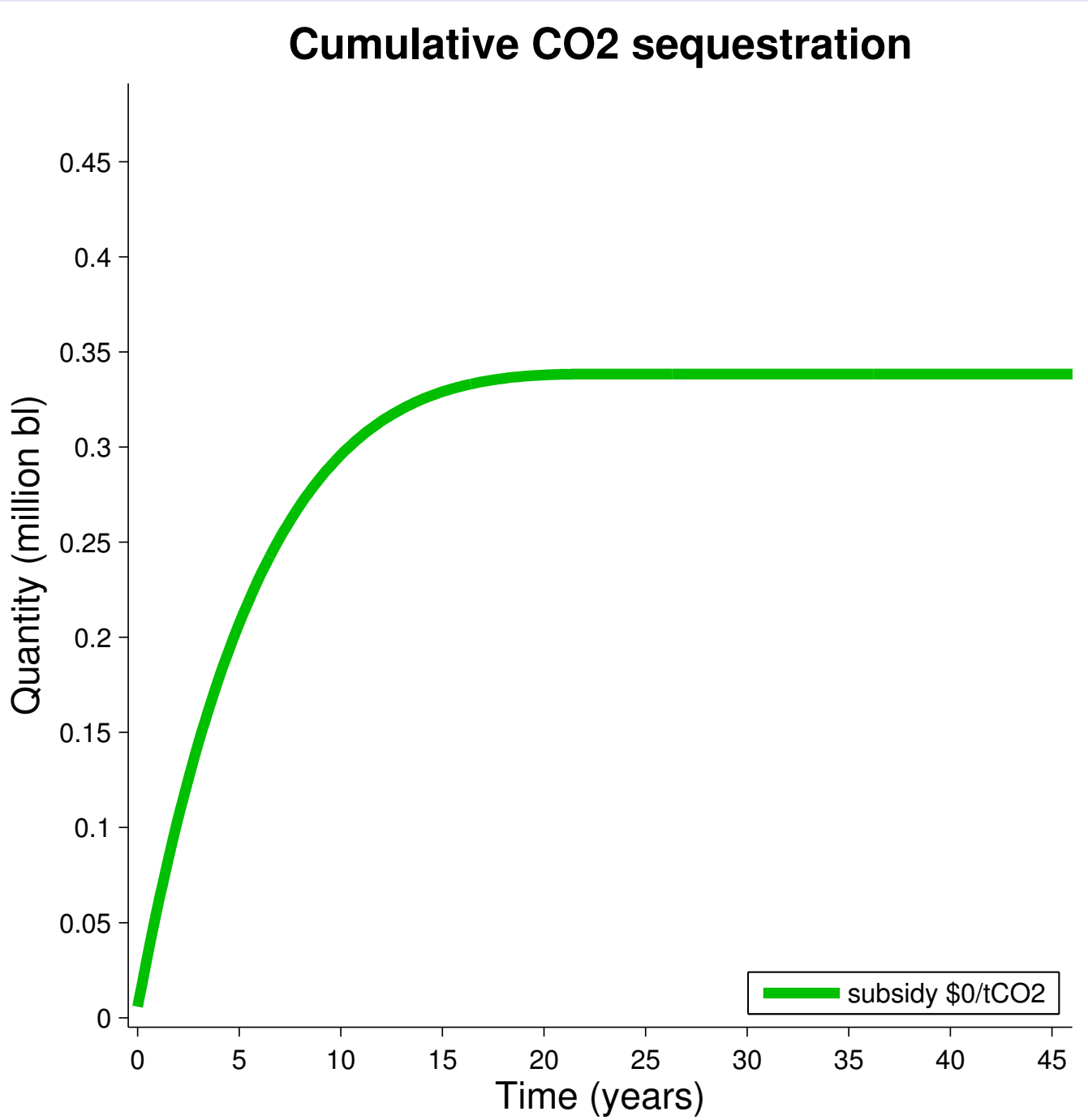

Flow rates as function of CO2 injection fraction
oil production
CO2 sequestration
Rates (fraction of remaining reserves/year)
0.14
0.1225
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.625
0.7
0.8
0.9
1
CO2 injection fraction

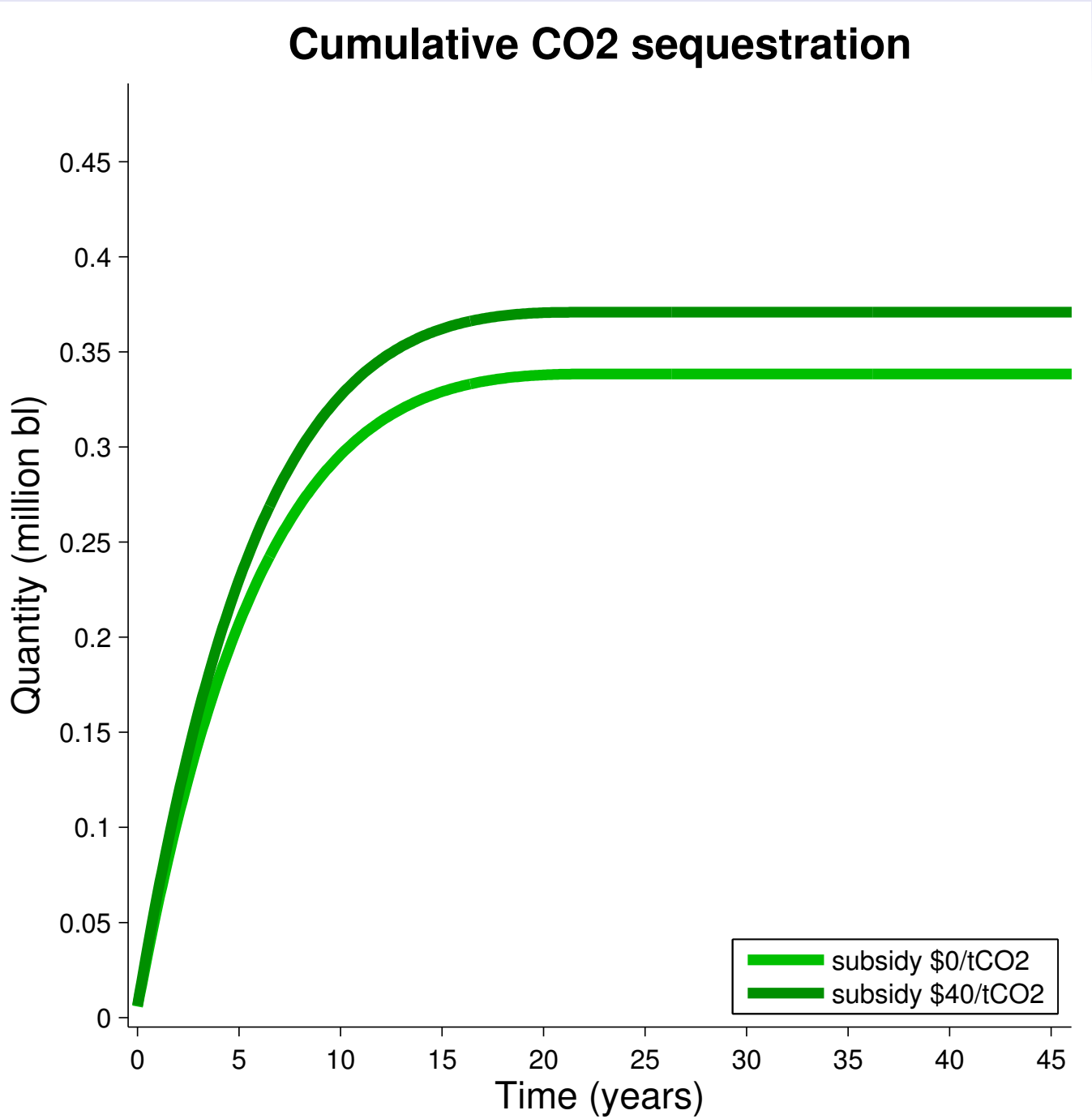

Flow CO2 injection
subsidy $0/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)

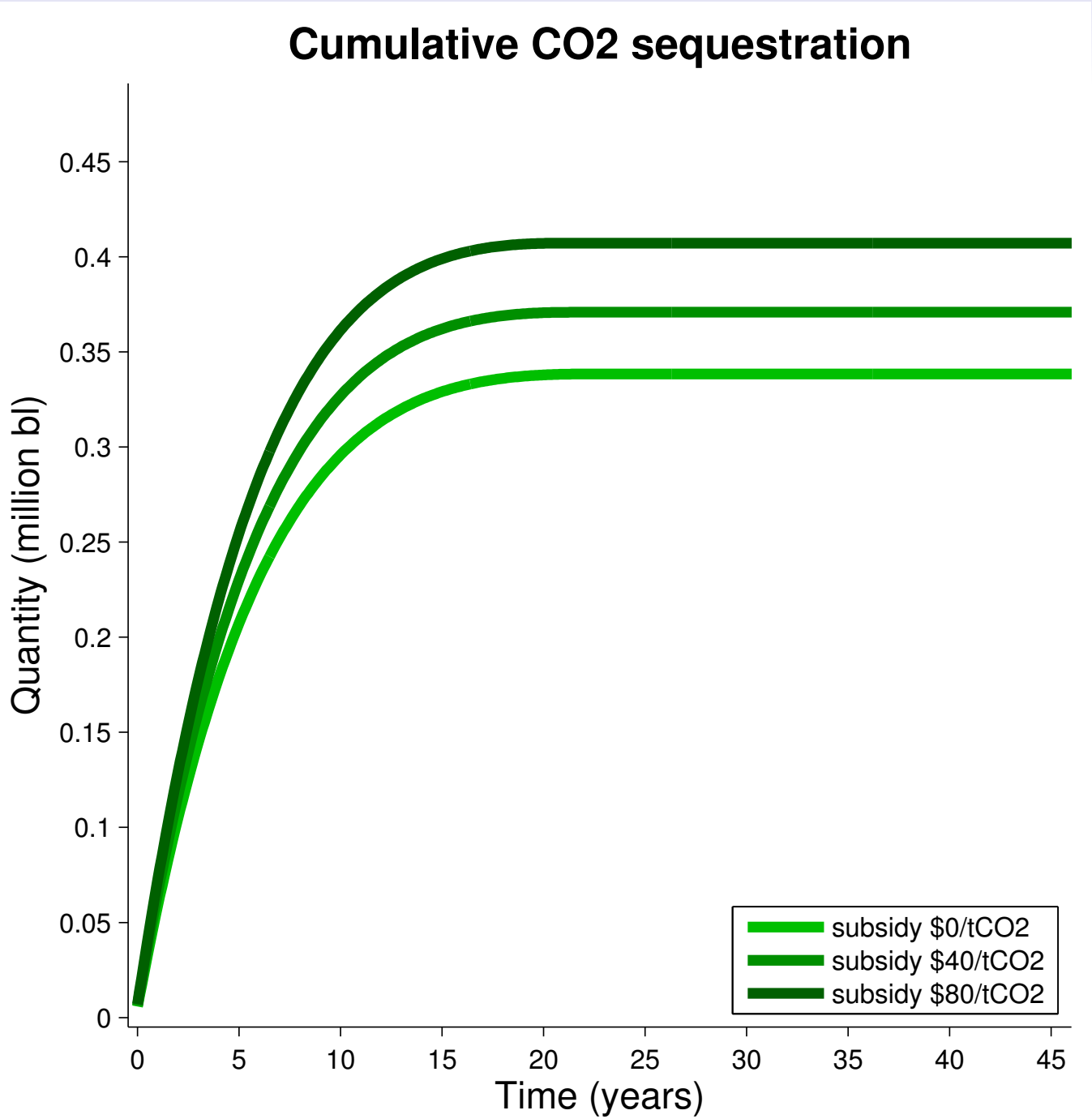

Flow CO2 injection
subsidy $0/tCO2
subsidy $40/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)

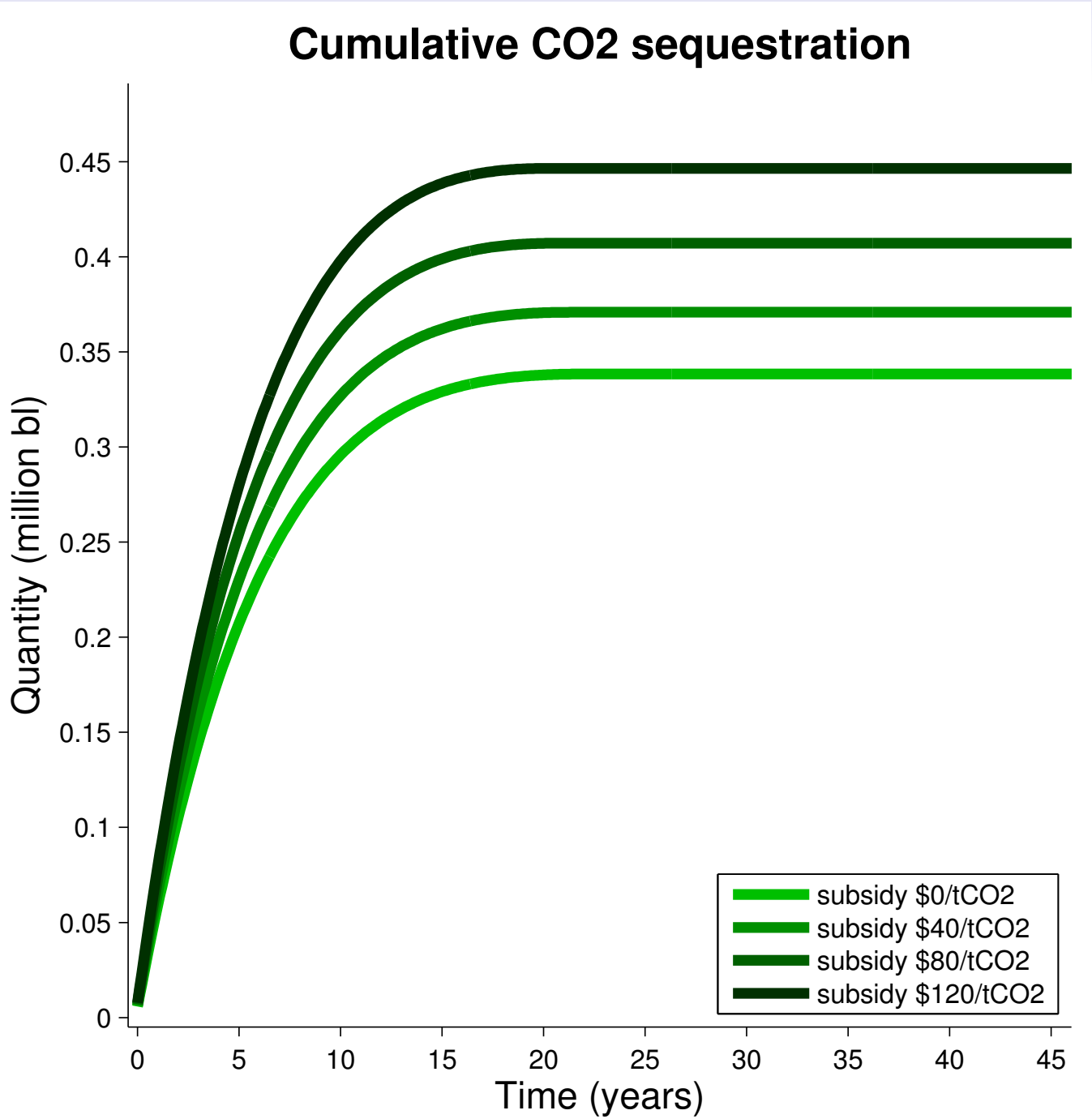

Flow CO2 injection
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)

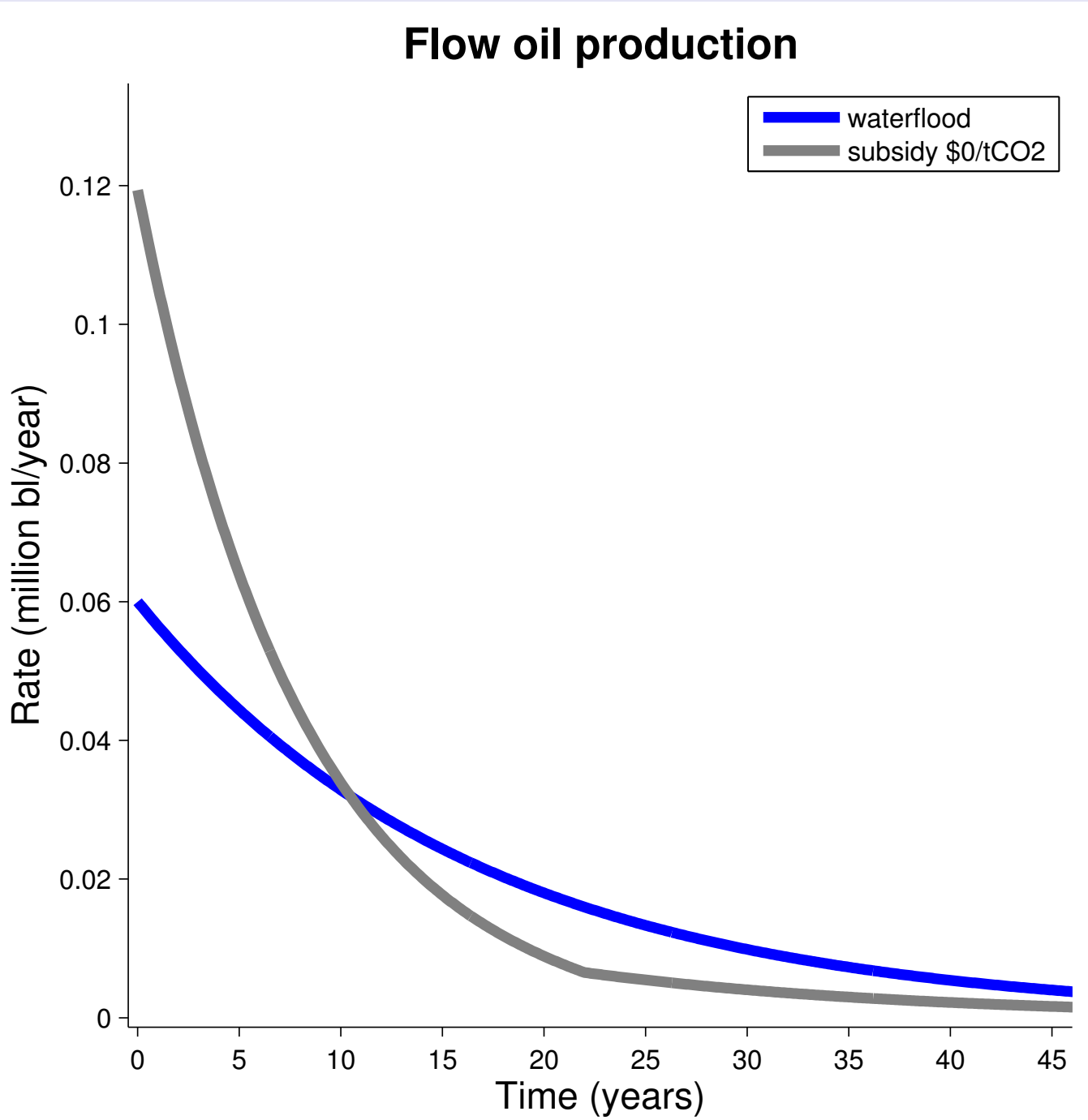

Flow CO2 injection
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2
subsidy $120/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)

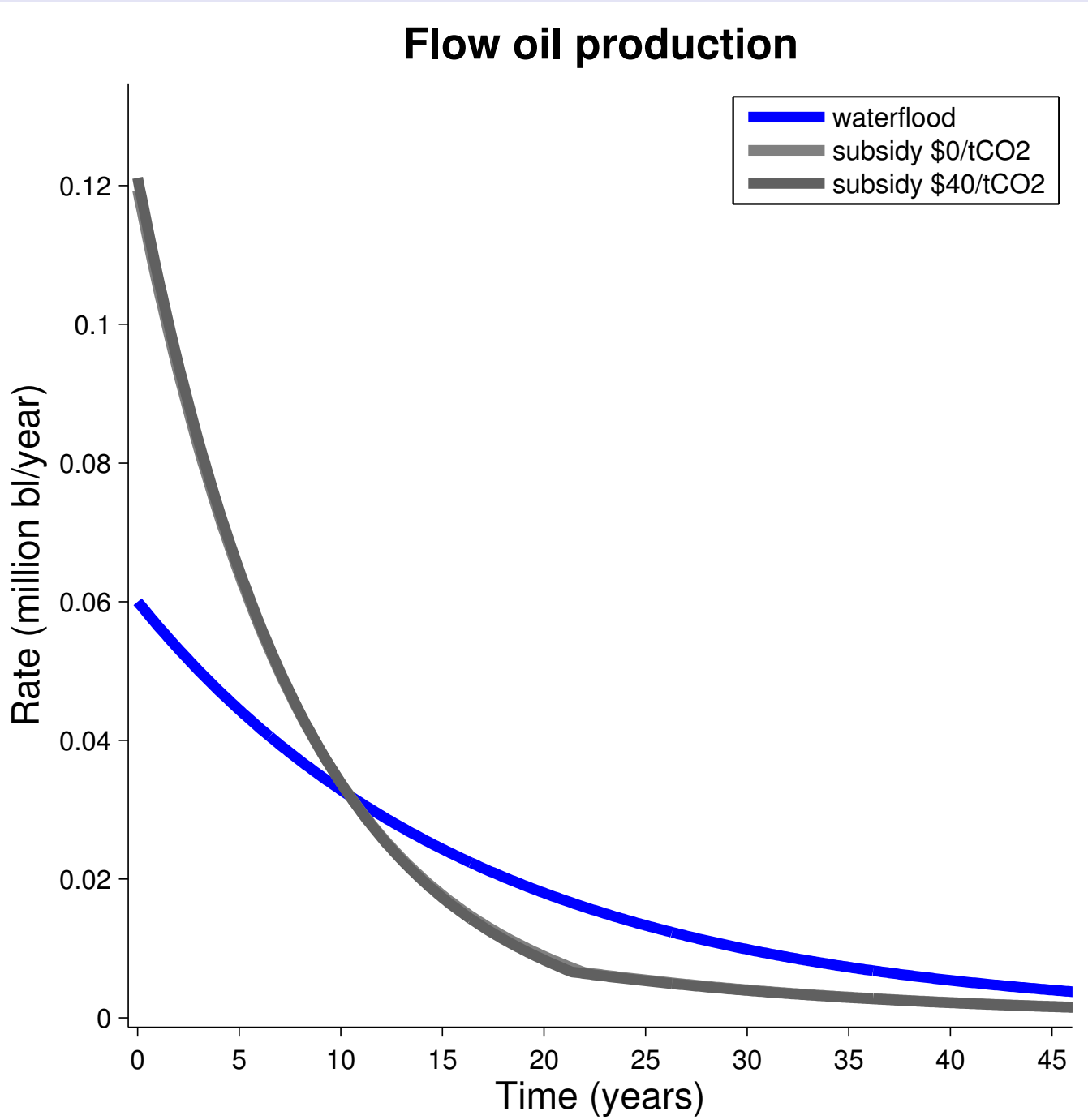

Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45
Time (years)
subsidy $0/tCO2

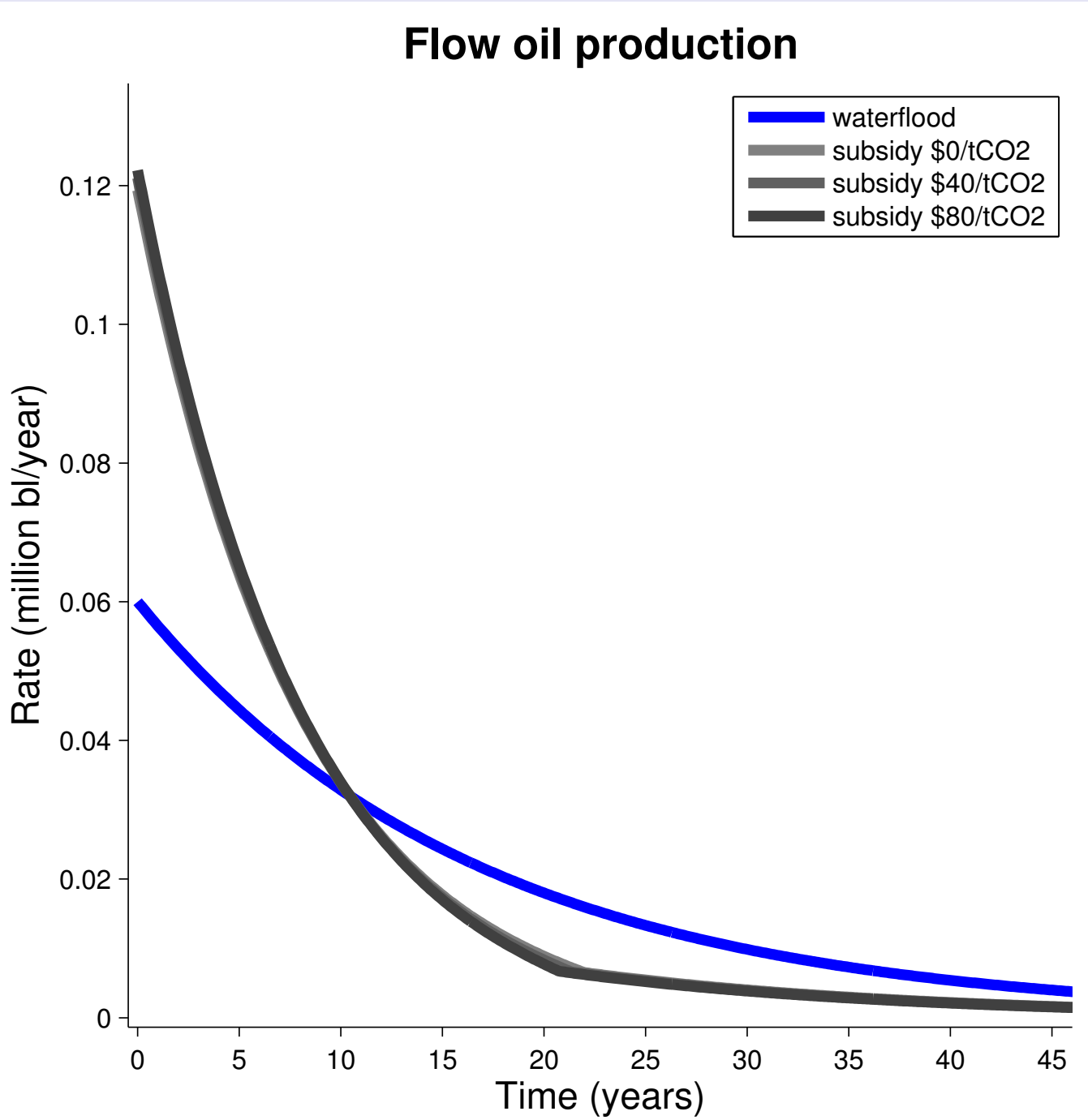

Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45
Time (years)
subsidy $0/tCO2
subsidy $40/tCO2

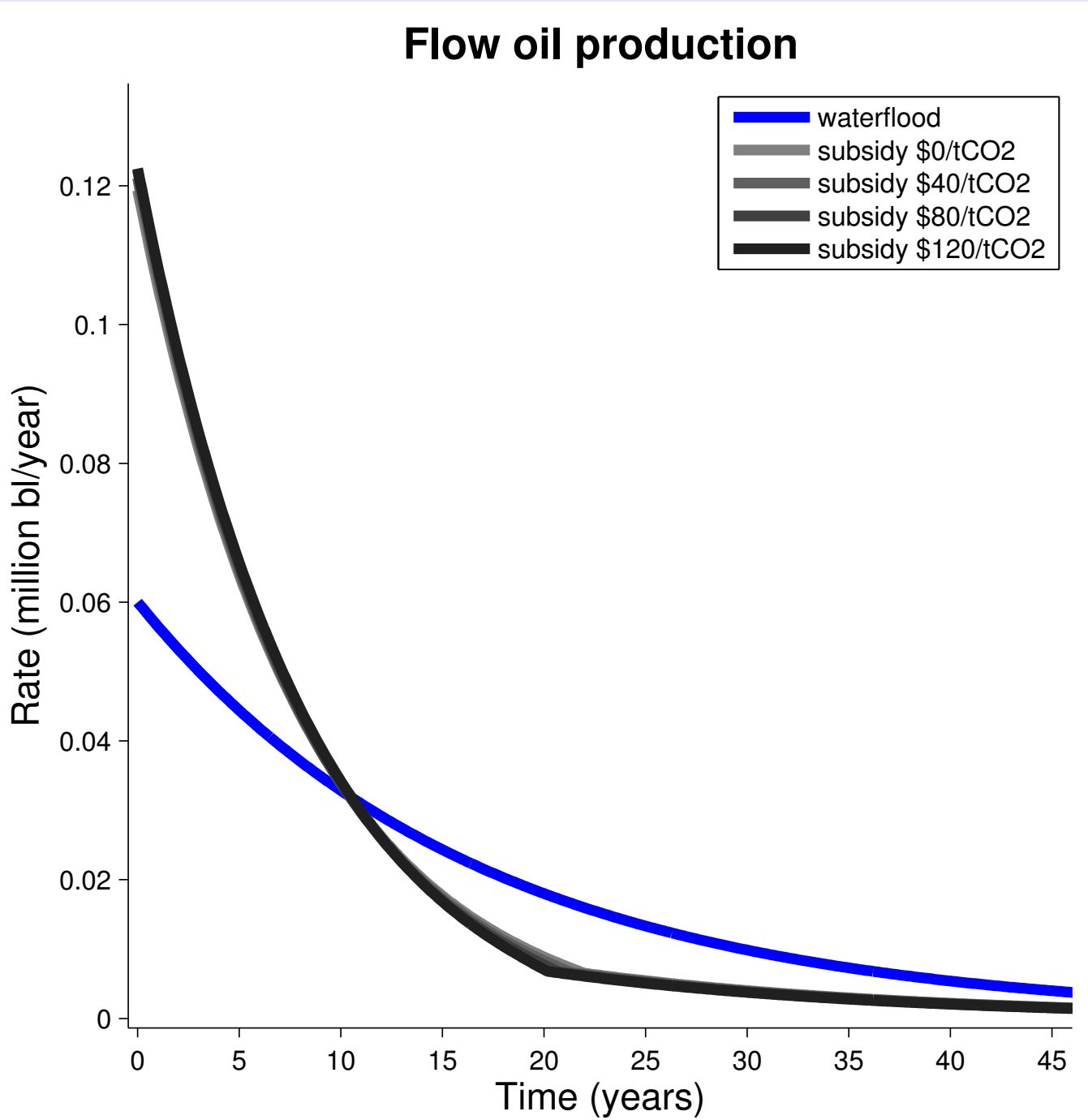

Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45
Time (years)
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2

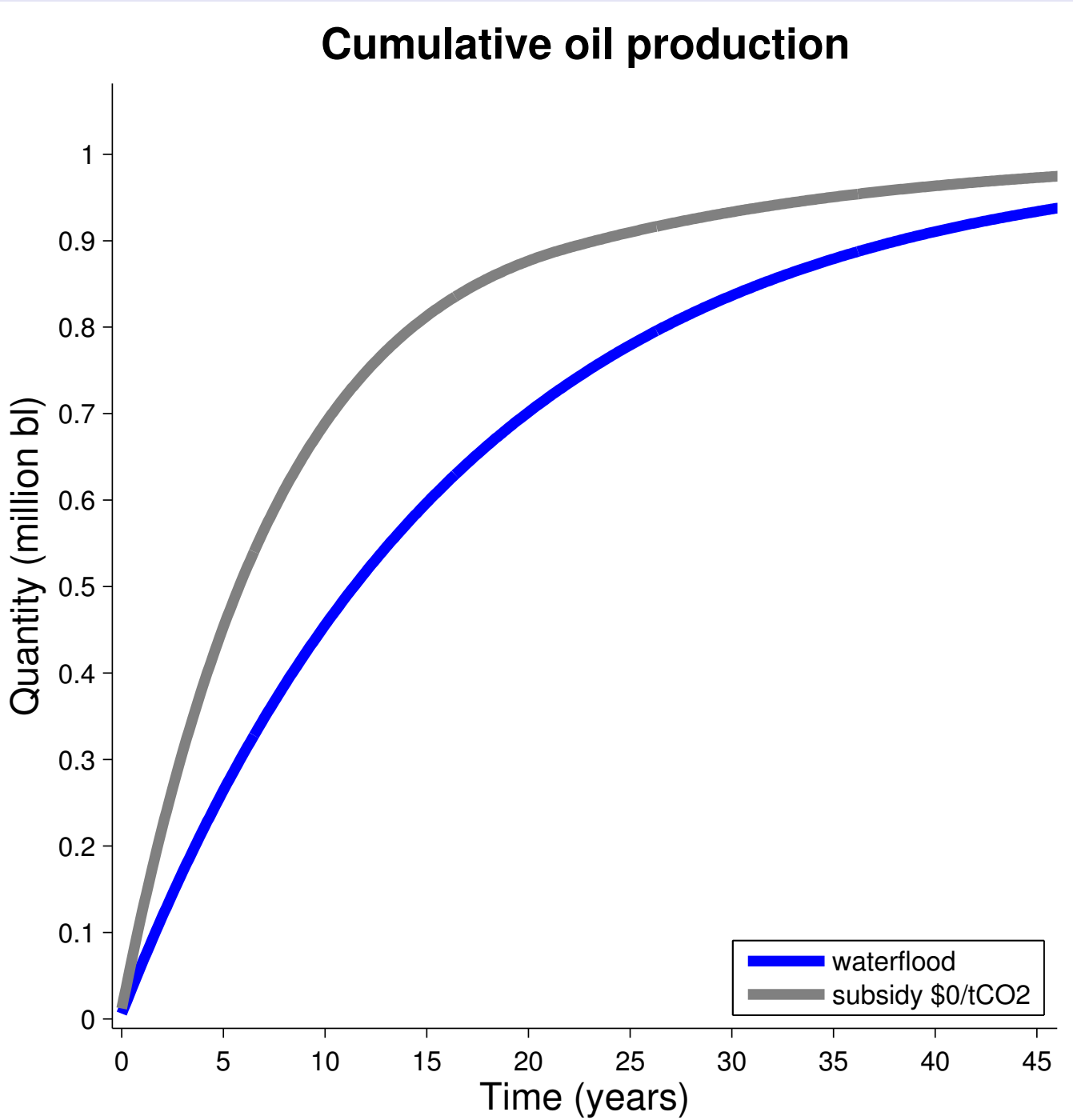

Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
5
10
15
20
25
30
35
40
45
Time (years)
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2
subsidy $120/tCO2

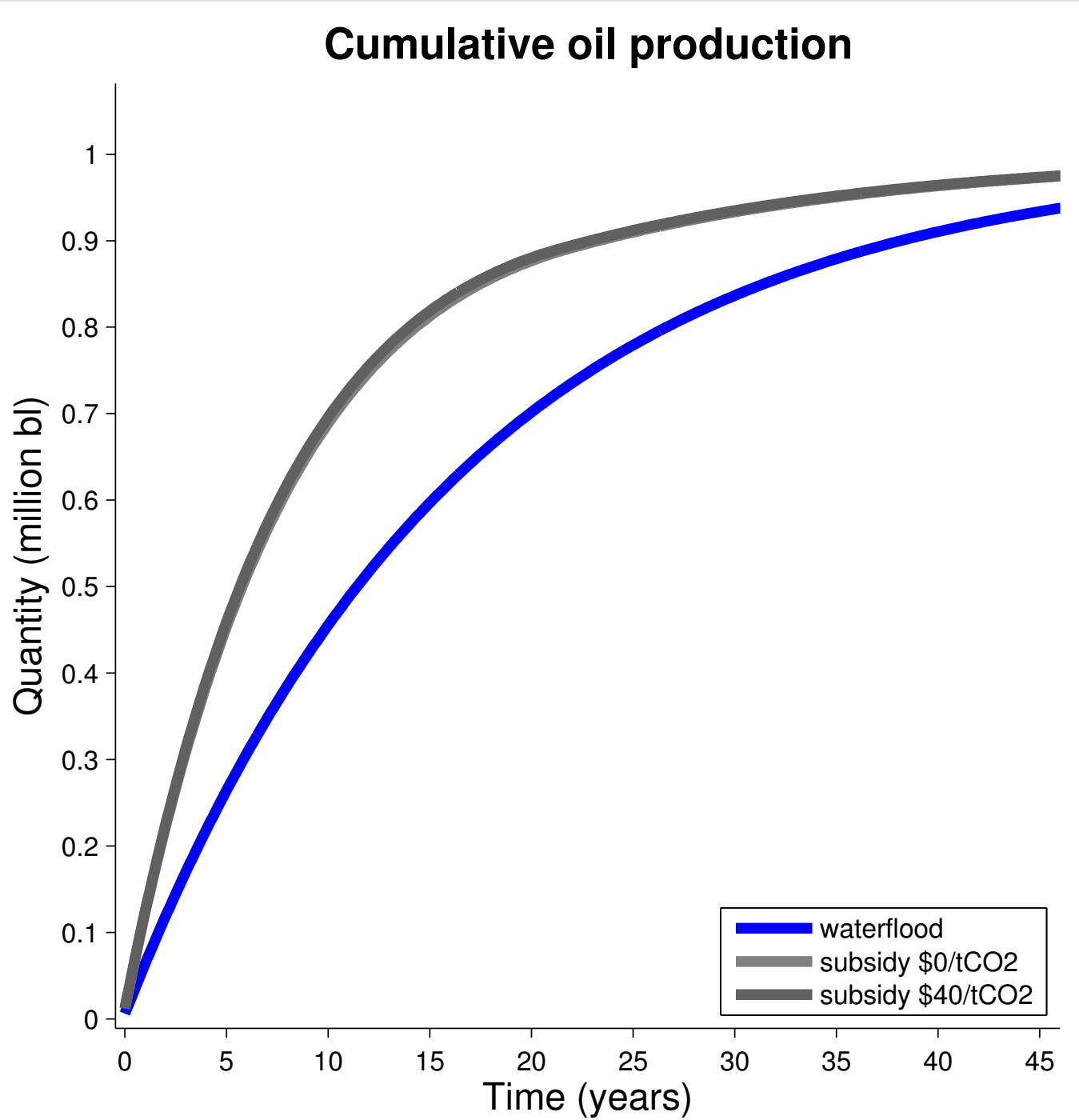

Flow oil production
waterflood
subsidy $0/tCO2
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)

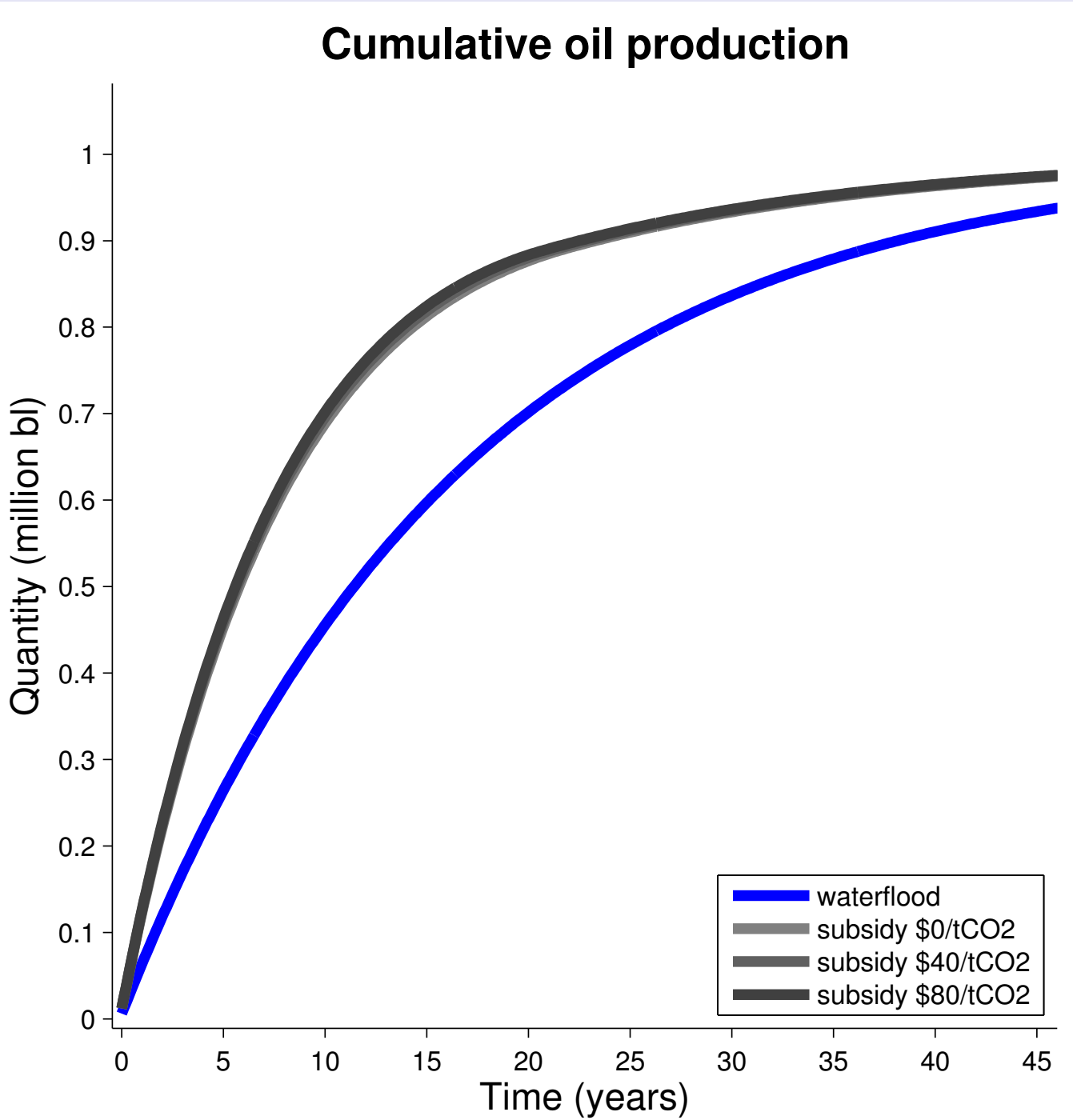

Flow oil production
waterflood
subsidy $0/tCO2
subsidy $40/tCO2
Rate (million bl/year)
0
0.02
0.04
0.06
0.08
0.1
0.12
0
5
10
15
20
25
30
35
40
45
Time (years)

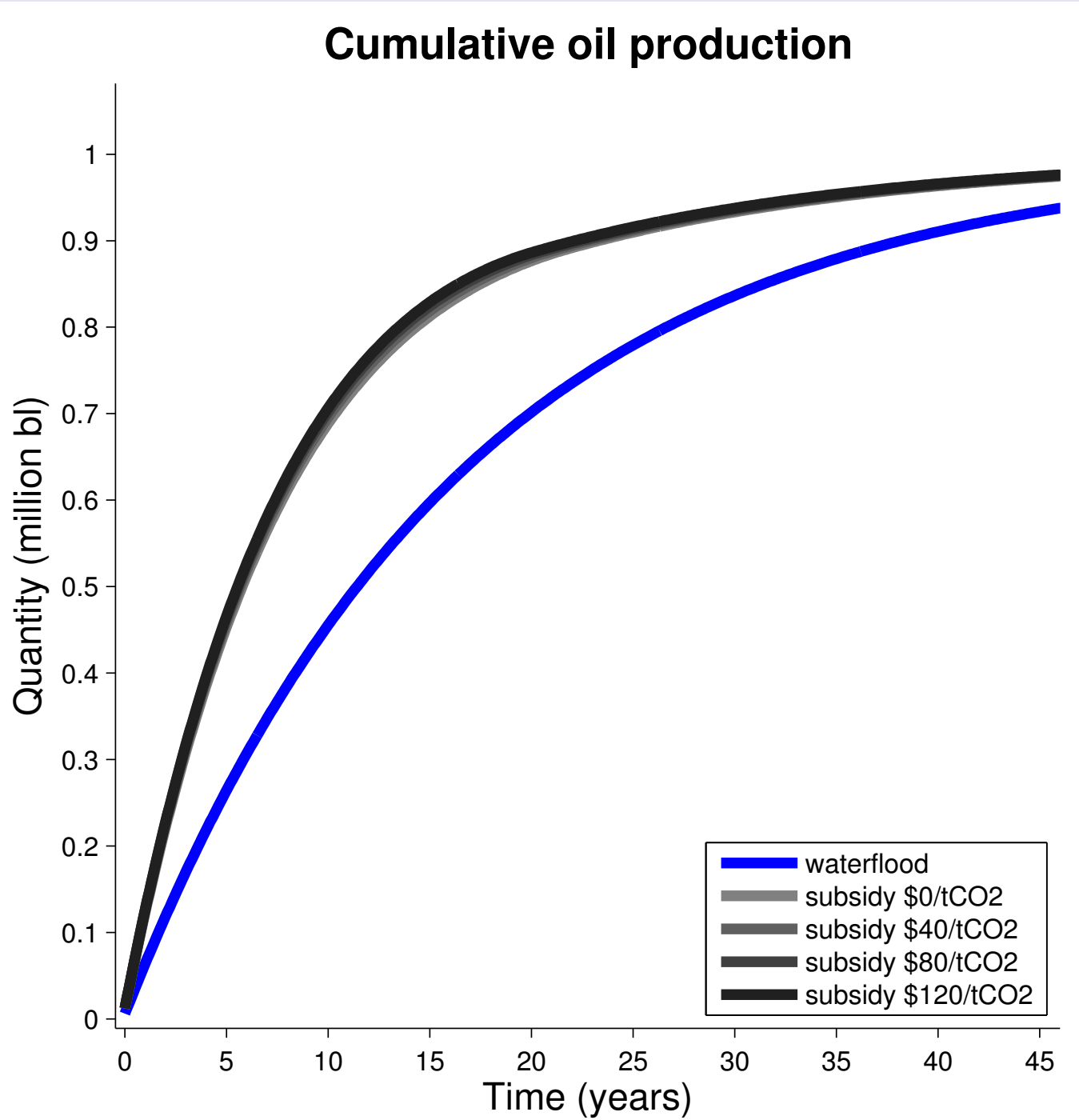

Flow oil production
waterflood
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)


Flow oil production
waterflood
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2
subsidy $120/tCO2
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)


Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
subsidy $0/tCO2


Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
subsidy $0/tCO2
subsidy $40/tCO2


Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2


Cumulative oil production
Quantity (million bl)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
45
Time (years)
waterflood
subsidy $0/tCO2
subsidy $40/tCO2
subsidy $80/tCO2
subsidy $120/tCO2

CO_2-EOR profits

$$NPV = \underbrace{p_{oil}}_{\substack{\text{weight} \\ \text{on oil} \\ \text{production}}} Q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

$\approx \$100 \rightarrow \$200$

CO_2-EOR profits

$$NPV = \underbrace{p_{oil}}_{\substack{\text{weight} \\ \text{on oil} \\ \text{production}}} Q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

$$\approx \$100 \rightarrow \$200$$

CO_2-EOR profits

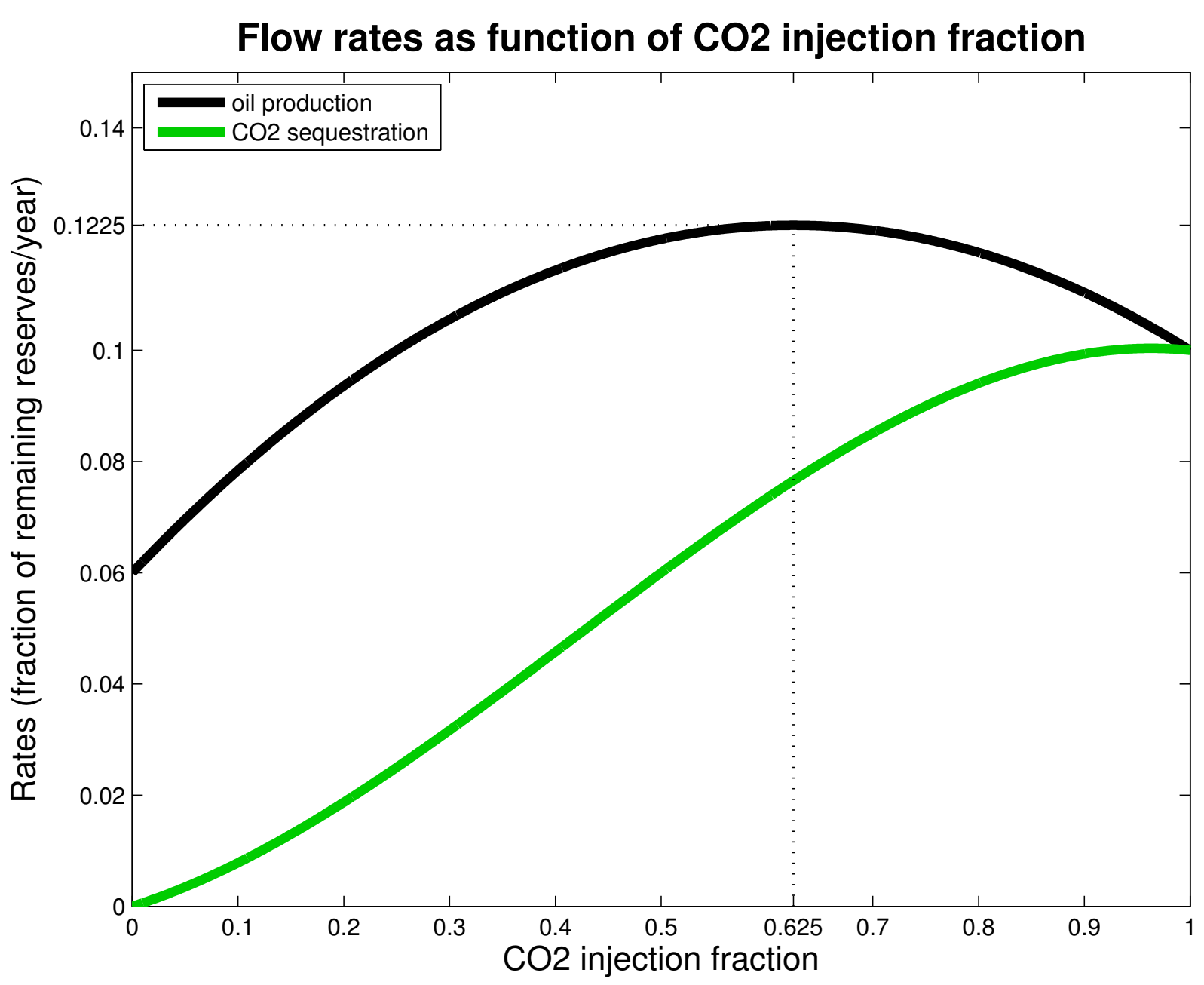
$$NPV = \underbrace{p_{oil}}_{\substack{\text{weight} \\ \text{on oil} \\ \text{production}}} Q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight} \\ \text{on } CO_2 \\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other} \\ \text{costs}}}$$

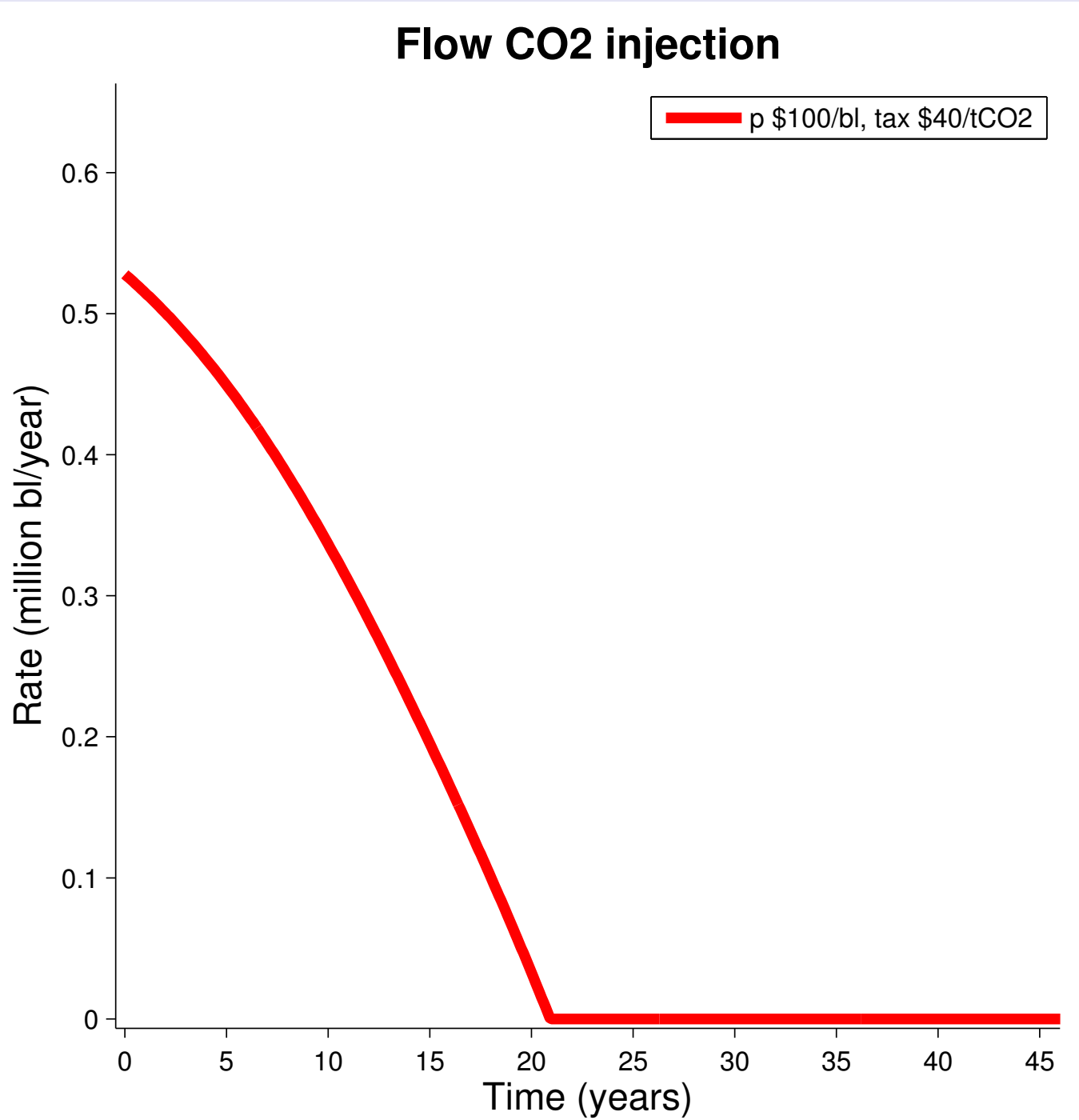
$\approx \$100 \rightarrow \$200$ $\quad$ $\approx \$1 \rightarrow \$5$

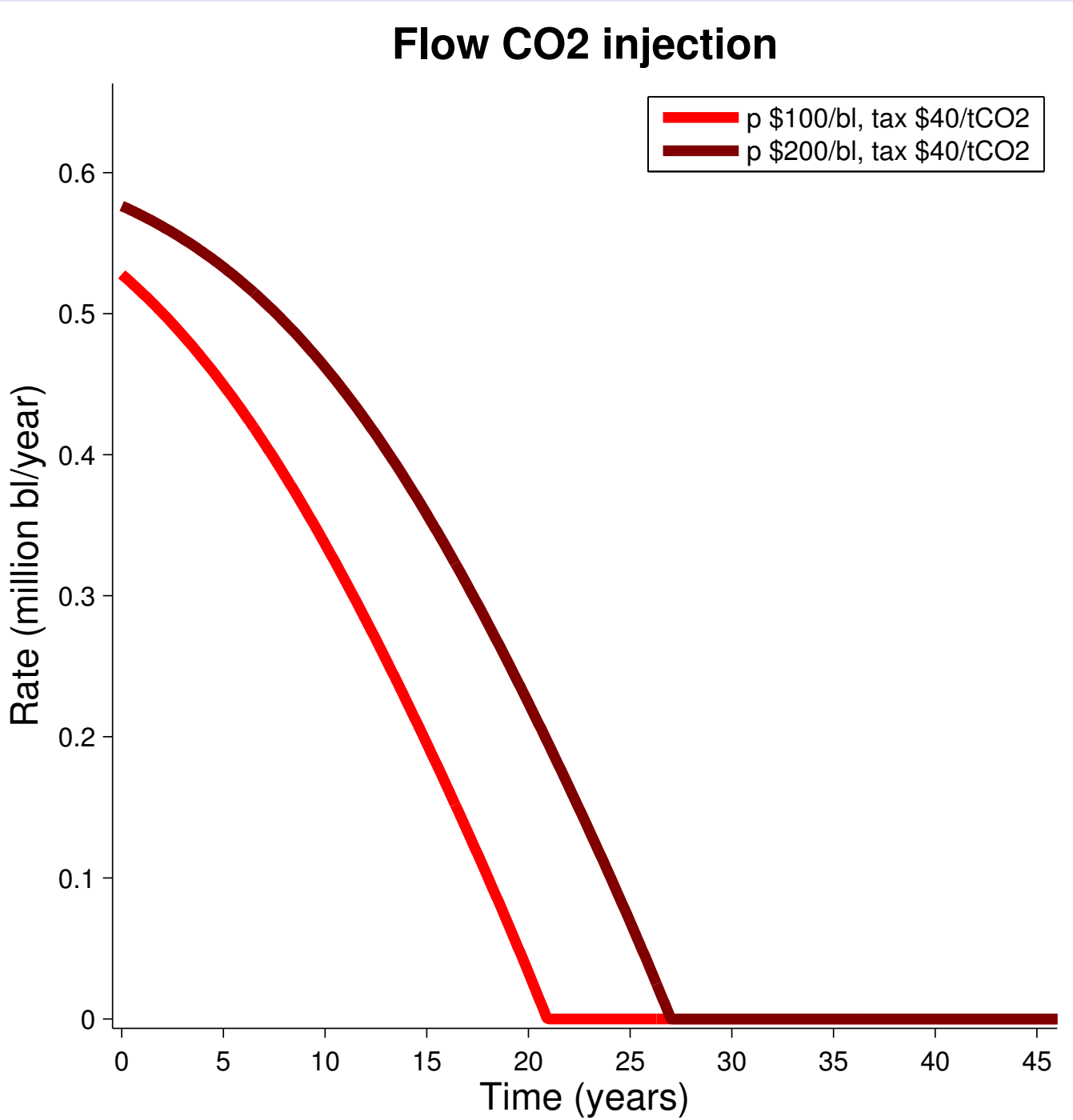
CO_2-EOR profits

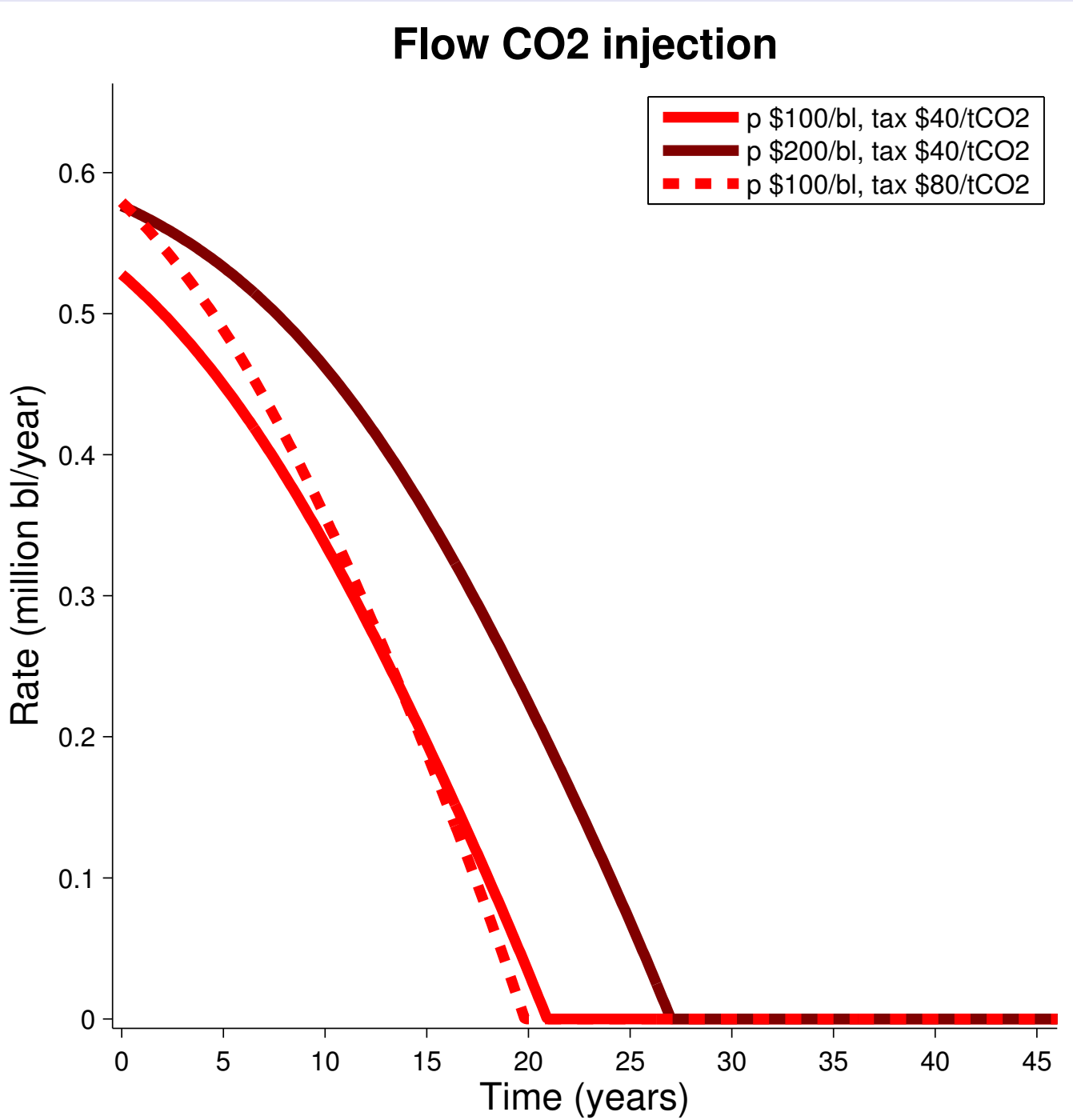
$$NPV = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

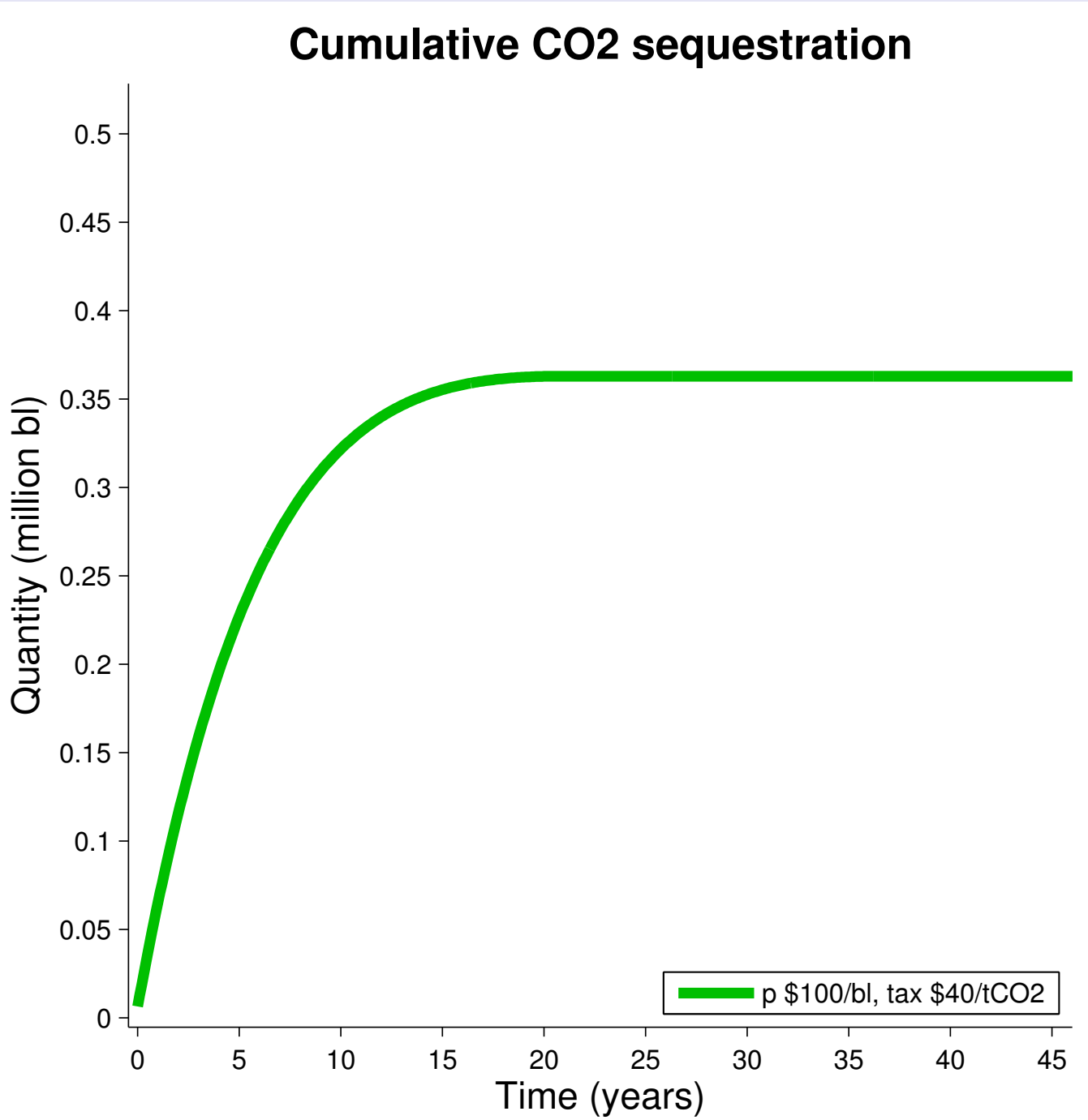
$\approx \$100 \rightarrow \$200$ $\quad$ $\approx \$1 \rightarrow \$5$

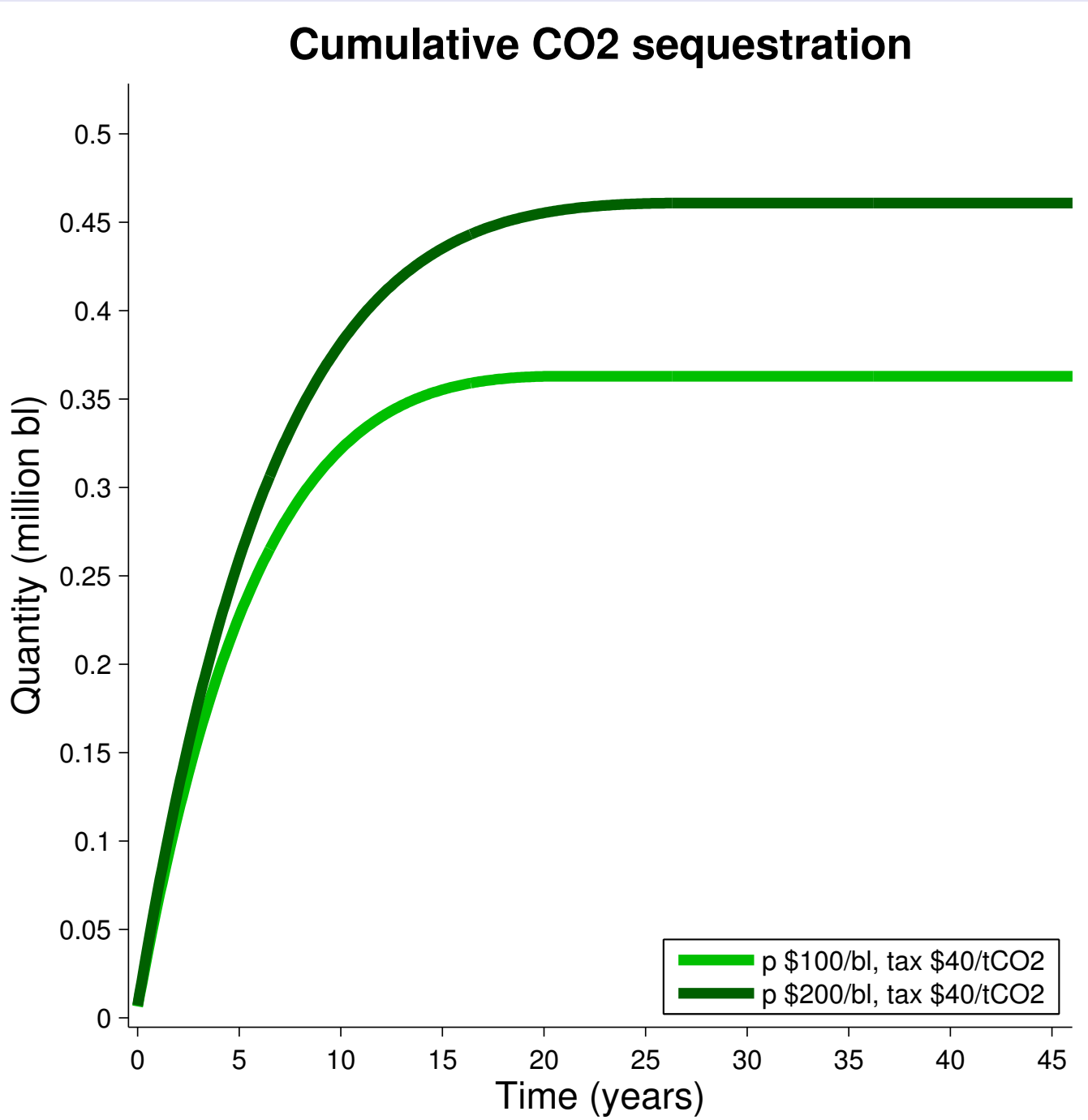

Flow rates as function of CO2 injection fraction
oil production
CO2 sequestration
Rates (fraction of remaining reserves/year)
0.14
0.1225
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.625
0.7
0.8
0.9
1
CO2 injection fraction

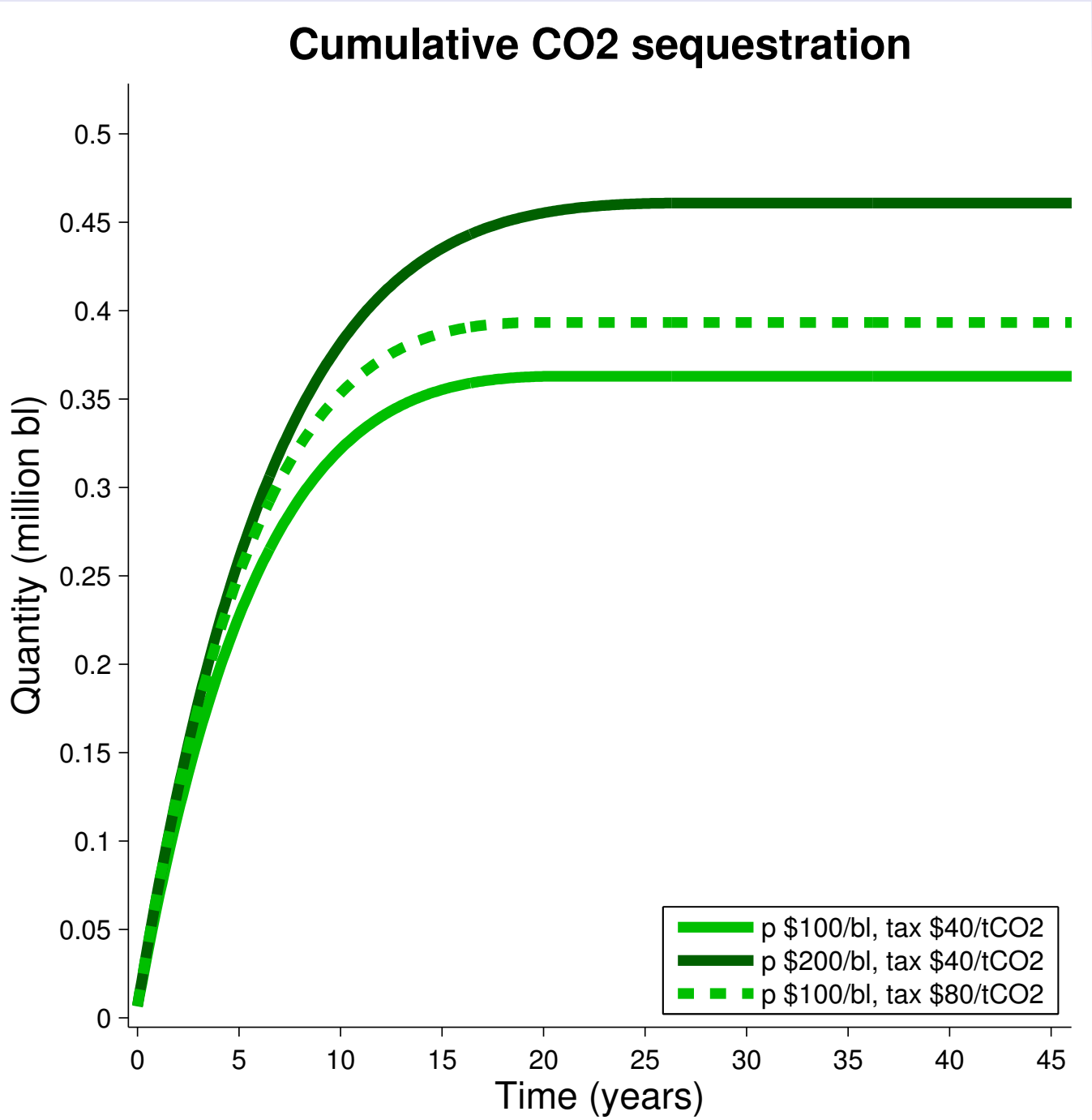

Flow CO2 injection
p $100/bl, tax $40/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)


Flow CO2 injection
p $100/bl, tax $40/tCO2
p $200/bl, tax $40/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)


Flow CO2 injection
p $100/bl, tax $40/tCO2
p $200/bl, tax $40/tCO2
p $100/bl, tax $80/tCO2
Rate (million bl/year)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30
35
40
45
Time (years)


Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)
p $100/bl, tax $40/tCO2


Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)
p $100/bl, tax $40/tCO2
p $200/bl, tax $40/tCO2


Cumulative CO2 sequestration
Quantity (million bl)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)
p $100/bl, tax $40/tCO2
p $200/bl, tax $40/tCO2
p $100/bl, tax $80/tCO2

So . . .

So . . .

. . . are high oil prices the environmentalist's best friend?

So . . .

. . . are high oil prices the environmentalist's best friend?

- On the demand side: discourage oil use

So . . .

. . . are high oil prices the environmentalist's best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO_2 storage through EOR

So . . .

. . . are high oil prices the environmentalist's best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO_2 storage through EOR

Not necessarily, for two reasons:

So . . .

. . . are high oil prices the environmentalist's best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO_2 storage through EOR

Not necessarily, for two reasons:

- *Increasing* oil prices may *reduce* CO_2 storage through EOR

CO_2-EOR profits

$$NPV = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

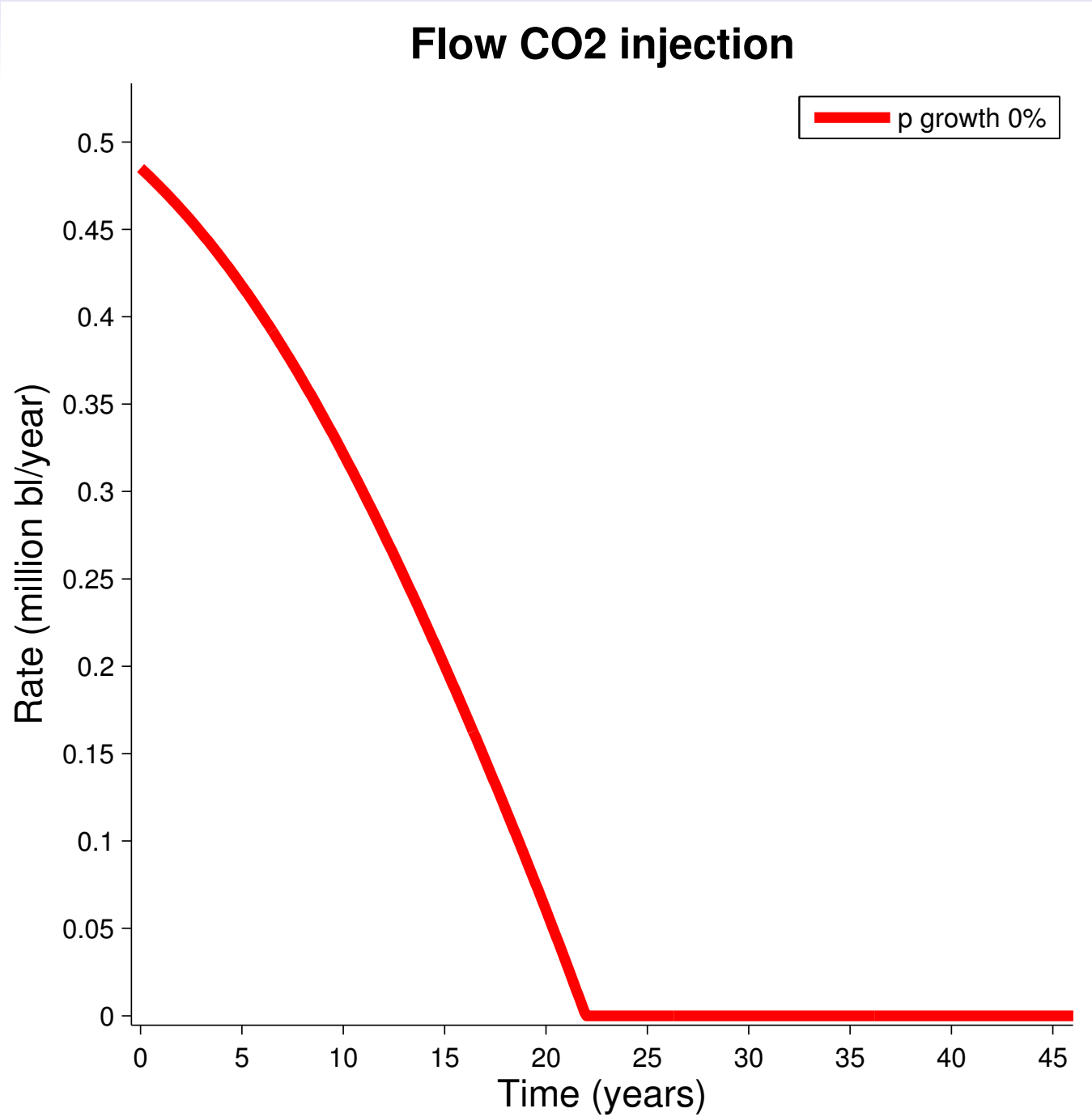
$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

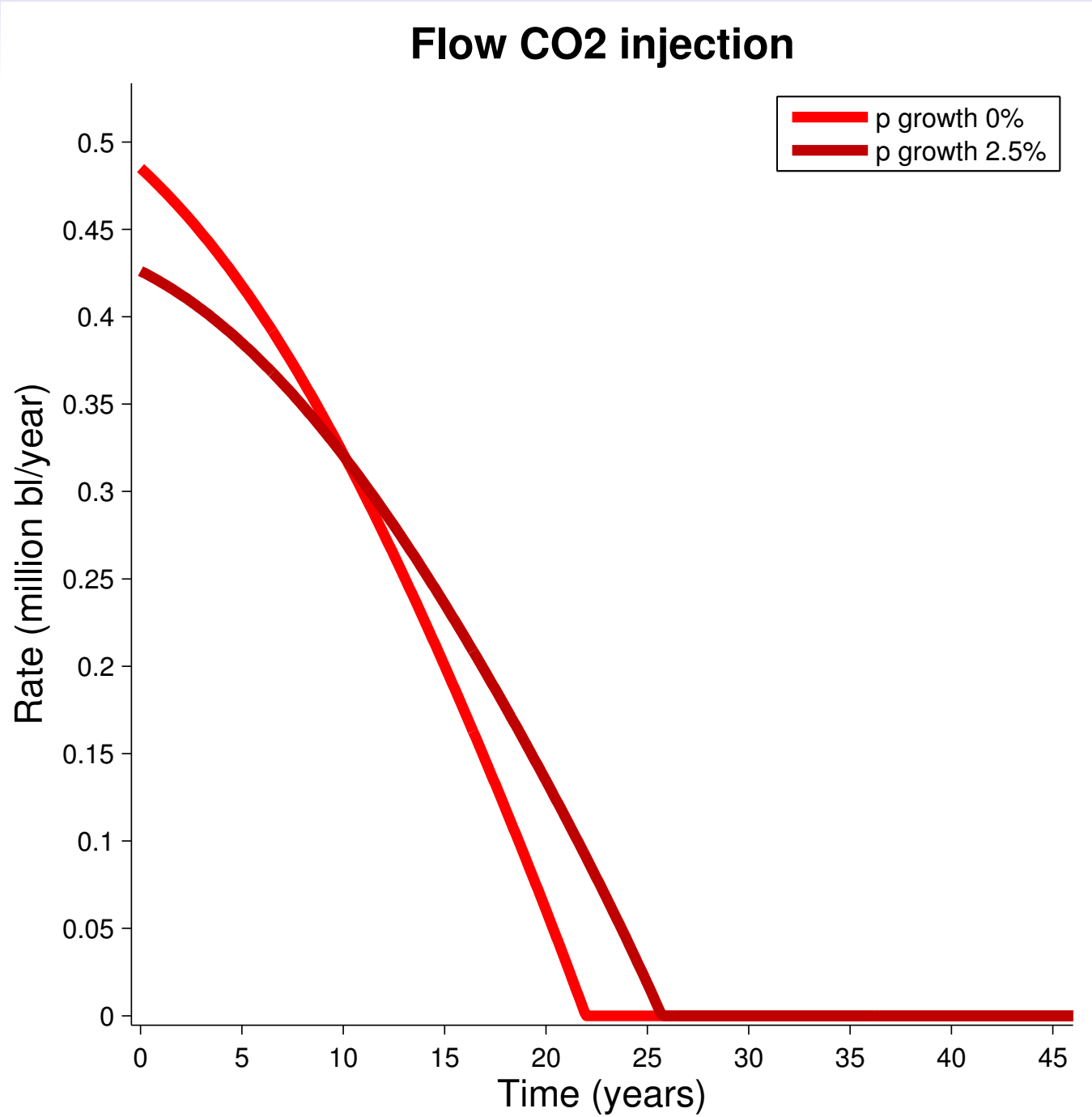
CO_2-EOR profits

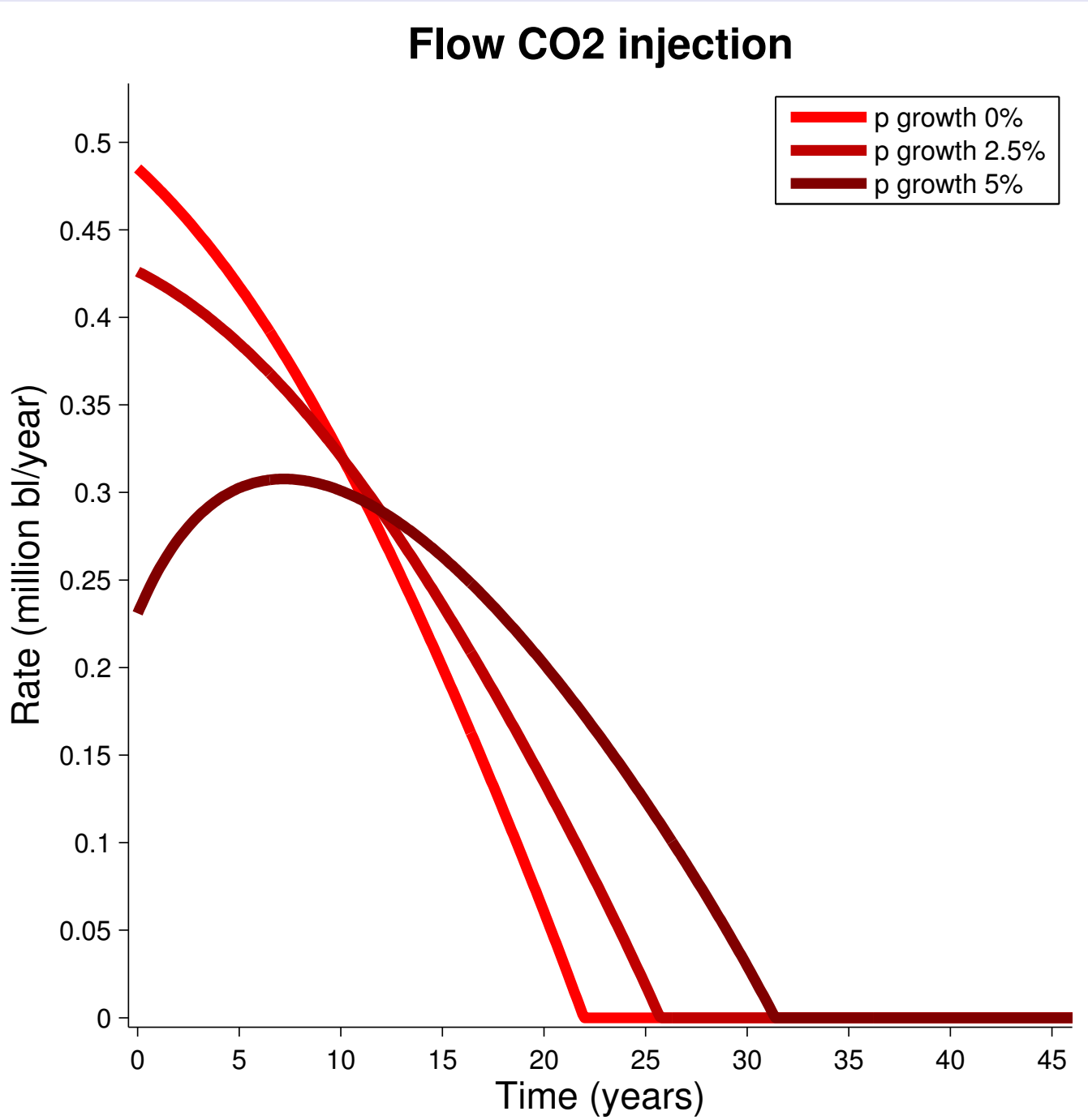
$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

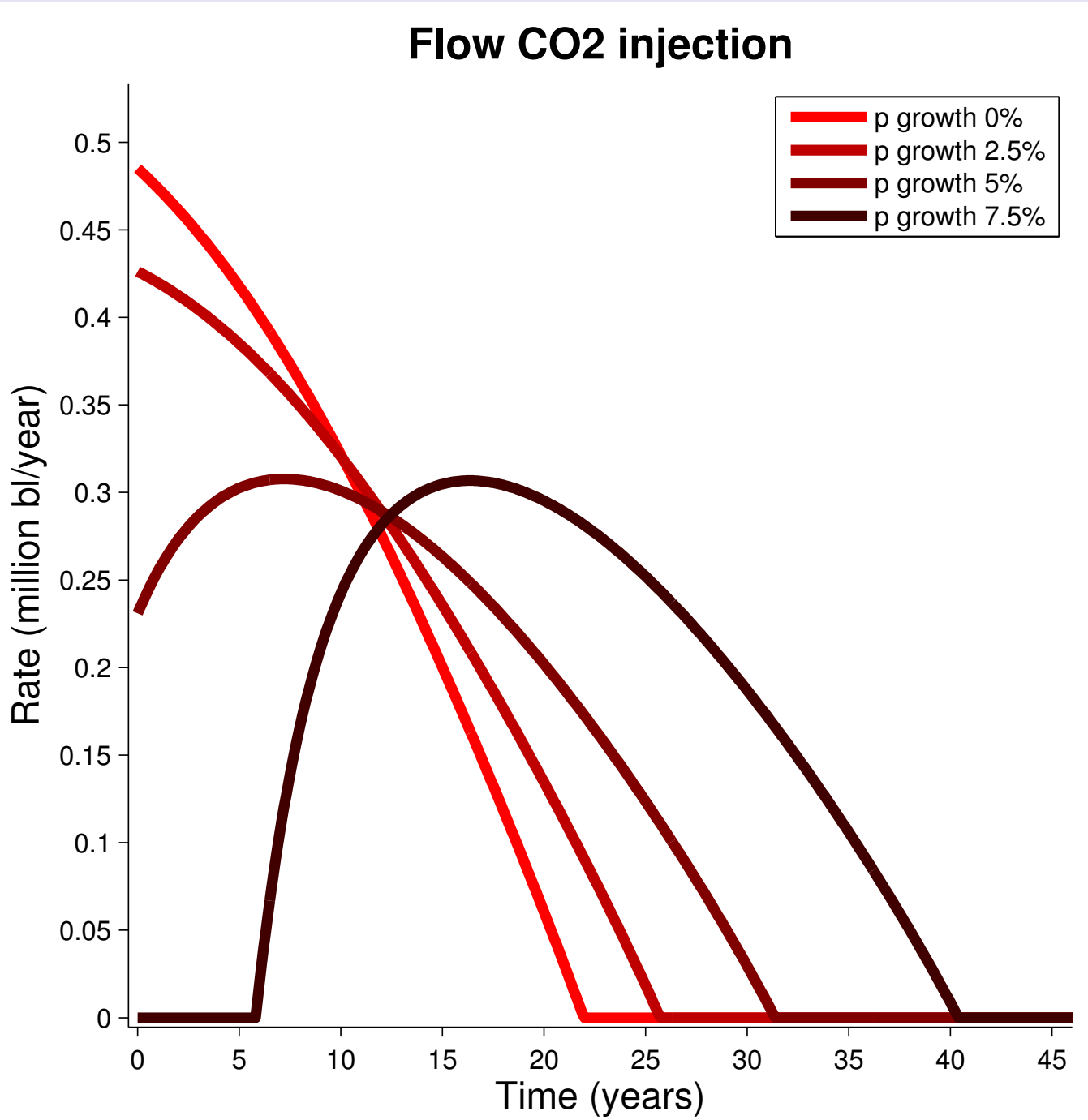
CO_2-EOR profits

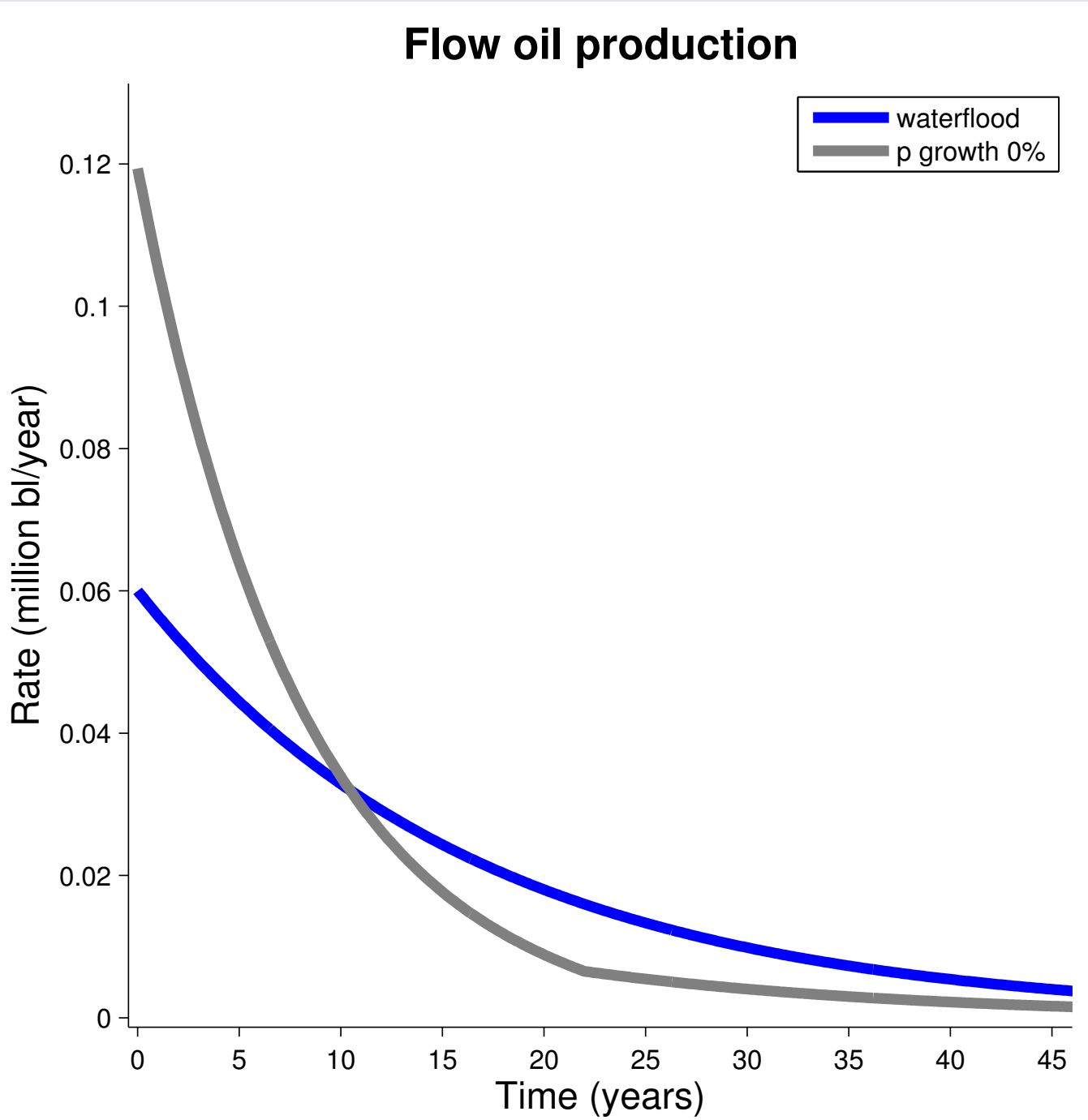
$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{oil}^{prd} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

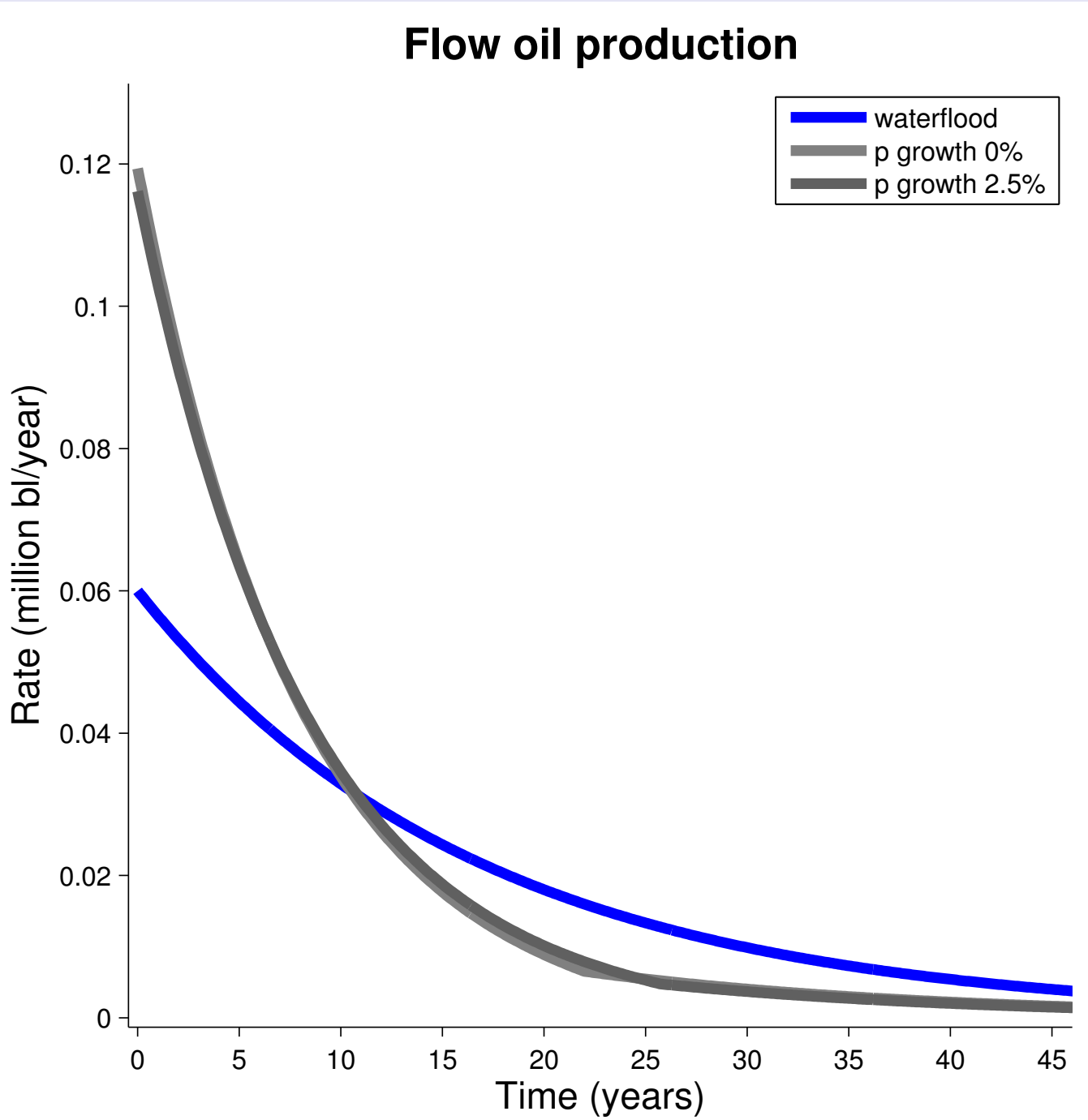

Flow CO2 injection
p growth 0%
Rate (million bl/year)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)

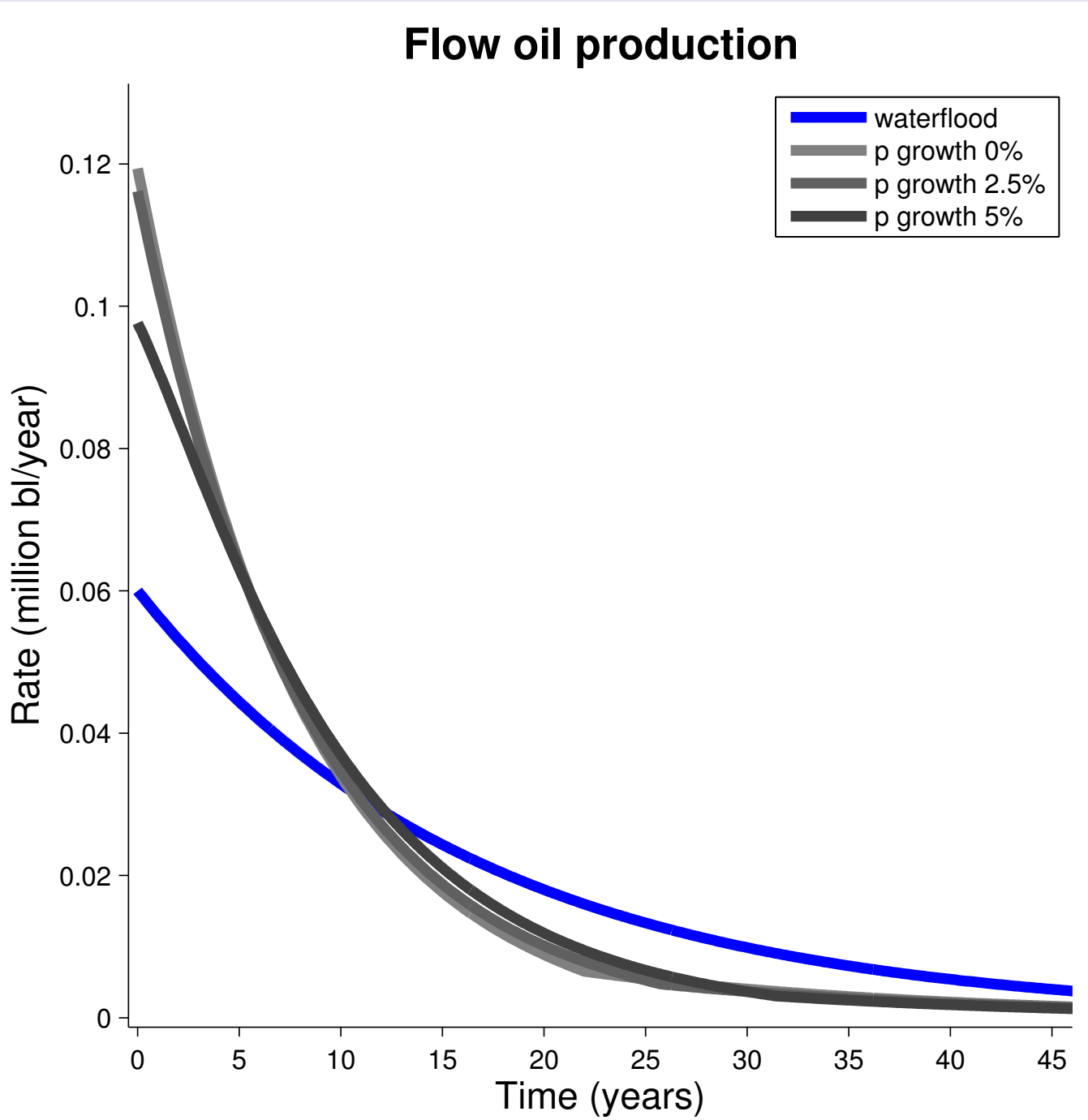

Flow CO2 injection
p growth 0%
p growth 2.5%
Rate (million bl/year)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)

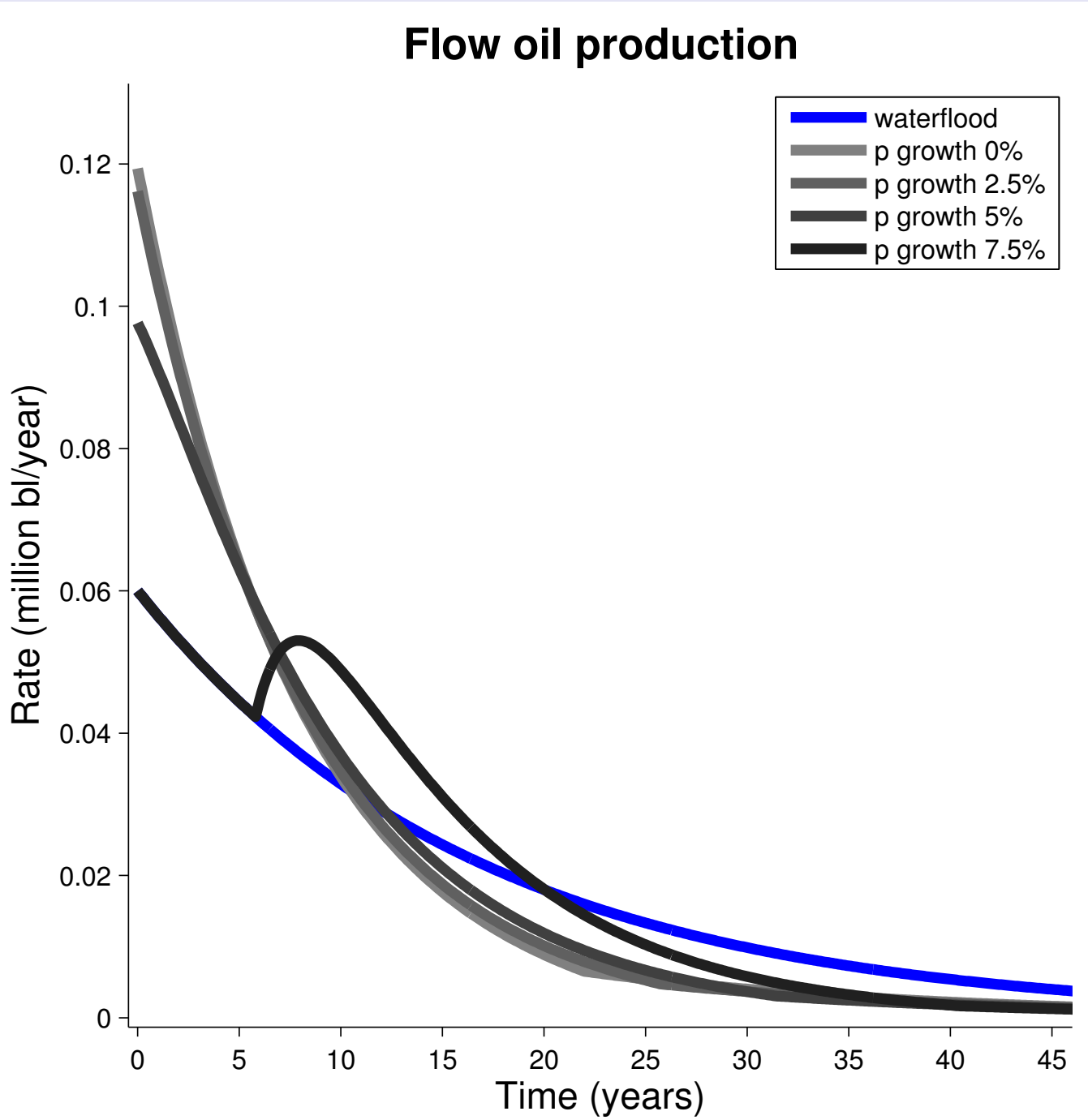

Flow CO2 injection
p growth 0%
p growth 2.5%
p growth 5%
Rate (million bl/year)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)

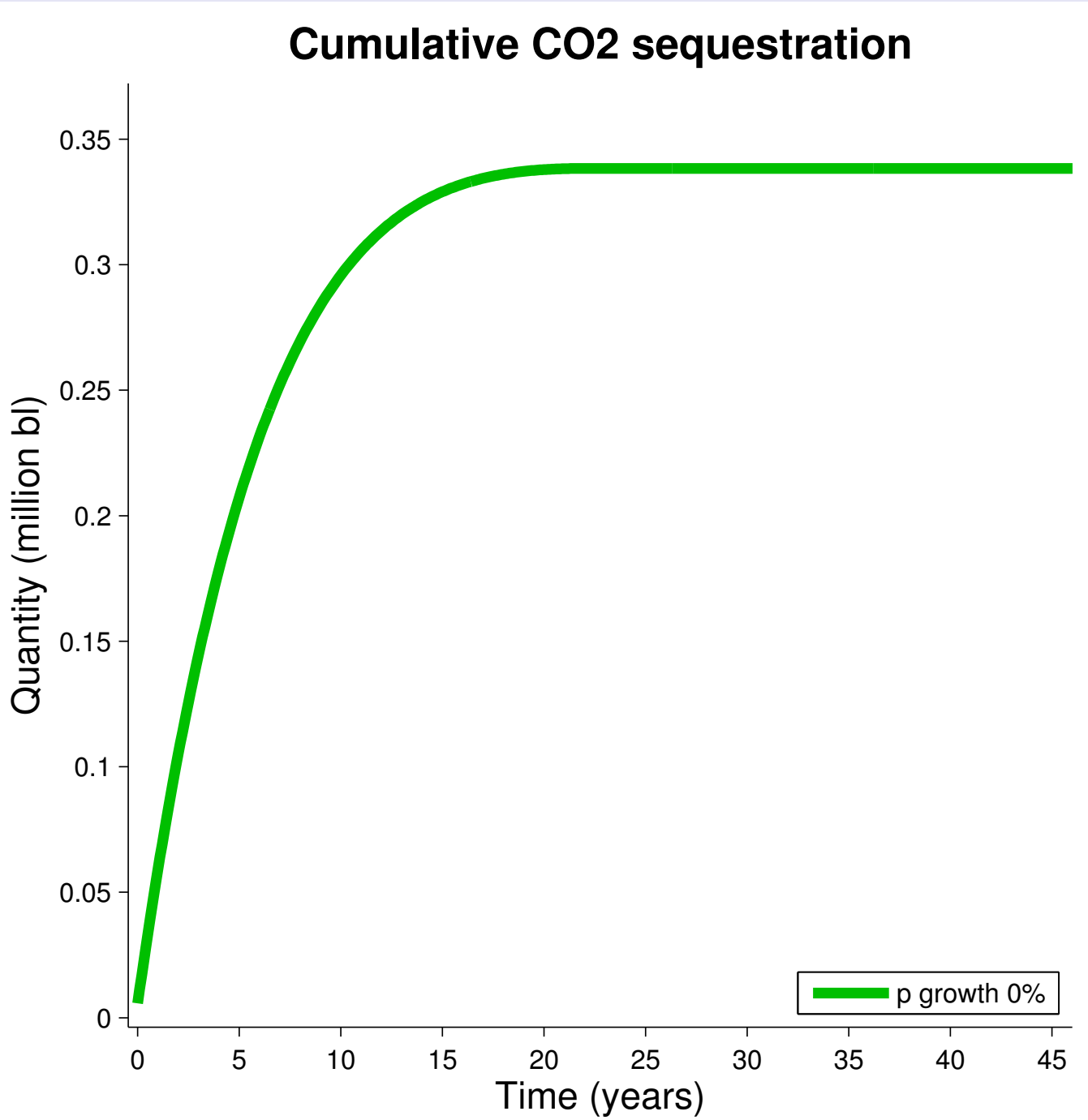

Flow CO2 injection
p growth 0%
p growth 2.5%
p growth 5%
p growth 7.5%
Rate (million bl/year)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
5
10
15
20
25
30
35
40
45
Time (years)

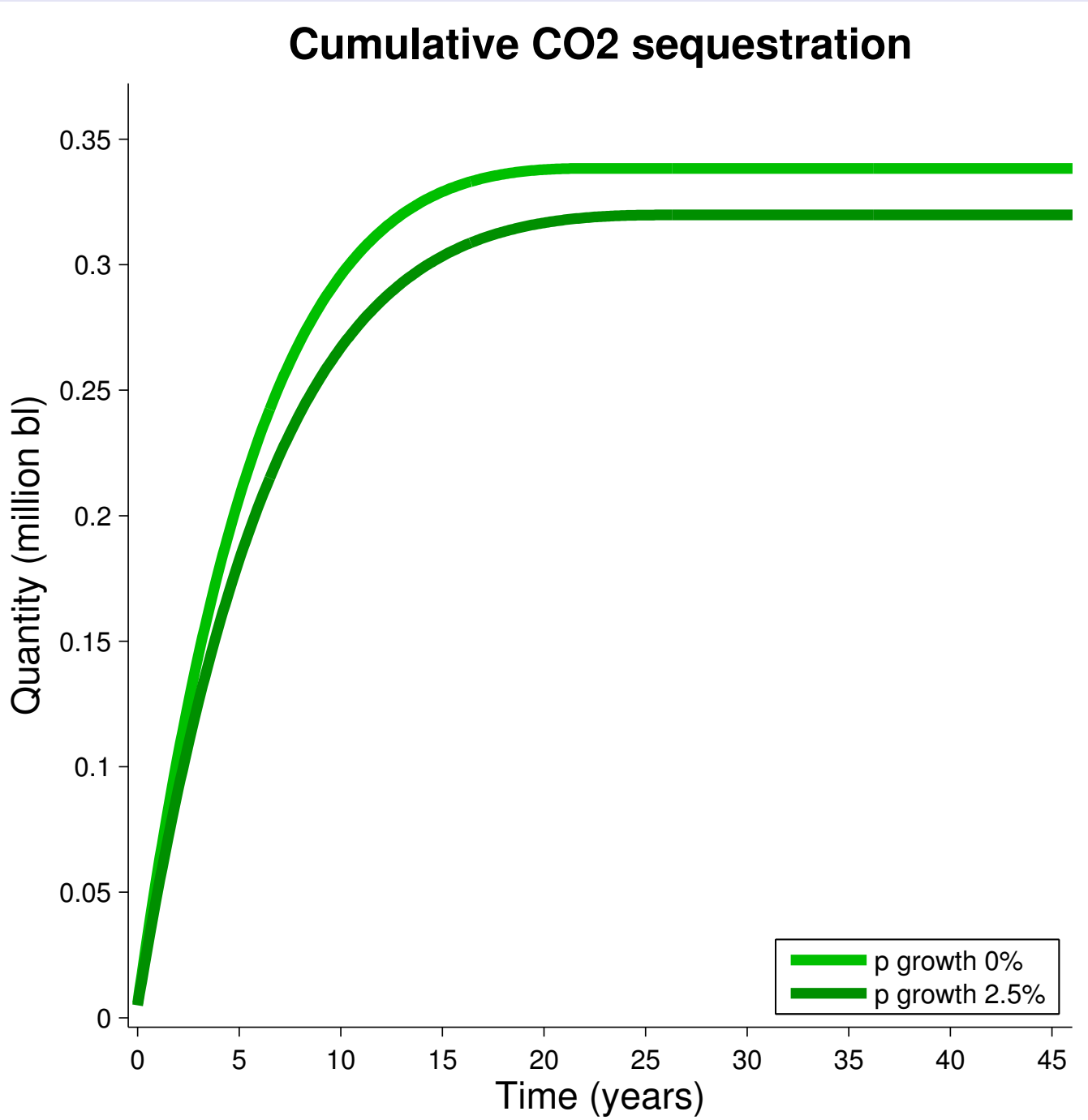

Flow oil production
waterflood
p growth 0%
Rate (million bl/year)
0
0.02
0.04
0.06
0.08
0.1
0.12
0
5
10
15
20
25
30
35
40
45
Time (years)

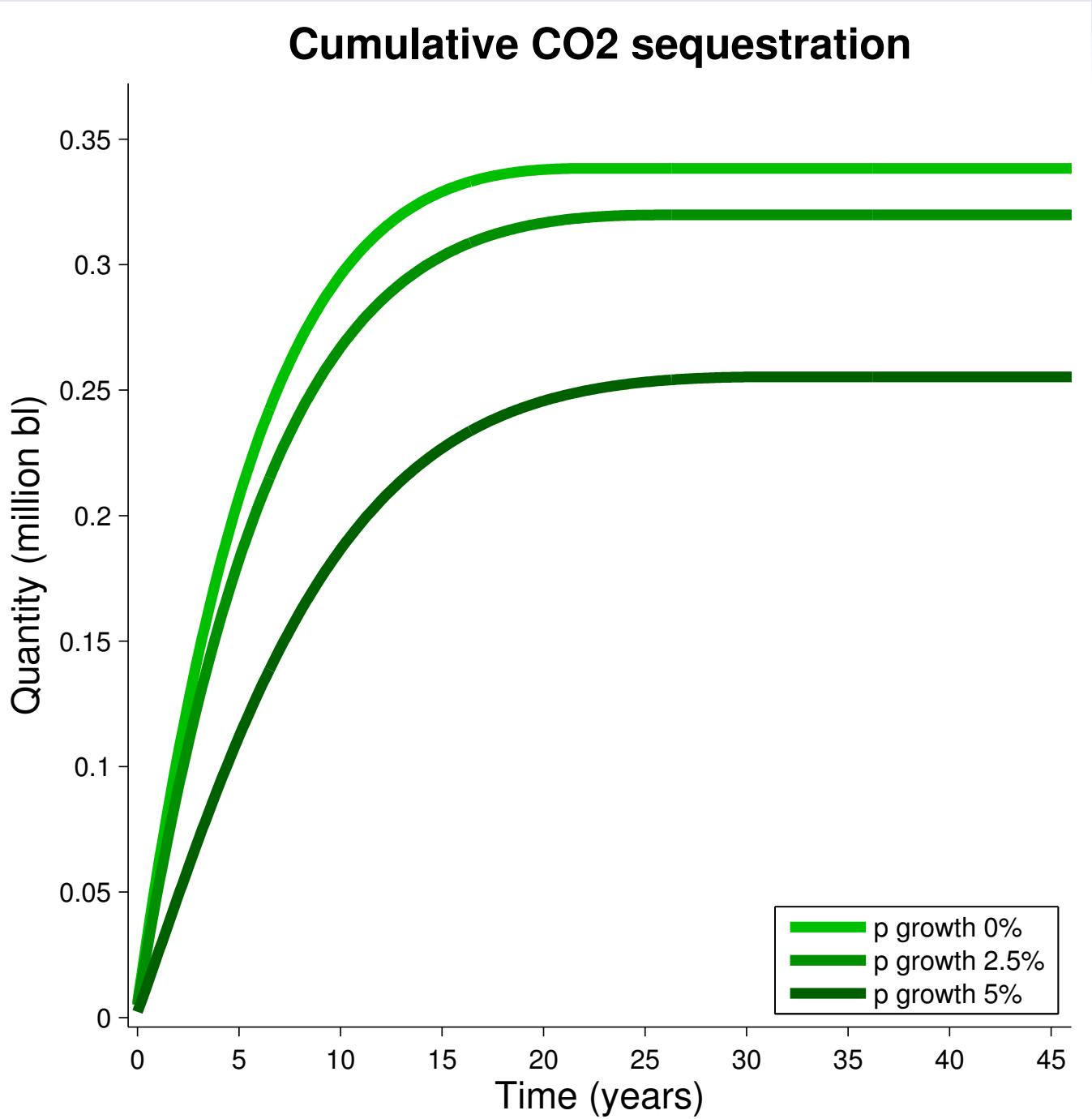

Flow oil production
waterflood
p growth 0%
p growth 2.5%
Rate (million bl/year)
0
0.02
0.04
0.06
0.08
0.1
0.12
0
5
10
15
20
25
30
35
40
45
Time (years)

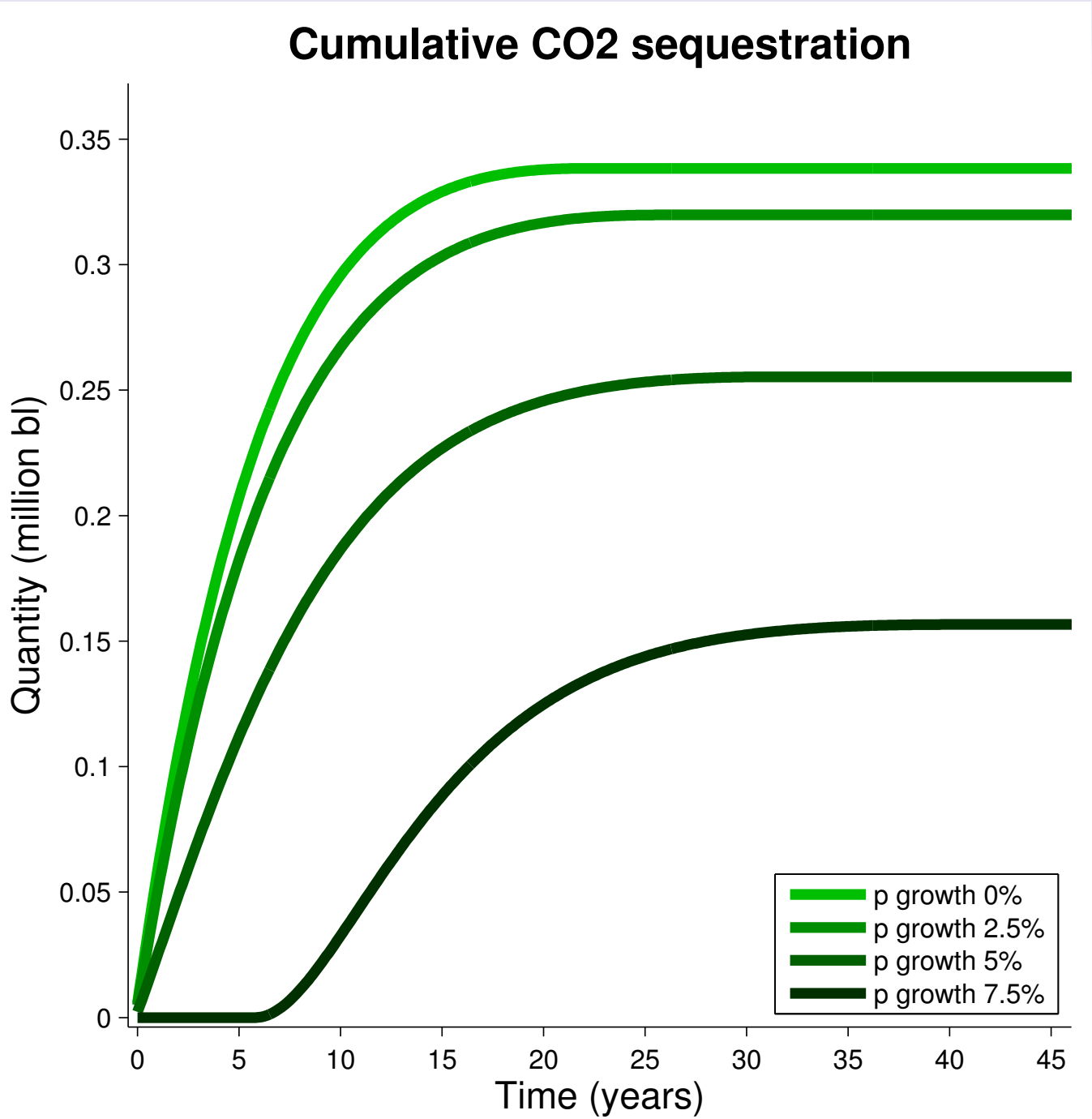

Flow oil production
waterflood
p growth 0%
p growth 2.5%
p growth 5%
Rate (million bl/year)
0
0.02
0.04
0.06
0.08
0.1
0.12
0
5
10
15
20
25
30
35
40
45
Time (years)


Flow oil production
waterflood
p growth 0%
p growth 2.5%
p growth 5%
p growth 7.5%
Rate (million bl/year)
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
Time (years)


Cumulative CO2 sequestration
Quantity (million bl)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
Time (years)
p growth 0%


Cumulative CO2 sequestration
Quantity (million bl)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
Time (years)
p growth 0%
p growth 2.5%


Cumulative CO2 sequestration
Quantity (million bl)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
Time (years)
p growth 0%
p growth 2.5%
p growth 5%


Cumulative CO2 sequestration
Quantity (million bl)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
Time (years)
p growth 0%
p growth 2.5%
p growth 5%
p growth 7.5%

So . . .

. . . are high oil prices the environmentalist's best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO_2 storage through EOR

Not necessarily, for two reasons:

- *Increasing* oil prices may *reduce* CO_2 storage through EOR

So . . .

. . . are high oil prices the environmentalist's best friend?

- On the demand side: discourage oil use
- On the supply side: promote CO_2 storage through EOR

Not necessarily, for two reasons:

- *Increasing* oil prices may *reduce* CO_2 storage through EOR
- Promoting CO_2-EOR may increase *net* CO_2 emissions

Common misconception

Emissions from incremental oil produced with CO_2-EOR don't matter.

Common misconception

Emissions from incremental oil produced with CO_2-EOR don't matter.

> *"World oil production is determined by world oil demand and if CO_2-EOR projects were not undertaken, some other source of oil would step forward and fill the gap. Therefore, executing CO_2-EOR projects will not result in incremental aggregate refining and consumption emissions."*

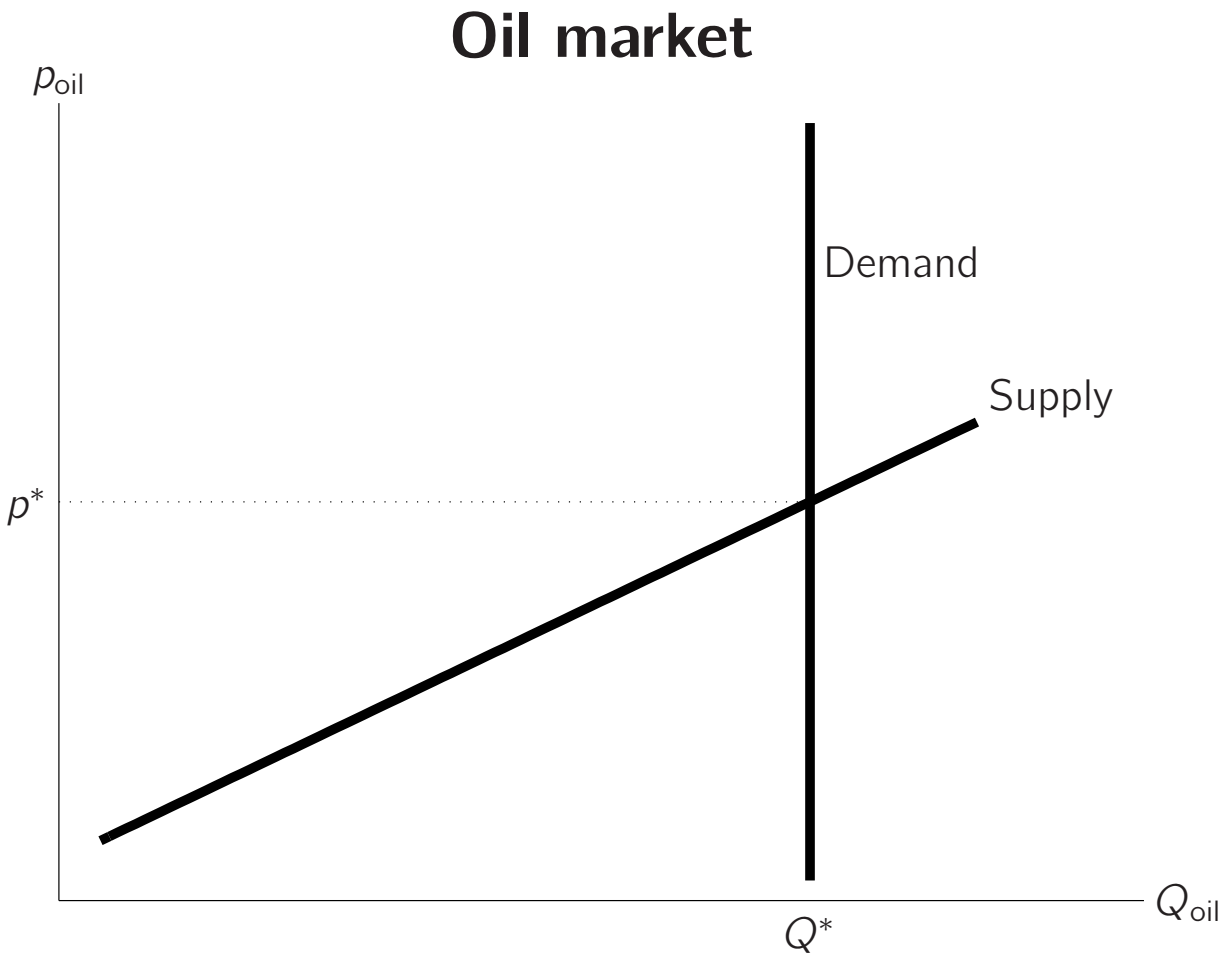
Faltinson, J. and Gunter, B. (2011). "Net CO_2 Stored in North American EOR Projects." *J. Can. Pet. Technol.* 50 (7/8): pp. 55–60.

Common misconception

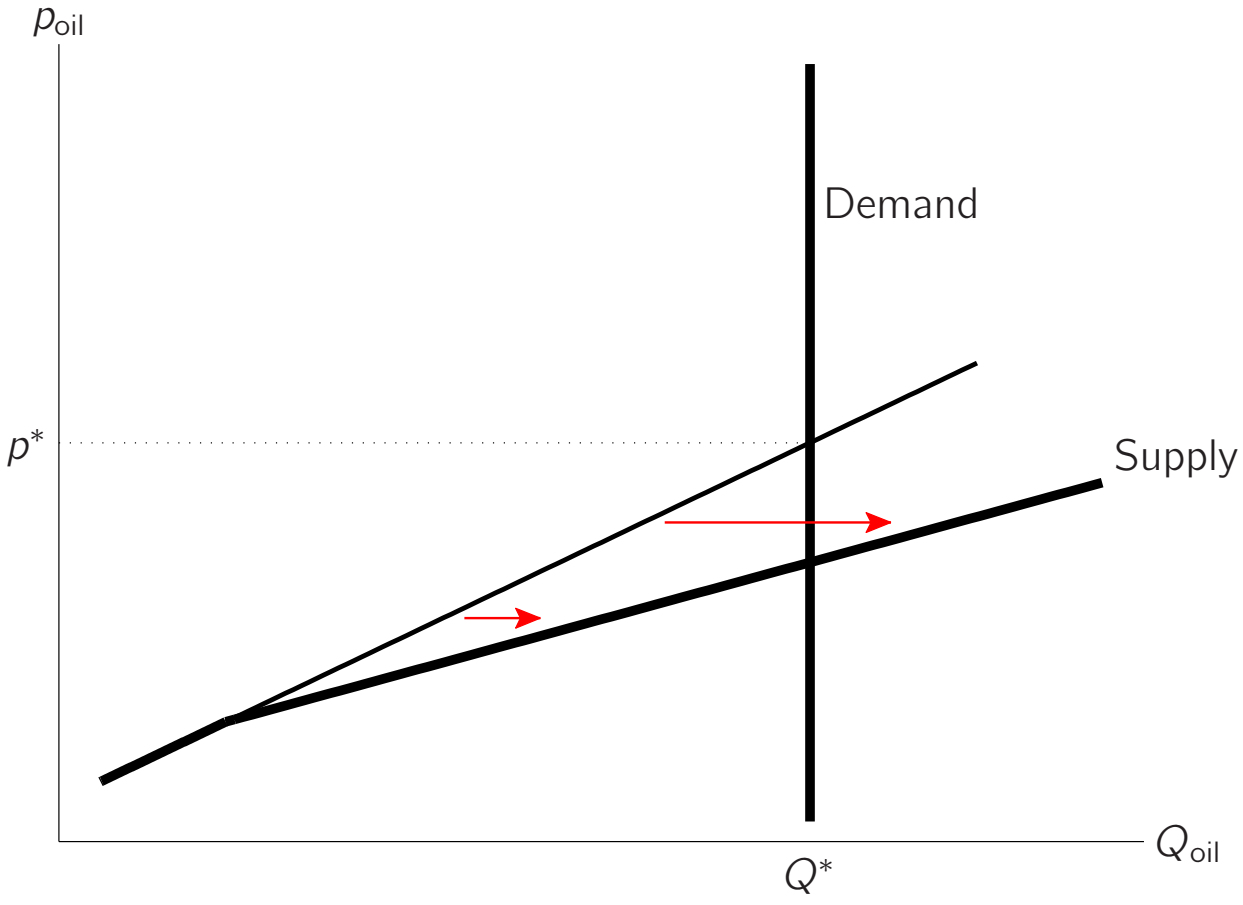
Emissions from incremental oil produced with CO_2-EOR don't matter.

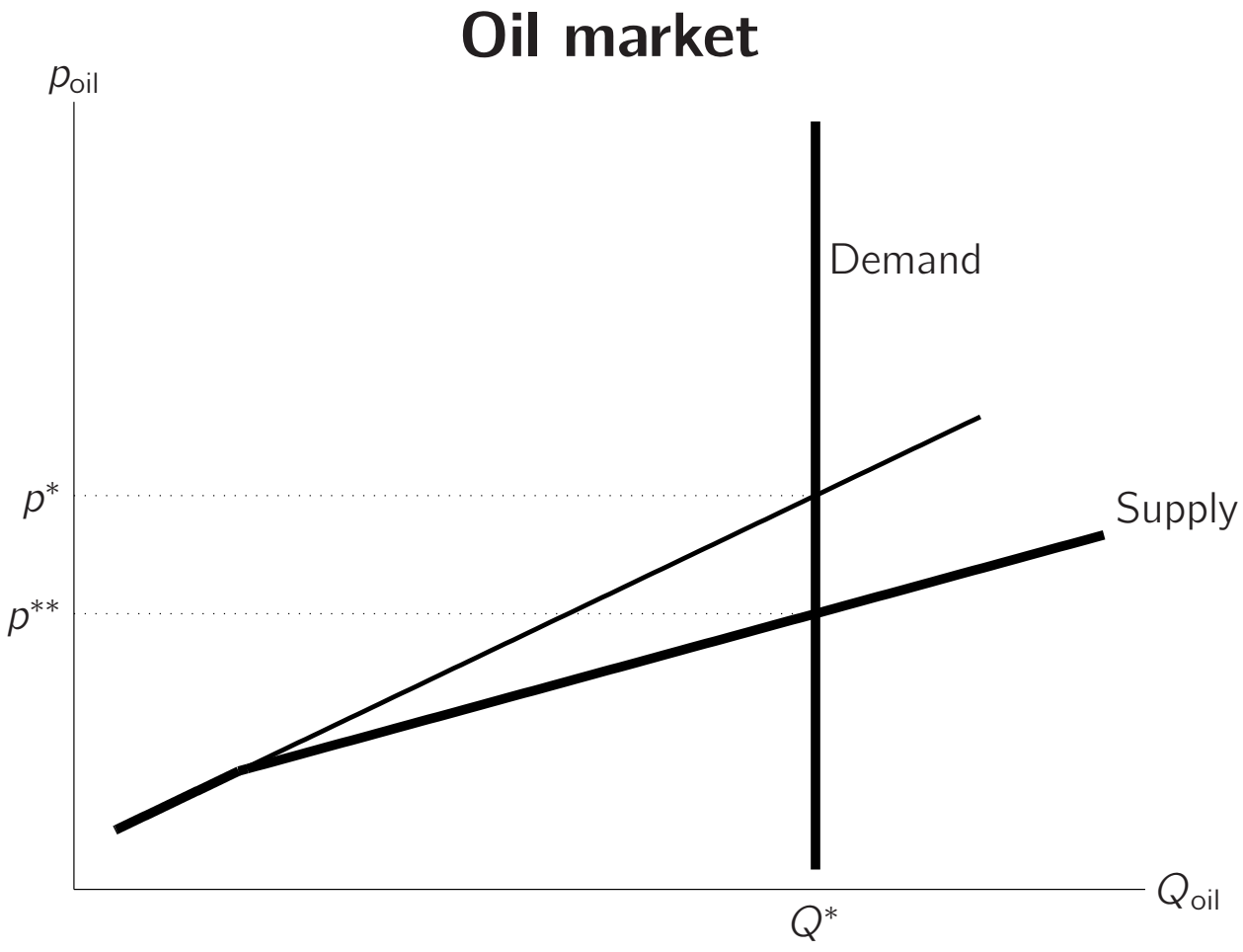
> *"World oil production is determined by world oil demand and if CO_2-EOR projects were not undertaken, some other source of oil would step forward and fill the gap. Therefore, executing CO_2-EOR projects will not result in incremental aggregate refining and consumption emissions."*

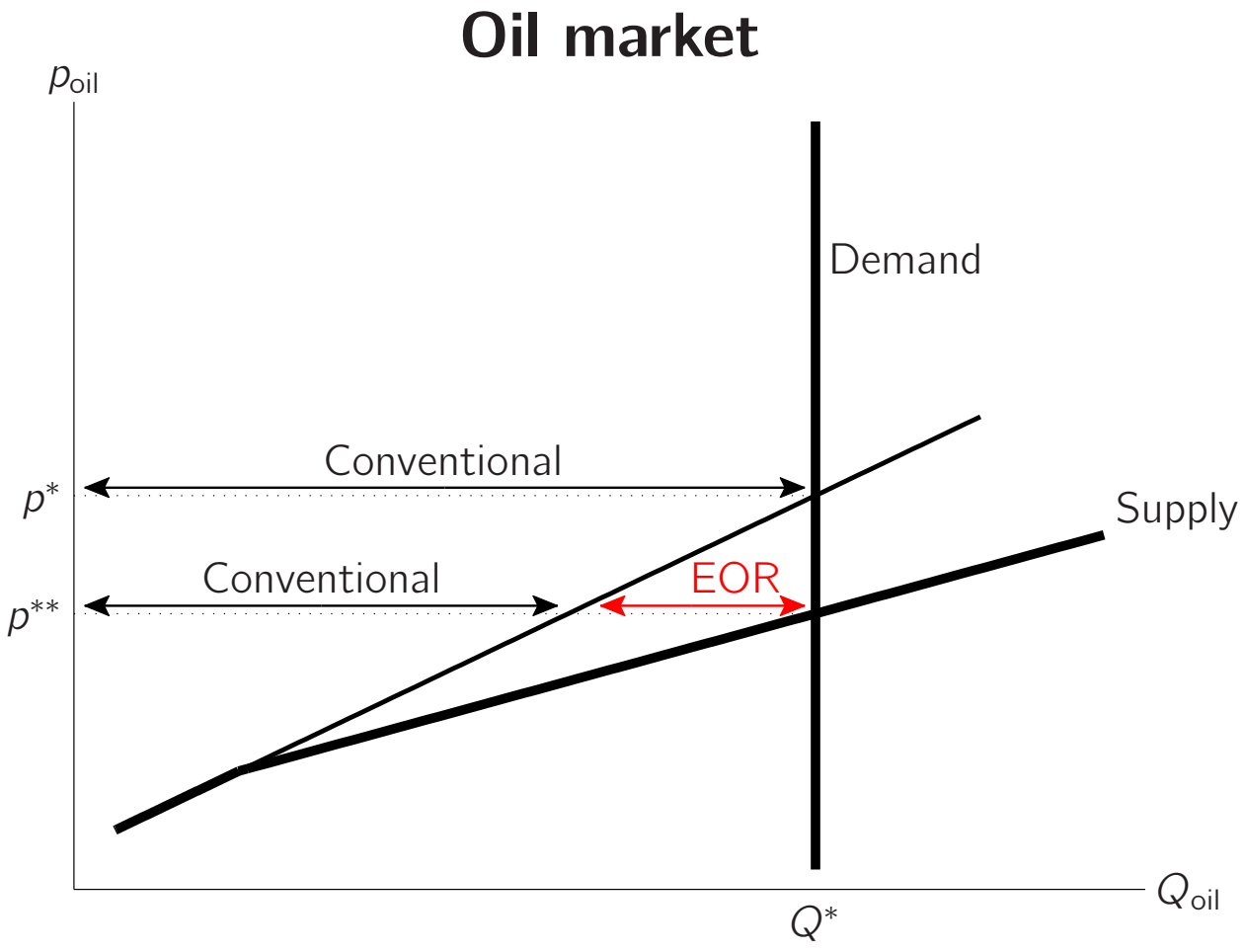
Faltinson, J. and Gunter, B. (2011). "Net CO_2 Stored in North American EOR Projects." *J. Can. Pet. Technol.* 50 (7/8): pp. 55–60.


Oil market
p_{oil}
Demand
Supply
p^*
Q_{oil}
Q^*

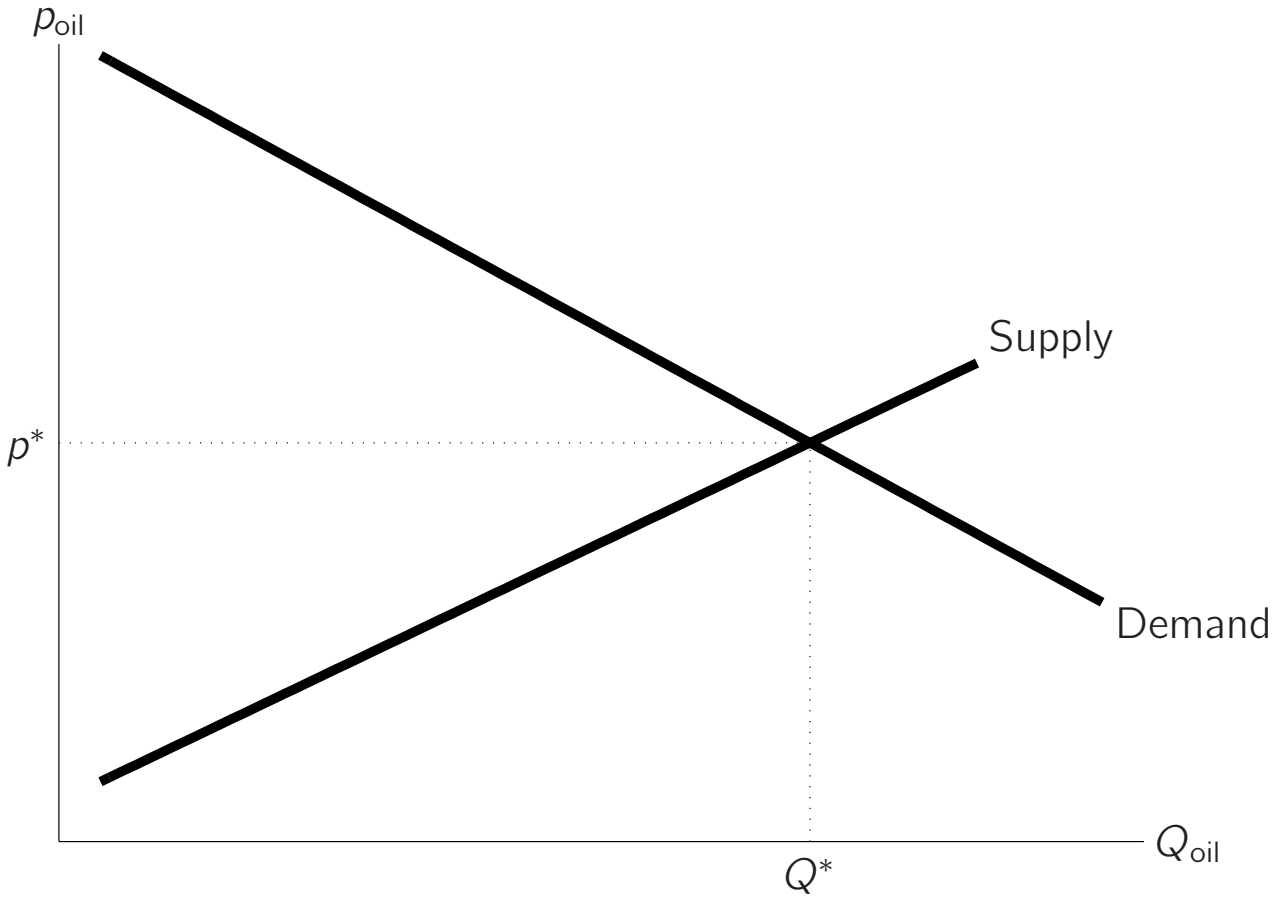
Oil market



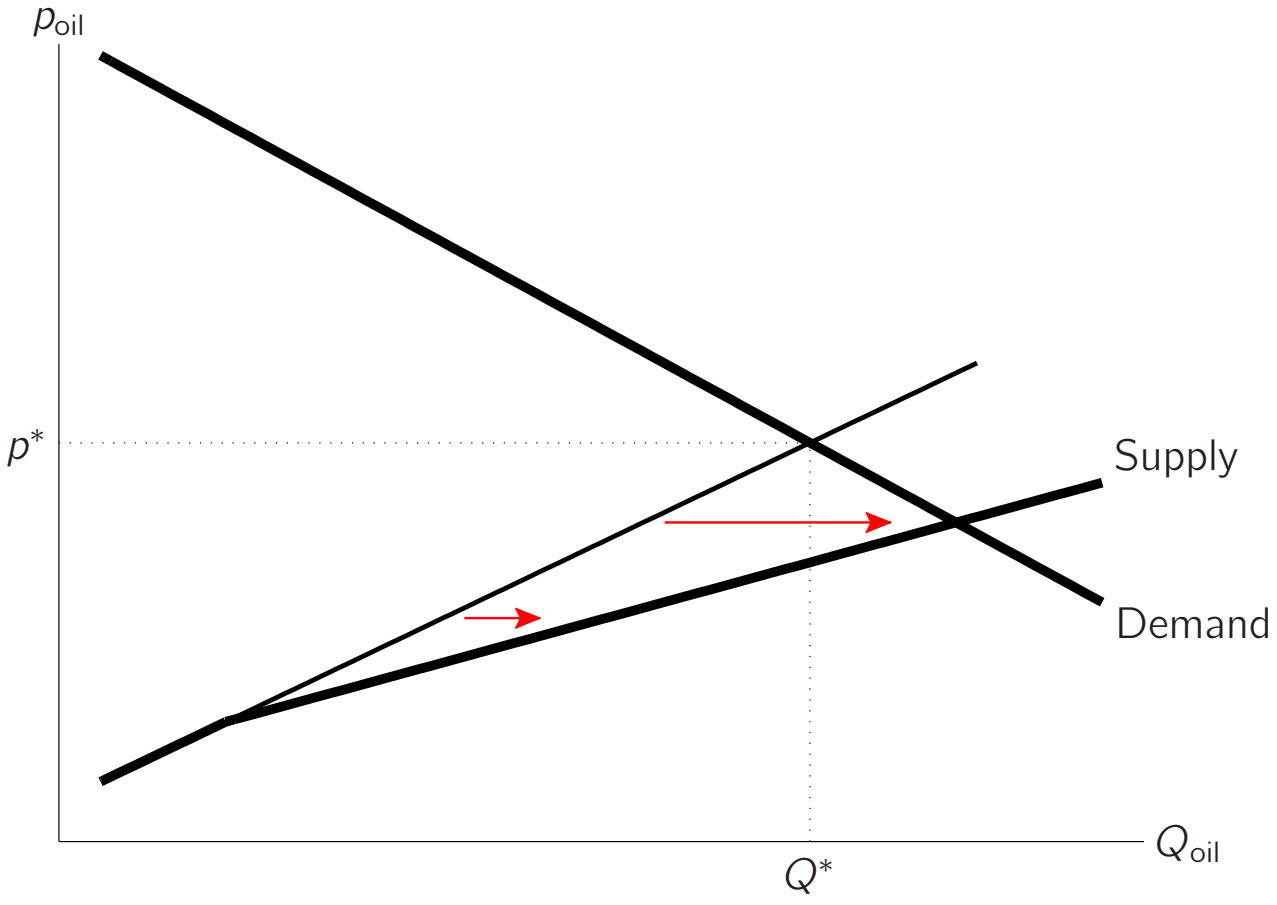

Oil market
p_{oil}
Demand
p^*
Supply
p^{**}
Q_{oil}
Q^*

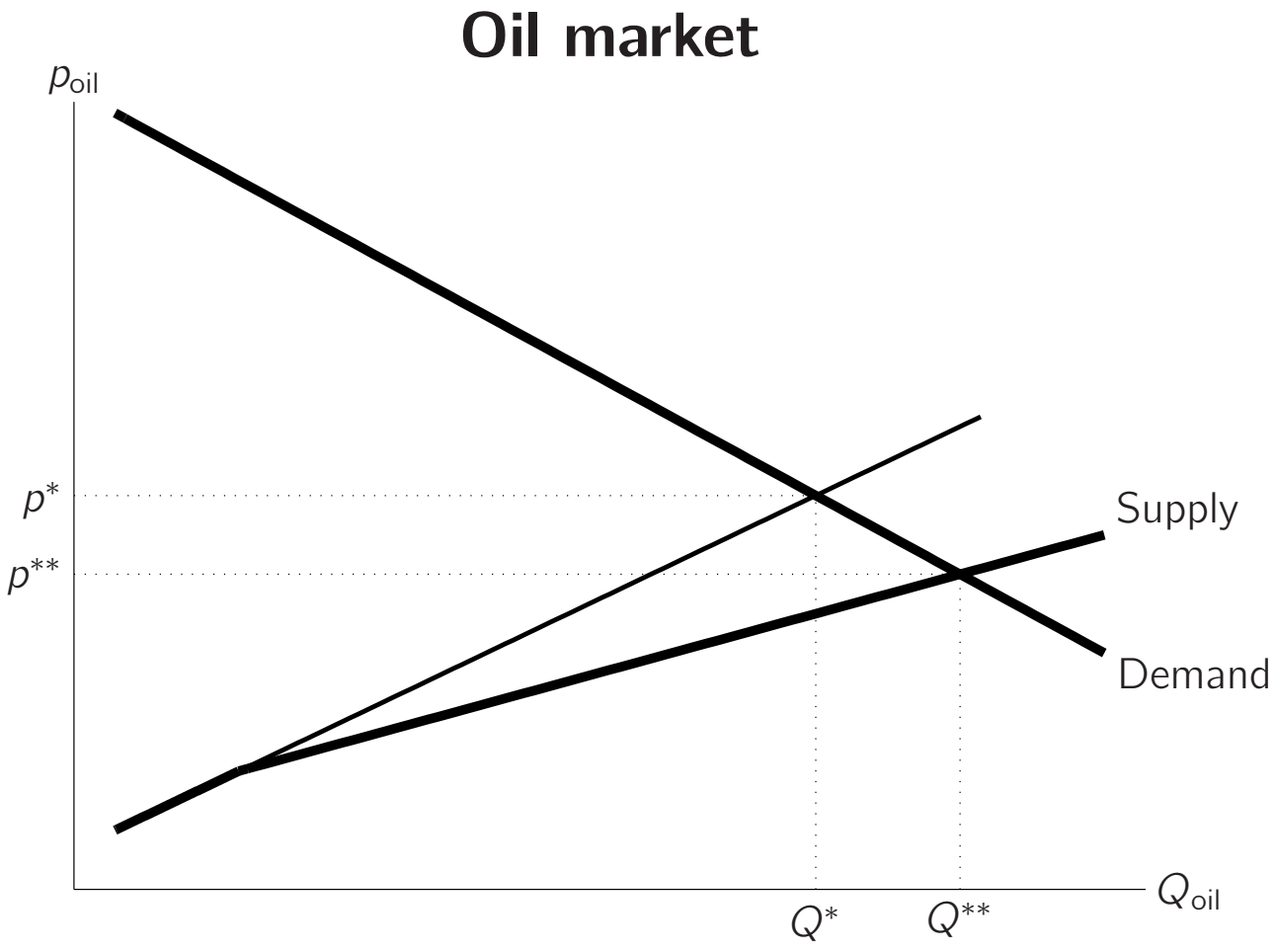

Oil market
p_{oil}
Demand
Conventional
p^*
Supply
Conventional
EOR
p^{**}
Q_{oil}
Q^*

Oil market

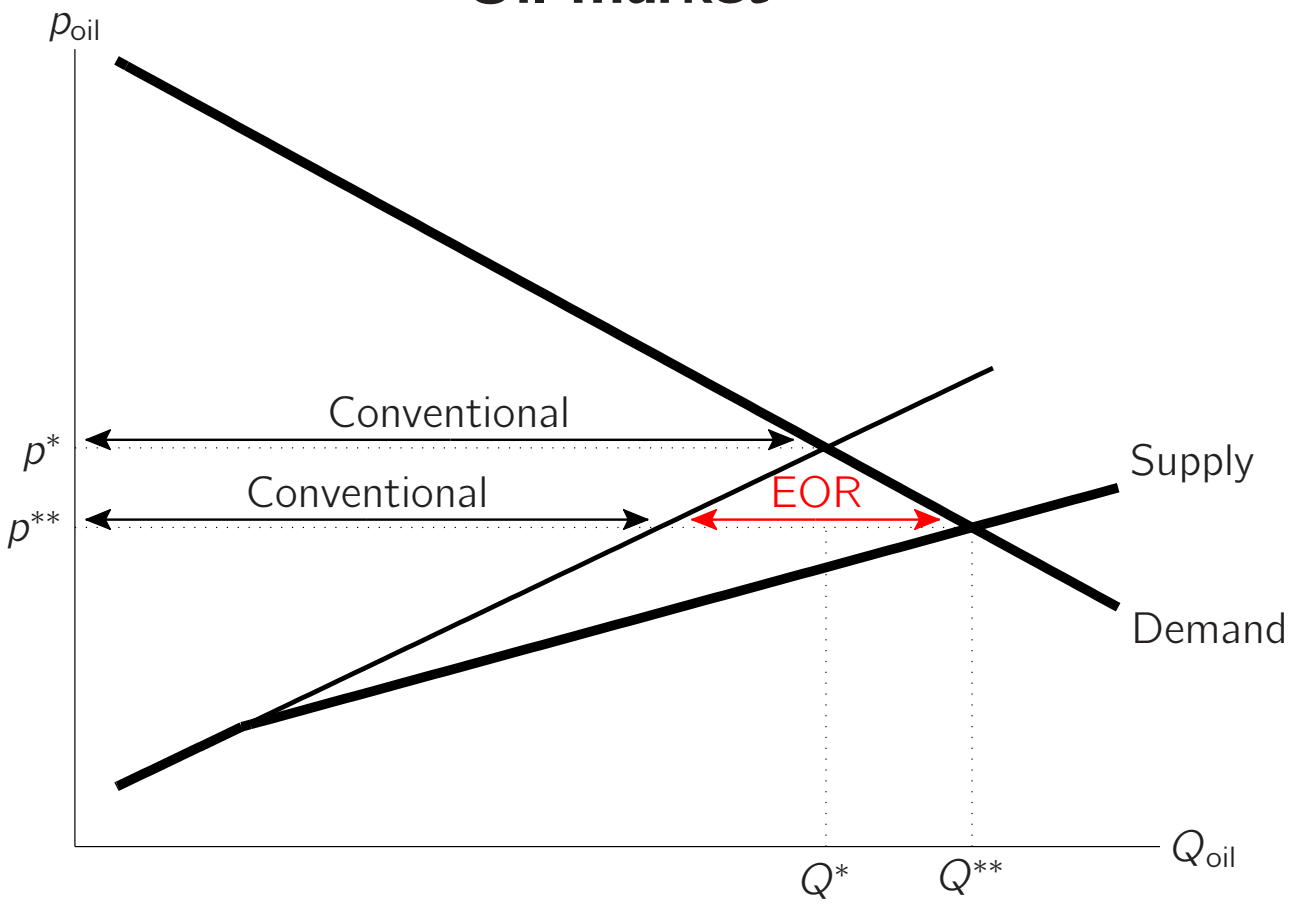


Oil market




Oil market
p_{oil}
p^*
p^{**}
Supply
Demand
Q_{oil}
Q^*
Q^{**}

Oil market


p_{oil}
Conventional
p^*
Conventional
p^{**}
EOR
Supply
Demand
Q_{oil}
Q^*
Q^{**}

Common misconception

So displacement of conventional oil is not one-for-one

Common misconception

So displacement of conventional oil is not one-for-one

Moreover, . . .

Common misconception

So displacement of conventional oil is not one-for-one

Moreover, . . .

- wind
- solar
- ethanol
- nuclear
- etc.

also “displace” conventional oil

Common misconception

So displacement of conventional oil is not one-for-one

Moreover, . . .

- wind
- solar
- ethanol
- nuclear
- etc.

also “displace” conventional oil

Does that make their net CO_2 emissions *negative*?

Optimal policy

Optimal policy

But if some CO_2-EOR projects generate positive net emissions, while others generate negative net emissions, what then is the optimal way of promoting it?

Optimal policy

But if some CO_2-EOR projects generate positive net emissions, while others generate negative net emissions, what then is the optimal way of promoting it?

Do we need taxes for some, and subsidies for others?

Optimal policy

Optimal policy

The optimal policy to promote CO_2-EOR is quite simply

Optimal policy

The optimal policy to promote CO_2-EOR is quite simply

- a tax on CO_2 emissions

  (equal to the per-unit emission damages)

Optimal policy

The optimal policy to promote CO_2-EOR is quite simply

- a tax on CO_2 emissions

  (equal to the per-unit emission damages)

which for CO_2-EOR producers acts exactly like

Optimal policy

The optimal policy to promote CO_2-EOR is quite simply

- a tax on CO_2 emissions

  (equal to the per-unit emission damages)

which for CO_2-EOR producers acts exactly like

- a subsidy on CO_2 sequestration

  (i.e., on *avoided* CO_2 emissions)

Optimal policy

The optimal policy to promote CO_2-EOR is quite simply

- a tax on CO_2 emissions

  (equal to the per-unit emission damages)

which for CO_2-EOR producers acts exactly like

- a subsidy on CO_2 sequestration

  (i.e., on *avoided* CO_2 emissions)

Optimal policy

The optimal policy to promote CO_2-EOR is quite simply

- a tax on CO_2 emissions

  (equal to the per-unit emission damages)

which for CO_2-EOR producers acts exactly like

- a subsidy on CO_2 sequestration

  (i.e., on *avoided* CO_2 emissions)

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{\left(t_{CO_2} - p_{CO_2} + c^{\text{rec}}\right)}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

- vent its CO_2

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$\left\{ \right.$ vent its CO_2 $\Rightarrow$ lose nothing

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at \$1/mcf} \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at \$1/mcf} \Rightarrow \text{lose nothing} \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\$1/\text{mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\text{\$1/mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

With a \$60/tCO_2 $\approx$ \$3/mcf emissions tax, the plant can either

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\$1/\text{mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

With a $\$60/tCO_2 \approx \$3/mcf$ emissions tax, the plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose \$3/mcf} \\ \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\text{\$1/mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

With a \$60/tCO_2 $\approx$ \$3/mcf emissions tax, the plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose \$3/mcf} \\ \text{capture it at cost of \$1/mcf and sell at \$}-2\text{/mcf} \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\$1/\text{mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

With a \$60/tCO_2 $\approx$ \$3/mcf emissions tax, the plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose \$3/mcf} \\ \text{capture it at cost of \$1/mcf and sell at } \$-2/\text{mcf} \Rightarrow \text{lose \$3/mcf} \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\text{\$1/mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

With a \$60/tCO_2 $\approx$ \$3/mcf emissions tax, the plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose \$3/mcf} \\ \text{capture it at cost of \$1/mcf and sell at \$}-2\text{/mcf} \Rightarrow \text{lose \$3/mcf} \end{cases}$$

Numerical example

Without a tax on its CO_2 emissions, an ammonia plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose nothing} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\$1/\text{mcf}}_{p_{CO_2}} \Rightarrow \text{lose nothing} \end{cases}$$

With a \$60/tCO_2 $\approx$ \$3/mcf emissions tax, the plant can either

$$\begin{cases} \text{vent its } CO_2 \Rightarrow \text{lose \$3/mcf} \\ \text{capture it at cost of \$1/mcf and sell at } \underbrace{\$-2/\text{mcf}}_{p_{CO_2} - t_{CO_2}} \Rightarrow \text{lose \$3/mcf} \end{cases}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(-p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}}$$

$$+\underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(-[p_{CO_2} - t_{CO_2}] + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{\left(t_{CO_2} - p_{CO_2} + c^{\text{rec}}\right)}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{\text{oil}}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{\text{oil}}^{\text{prd}} + \underbrace{(s_{CO_2} - p_{CO_2} + c^{\text{rec}})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{\text{seq}} - \underbrace{c^{\text{rec}}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{\text{inj}} - \underbrace{C^{\text{oth}}}_{\substack{\text{other}\\ \text{costs}}}$$

CO_2-EOR profits

$$NPV = -\underbrace{I}_{\substack{\text{up-front}\\ \text{investment}\\ \text{cost}}} + \underbrace{p_{oil}}_{\substack{\text{weight}\\ \text{on oil}\\ \text{production}}} Q_{oil}^{prd} + \underbrace{(t_{CO_2} - p_{CO_2} + c^{rec})}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{sequestration}}} Q_{CO_2}^{seq} - \underbrace{c^{rec}}_{\substack{\text{weight}\\ \text{on } CO_2\\ \text{recycling}}} Q_{CO_2}^{inj} - \underbrace{C^{oth}}_{\substack{\text{other}\\ \text{costs}}}$$

Summary

Summary

- Engineers and economists need to collaborate

Summary

- Engineers and economists need to collaborate
- *NPV*-maximizing CO_2-injection rates tend to fall over time

Summary

- Engineers and economists need to collaborate
- *NPV*-maximizing CO_2-injection rates tend to fall over time
- Oil prices drive CO_2 storage more than storage subsidies do

Summary

- Engineers and economists need to collaborate
- *NPV*-maximizing CO_2-injection rates tend to fall over time
- Oil prices drive CO_2 storage more than storage subsidies do
  - but not necessarily positively

Summary

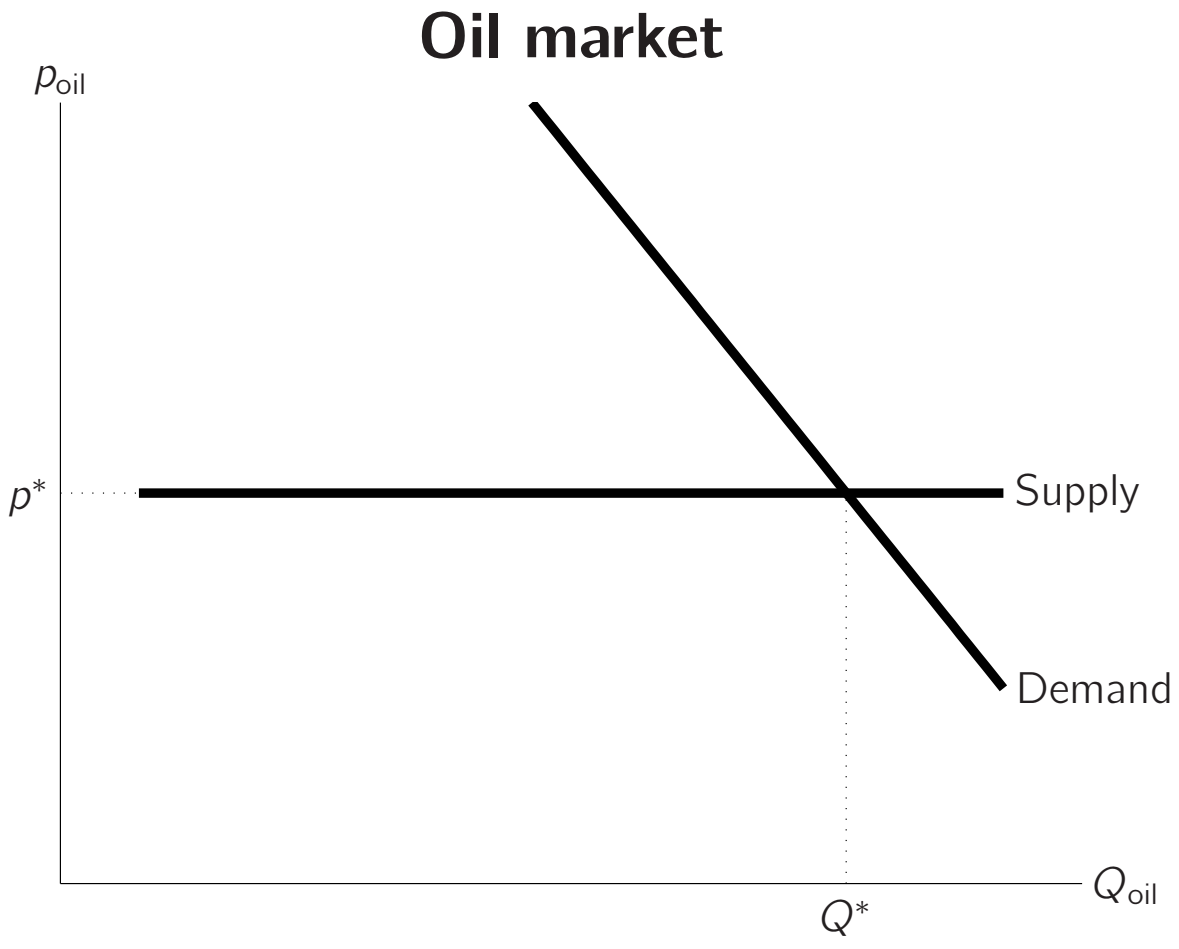
- Engineers and economists need to collaborate
- *NPV*-maximizing CO_2-injection rates tend to fall over time
- Oil prices drive CO_2 storage more than storage subsidies do
  - but not necessarily positively
- Emissions from consumption of incremental EOR barrels do matter

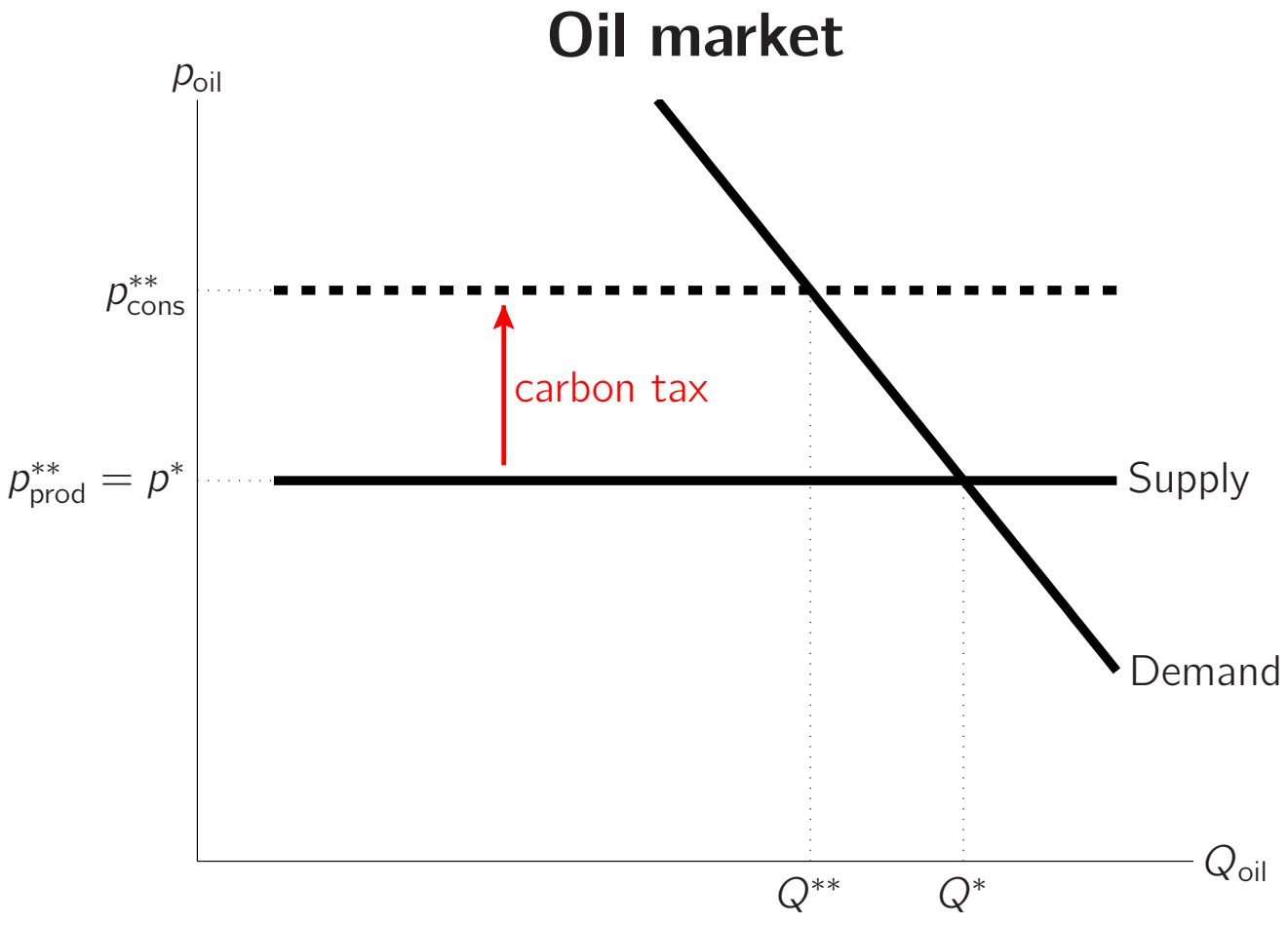
Summary

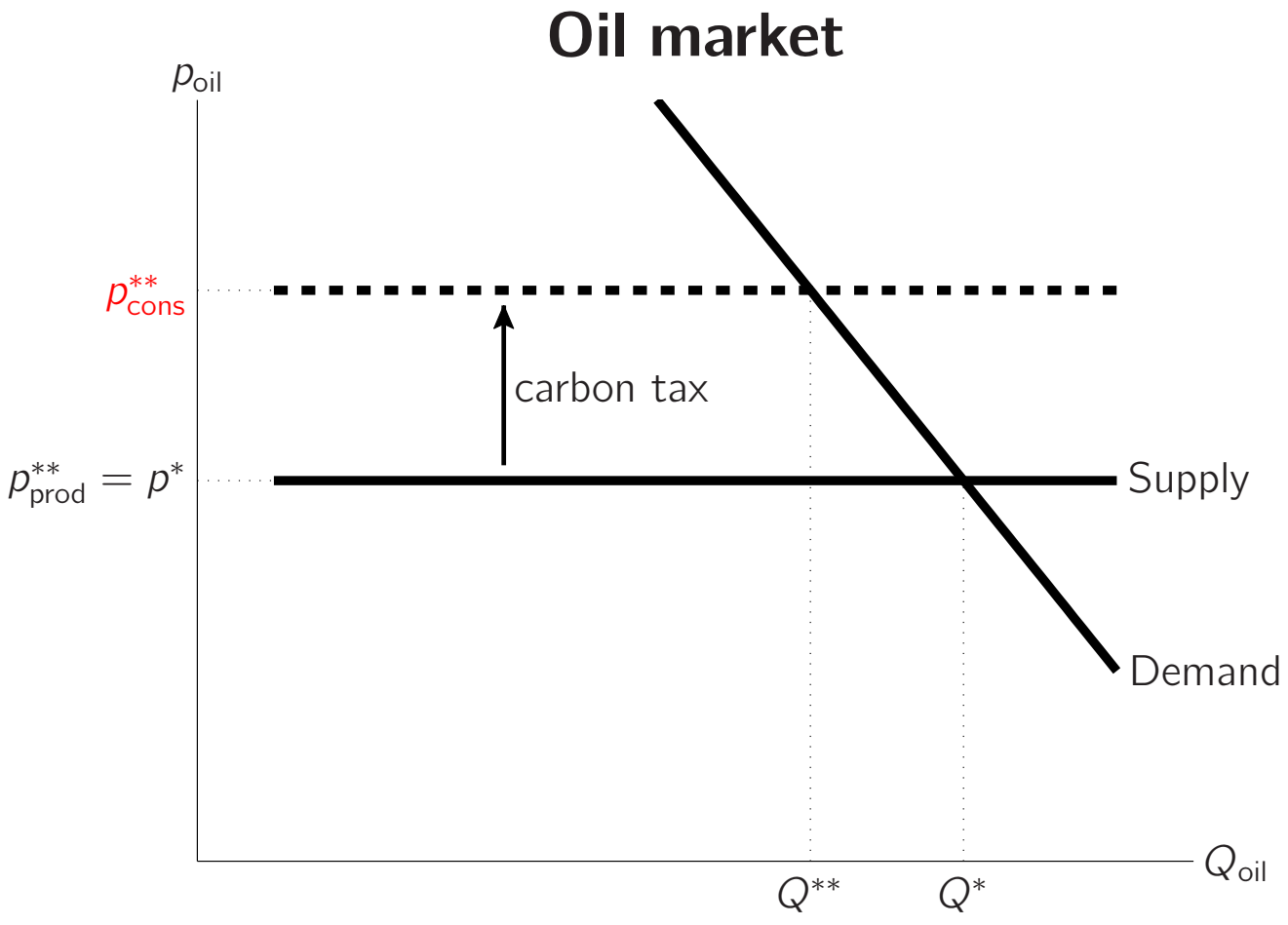
- Engineers and economists need to collaborate
- *NPV*-maximizing CO_2-injection rates tend to fall over time
- Oil prices drive CO_2 storage more than storage subsidies do
  - but not necessarily positively
- Emissions from consumption of incremental EOR barrels do matter
- The optimal policy to promote CO_2-EOR is a tax on CO_2 emissions

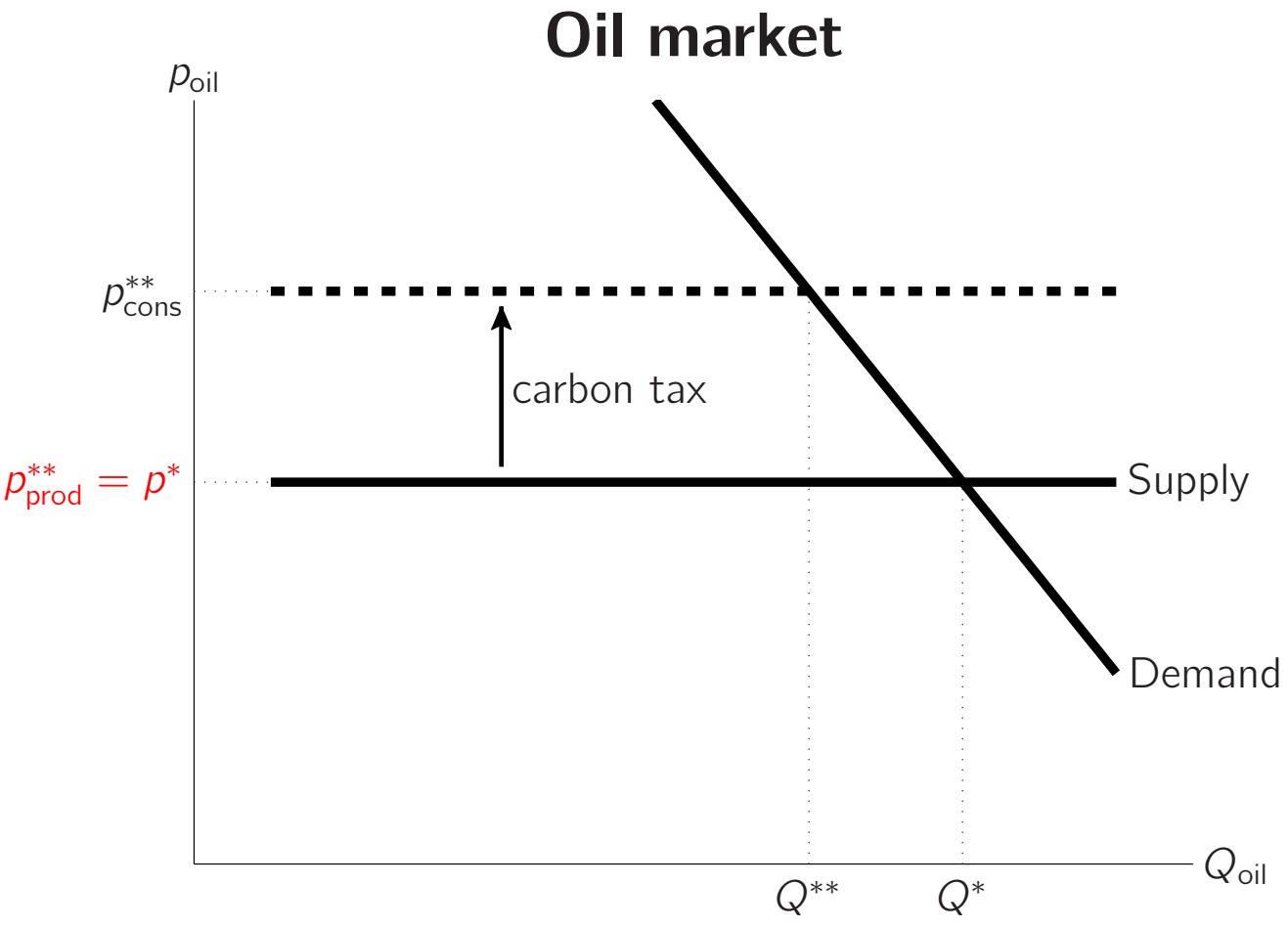
Summary

- Engineers and economists need to collaborate
- *NPV*-maximizing CO_2-injection rates tend to fall over time
- Oil prices drive CO_2 storage more than storage subsidies do
  - but not necessarily positively
- Emissions from consumption of incremental EOR barrels do matter
- The optimal policy to promote CO_2-EOR is a tax on CO_2 emissions
  - but producers may not benefit from such a tax

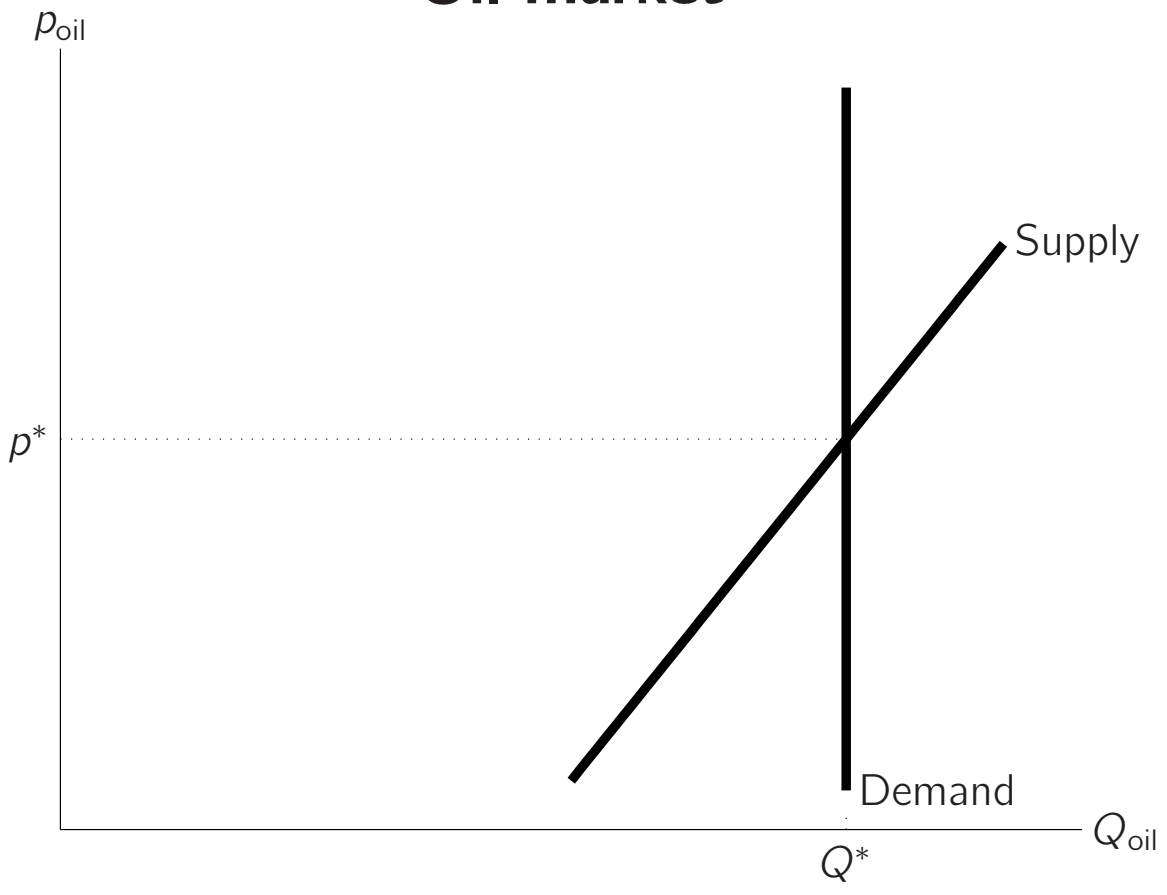

Oil market
p_{oil}
p^*
Supply
Demand
Q_{oil}
Q^*

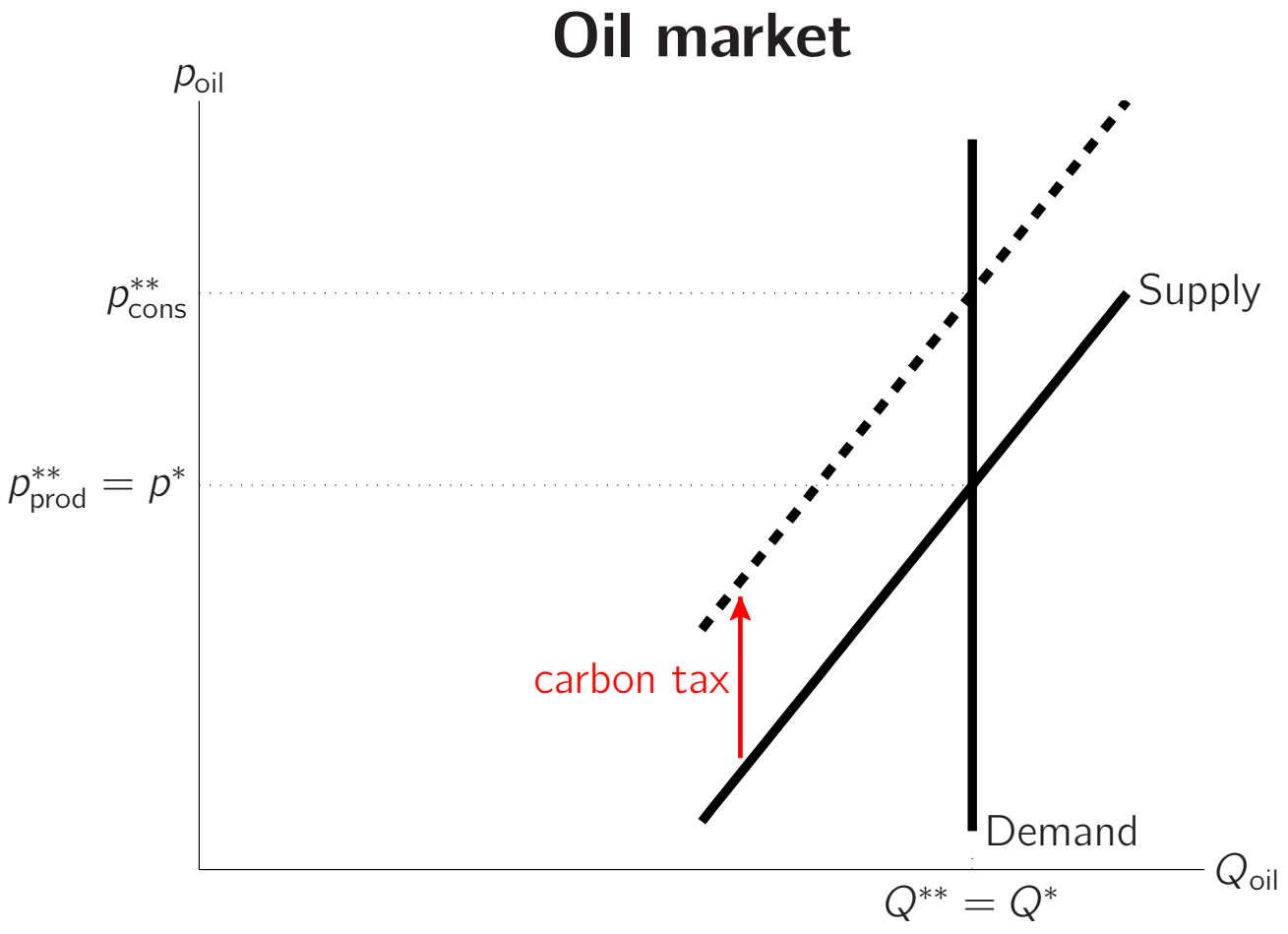

Oil market
p_{oil}
p^{**}_{cons}
carbon tax
$p^{**}_{prod} = p^*$
Supply
Demand
Q_{oil}
Q^{**}
Q^*


Oil market
p_{oil}
p^{**}_{cons}
carbon tax
$p^{**}_{prod} = p^*$
Supply
Demand
Q_{oil}
Q^{**}
Q^*

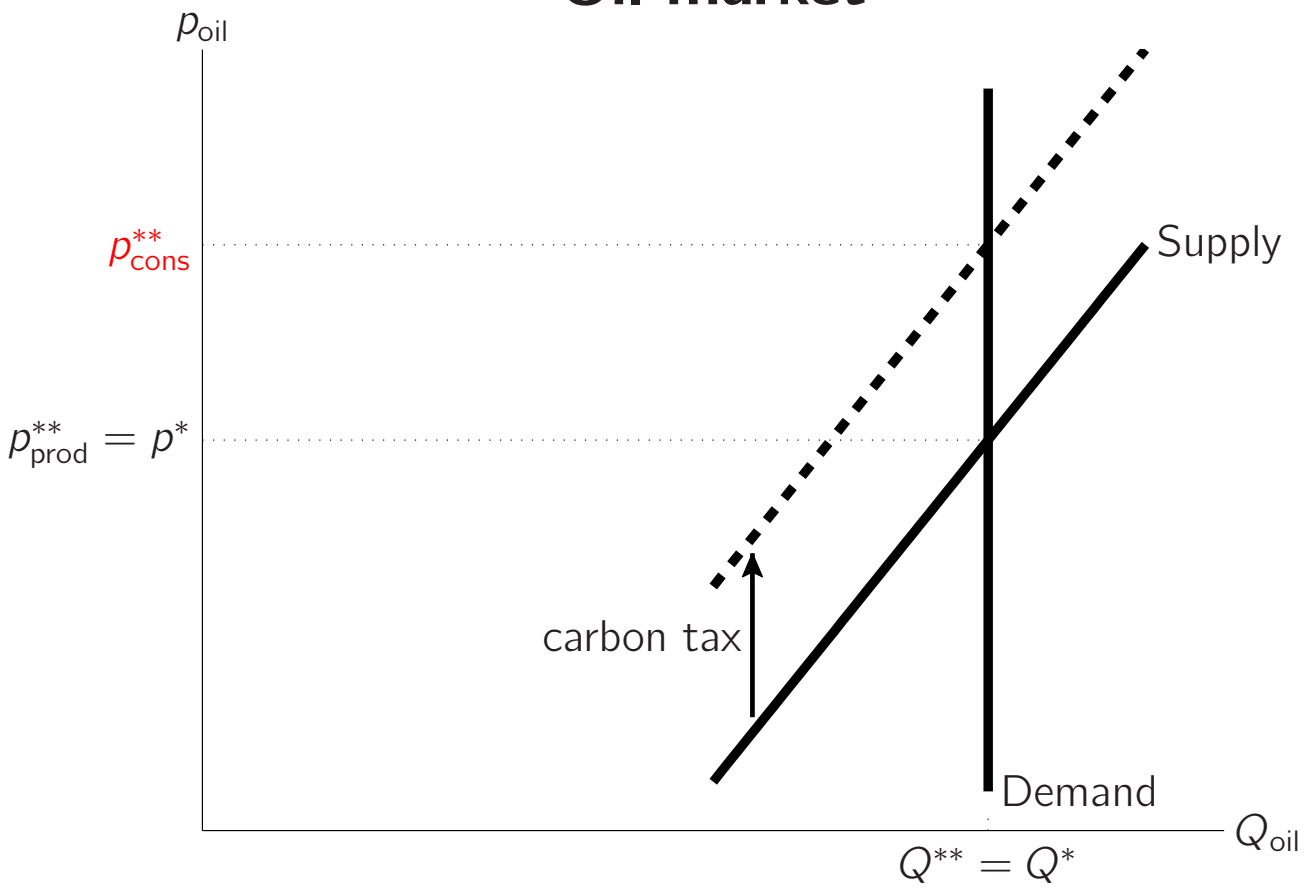

Oil market
p_{oil}
p^{**}_{cons}
carbon tax
$p^{**}_{prod} = p^{*}$
Supply
Demand
Q_{oil}
Q^{**}
Q^{*}

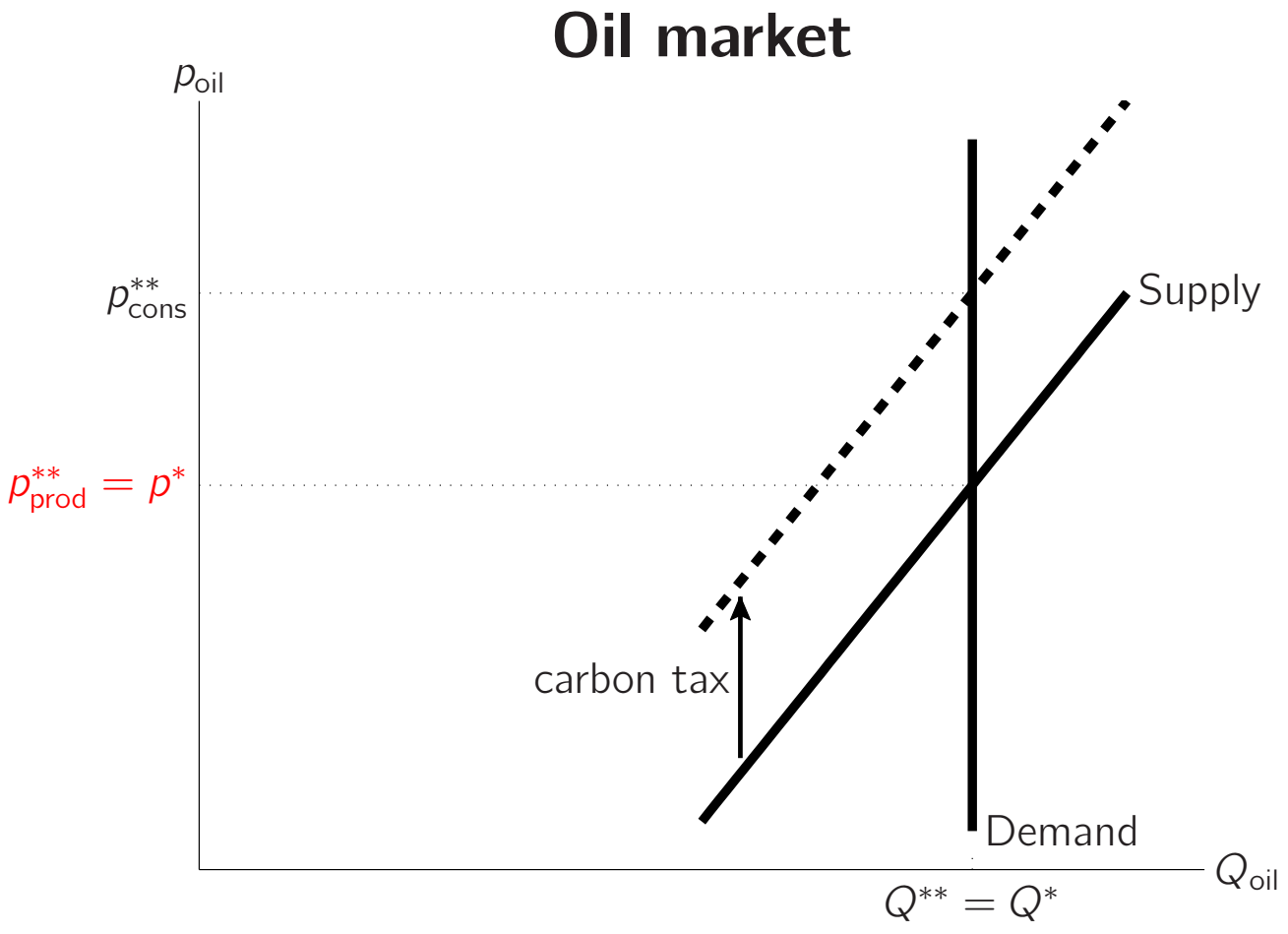
Oil market



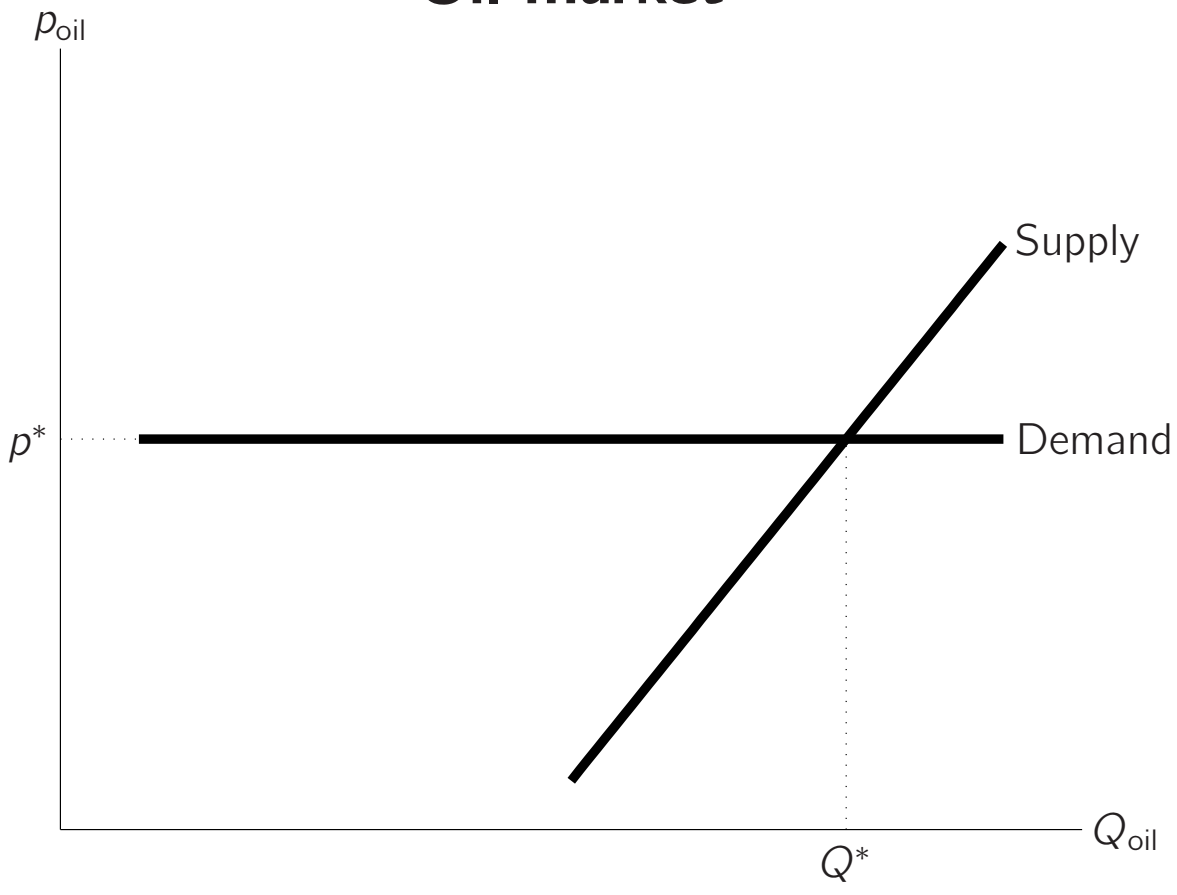

Oil market
p_{oil}
p^{**}_{cons}
$p^{**}_{prod} = p^*$
Supply
carbon tax
Demand
Q_{oil}
$Q^{**} = Q^*$

Oil market

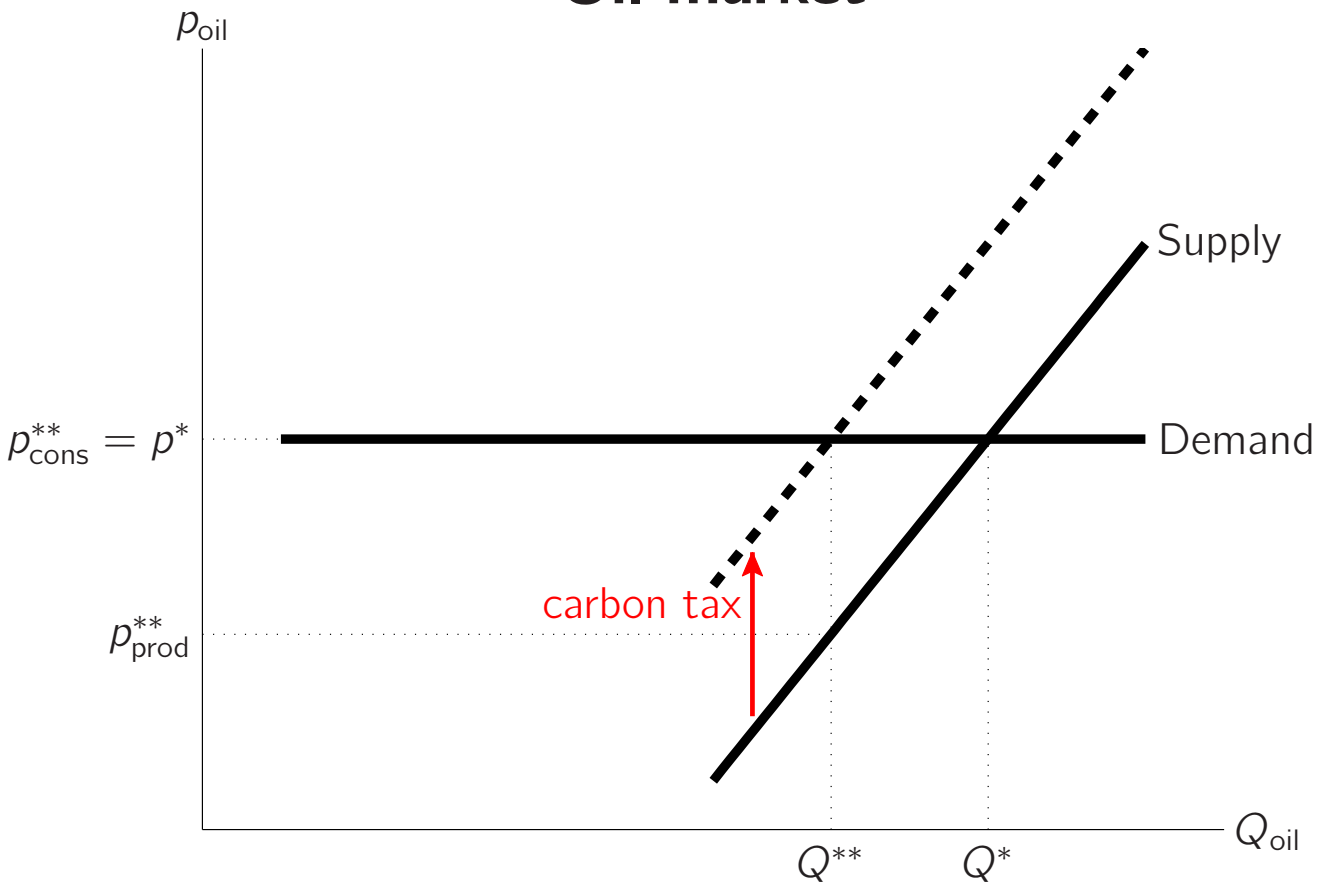



Oil market
p_{oil}
p^{**}_{cons}
$p^{**}_{prod} = p^*$
Supply
carbon tax
Demand
Q_{oil}
$Q^{**} = Q^*$

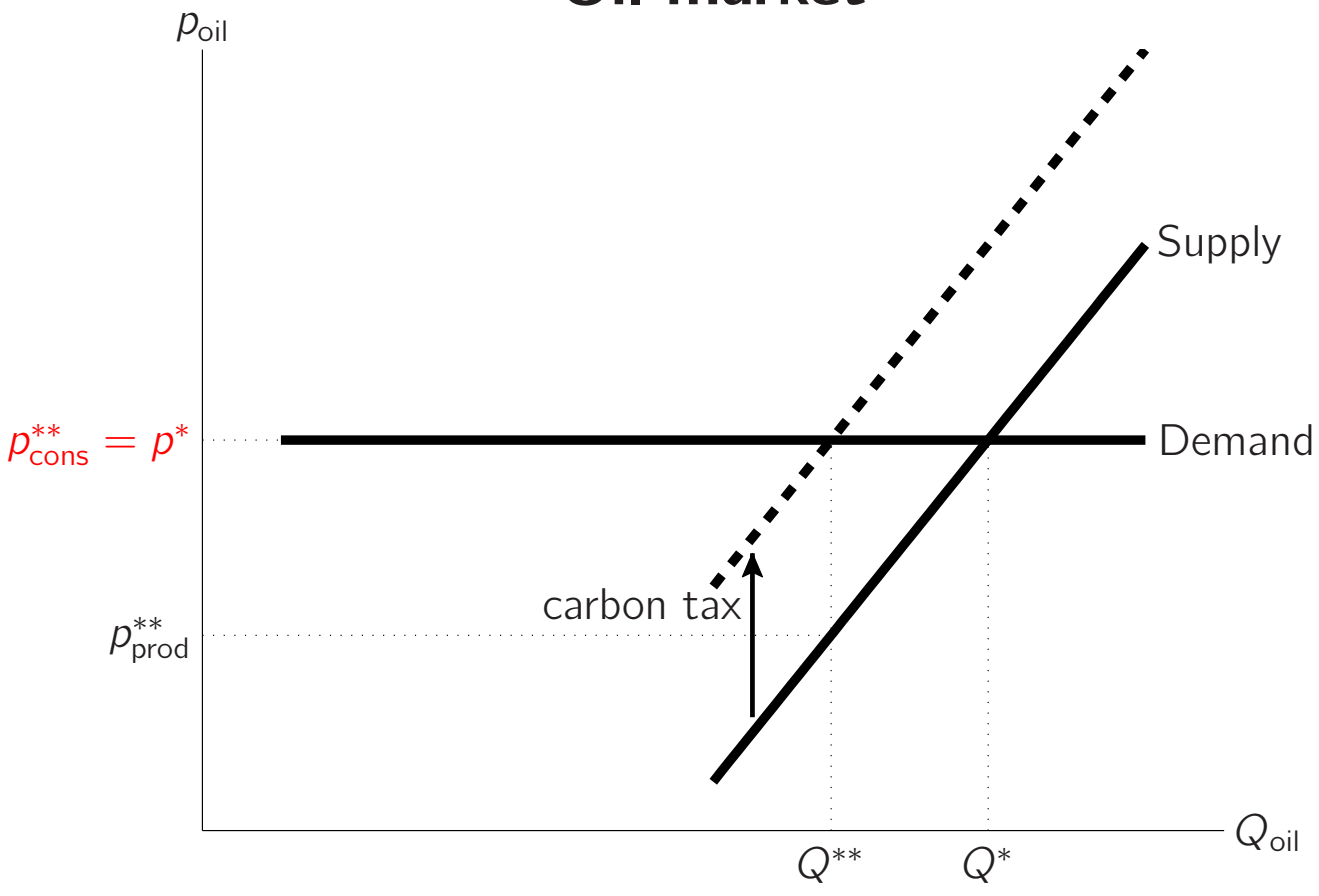
Oil market



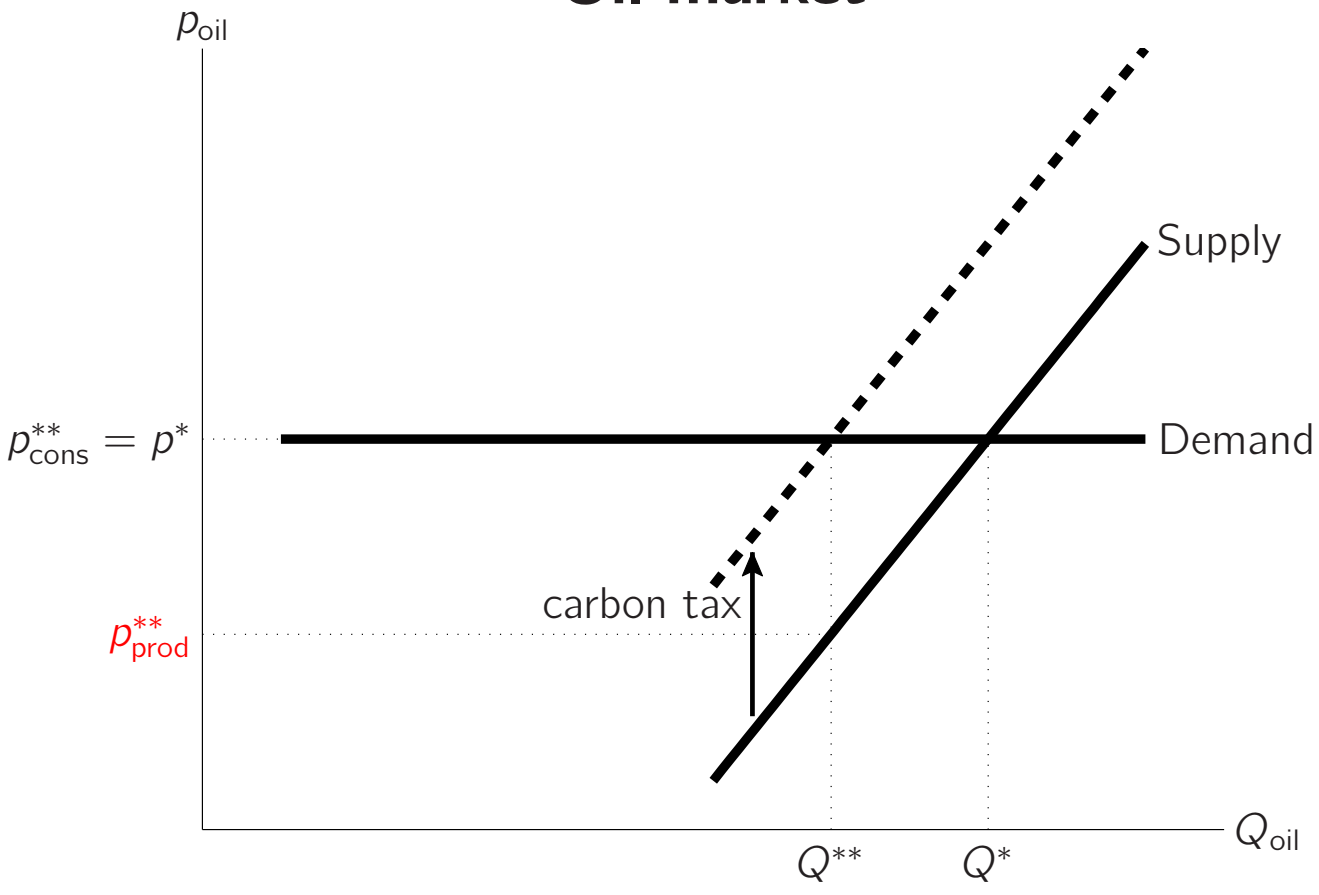
Oil market

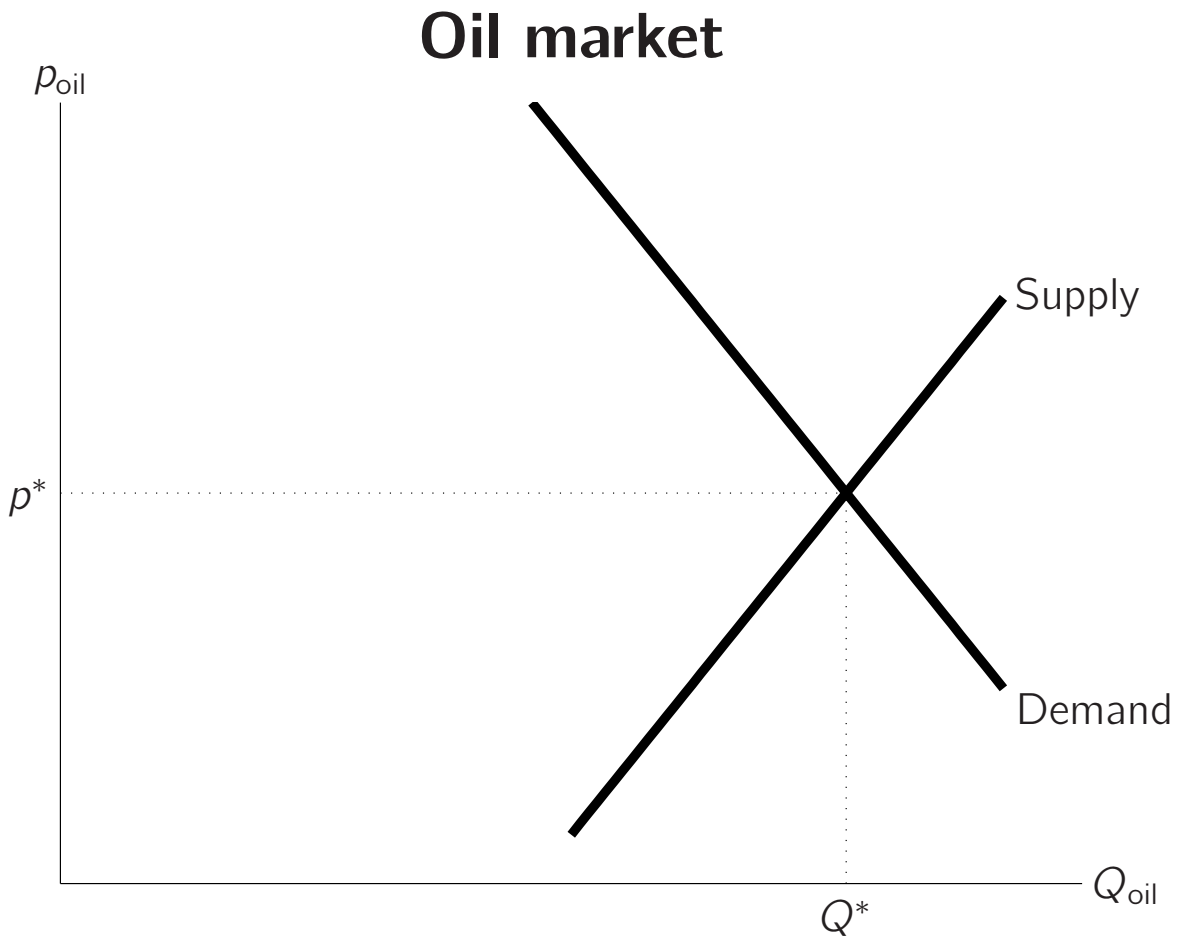

p_{oil}
Supply
$p^{**}_{\text{cons}} = p^*$
Demand
carbon tax
p^{**}_{prod}
Q_{oil}
Q^{**}
Q^*

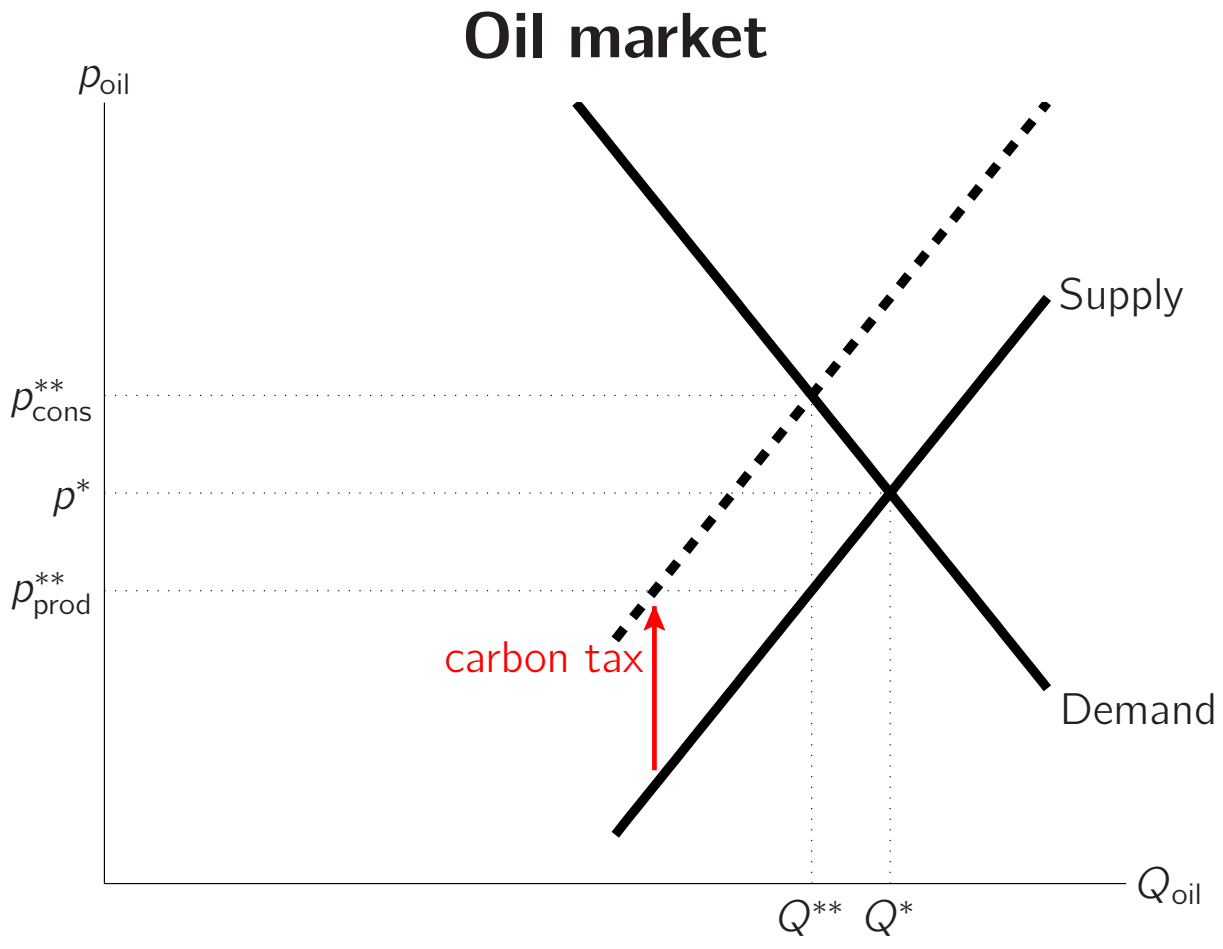
Oil market

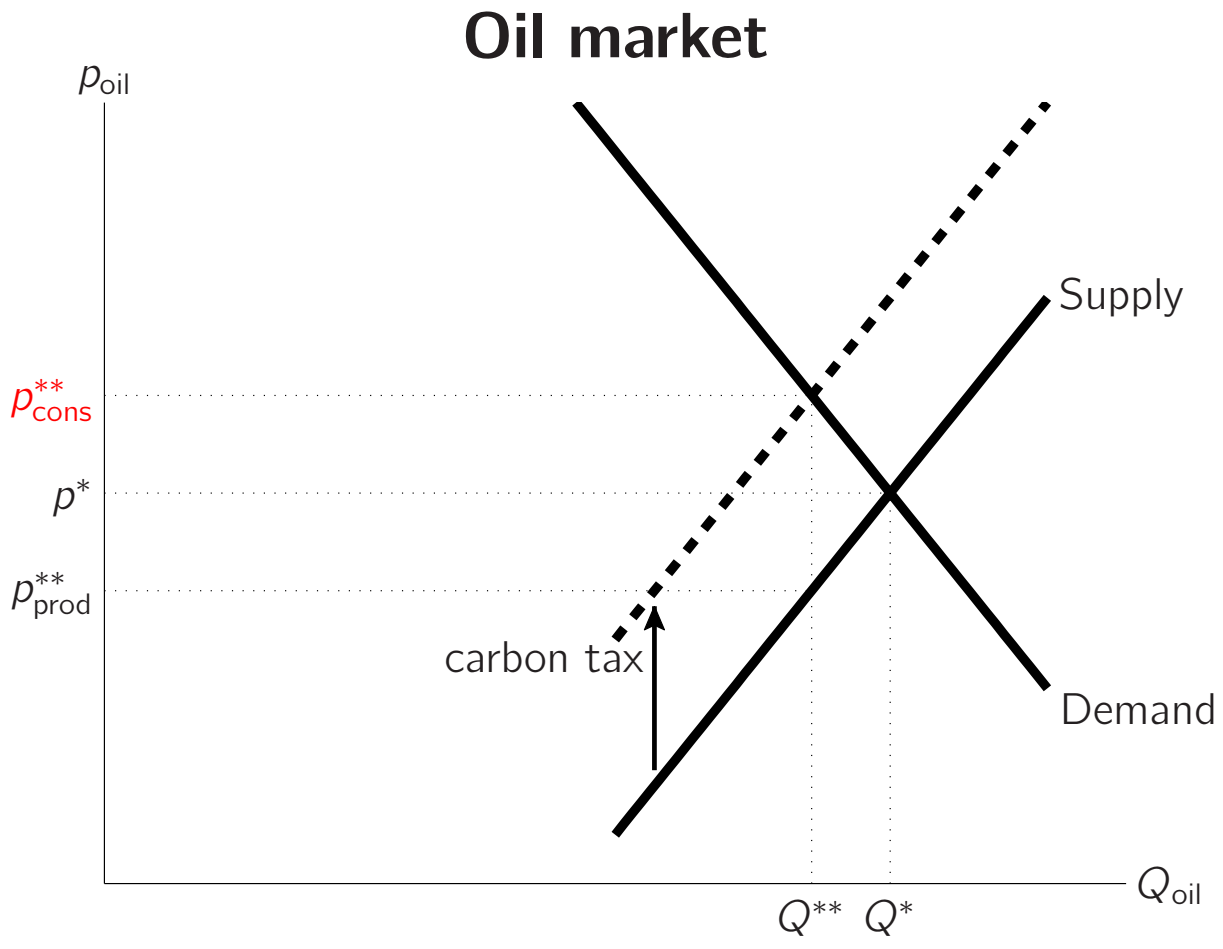


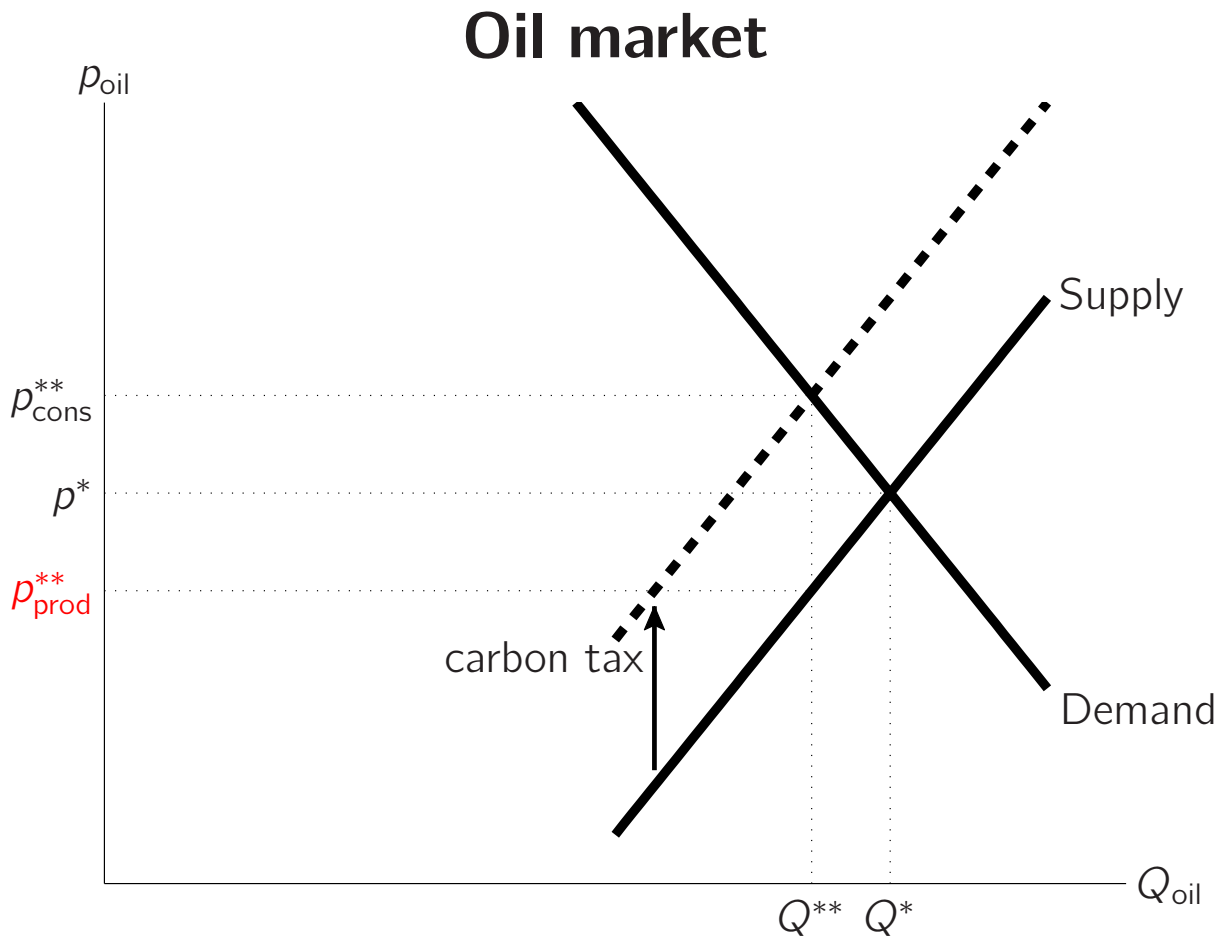
Oil market

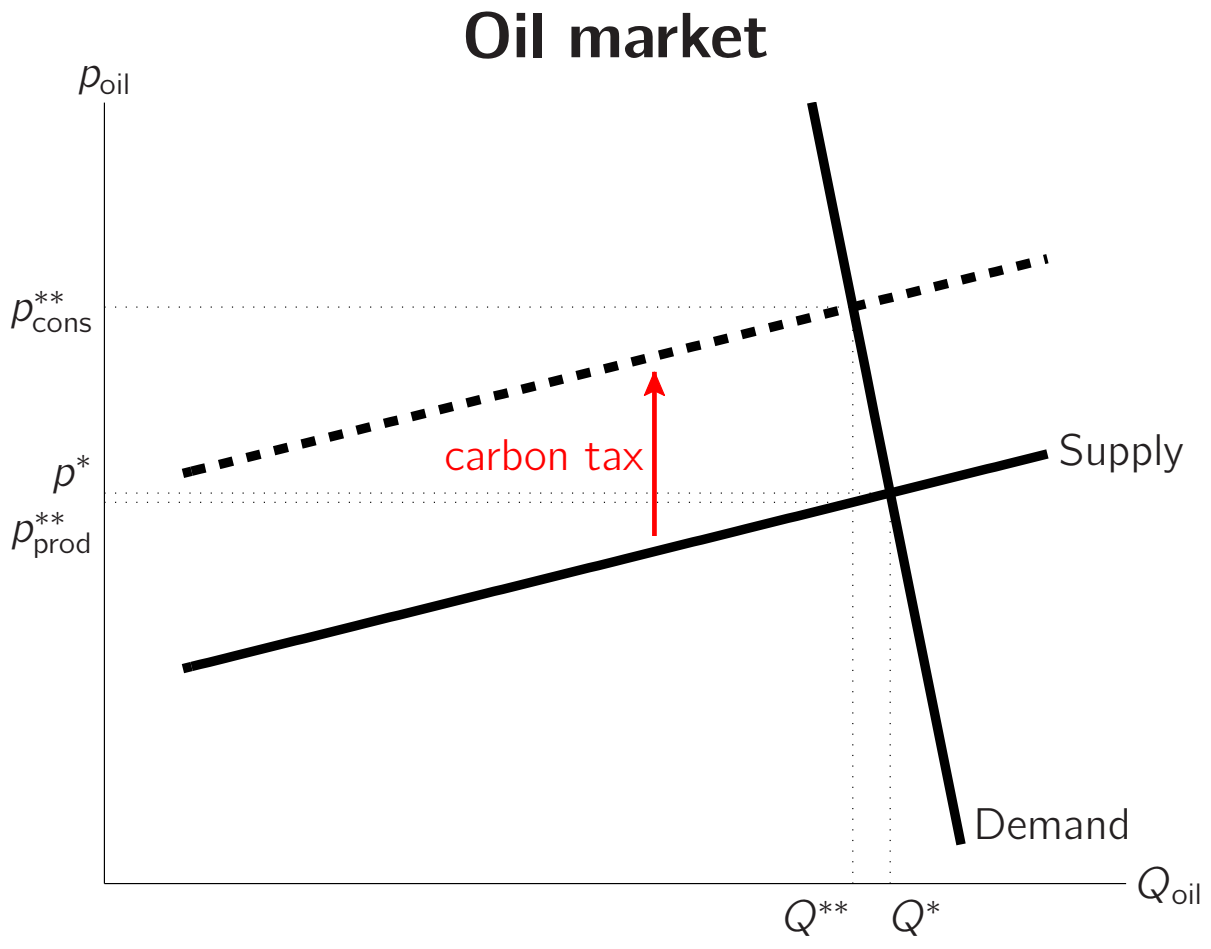

p_{oil}
Supply
$p^{**}_{\text{cons}} = p^*$
Demand
carbon tax
p^{**}_{prod}
Q_{oil}
Q^{**}
Q^*

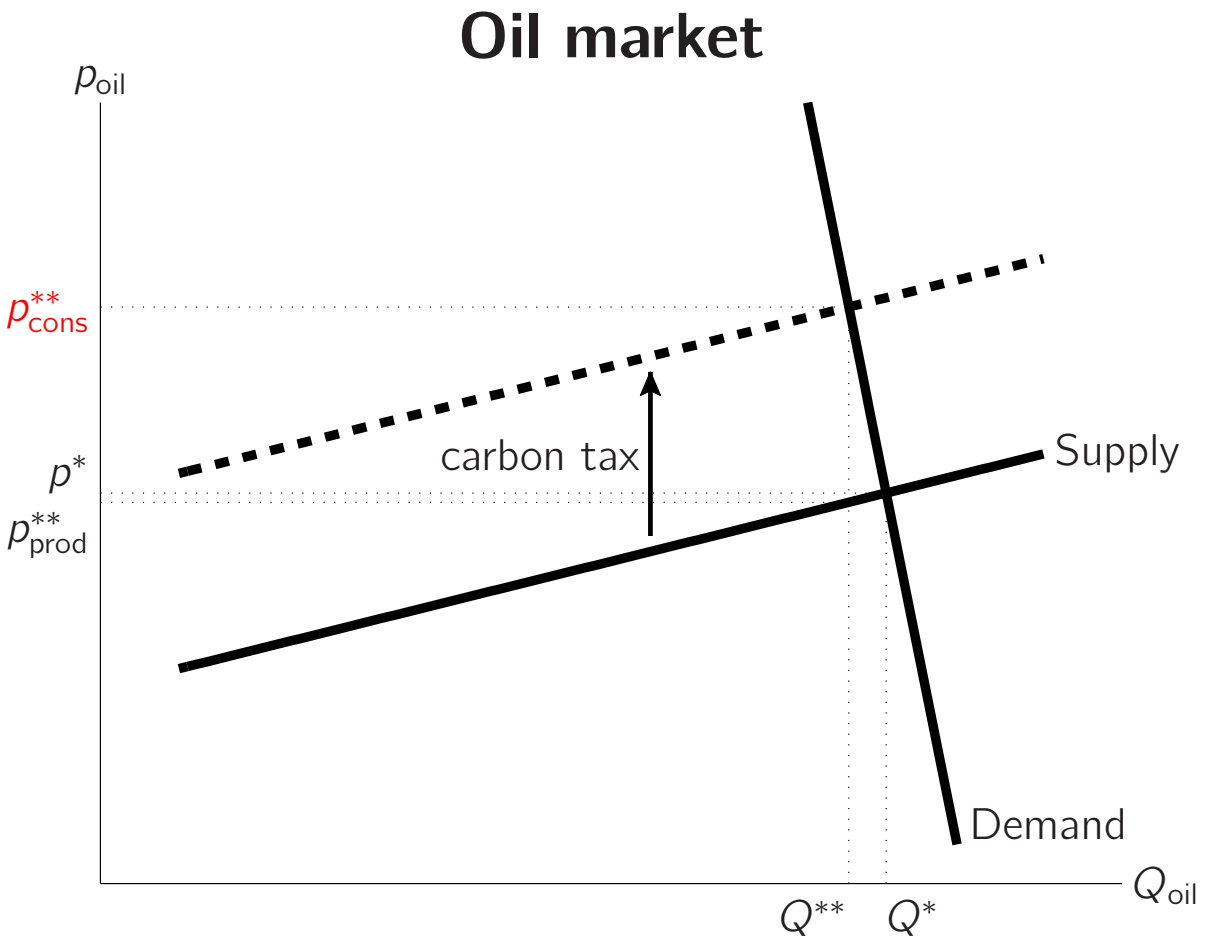

Oil market
p_{oil}
Supply
p^*
Demand
Q_{oil}
Q^*

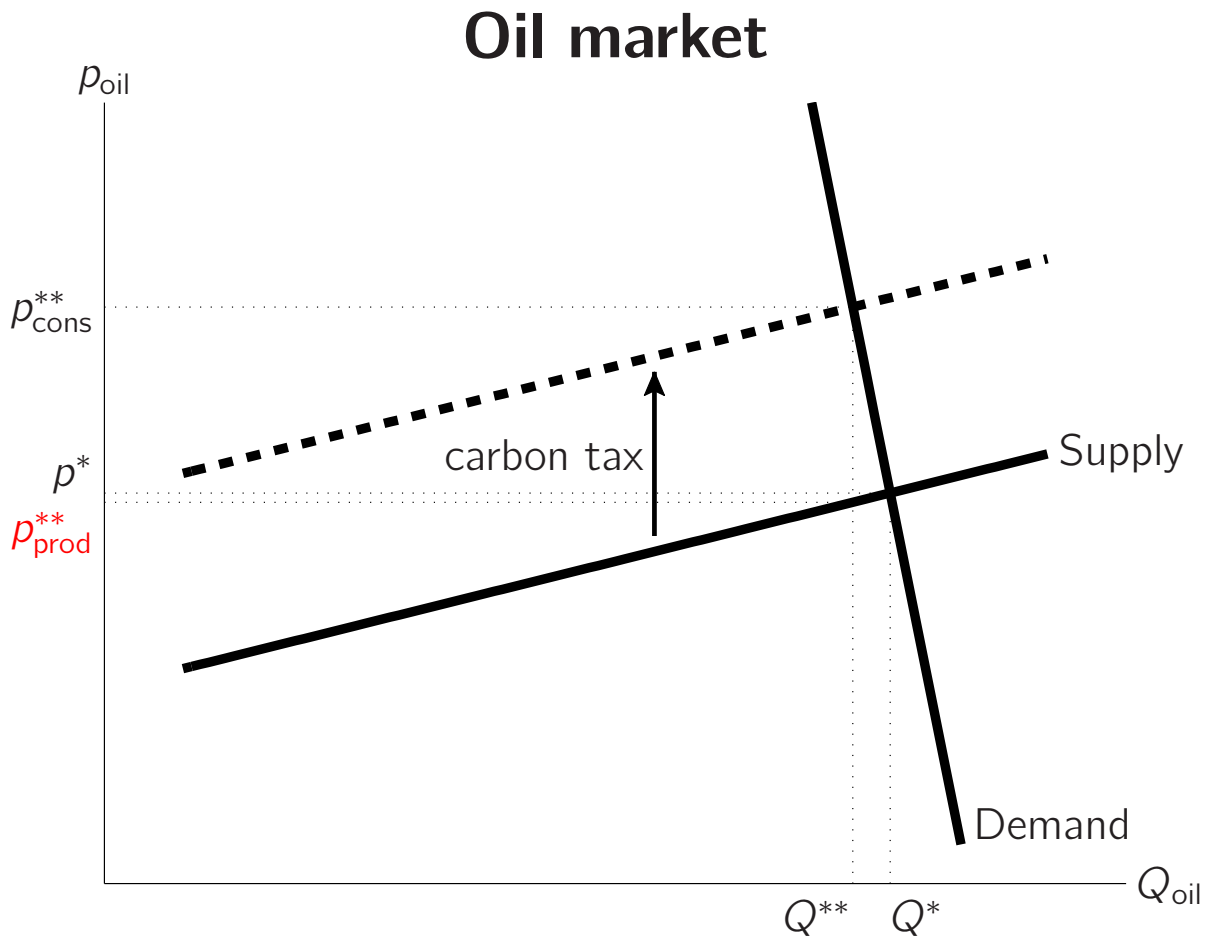

Oil market
p_{oil}
p^{**}_{cons}
p^{*}
p^{**}_{prod}
carbon tax
Supply
Demand
Q_{oil}
Q^{**}
Q^{*}


Oil market
p_{oil}
p^{**}_{cons}
p^{*}
p^{**}_{prod}
carbon tax
Supply
Demand
Q_{oil}
Q^{**} Q^{*}

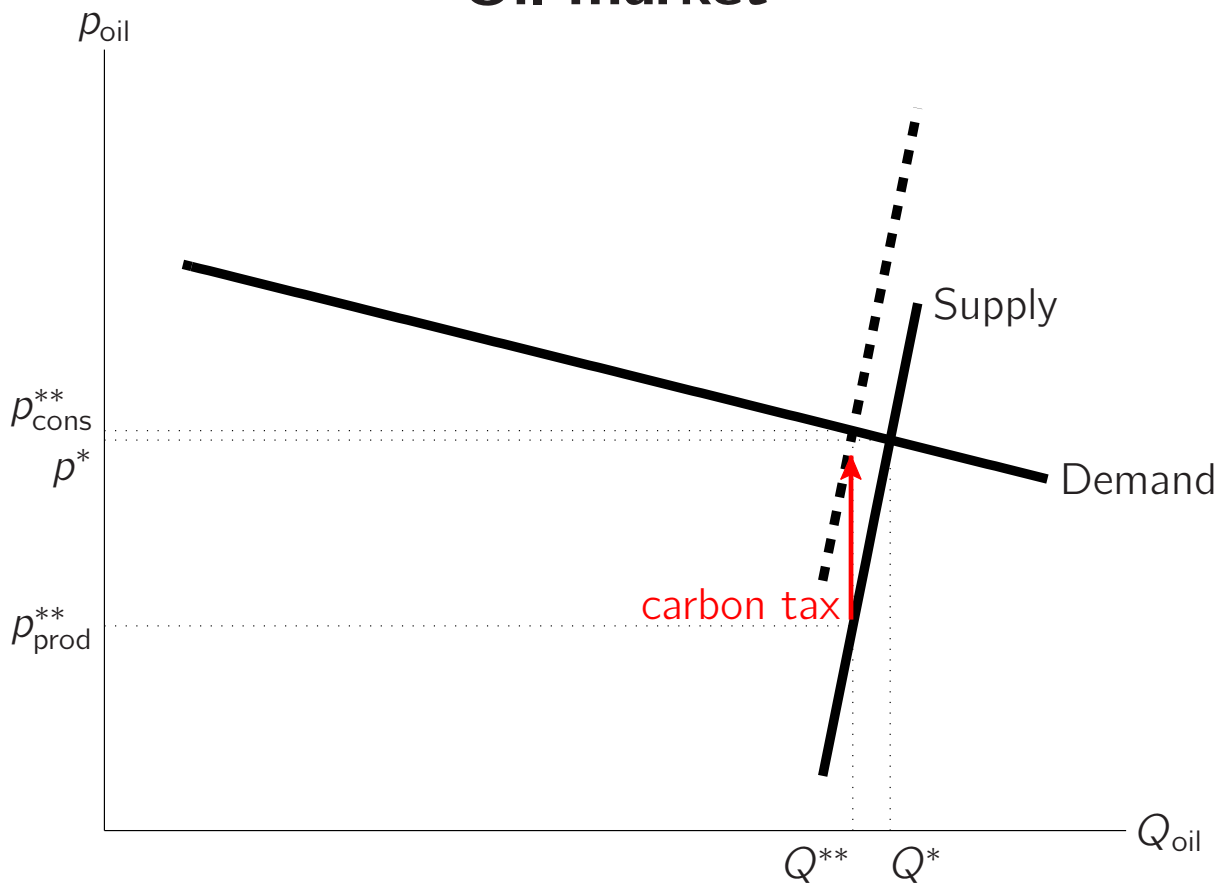

Oil market
p_{oil}
p^{**}_{cons}
p^{*}
p^{**}_{prod}
carbon tax
Supply
Demand
Q_{oil}
Q^{**}
Q^{*}


Oil market
p_{oil}
p^{**}_{cons}
p^{*}
p^{**}_{prod}
carbon tax
Supply
Demand
Q_{oil}
Q^{**}
Q^{*}

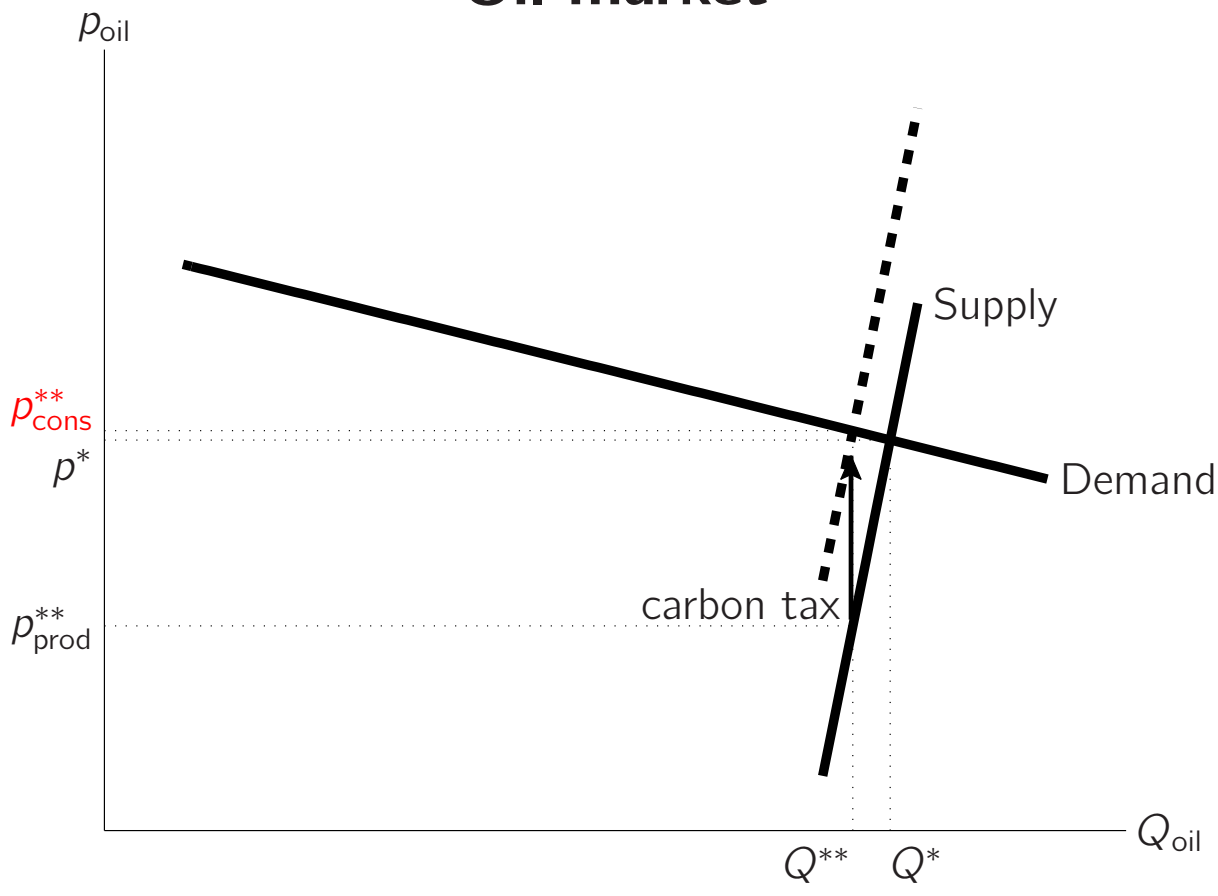

Oil market
p_{oil}
p^{**}_{cons}
p^{*}
p^{**}_{prod}
carbon tax
Supply
Demand
Q_{oil}
Q^{**}
Q^{*}


Oil market
p_{oil}
p^{**}_{cons}
p^*
p^{**}_{prod}
carbon tax
Supply
Demand
Q_{oil}
Q^{**}
Q^*

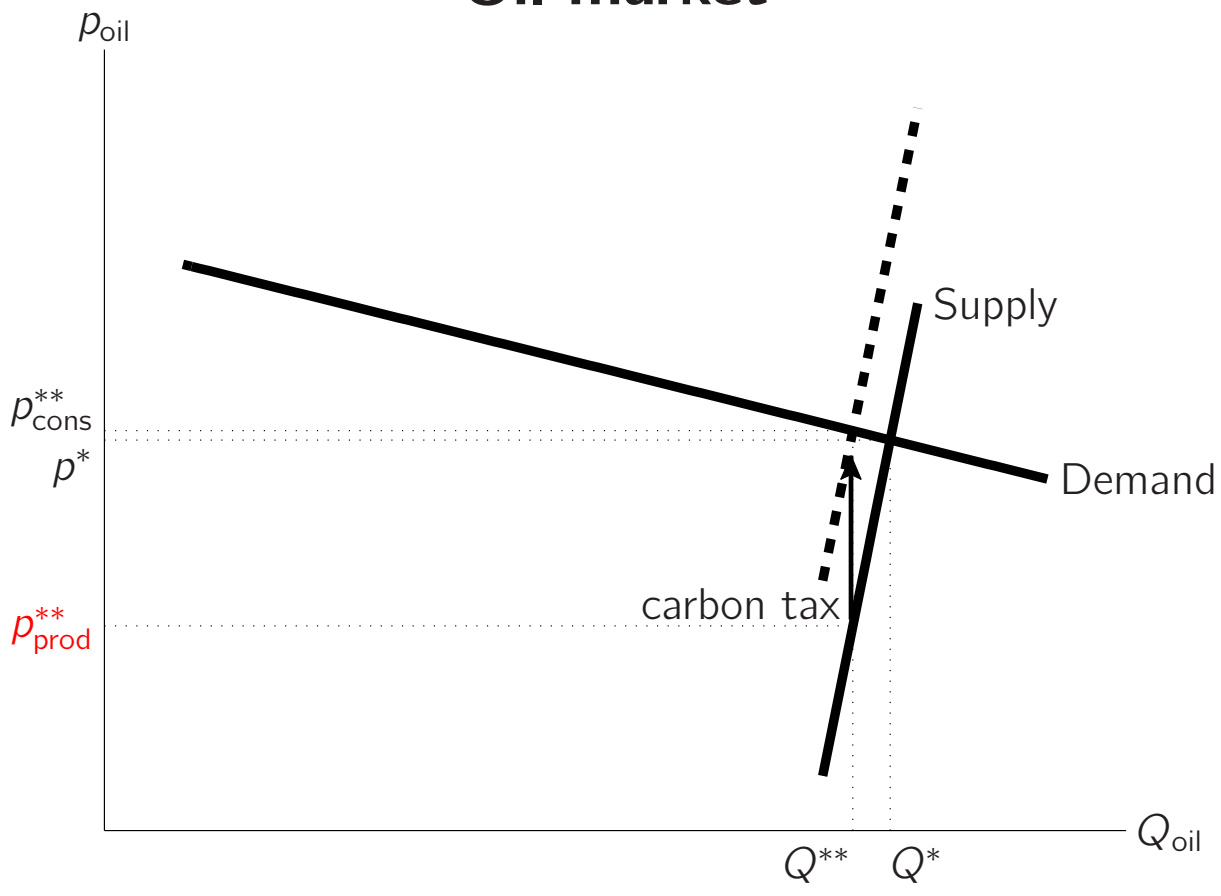
Oil market



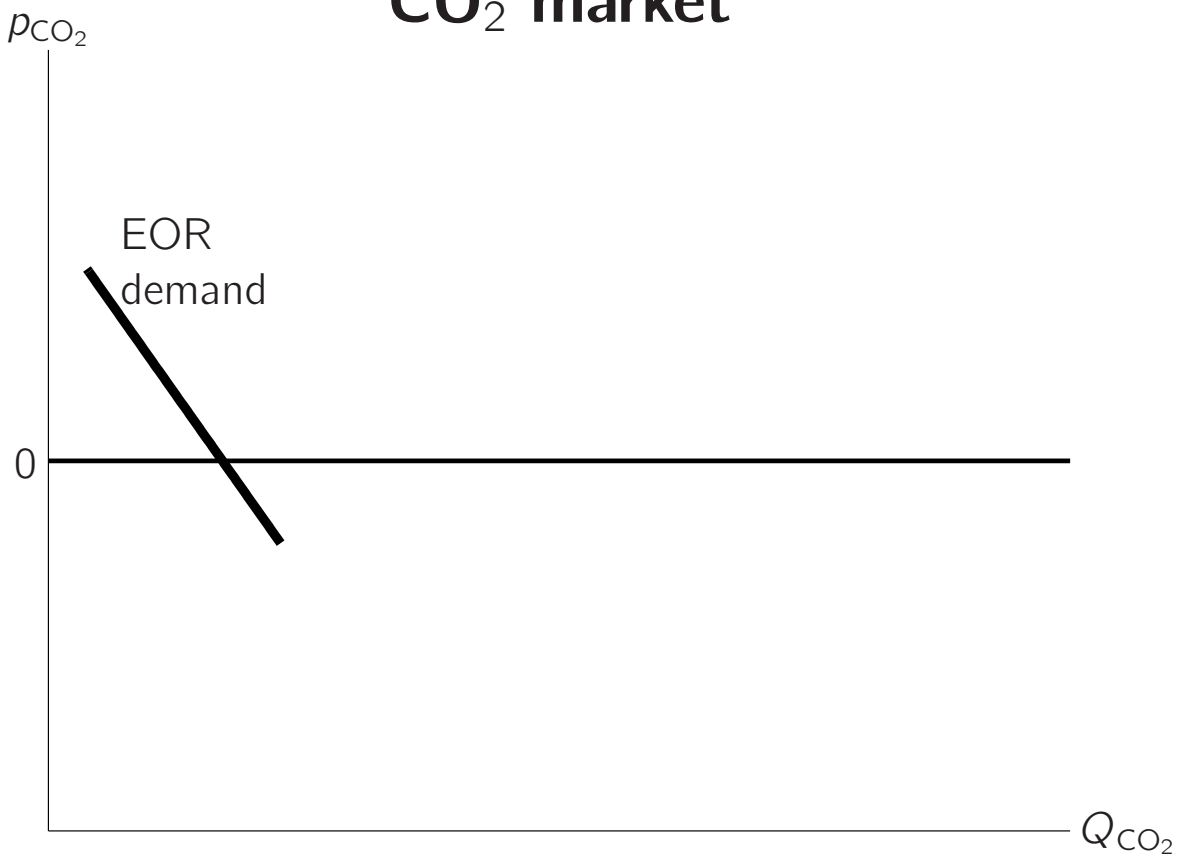
Oil market



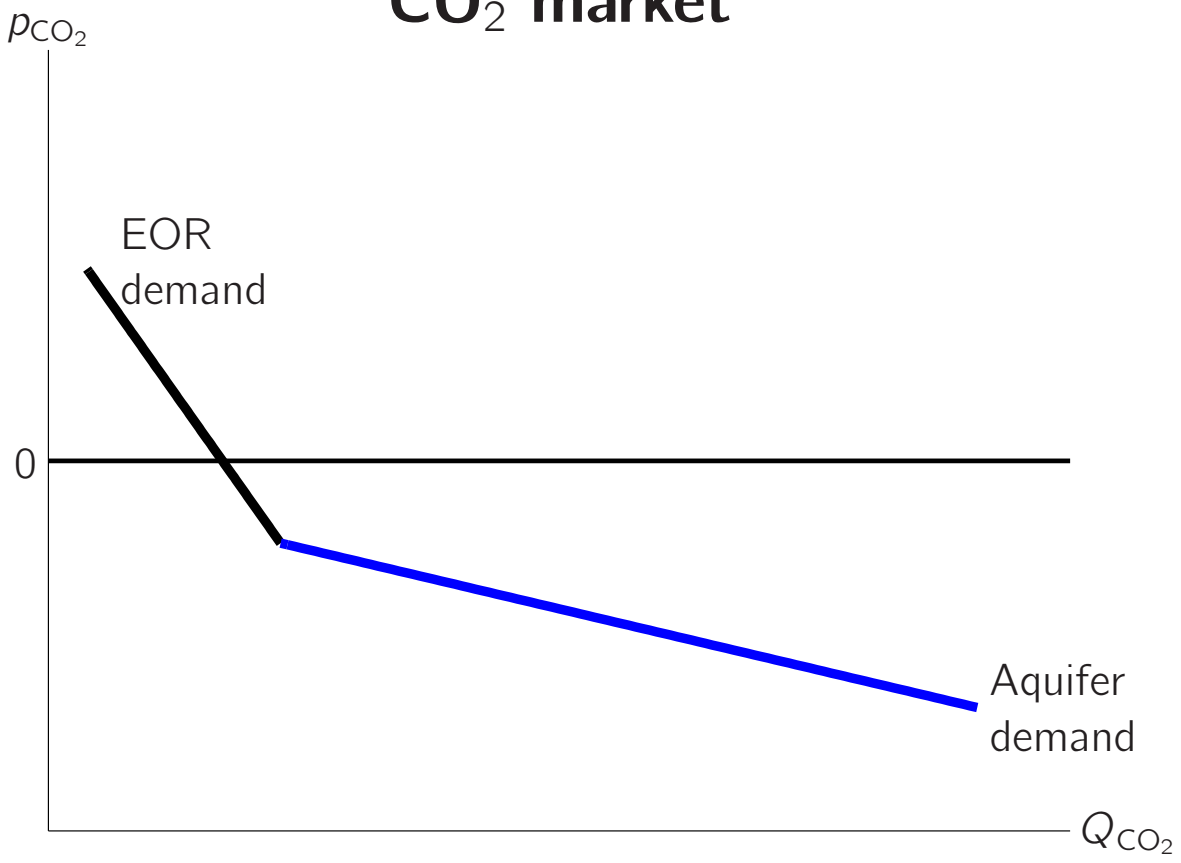
Oil market



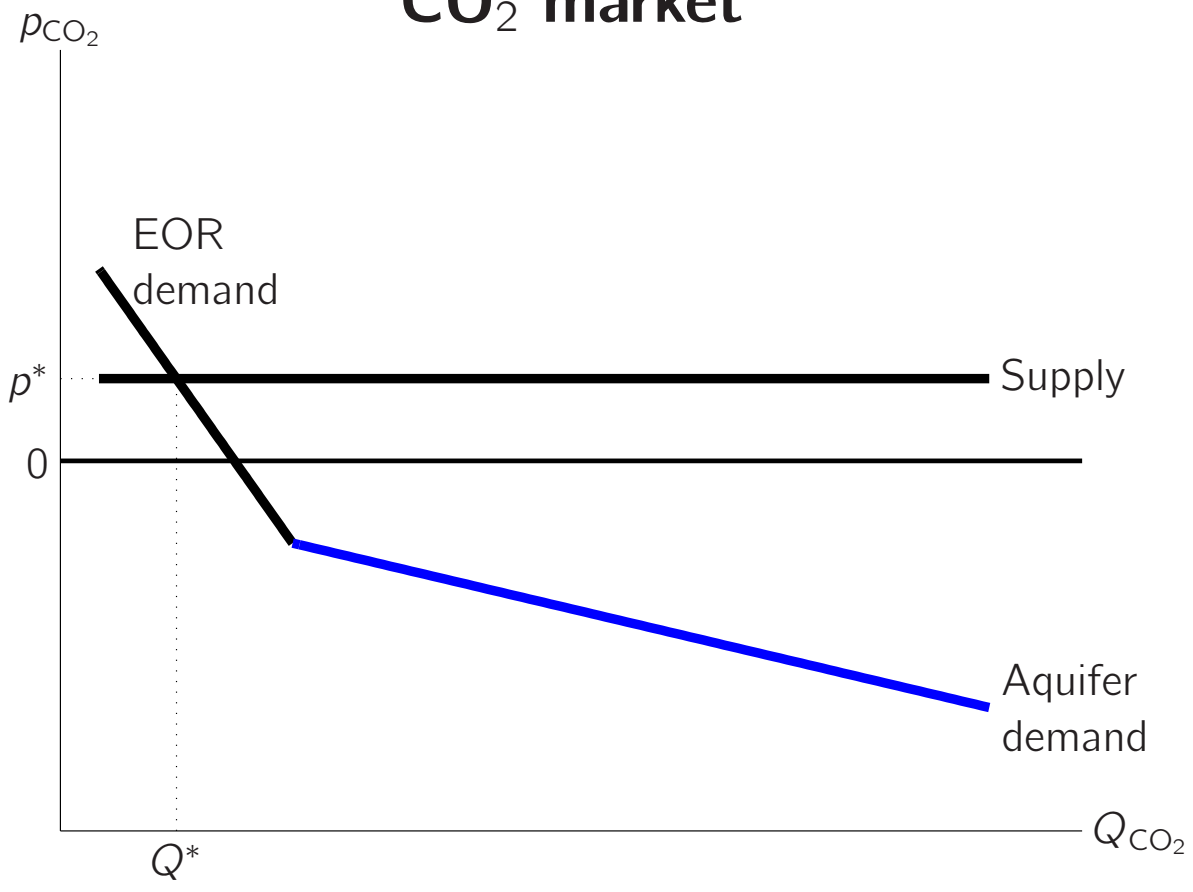
CO_2 market



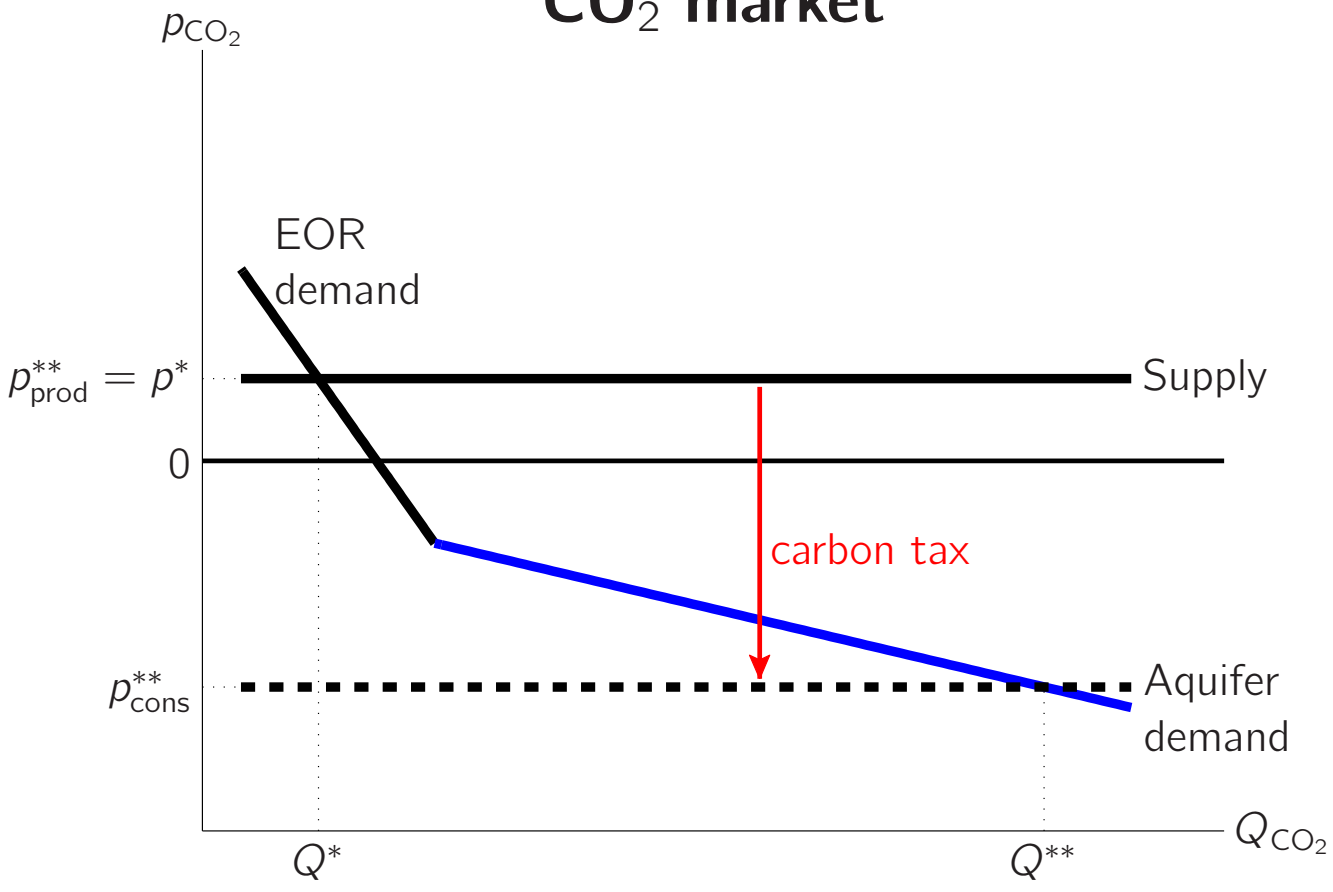
CO_2 market



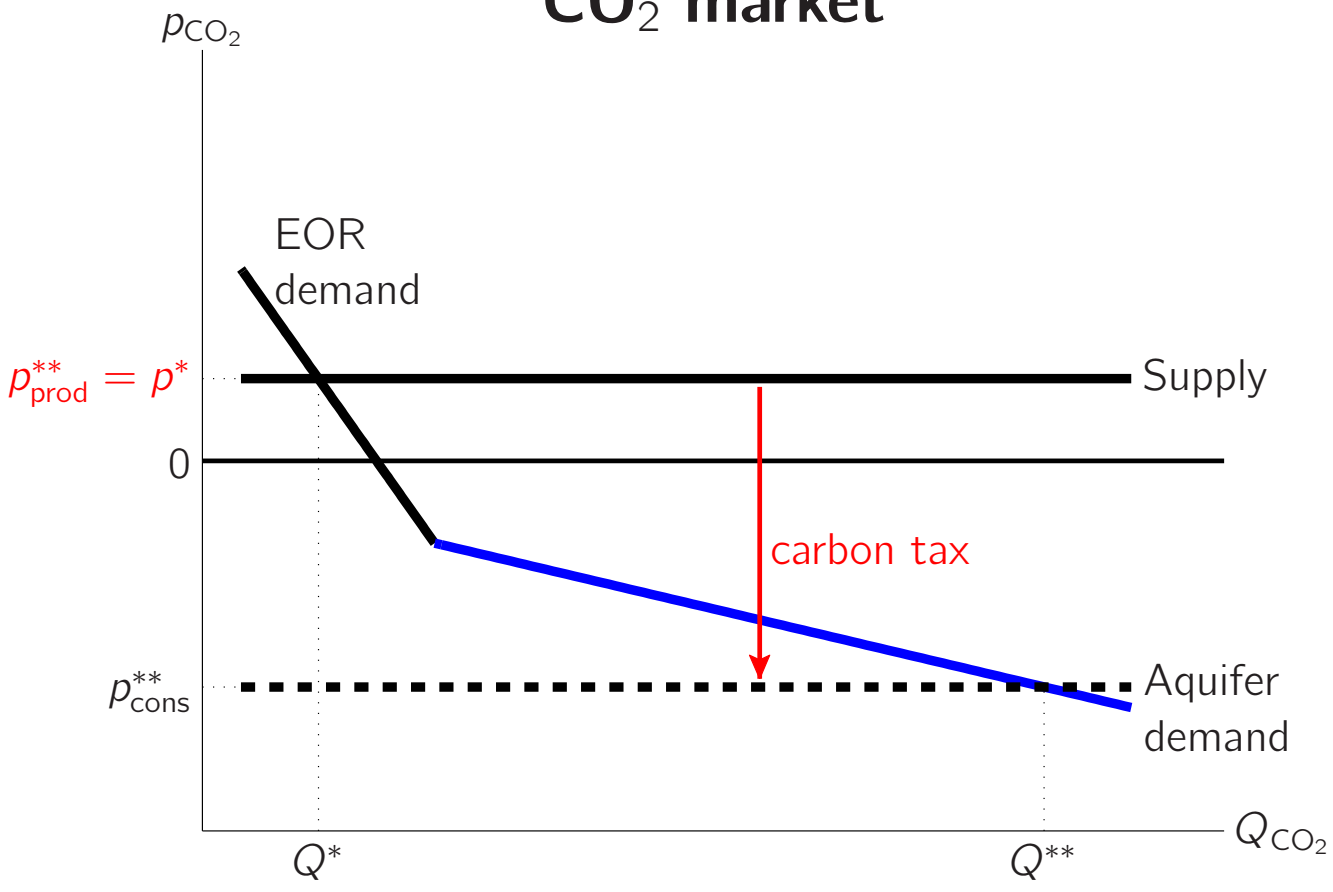
CO_2 market



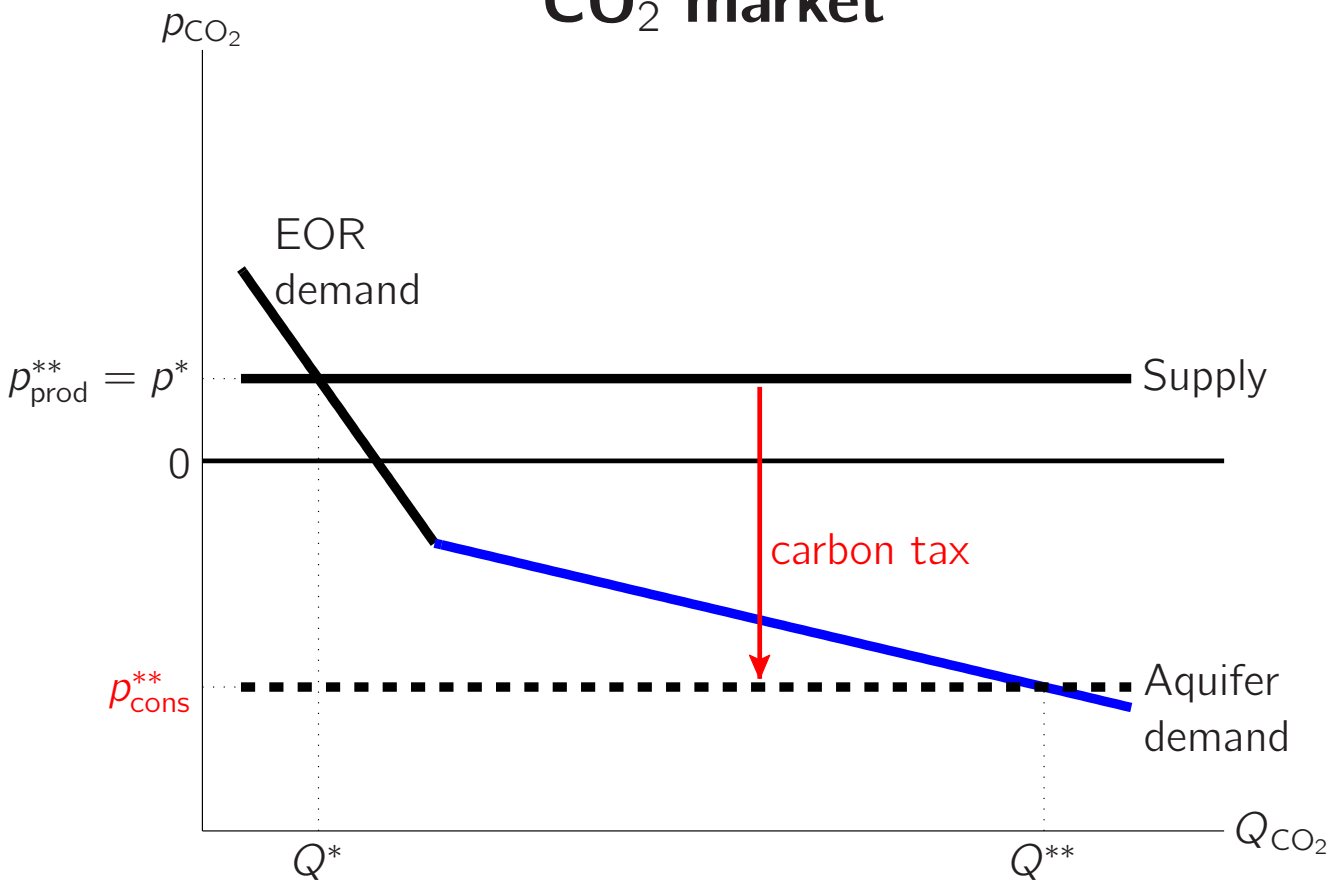
CO_2 market

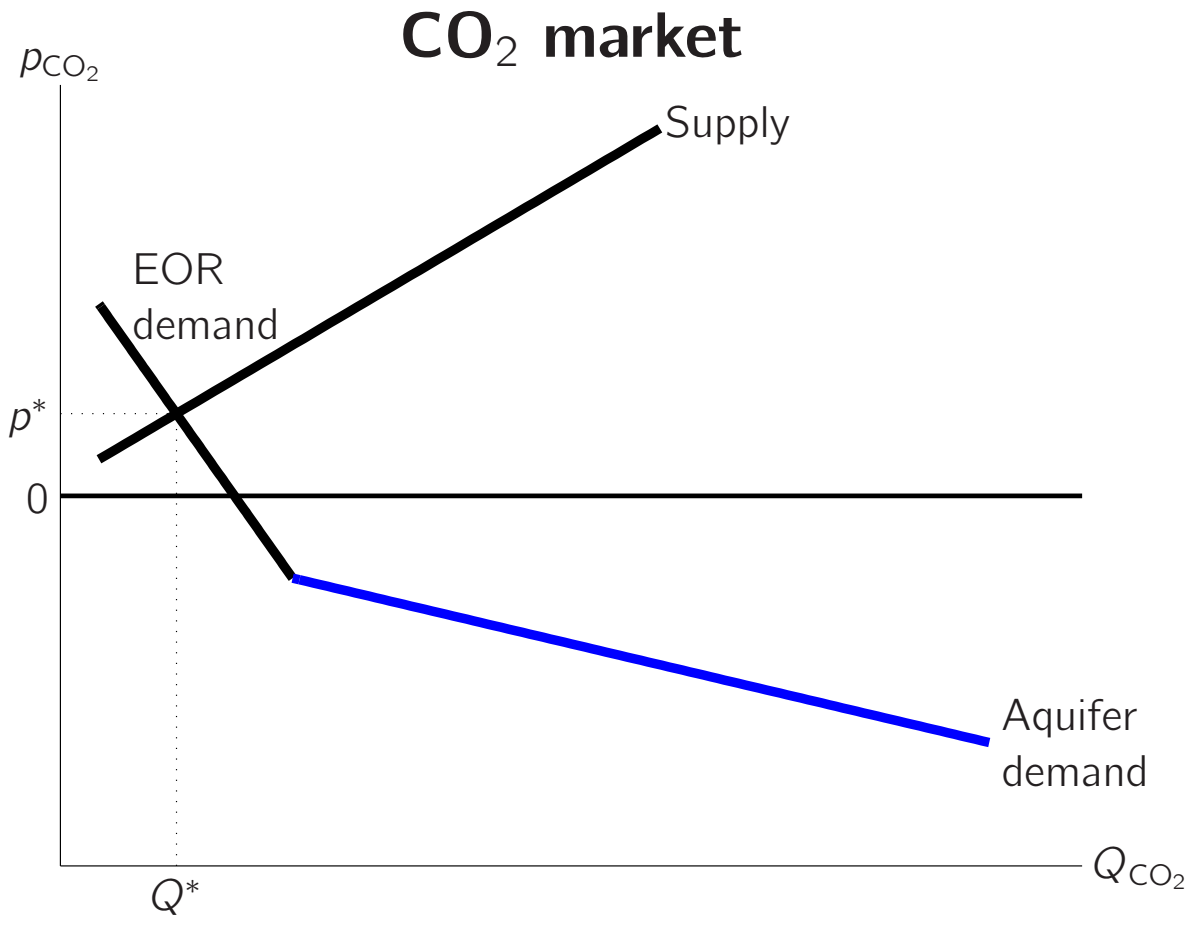

p_{CO_2}
EOR
demand
$p^{**}_{prod} = p^*$
Supply
0
carbon tax
p^{**}_{cons}
Aquifer
demand
Q_{CO_2}
Q^*
Q^{**}

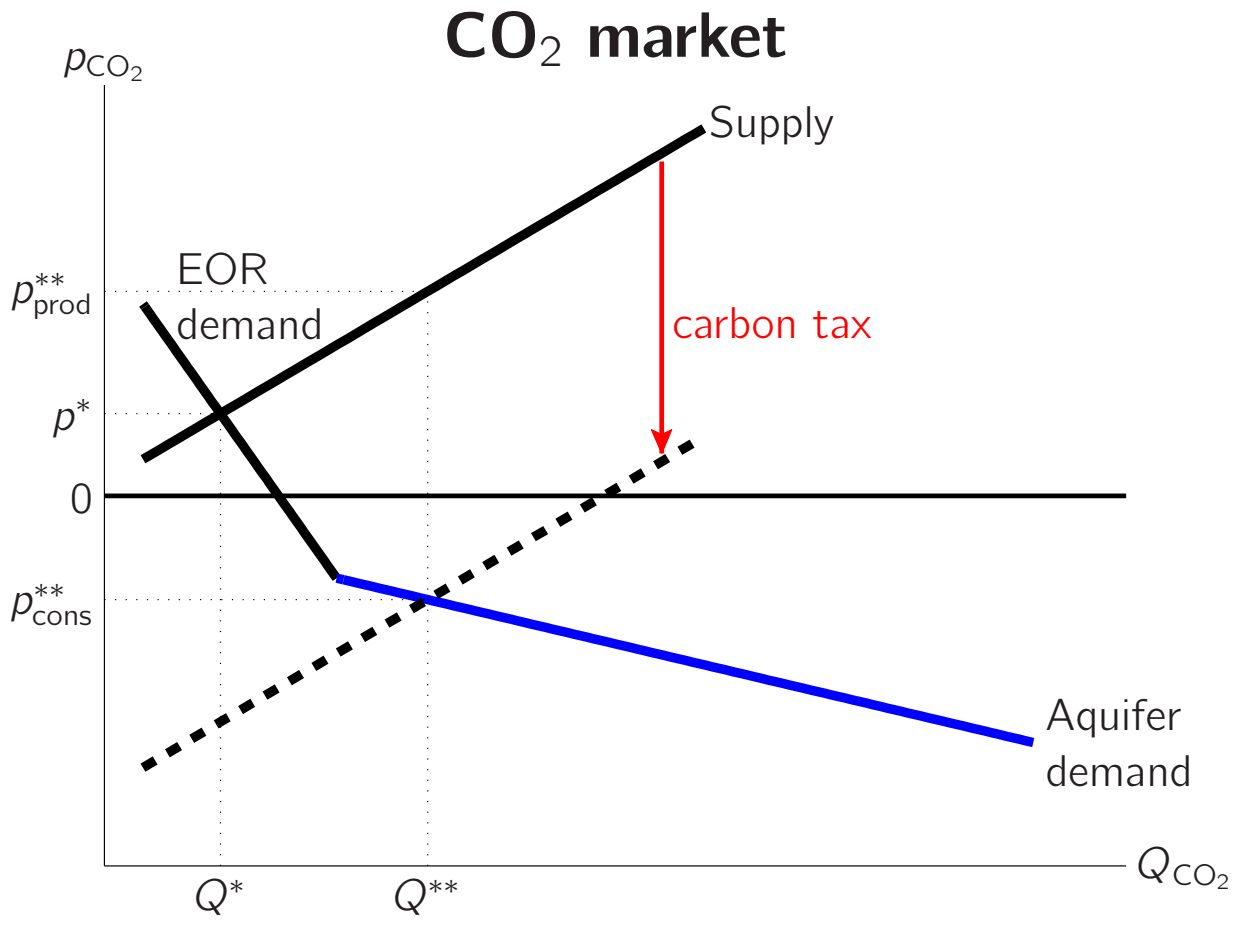
CO_2 market

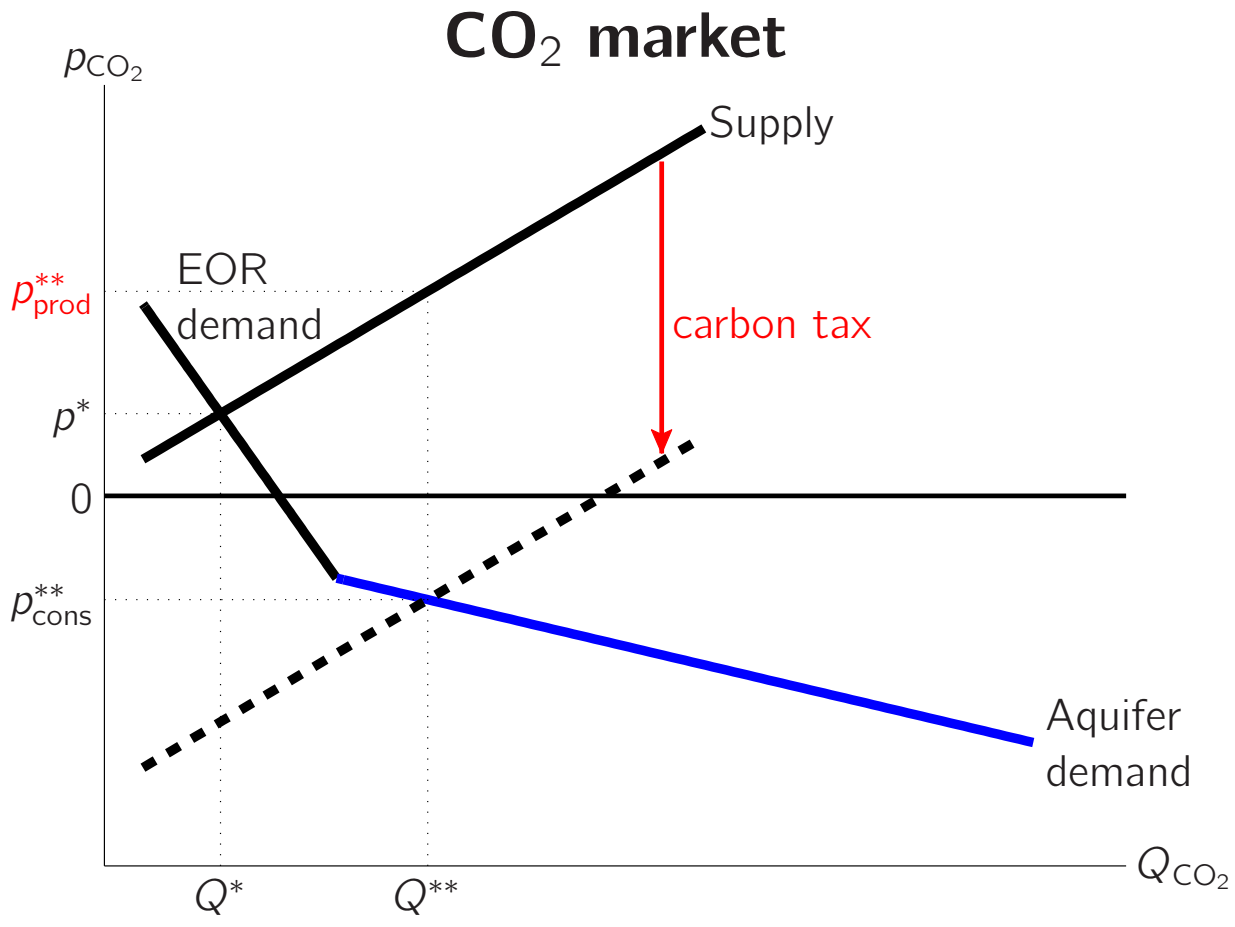

p_{CO_2}
EOR
demand
$p^{**}_{prod} = p^*$
Supply
0
carbon tax
p^{**}_{cons}
Aquifer
demand
Q_{CO_2}
Q^*
Q^{**}

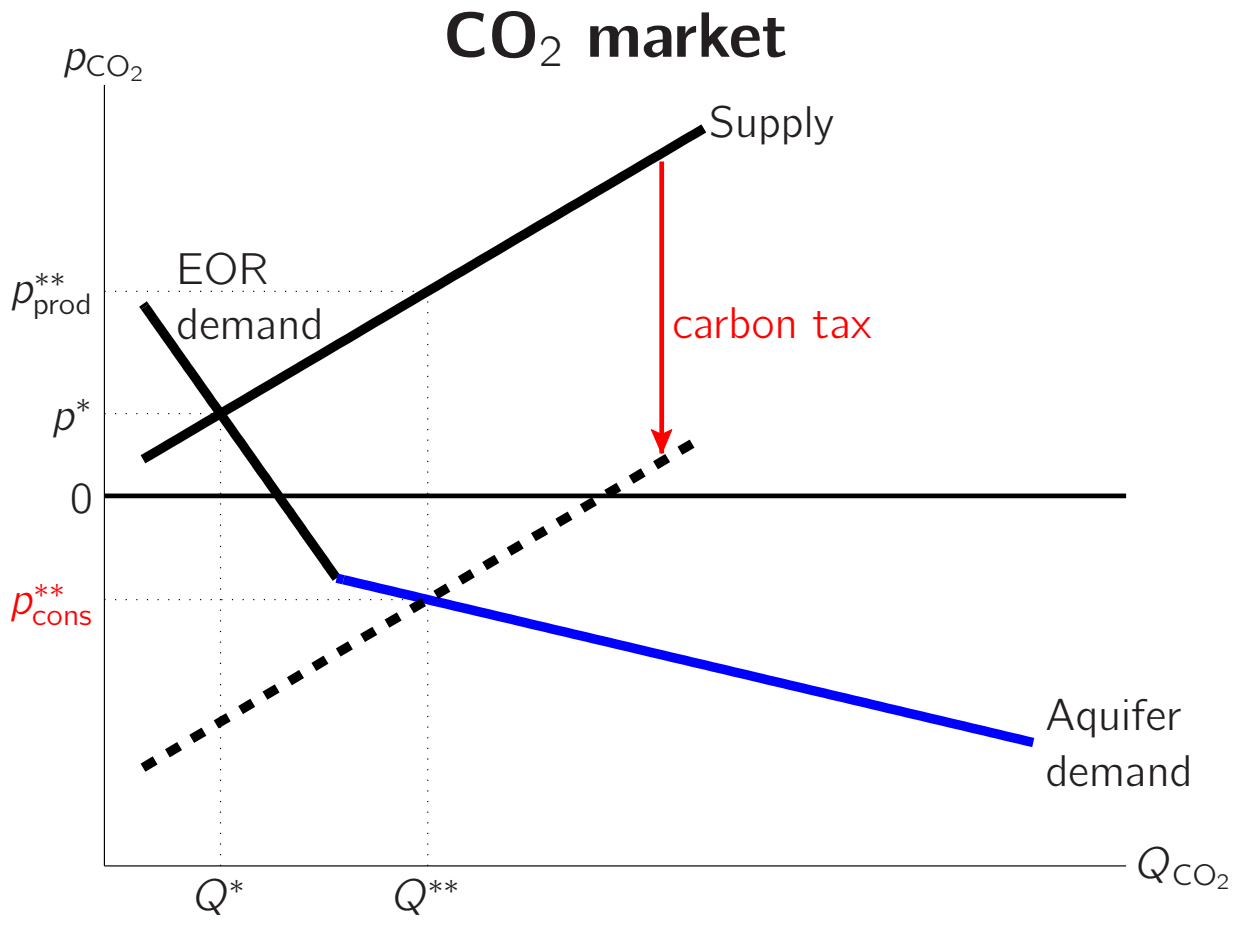
CO_2 market


p_{CO_2}
EOR
demand
$p^{**}_{prod} = p^*$
Supply
0
carbon tax
p^{**}_{cons}
Aquifer
demand
Q_{CO_2}
Q^*
Q^{**}

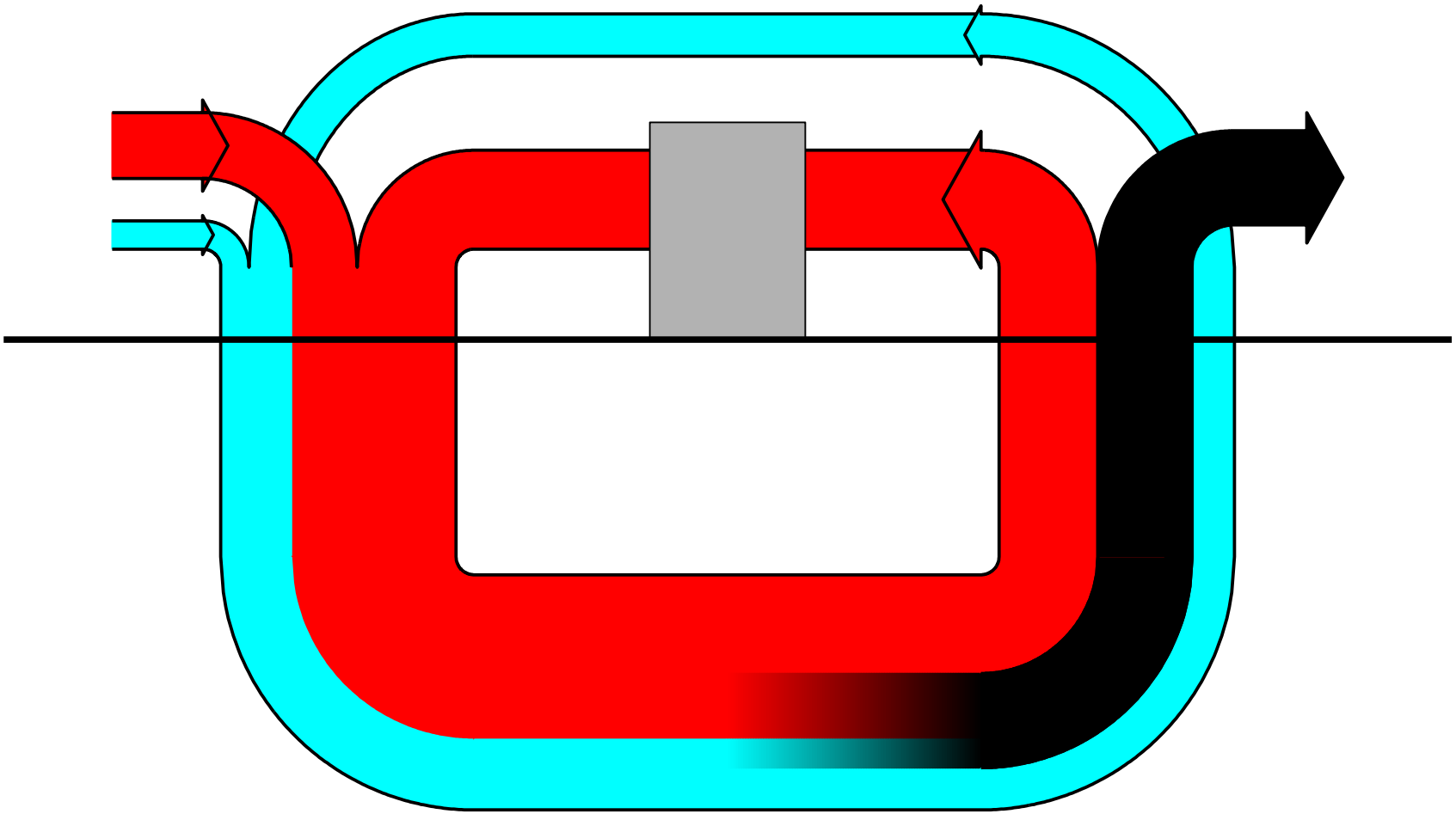

CO_2 market
p_{CO_2}
Supply
EOR
demand
p^*
0
Aquifer
demand
Q_{CO_2}
Q^*


CO_2 market
p_{CO_2}
Supply
EOR
demand
carbon tax
p^{**}_{prod}
p^*
0
p^{**}_{cons}
Aquifer
demand
Q_{CO_2}
Q^*
Q^{**}

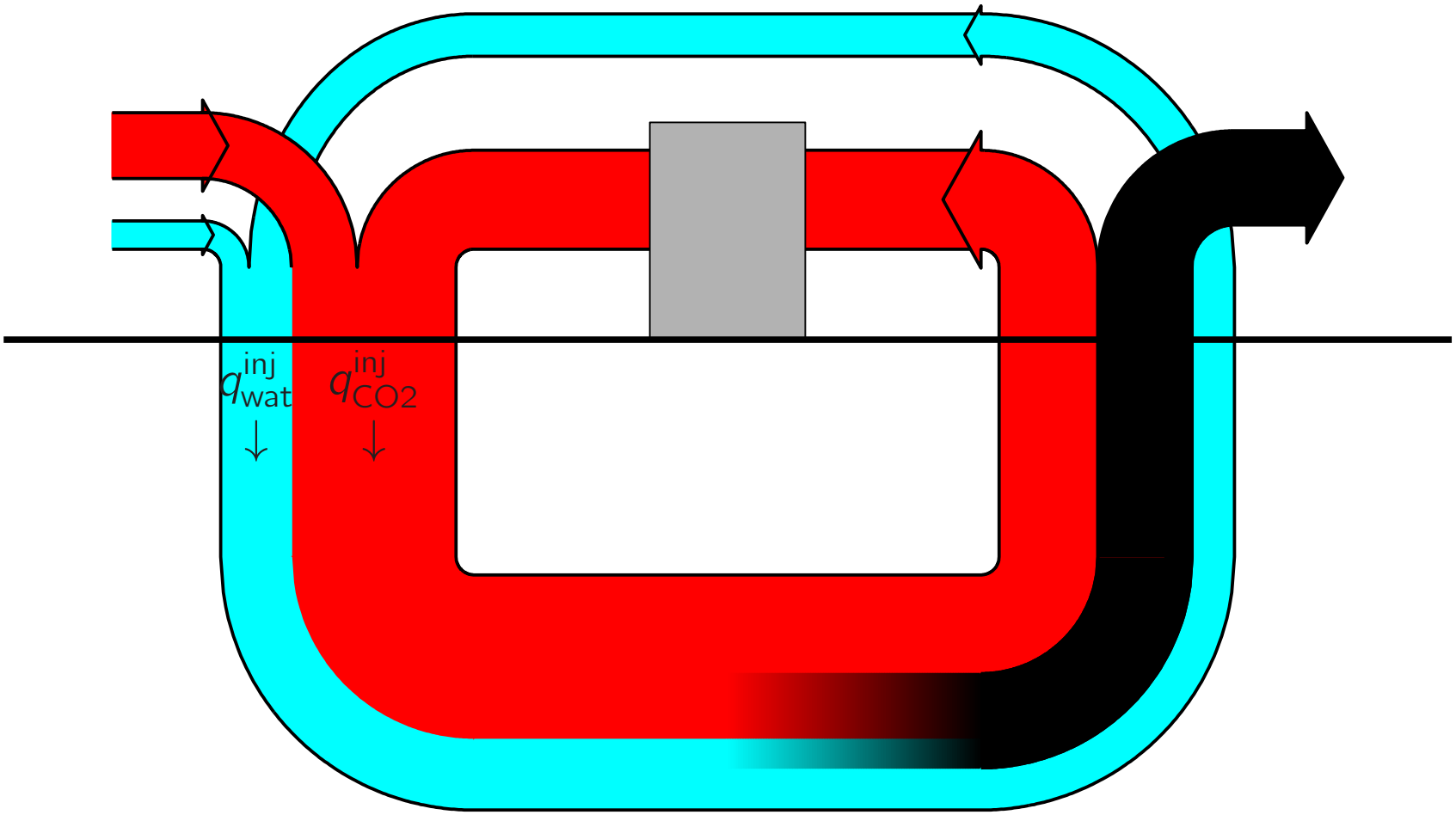

CO_2 market
p_{CO_2}
Supply
EOR
demand
carbon tax
p^{**}_{prod}
p^*
0
p^{**}_{cons}
Aquifer
demand
Q_{CO_2}
Q^*
Q^{**}


CO_2 market
p_{CO_2}
Supply
EOR
demand
carbon tax
p^{**}_{prod}
p^*
0
p^{**}_{cons}
Aquifer
demand
Q_{CO_2}
Q^*
Q^{**}

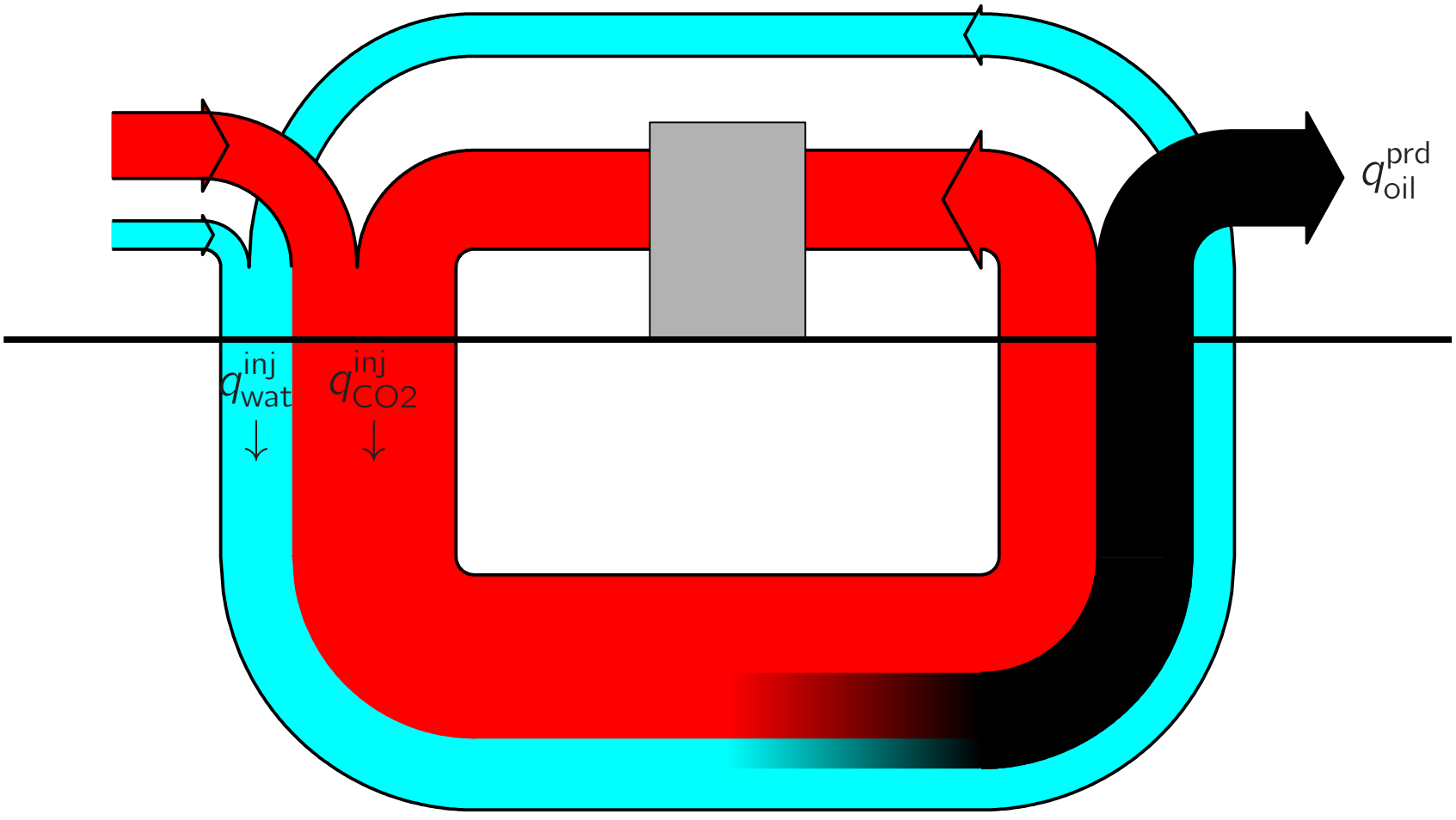
CO_2-EOR Flows



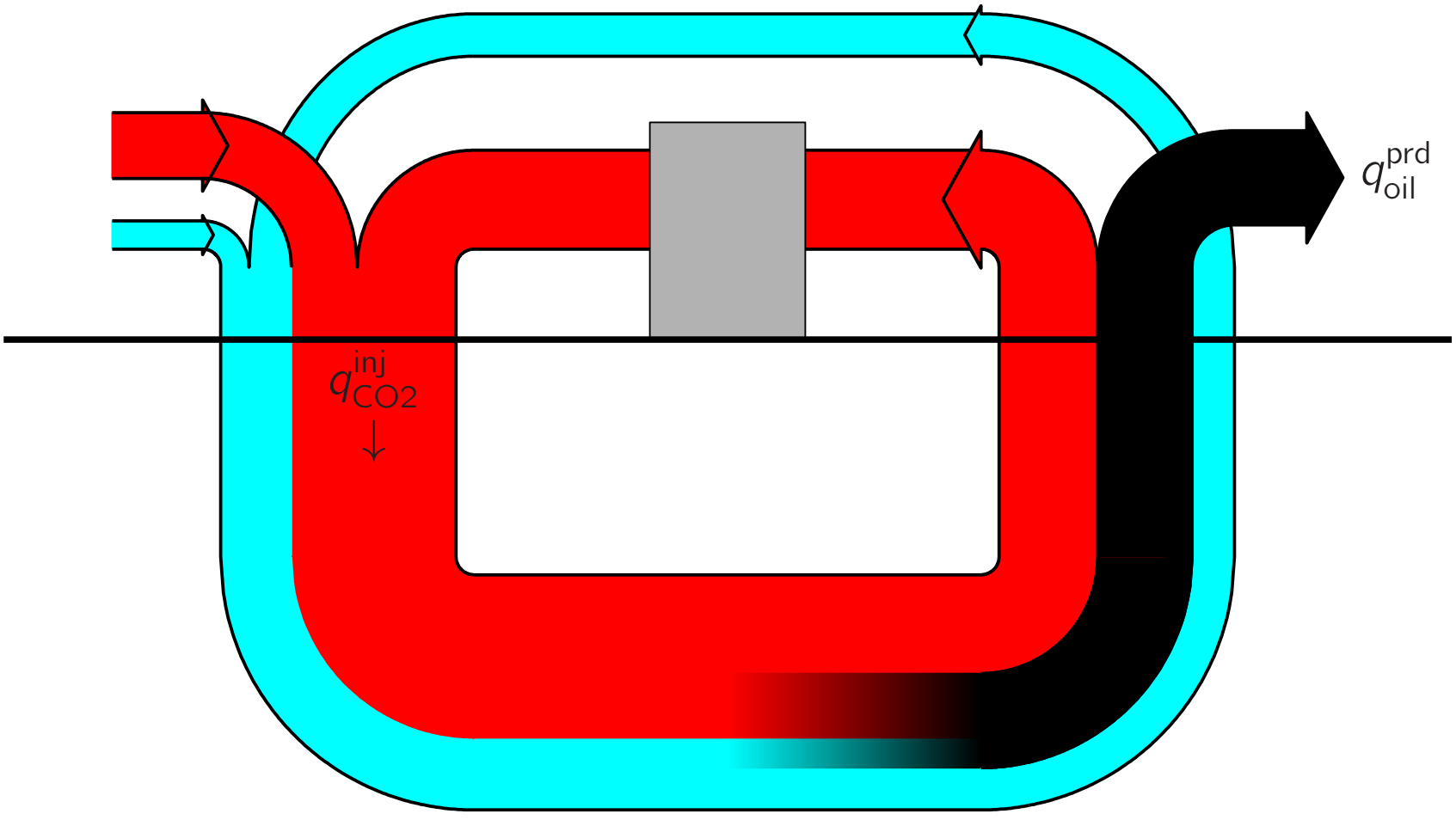
CO_2-EOR Flows



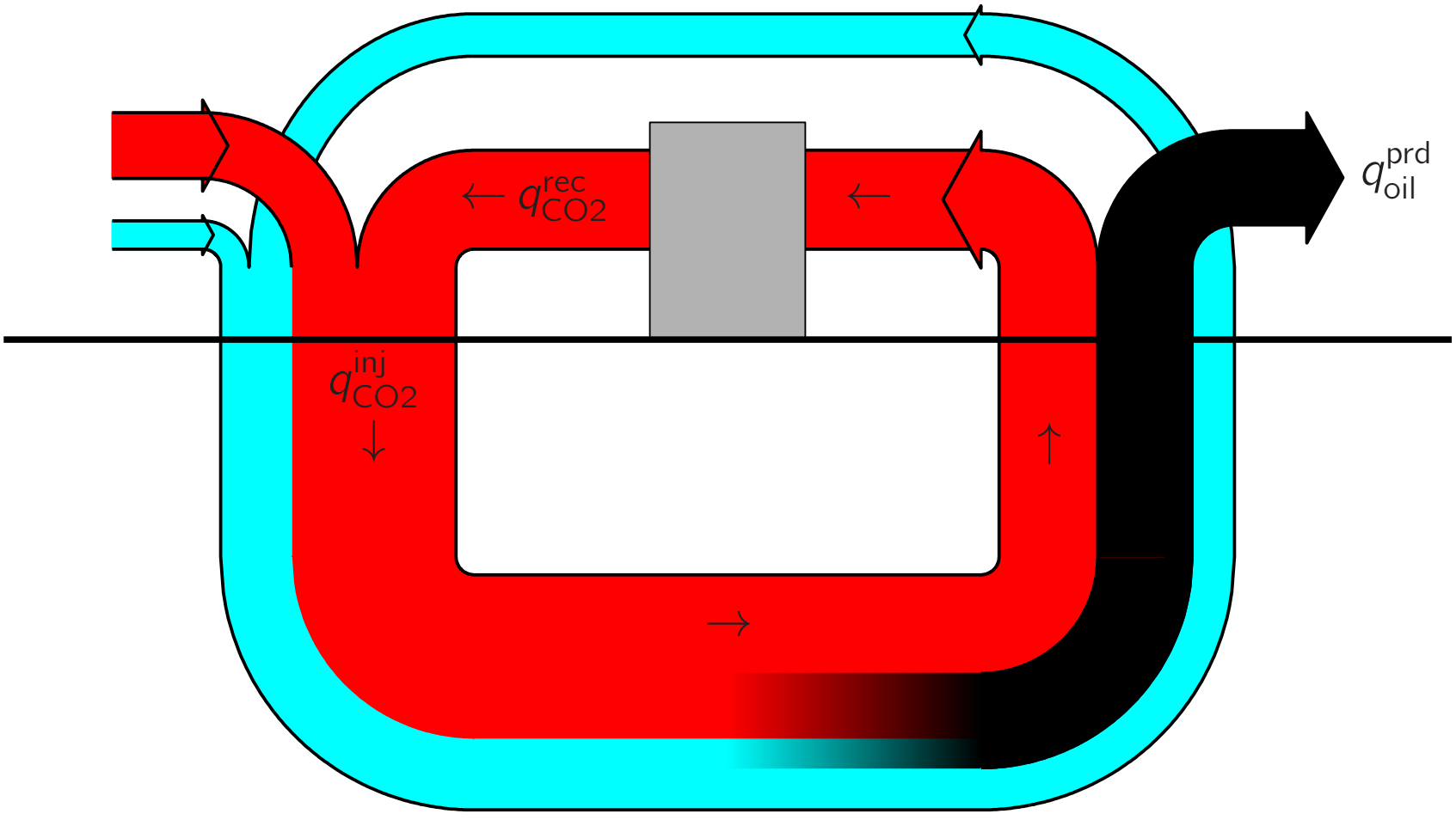
CO_2-EOR Flows



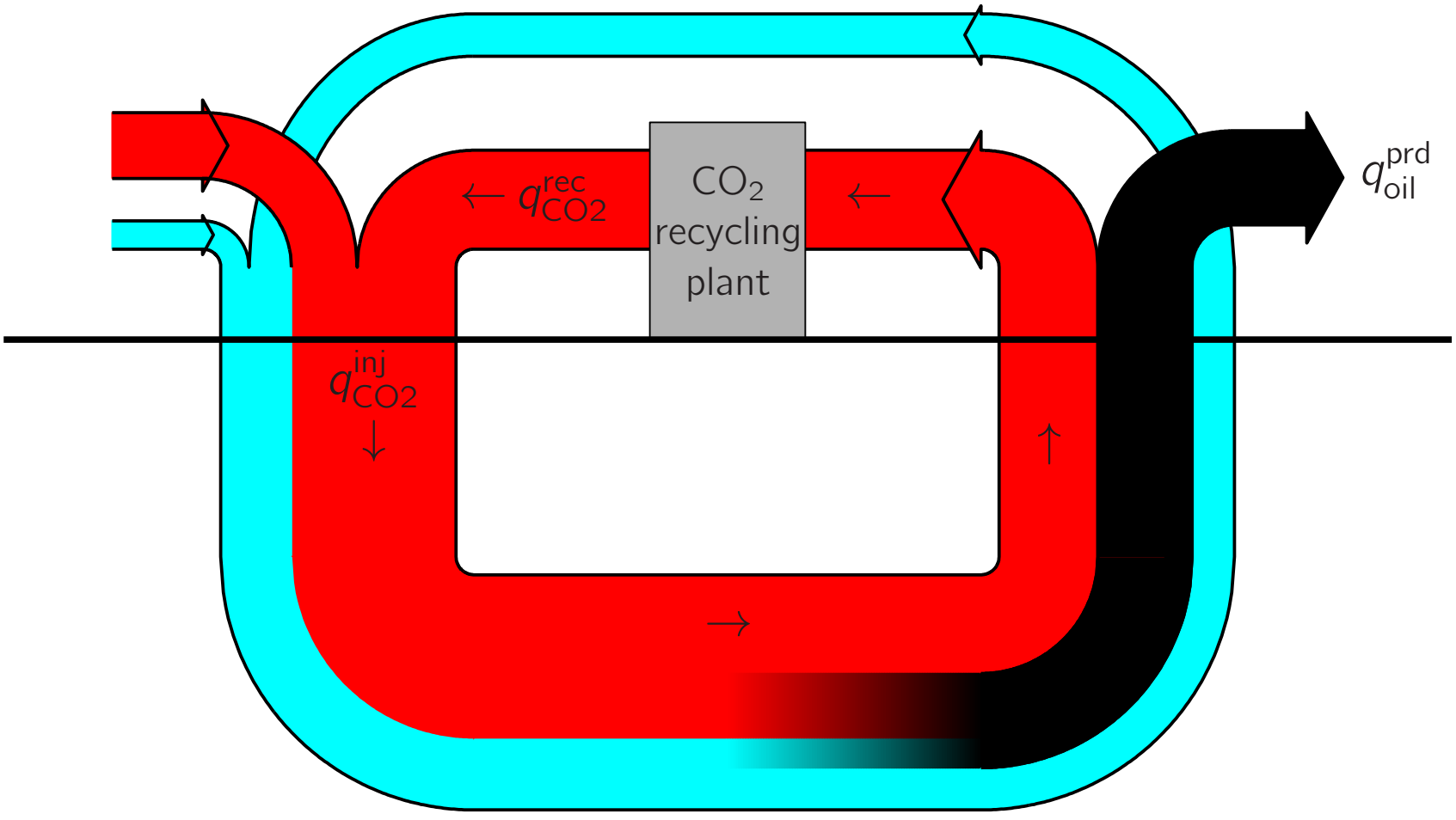
CO_2-EOR Flows



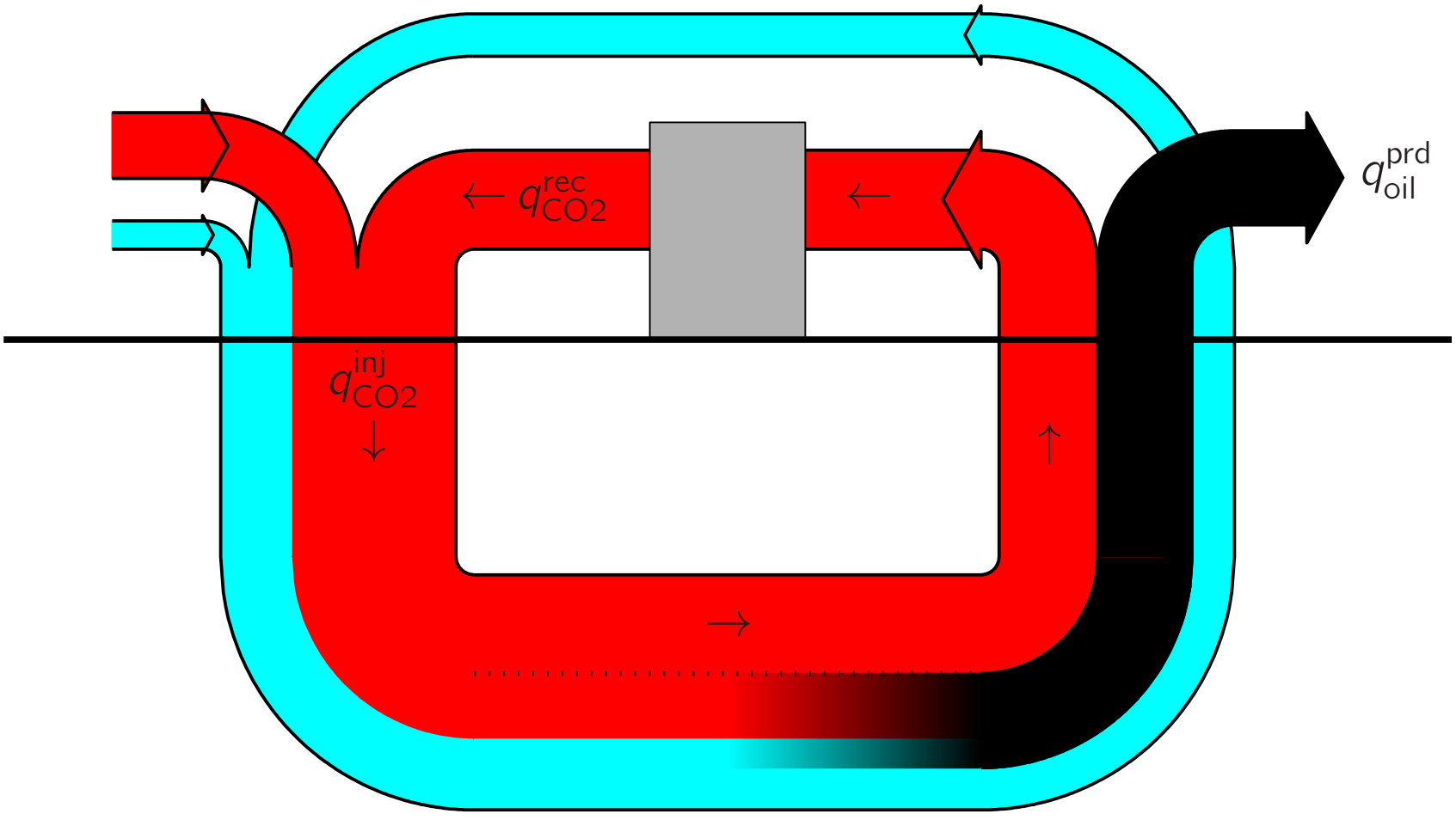
CO_2-EOR Flows



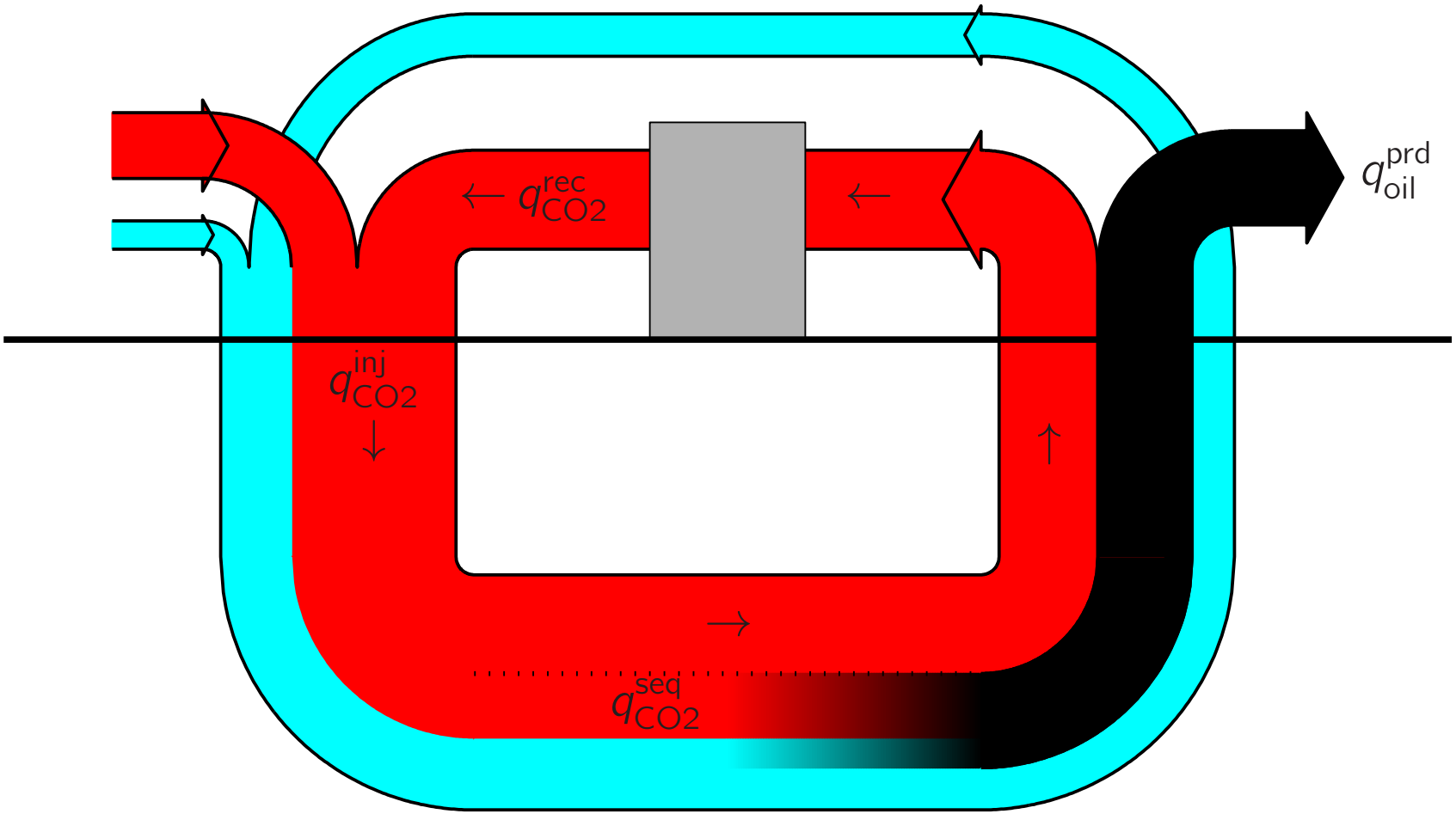
CO_2-EOR Flows



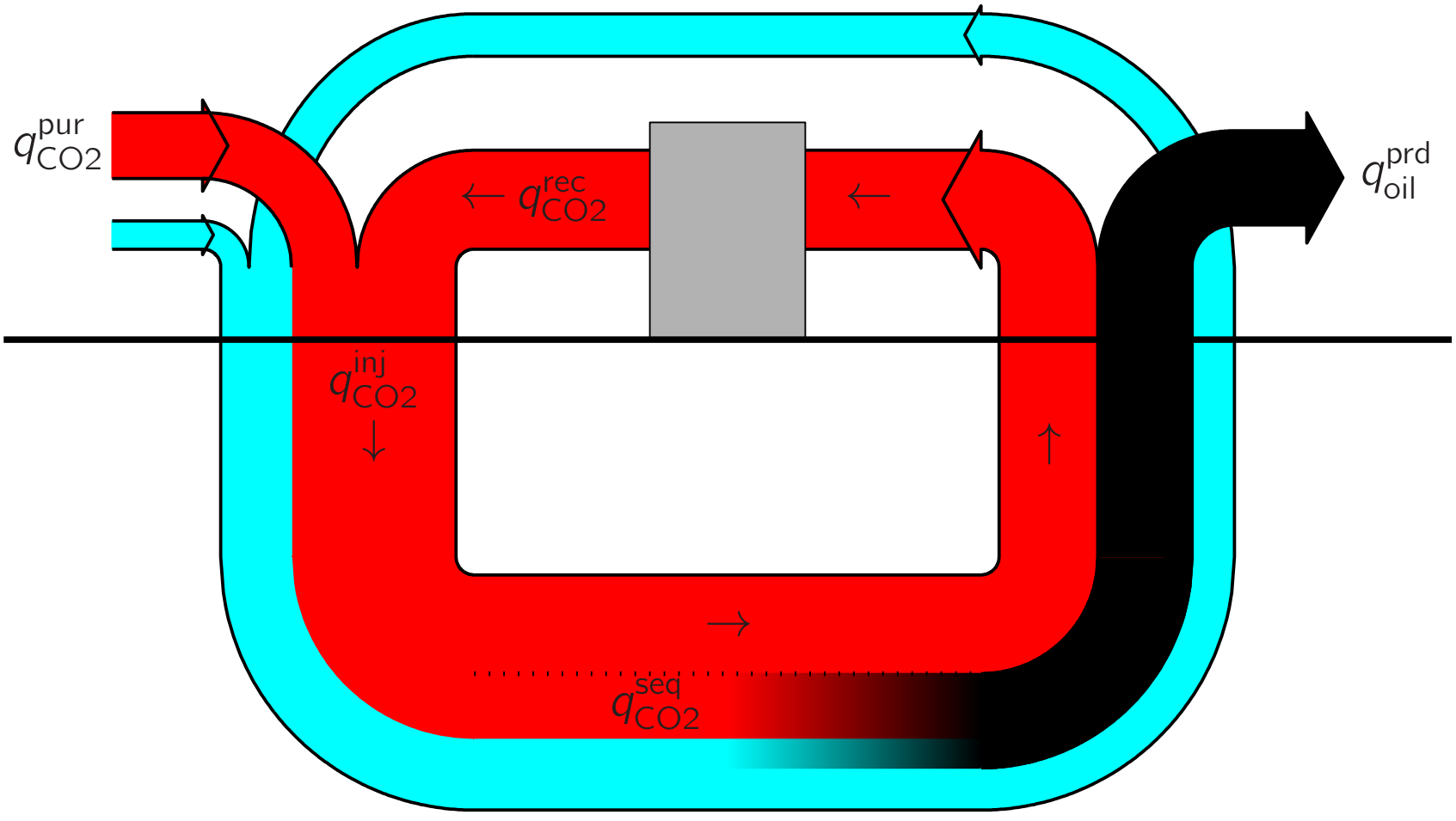
CO_2-EOR Flows



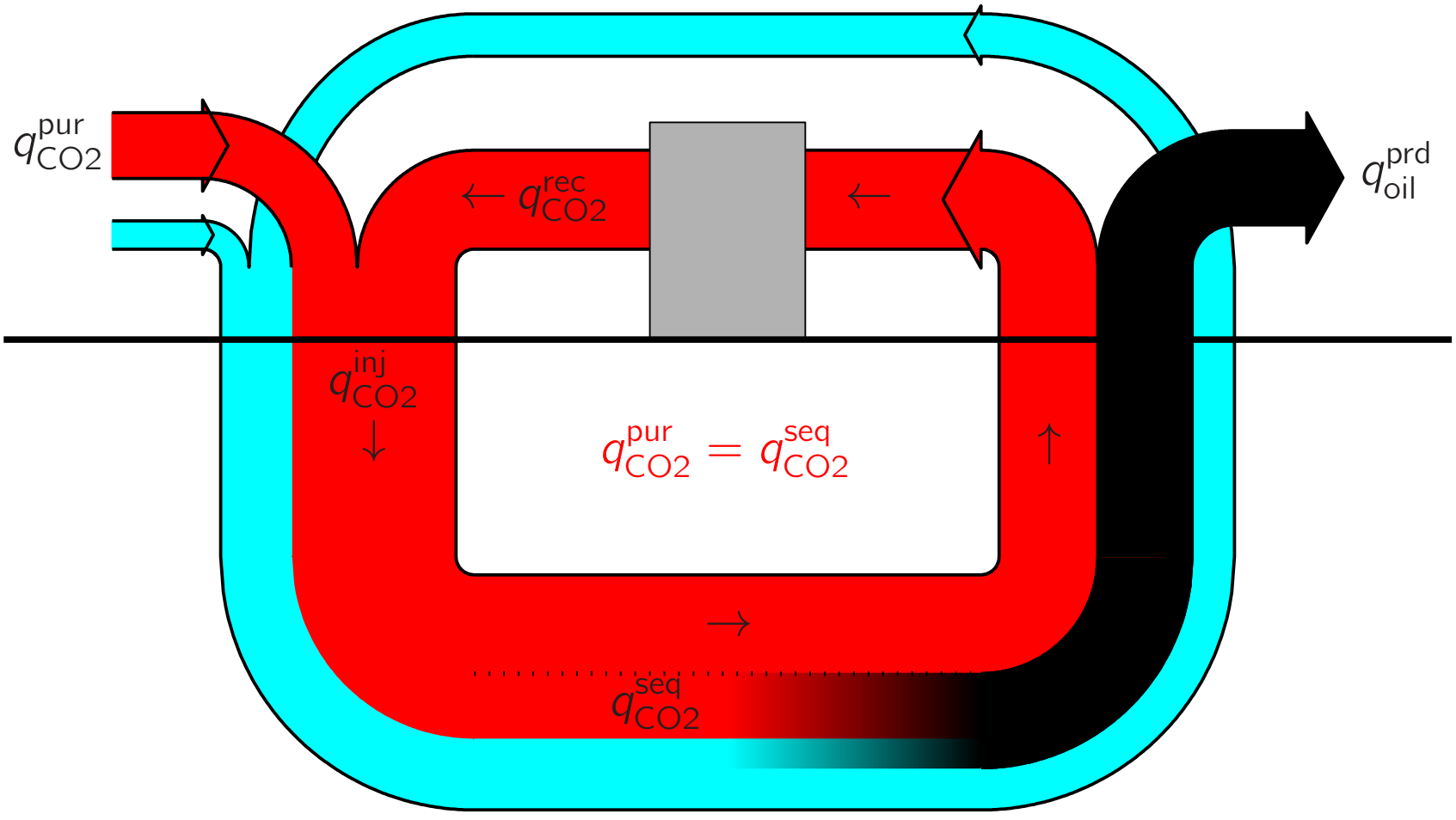
CO_2-EOR Flows



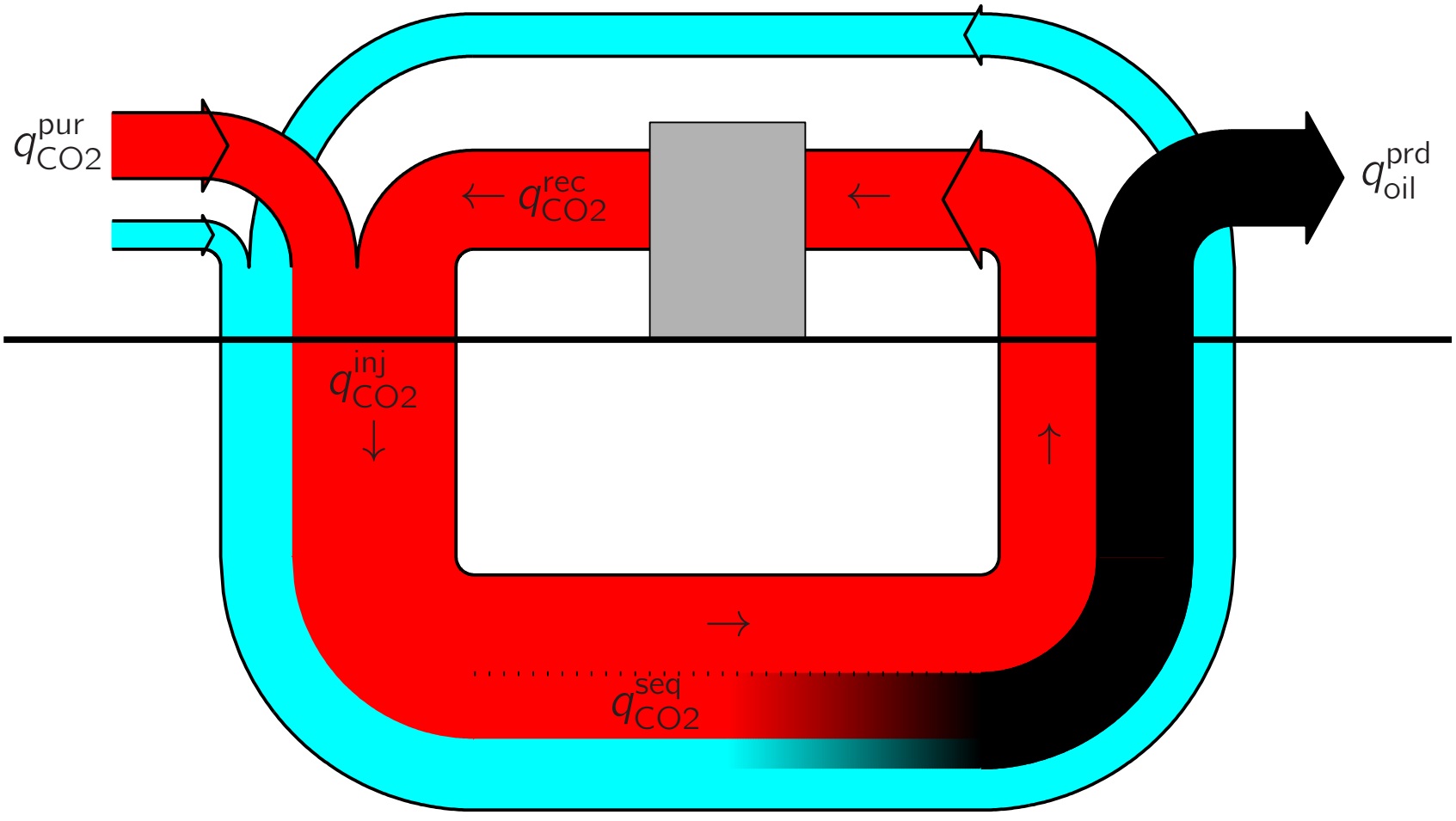
CO_2-EOR Flows



CO_2-EOR Flows



CO_2-EOR Flows



CO_2-EOR Flows

