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Market equilibria of prosumers under market power: Analysis of combined oligopoly and oligopsony in electricity markets

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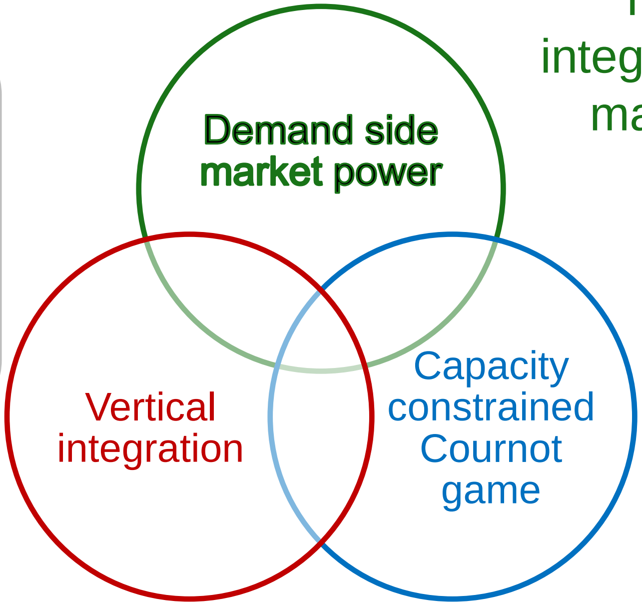
Introduction

Demand side market power:
- flexibility resources
- combined oligopoly and oligoposony markets

The ability of vertically integrated players to exercise market power is missing.

Vertical integration:
- between generator and retailer
- impacts on market price, market power, social welfare and long-term investment decisions

The effects of players production constrains is missing.



Capacity constrained Cournot game:
- characteristics and uniqueness
- effects of capacity constrains on strategies

The implications within the context of a double-sided Cournot game and a double-side player is missing.

Model setup
Assumptions

Market setting:

A wholesale electricity market, where the released production can be sold to a retail market at a fixed price, α.

- **Demand side:** linear inverse demand curve, $p = p(Q) = p_0 - \beta Q$, where $Q = q - q_r$.
  (q: electricity generation, q_r: released generation, p: electricity market price, β: slope of the demand curve, p_0: intercept of the demand curve)
- **Supply side:** linear cost generation

Player scenarios:

Players produce/consume homogenous products under capacity constraints to maximize their profits.

- **Integrated player**: owns both traditional generation plants and flexible demand
- **Separated players:** different players own traditional generation plants and flexible demand separately
- To better model the market power level of market participants, we introduce the **conjectural variation (CV)** approach.

Model setup

Integrated player

$$\max\ (c-p)q + (p-\alpha)q_r$$

$$\text{s.t.} \begin{cases} 0 \le q \le X \\ 0 \le q_r \le X_r \end{cases}$$

$$\theta = -\frac{1}{\beta}\frac{\partial p}{\partial q} = \frac{1}{\beta}\frac{\partial p}{\partial q_r}$$

Separated players

Producer: $\max\ cq - pq$

$$\text{s.t. } 0 \le q \le X$$

$$\theta = -\frac{1}{\beta}\frac{\partial p}{\partial q}$$

Consumer: $\max\ pq_r - \alpha q_r$

$$\text{s.t. } 0 \le q_r \le X_r$$

$$\theta_r = \frac{1}{\beta}\frac{\partial p}{\partial q_r}$$

q	electricity generation	α	retailed hydrogen price, $0 < \alpha$
q_r	released generation	β	slope of the demand curve, $0 < \beta$
c	electricity generation cost, $0 < c$	p_0	intercept of the demand curve, $0 < p_0$
p	electricity price	X	production capacity, $0 < X$
X_r	released production capacity, $0 < X_r$	θ, θ_r	CV parameters, $\in [0,1]$

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Optimal strategies of integrated players

Case	q	q_r	Condition (KKT of q_1 or q_r)
1	0	0	$\alpha \leq p_0 \leq c$
2	$\frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c)$	0	$\alpha \leq c$ $0 < \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c) < X \ (\Rightarrow p_0 > c)$
3	0	$\frac{1}{1+\theta}\frac{1}{\beta}(\alpha - p_0)$	$c \geq \alpha$ $0 < \frac{1}{1+\theta}\frac{1}{\beta}(\alpha - p_0) < X_r \ (\Rightarrow \alpha > p_0)$
4	X	0	$X \leq \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c) \ (\Rightarrow p_0 > c)$ $X \leq \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - \alpha) \ (\Rightarrow p_0 > \alpha)$
5	0	X_r	$X_r \leq \frac{1}{1+\theta}\frac{1}{\beta}(c - p_0) \ (\Rightarrow c \geq p_0)$ $X_r \leq \frac{1}{1+\theta}\frac{1}{\beta}(\alpha - p_0) \ (\Rightarrow \alpha \geq p_0)$
6	q (free)	$q - \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c)$	$c = \alpha$ $0 < q < X$ $\frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c) < q < X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c)$
7	X	$X - \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - \alpha)$	$\alpha \geq c$ $\frac{1}{1+\theta}\frac{1}{\beta}(p_0 - \alpha) < X < X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - \alpha)$
8	$X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c)$	X_r	$\alpha \geq c$ $0 < X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c) < X$
9	X	X_r	$\alpha \geq c$ $X \leq X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - c)$ $X \geq X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0 - \alpha)$

Optimal strategies of separated players

Case	q	q_r	Condition (KKT of q, or q_r)
1	0	0	$\alpha \le p_0 \le c$
2	$\frac{1}{1+\theta}\frac{1}{\beta}(p_0-c)$	0	$c \ge \alpha - \theta(p_0-\alpha)$ $0 < \frac{1}{1+\theta}\frac{1}{\beta}(p_0-c) < X \quad (\Rightarrow c < p_0 \overset{(q_r)}{\Rightarrow} \alpha < p_0)$
3	0	$\frac{1}{1+\theta_r}\frac{1}{\beta}(\alpha-p_0)$	$c \ge \alpha + \theta_r(p_0-c)$ $0 < \frac{1}{1+\theta_r}\frac{1}{\beta}(\alpha-p_0) < X_r \ (\Rightarrow \alpha > p_0 \Rightarrow c > p_0)$
4	X	0	$X \le \frac{1}{1+\theta}\frac{1}{\beta}(p_0-c) \quad (\Rightarrow c < p_0)$ $X \le \frac{1}{\beta}(p_0-\alpha) \quad (\Rightarrow \alpha < p_0)$
5	0	X_r	$X_r \le \frac{1}{\beta}(c-p_0) \ (\Rightarrow c \ge p_0)$ $X_r \le \frac{1}{1+\theta_r}\frac{1}{\beta}(\alpha-p_0) \ (\Rightarrow \alpha \ge p_0)$
6	$\frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c+\theta_r(p_0-c)\big)$	$\frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c-\theta(p_0-\alpha)\big)$	Market power: $\neg(\theta=\theta_r=0)$: $0 < \frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c+\theta_r(p_0-c)\big) < X \ (\Rightarrow \alpha > c-\theta_r(p_0-c))$ $0 < \frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c-\theta(p_0-\alpha)\big) < X_r \ (\Rightarrow c < \alpha-\theta(p_0-\alpha))$
6	q (free)	$q-\frac{1}{\beta}(p_0-\alpha)$	Perfect competition: $\theta=\theta_r=0$: $c=\alpha$ $0<q<X$ $\frac{1}{\beta}(p_0-\alpha) < q < X_r + \frac{1}{\beta}(p_0-\alpha)$
7	X	$\frac{1}{1+\theta_r}X - \frac{1}{1+\theta_r}\frac{1}{\beta}(p_0-\alpha)$	$\begin{cases} X \le \frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c+\theta_r(p_0-c)\big) & \text{if } \neg(\theta=\theta_r=0),\ (\Rightarrow \alpha > c-\theta_r(p_0-c)) \\ \alpha \ge c & \text{if } \quad \theta=\theta_r=0 \end{cases}$ $0 < \frac{1}{1+\theta_r}X - \frac{1}{1+\theta_r}\frac{1}{\beta}(p_0-\alpha) < X_r \ (\overset{(q)}{\Rightarrow} c < \alpha-\theta(p_0-\alpha))$
8	$\frac{1}{1+\theta}X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0-c)$	X_r	$\begin{cases} X_r \le \frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c-\theta(p_0-\alpha)\big) & \text{if } \neg(\theta=\theta_r=0),\ (\Rightarrow c < \alpha-\theta(p_0-\alpha)) \\ \alpha \ge c & \text{if } \quad \theta=\theta_r=0 \end{cases}$ $0 < \frac{1}{1+\theta}X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0-c) < X$
9	X	X_r	$X \le \frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c+\theta_r(p_0-c)\big)$ if $\neg(\theta=\theta_r=0)$ $(\Rightarrow \alpha > c-\theta_r(p_0-c))$ $X_r \le \frac{1}{\theta\theta_r+\theta+\theta_r}\frac{1}{\beta}\big(\alpha-c-\theta(p_0-\alpha)\big)$ if $\neg(\theta=\theta_r=0)$ $(\Rightarrow c < \alpha-\theta(p_0-\alpha))$ $X \le \frac{1}{1+\theta}X_r + \frac{1}{1+\theta}\frac{1}{\beta}(p_0-c)$ $X_r \le \frac{1}{1+\theta_r}X - \frac{1}{1+\theta_r}\frac{1}{\beta}(p_0-\alpha) \ (\Rightarrow X > \frac{1}{\beta}(p_0-\alpha))$

Optimal strategies of integrated and separated players

Comparing the strategies of integrated player and separated players, we found:

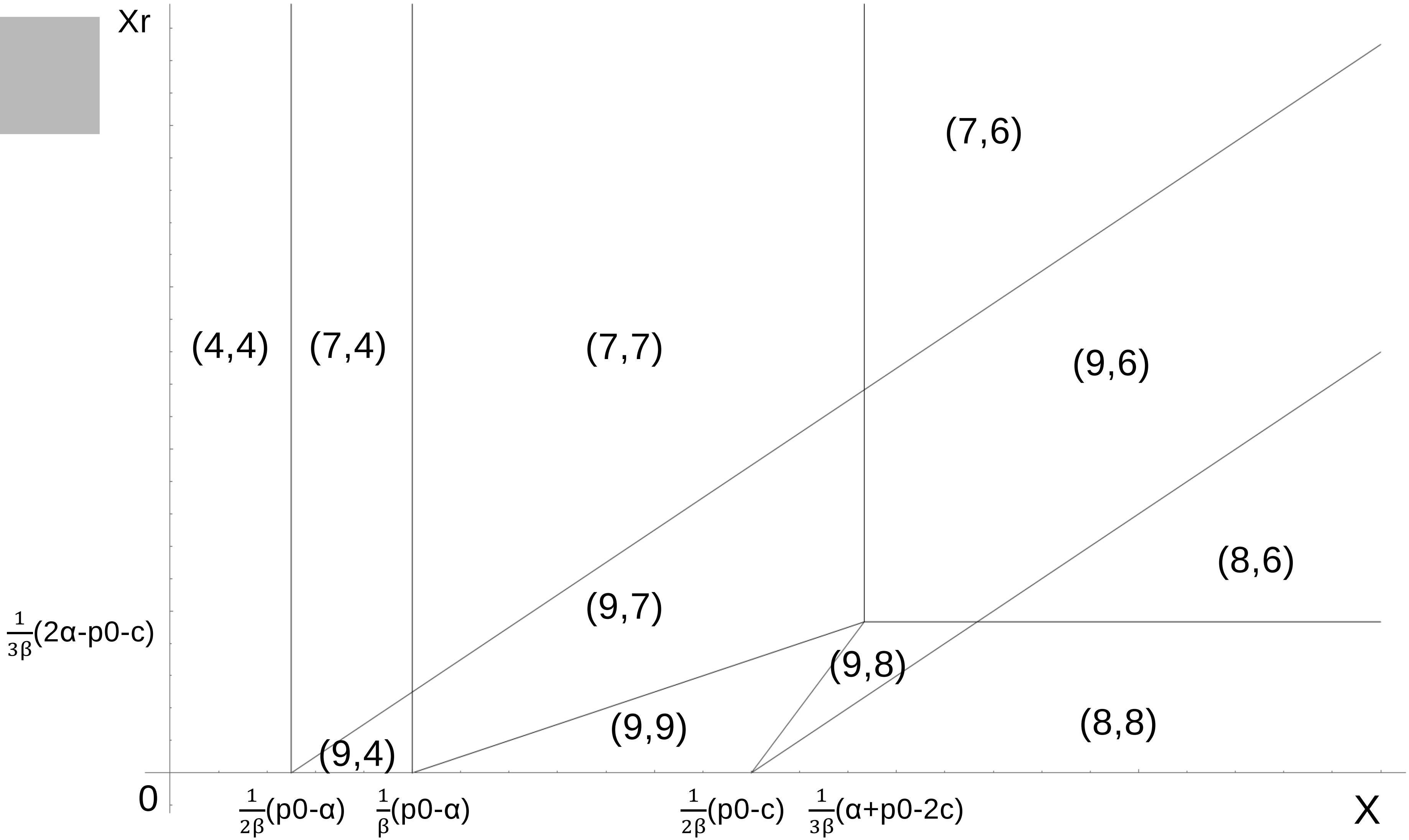
- If $\theta = \theta_r = 0$, the strategies of integrated and separated players converge.
- For the integrated player, only net-generation matters.

Outcomes focusing on **Power-to-H_2 players**

Conditions: c<α<p0, c+p0<2α ($\theta = \theta_r = 1$)

Region	Conditions	Optimal solutions	
(*Integrated* ∩ *Separated*)		*Integrated*	*Separated*
$(4 \cap 4)$	$X \leq \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = 0$	$q = X$ $q_r = 0$
$(9 \cap 4)$	$\frac{1}{2\beta}(p_0 - \alpha) < X$ $X < \frac{1}{\beta}(p_0 - \alpha)$ $X_r < X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = X_r$	$q = X$ $q_r = 0$
$(7 \cap 4)$	$\frac{1}{2\beta}(p_0 - \alpha) < X$ $X < \frac{1}{\beta}(p_0 - \alpha)$ $X_r > X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = 0$
$(9 \cap 9)$	$\frac{1}{\beta}(p_0 - \alpha) < X$ $X < \frac{1}{2\beta}(p_0 - c)$ $X_r < \frac{1}{2}X - \frac{1}{2\beta}(p_0 - \alpha)$ $X_r > 2X - \frac{1}{\beta}(p_0 - c)$	$q = X$ $q_r = X_r$	$q = X$ $q_r = X_r$
$(9 \cap 7)$	$\frac{1}{\beta}(p_0 - \alpha) < X$ $X < \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $X_r > \frac{1}{2}X - \frac{1}{2\beta}(p_0 - \alpha)$ $X_r < X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = X_r$	$q = X$ $q_r = \frac{1}{2}X - \frac{1}{2\beta}(p_0 - \alpha)$
$(7 \cap 7)$	$\frac{1}{\beta}(p_0 - \alpha) < X$ $X < \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $X_r > X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = \frac{1}{2}X - \frac{1}{2\beta}(p_0 - \alpha)$
$(8 \cap 8)$	$X > \frac{1}{2\beta}(p_0 - c)$ $X_r < X - \frac{1}{2\beta}(p_0 - c)$ $X_r < \frac{1}{3\beta}(2\alpha - p_0 - c)$	$q = X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$	$q = \frac{1}{2}X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$
$(9 \cap 8)$	$X > \frac{1}{2\beta}(p_0 - c)$ $X_r < 2X - \frac{1}{\beta}(p_0 - c)$ $X_r > X - \frac{1}{2\beta}(p_0 - c)$ $X_r < \frac{1}{3\beta}(2\alpha - p_0 - c)$	$q = X$ $q_r = X_r$	$q = \frac{1}{2}X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$
$(9 \cap 6)$	$X > \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $X_r > X - \frac{1}{2\beta}(p_0 - c)$ $X_r < X - \frac{1}{2\beta}(p_0 - \alpha)$ $X_r > \frac{1}{3\beta}(2\alpha - p_0 - c)$	$q = X$ $q_r = X_r$	$q = \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $q_r = \frac{1}{3\beta}(2\alpha - p_0 - c)$
$(7 \cap 6)$	$X > \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $X_r > X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $q_r = \frac{1}{3\beta}(2\alpha - p_0 - c)$
$(8 \cap 6)$	$X_r < X - \frac{1}{2\beta}(p_0 - c)$ $X_r > \frac{1}{3\beta}(2\alpha - p_0 - c)$	$q = X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$	$q = \frac{1}{3\beta}(\alpha + p_0 - 2c)$ $q_r = \frac{1}{3\beta}(2\alpha - p_0 - c)$

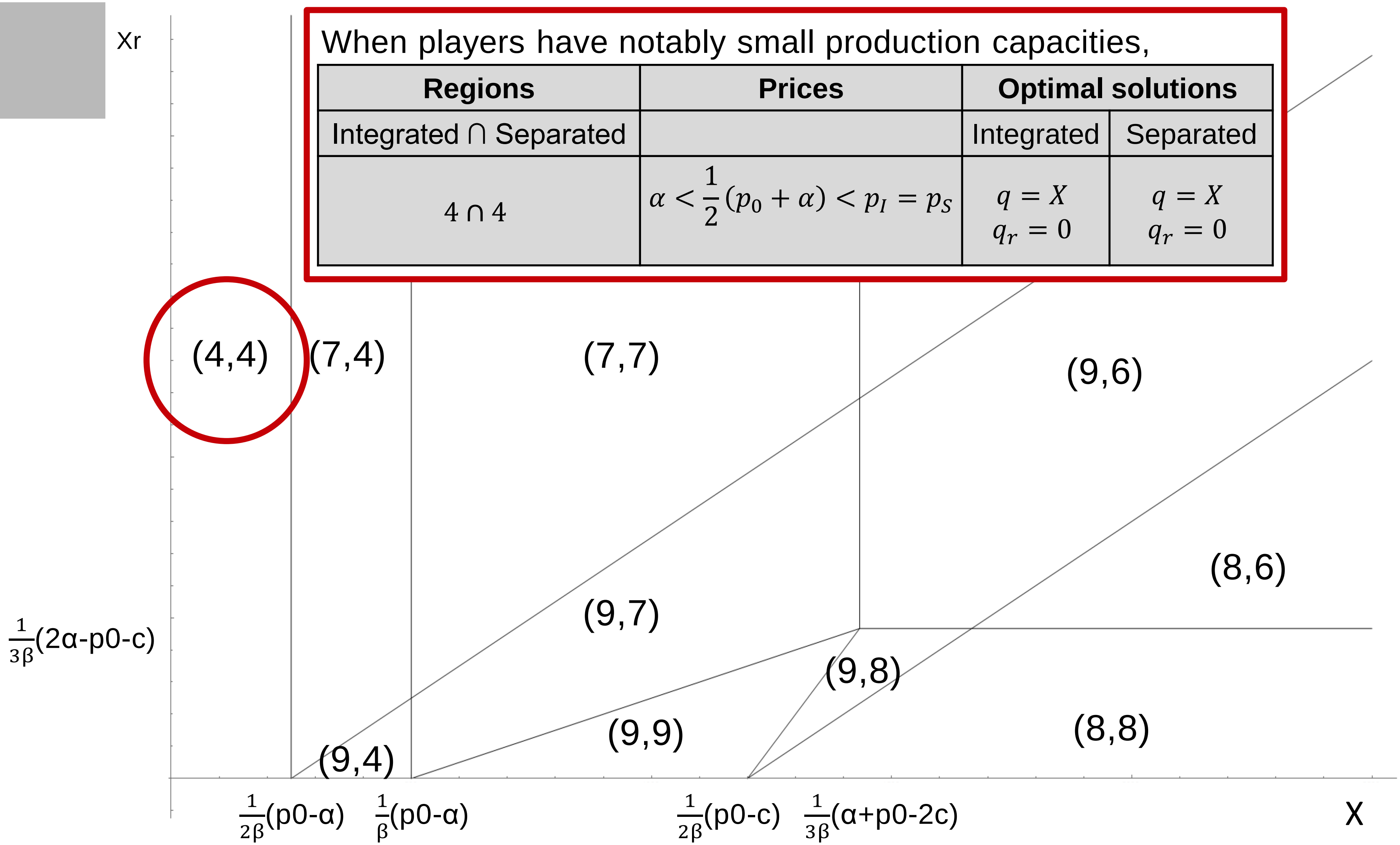
Outcomes focusing on **Power-to-H_2 players**
Outcome regions (11 regions)



Outcomes focusing on Power-to-H_2 players

When players have notably small production capacities,

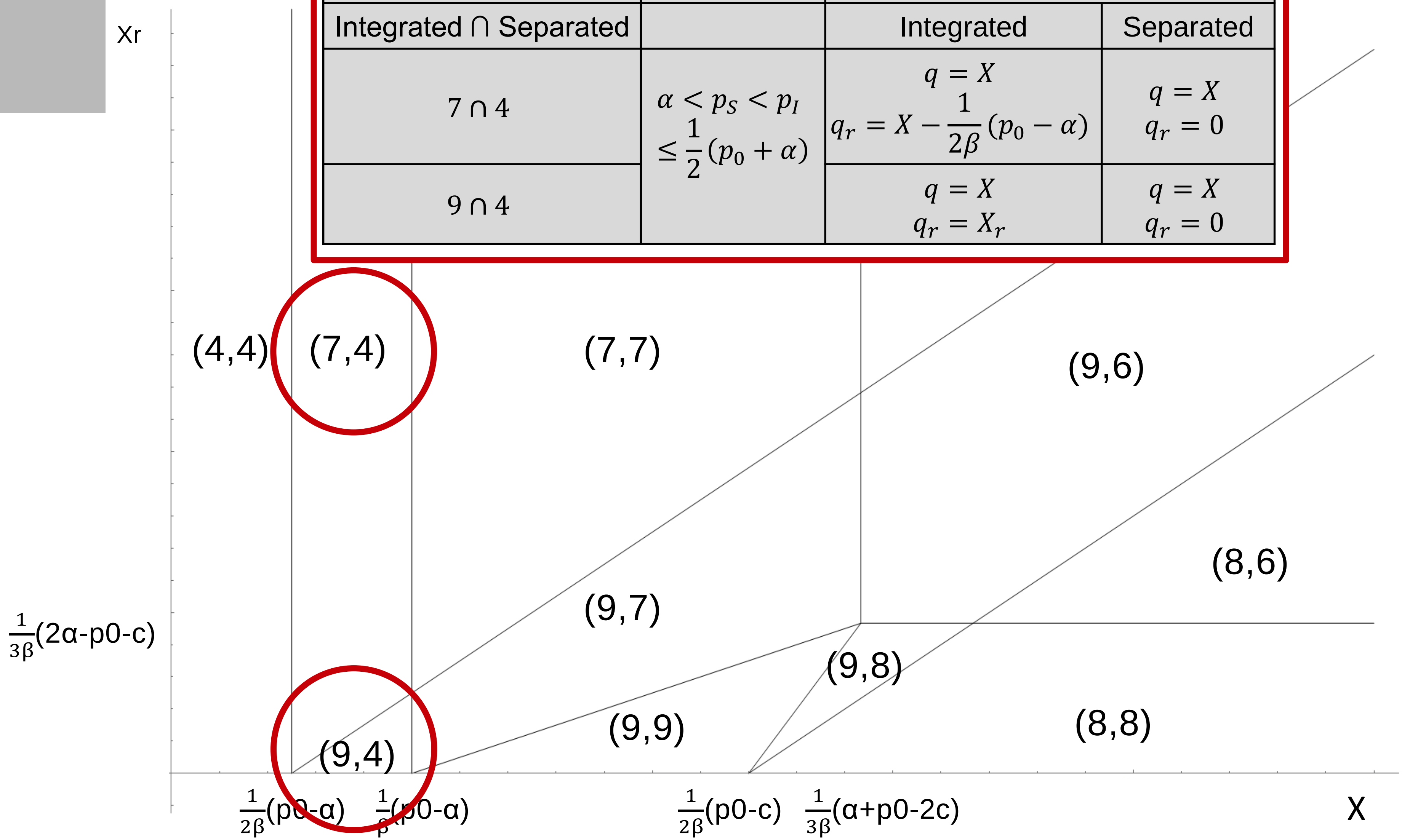
Regions	Prices	Optimal solutions	
Integrated ∩ Separated		Integrated	Separated
4 ∩ 4	$\alpha < \frac{1}{2}(p_0 + \alpha) < p_I = p_S$	$q = X$ $q_r = 0$	$q = X$ $q_r = 0$



Outcomes focusing on Power-to-H_2 players

When players have relatively small production capacities,

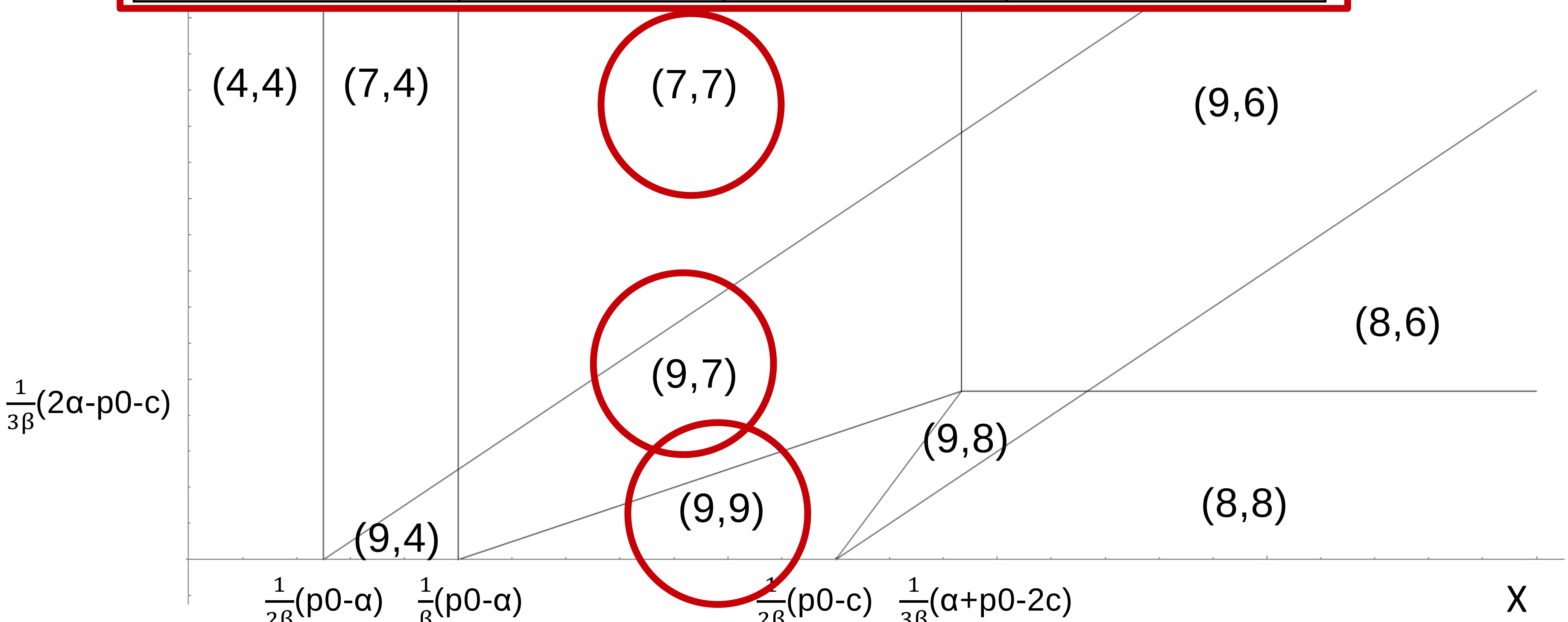
Regions	Prices	Optimal solutions	
Integrated ∩ Separated		Integrated	Separated
7 ∩ 4	$\alpha < p_S < p_I \leq \frac{1}{2}(p_0 + \alpha)$	$q = X$ $q_r = X - \frac{1}{2\beta}(p_0 - \alpha)$	$q = X$ $q_r = 0$
9 ∩ 4		$q = X$ $q_r = X_r$	$q = X$ $q_r = 0$



Outcomes focusing on **Power-to-H_2 players**

When players have moderate production capacities,

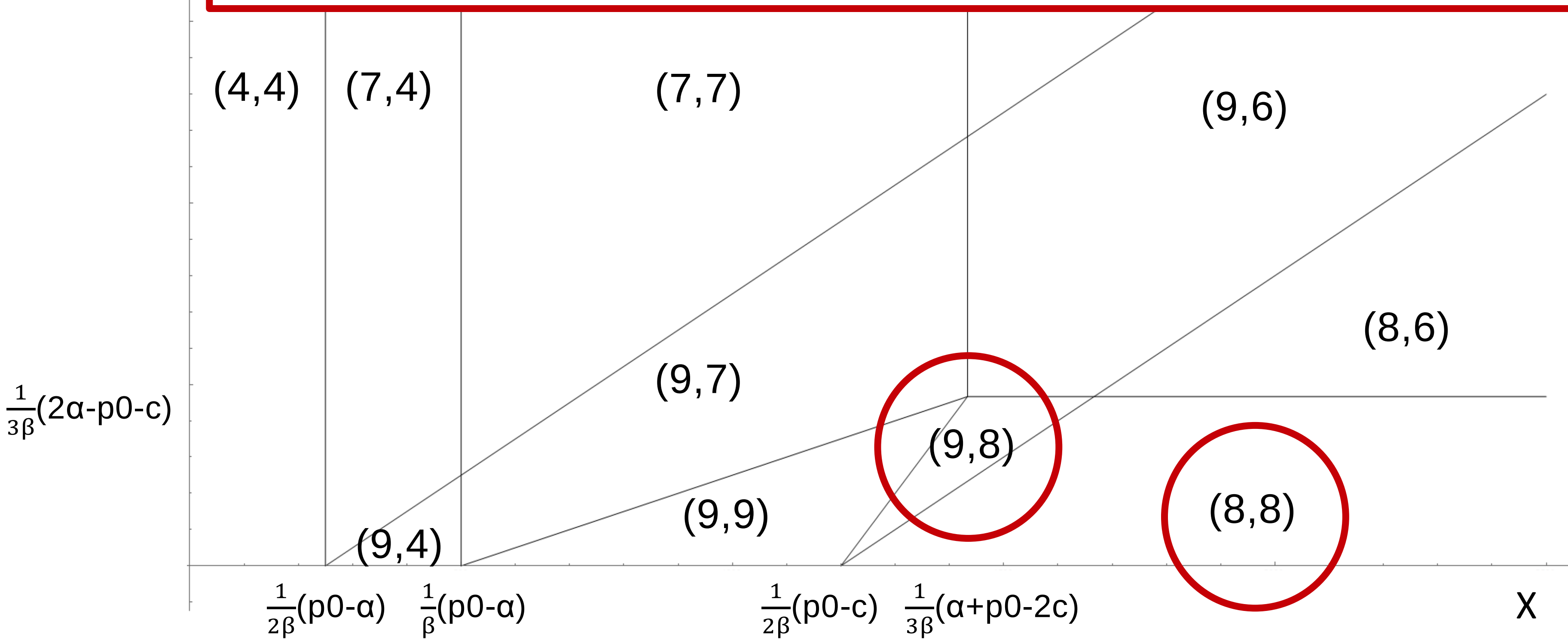
Regions	**Prices**	**Optimal solutions**	
Integrated ∩ Separated		Integrated	Separated
7 ∩ 7	$\frac{1}{3}(p_0+\alpha+c) < p_S \le p_I \le \frac{1}{2}(p_0+\alpha)$	$q = X$ $q_r = X - \frac{1}{2\beta}(p_0-\alpha)$	$q = X$ $q_r = \frac{1}{2}X - \frac{1}{2\beta}(p_0-\alpha)$
9 ∩ 7		$q = X$ $q_r = X_r$	$q = X$ $q_r = \frac{1}{2}X - \frac{1}{2\beta}(p_0-\alpha)$
9 ∩ 9		$q = X$ $q_r = X_r$	$q = X$ $q_r = X_r$



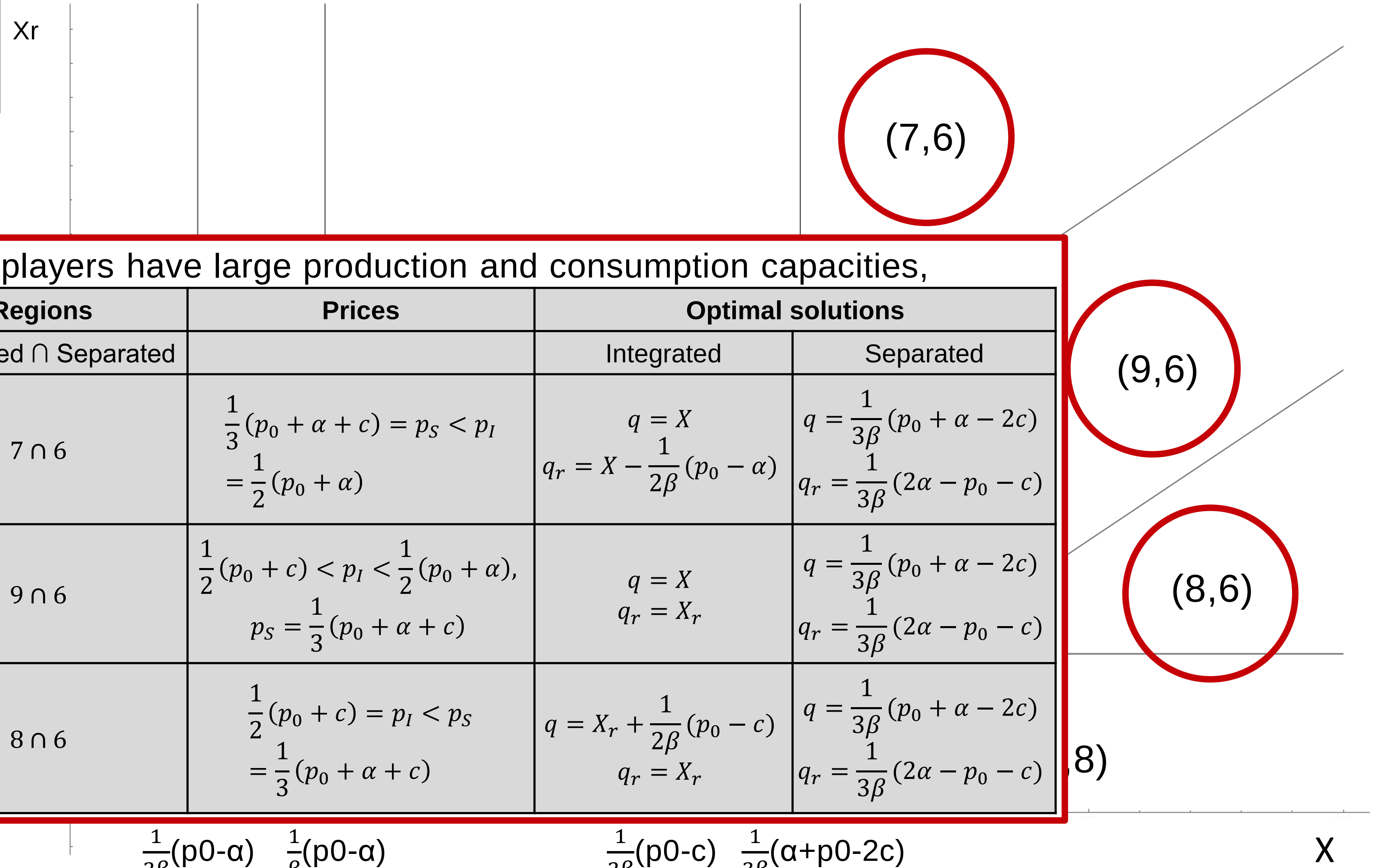
Outcomes focusing on Power-to-H_2 players

When players have relatively small consumption capacities,

Regions	Prices	Optimal solutions	
Integrated ∩ Separated		Integrated	Separated
9 ∩ 8	$\alpha < p_S < p_I \leq \frac{1}{2}(p_0 + \alpha)$	$q = X$ $q_r = X_r$	$q = \frac{1}{2}X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$
8 ∩ 8		$q = X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$	$q = \frac{1}{2}X_r + \frac{1}{2\beta}(p_0 - c)$ $q_r = X_r$



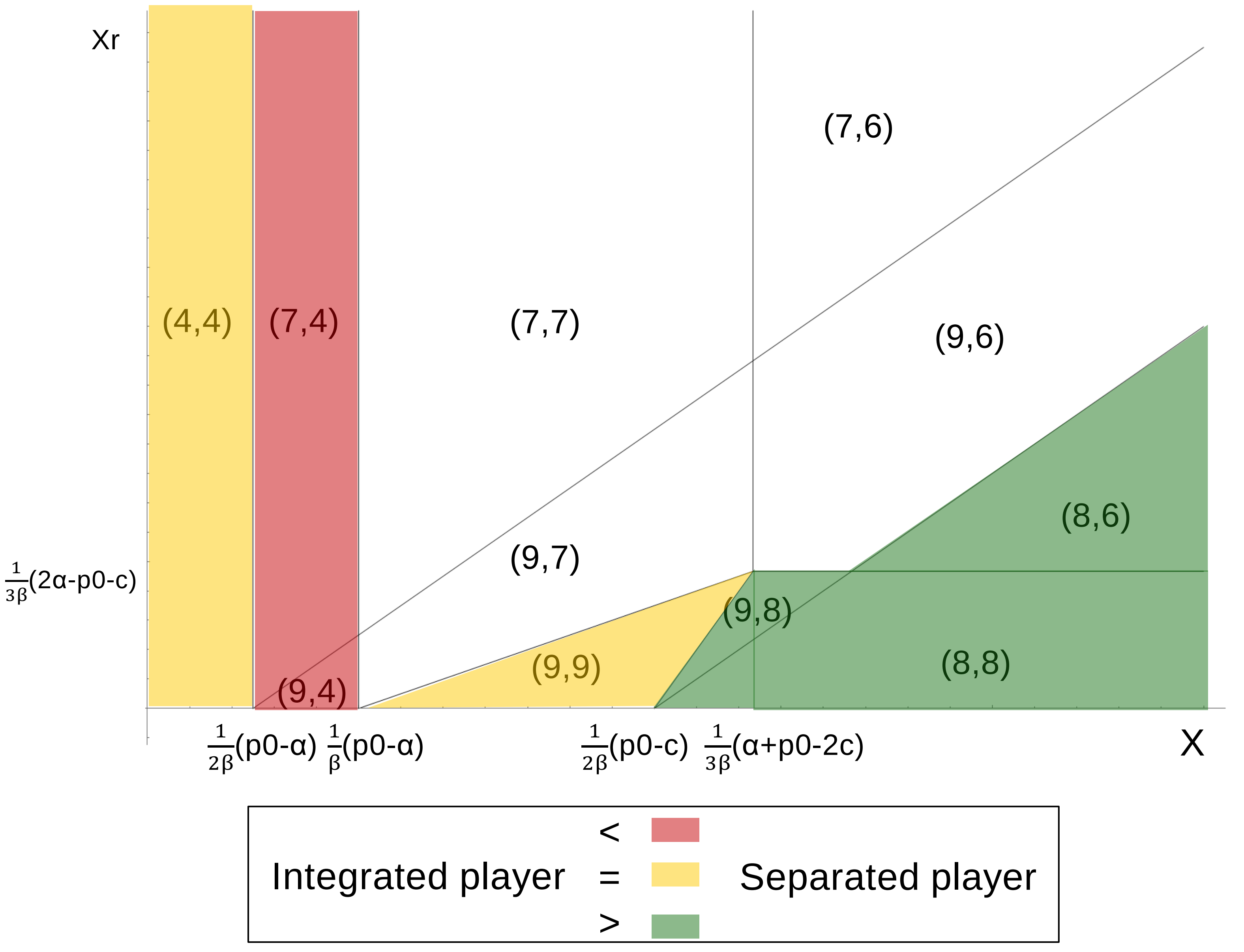
Outcomes focusing on Power-to-H_2 players



When players have large production and consumption capacities,

Regions	Prices	Optimal solutions	
Integrated ∩ Separated		Integrated	Separated
7 ∩ 6	$\frac{1}{3}(p_0+\alpha+c)=p_S<p_I$ $=\frac{1}{2}(p_0+\alpha)$	$q=X$ $q_r=X-\frac{1}{2\beta}(p_0-\alpha)$	$q=\frac{1}{3\beta}(p_0+\alpha-2c)$ $q_r=\frac{1}{3\beta}(2\alpha-p_0-c)$
9 ∩ 6	$\frac{1}{2}(p_0+c)<p_I<\frac{1}{2}(p_0+\alpha)$, $p_S=\frac{1}{3}(p_0+\alpha+c)$	$q=X$ $q_r=X_r$	$q=\frac{1}{3\beta}(p_0+\alpha-2c)$ $q_r=\frac{1}{3\beta}(2\alpha-p_0-c)$
8 ∩ 6	$\frac{1}{2}(p_0+c)=p_I<p_S$ $=\frac{1}{3}(p_0+\alpha+c)$	$q=X_r+\frac{1}{2\beta}(p_0-c)$ $q_r=X_r$	$q=\frac{1}{3\beta}(p_0+\alpha-2c)$ $q_r=\frac{1}{3\beta}(2\alpha-p_0-c)$

Social welfare



Conclusions

In summary,

- **Without market power**, the market outcomes in the case of integrated player and separated players are equal.
- **Production, released production level and total profits** in the integrated player case are larger than in the separated players' case.
- Whether the **social welfare** in the case of the integrated player is greater than that in the separated players is ambiguous.
  - Not only the technology configuration but also the proportional scale of different technologies employed by the players play an important role in energy industrial design.

Work not covered in the talk:

- Effects of increased market power levels on players' behaviours
- Nash-Cournot game vs Stackelberg game

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Thank you very much for your attention.

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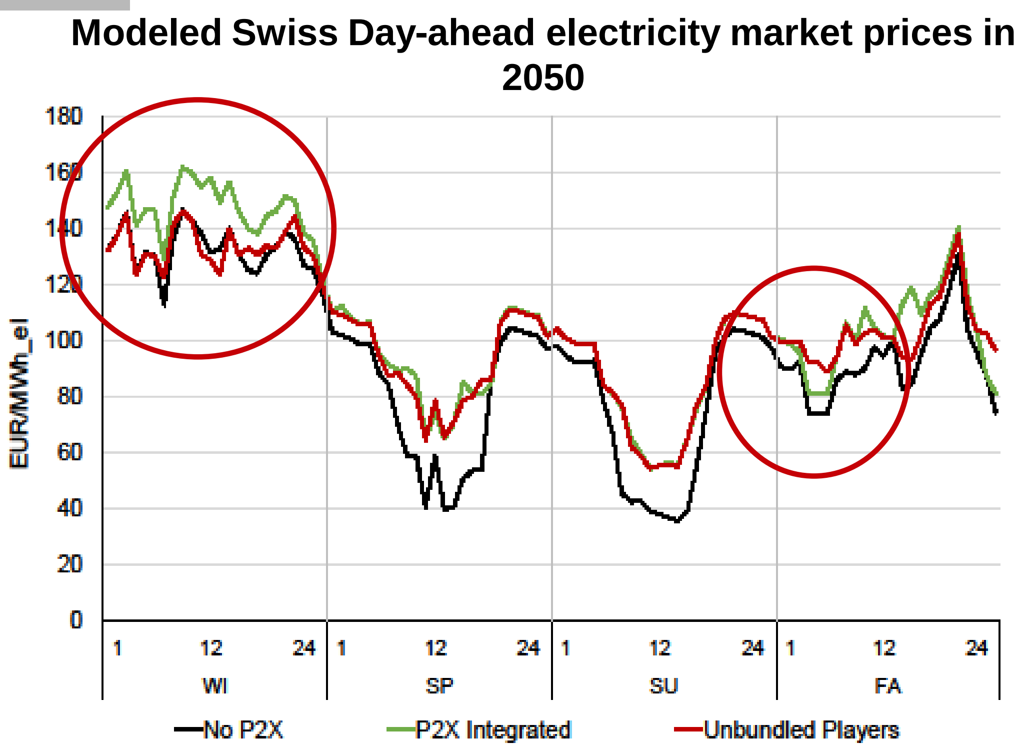
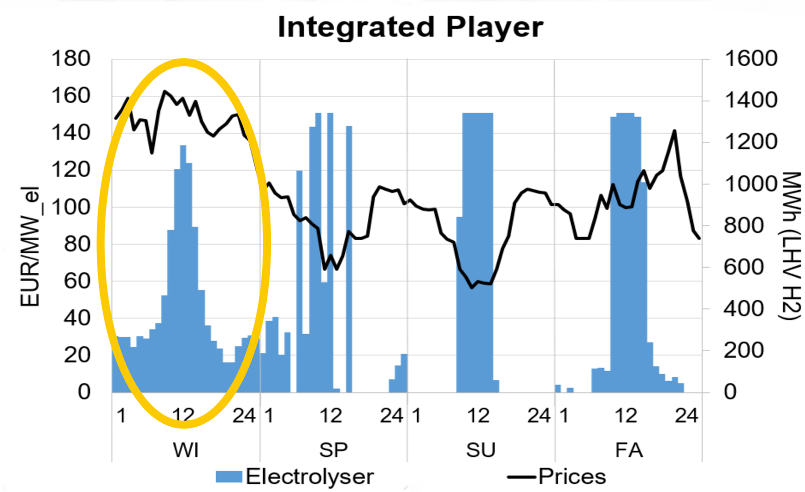
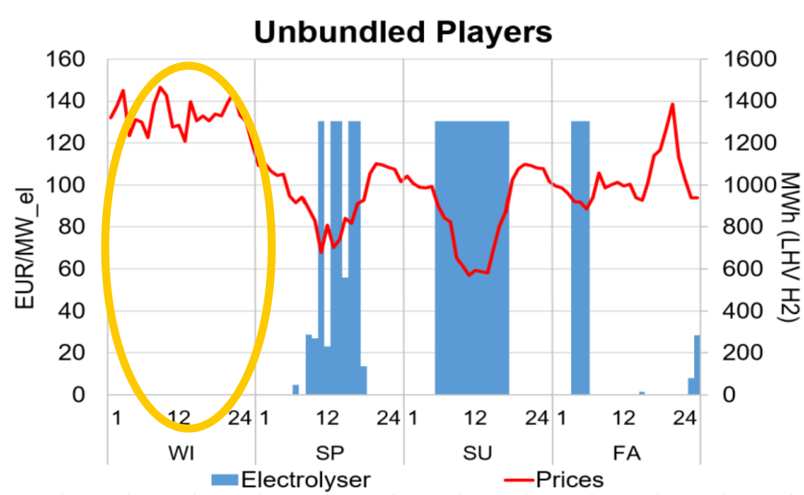
Numerical results when many large-scale P2X facilities join the markets







- **Integrated player**: owns both traditional generation plants and P2X plants
- **Separated players**: different players own traditional generation plants and P2X plants separately

- Should i change the title to :Comparison of integrated and separated production and consumption players in Nash-Cournot equilibrium under capacity constraints
- Change to a better figure