# Fun of Modeling Electricity Markets using Equilibrium Models


***Yihsu Chen, Ph.D.***

**School of Engineering**
**University of California, Santa Cruz**

**April, 2016**

# Menu

- All about me
- Background of electricity markets
- Basic models
- Results & discussions
- Other research

# All About Me: Yihsu Chen

B.S, Environmental Science and Engineering, Tunghai University, Taiwan, 1991-1995

M.S., Harvard University, School of Public Health, 1997-1999

Ph.D., Environmental Engineering, The Johns Hopkins University, 2000-2006

Assistant Professor, School of Social Sciences, Humanities and Arts, School of Engineering, University of California, Merced, 2006-2012

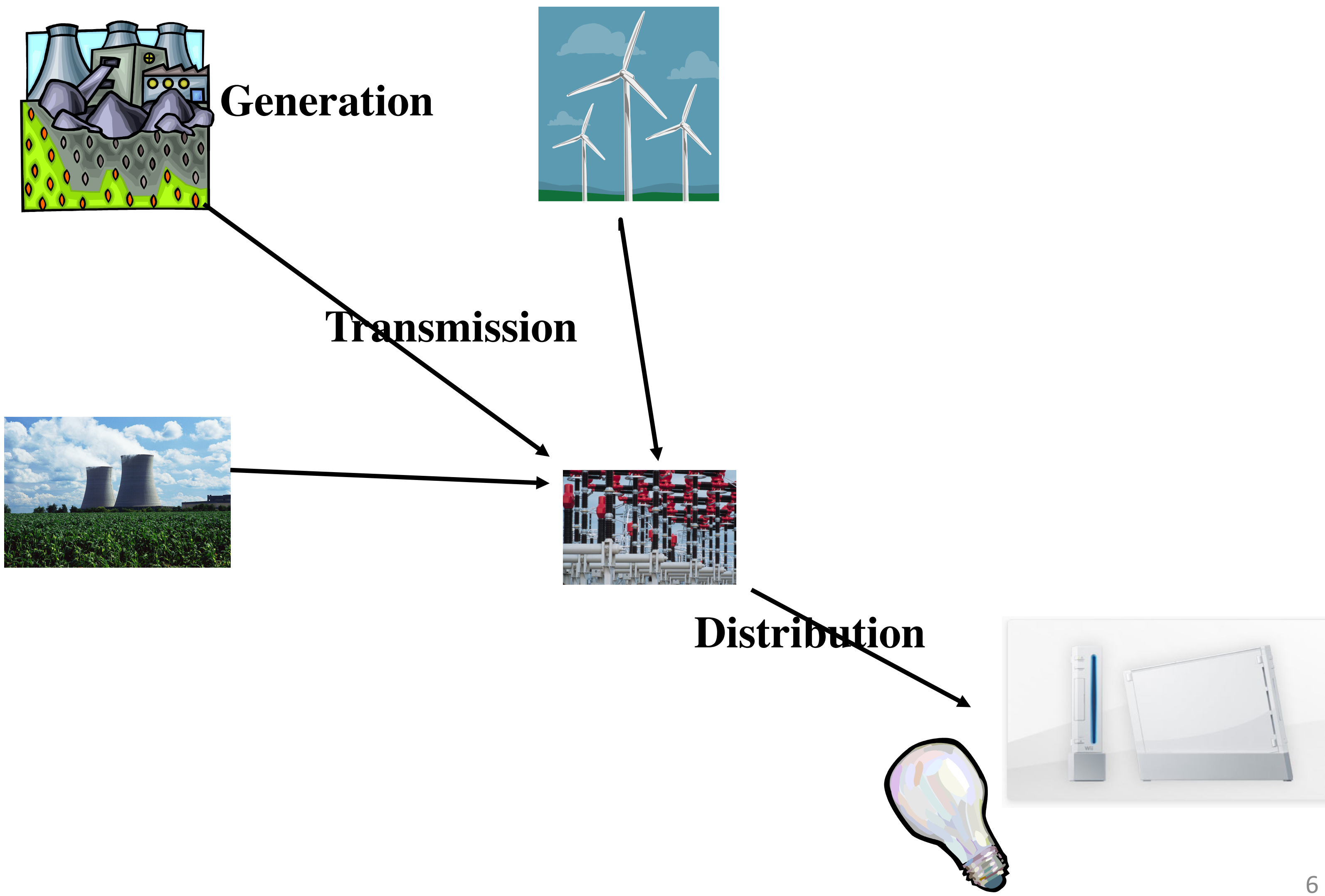
Associate Professor, School of Social Sciences, Humanities and Arts, School of Engineering, University of California, Merced, 2012-2015

Associate Professor, Technology Management, Baskin School of Engineering, University of California, Santa Cruz, 2015–

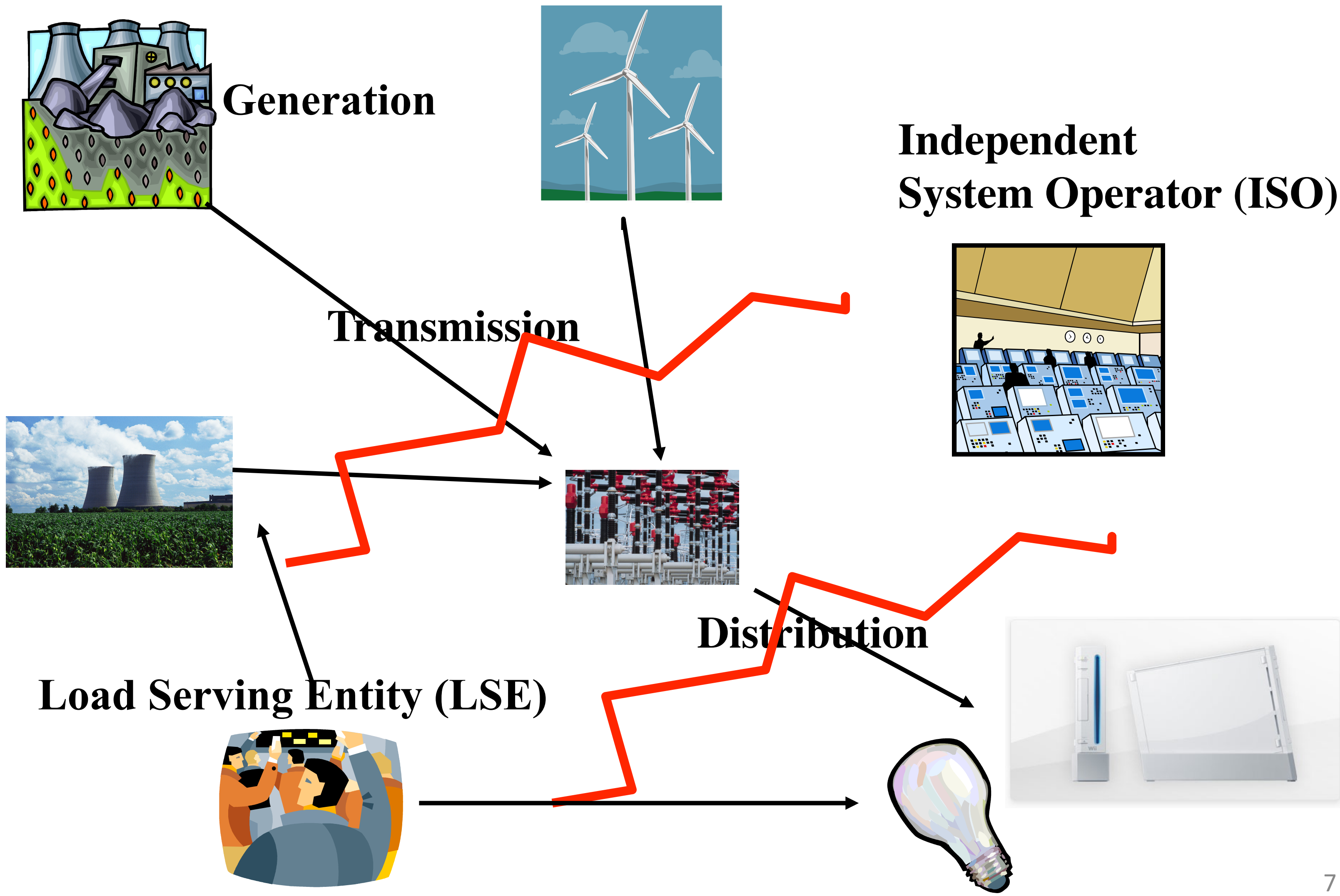
# Background: Electricity vs Ice Cream

| Electricity | Ice Cream |
| --- | --- |
| Homogeneous good (except green power) | Differential product (e.g., flavors: peach, strawberry, etc) |
| Real-time balance | Inventory (refrigerator, storage, etc) |
| No real-time pricing | You know prices at spot |
| Low short-run demand elasticity | High elasticity due to product substitution |
| Power follows Kirchhoff's laws | Transported by trucks and follows lights |
| Ancillary services (e.g., reactive power, spinning reserves) | Only need spoon and refrigerator |

# Background:
# Vertical Integrated Power Sector



# Background: Restructure or Deregulation



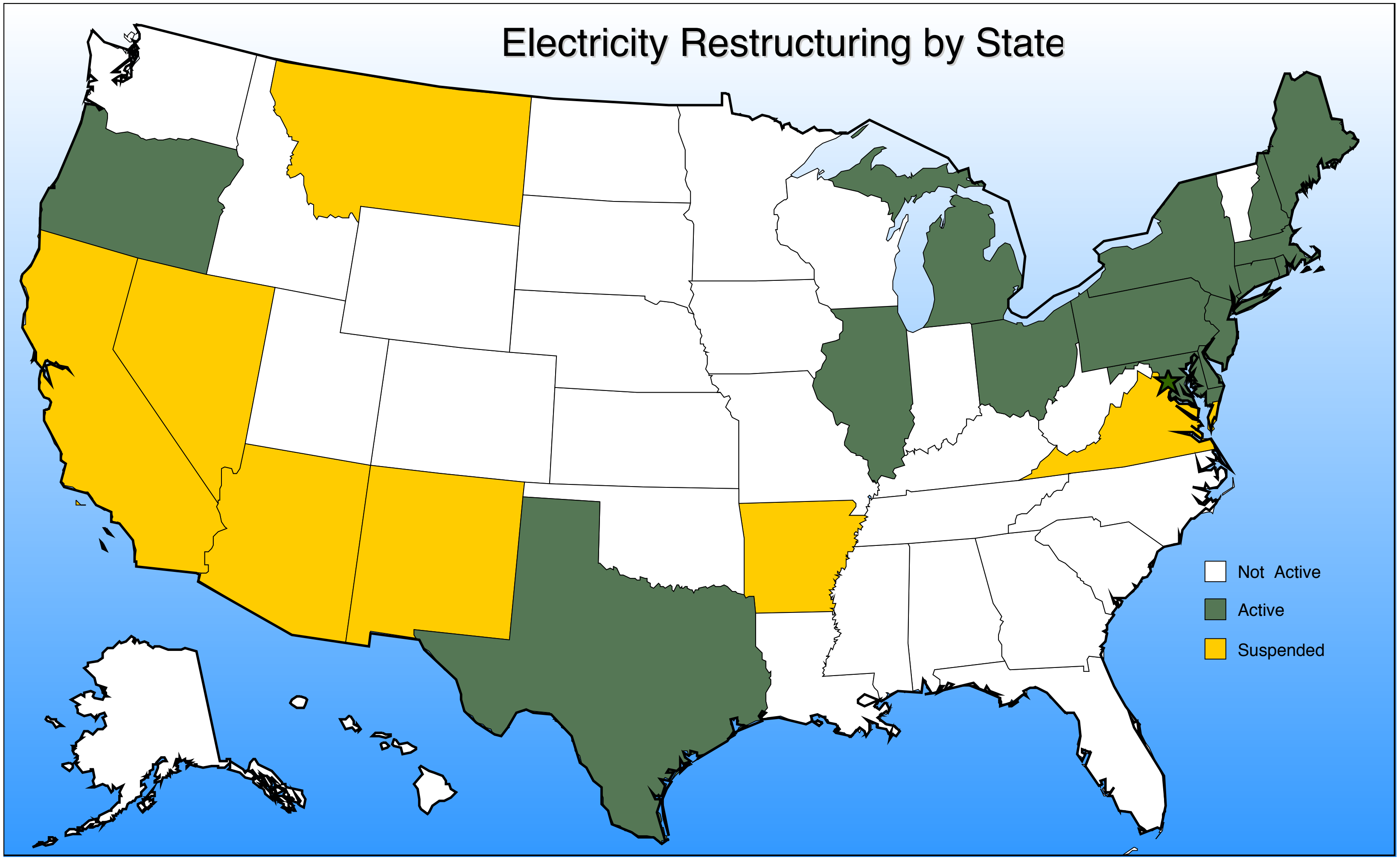
# Background: Why Deregulation?

- **Provide correct signal for long-term investment in generation capacity and transmission**
- **Improve economic efficiency**
  - **Productive efficiency: production frontier (lower costs), innovation**
  - **Allocative efficiency: quantities and prices**

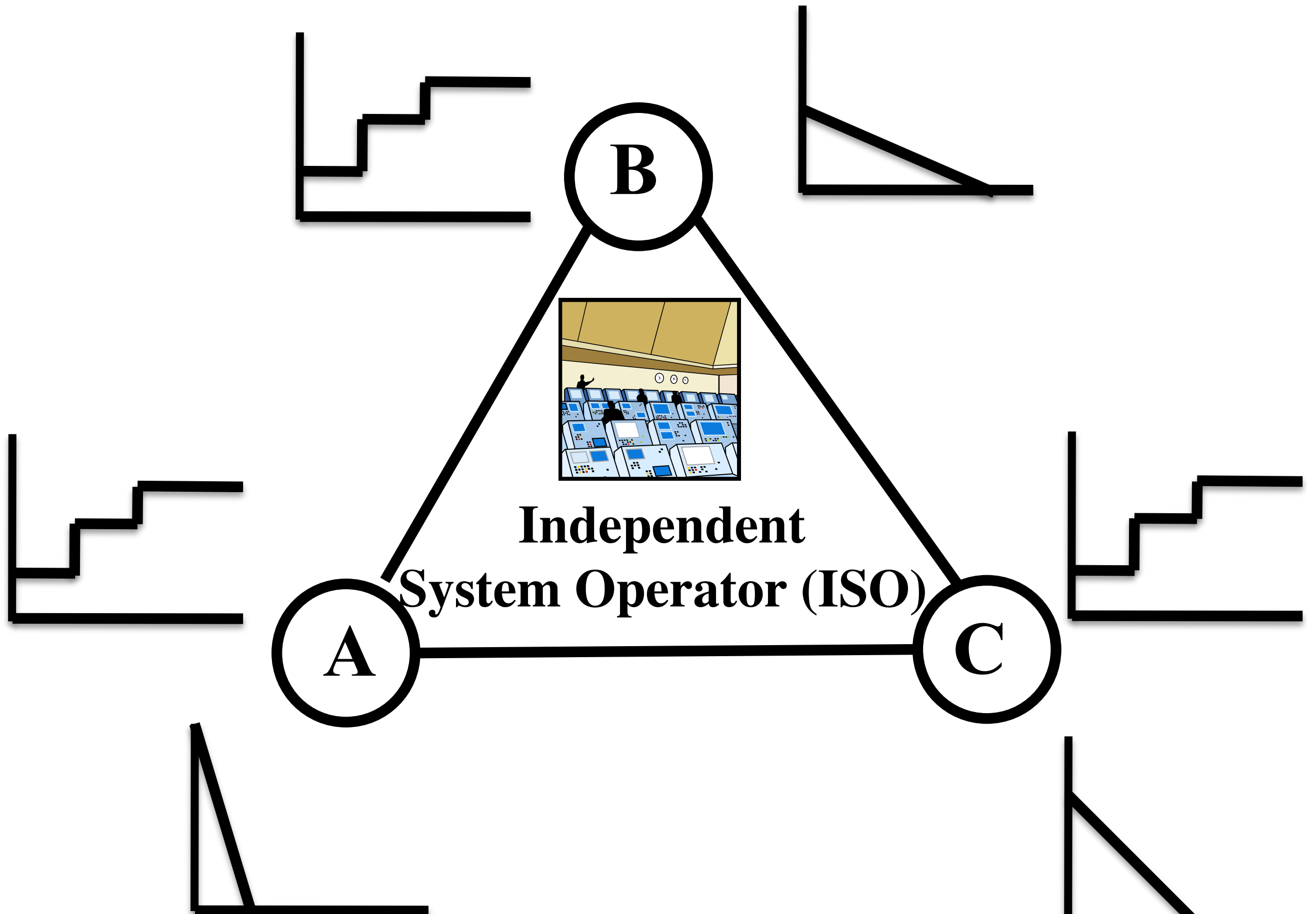
**Contemporary Federal and State leadership**

- **FERC Order 888, 889 (1996) and 2000 (Regional Transmission Organization, RTO) and Standard Market Design (2002), etc.**
- **CA and MA lead in 1995**
  - **most States were following until California 2000-2001 crisis**

# Background: A snapshot



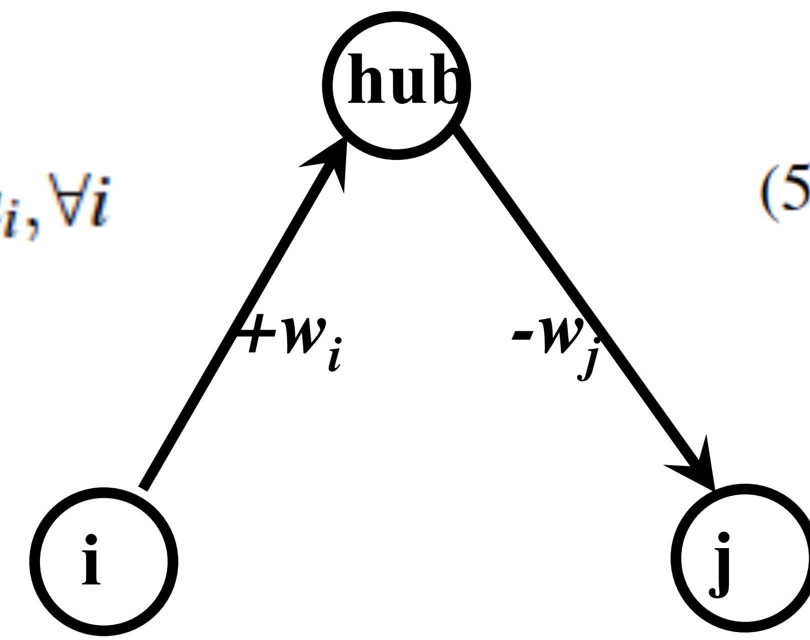
# Background: Electricity Markets



# Models: Producers & Market Clearing Conditions

$$\begin{aligned}
\underset{x_{fih}, s_{fi}}{\text{maximize}} \; & \textstyle\sum_j (p_j^E - w_j) s_{fj} - \sum_{i,h \in H(i,f)} (C_{fih} - w_i) x_{fih} \\
\text{subject to} \; & x_{fih} \leq X_{fih}, (\rho_{fih}) \\
& \textstyle\sum_j s_{fj} = \sum_{j,h \in H(j,f)} x_{fjh}, (\theta_f) \\
& x_{fih}, s_{fj} \geq 0.
\end{aligned} \quad (4)$$

$$y_i = \textstyle\sum_{f,h \in H(i,f)} x_{fih} - \sum_f s_{fi} - a_i, \forall i \quad (5)$$

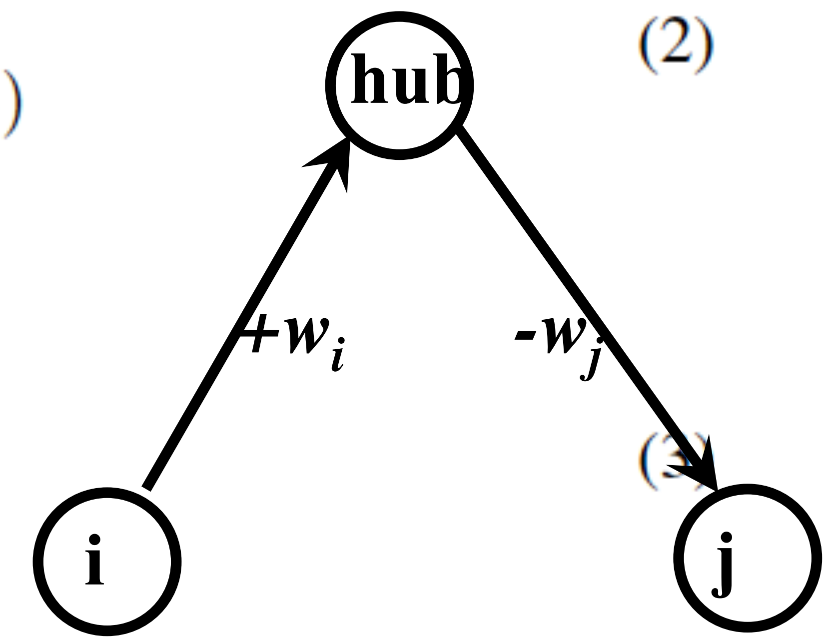


# Models: Consumers & ISO & Arbitrager

$$p_j^E = P_j^0 - \frac{P_j^0}{Q_j^0}\left(\sum_f s_{fj} + a_j\right), \forall j \quad (1)$$

$$\begin{aligned} &\underset{y_i}{\text{maximize}} \sum_i w_i y_i \\ &\text{subject to } \sum_i PTDF_{ki} y_i \le T_k, (\lambda_k) \end{aligned} \quad (2)$$

$$\begin{aligned} &\underset{a_i}{\text{maximize}} \sum_i (p_i^E - w_i) a_i \\ &\text{subject to } \sum_i a_i = 0 \end{aligned} \quad (3)$$



# Solving a duopoly (2 firms) game

Consider two firms with constant marginal cost $c$ facing a linear demand function: $p(Q)=a-Q$, where $Q=q_i + q_j$. For firm $i$, we have

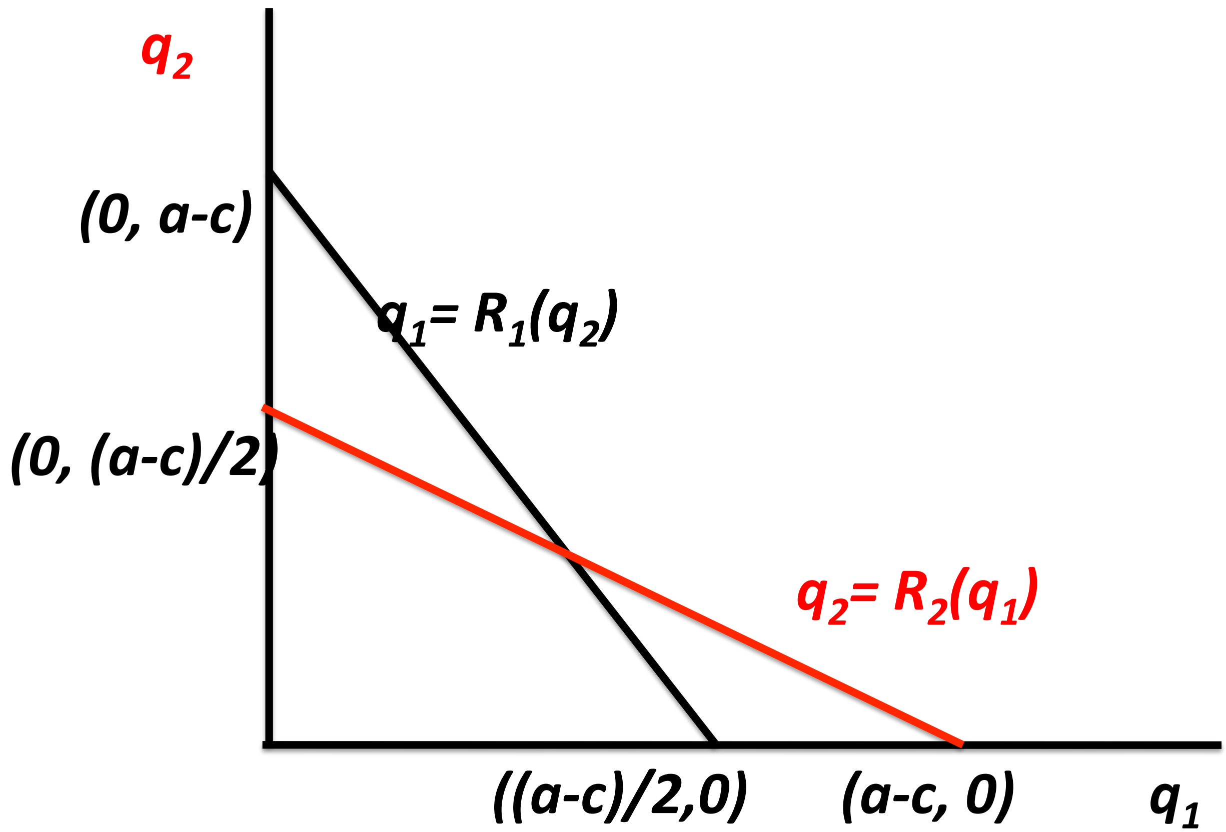
$$\text{Max } \pi_i(q_i, q_j) = p_i(Q)q_i - q_i \times c_i.$$

A *Nash Equilibrium* is defined by a pair of strategy $(q^*_i, q^*_j)$ such that for each $i$, we have $\pi_i(q_i^*, q_j^*) \geq \pi_i(q_i, q_j^*)$

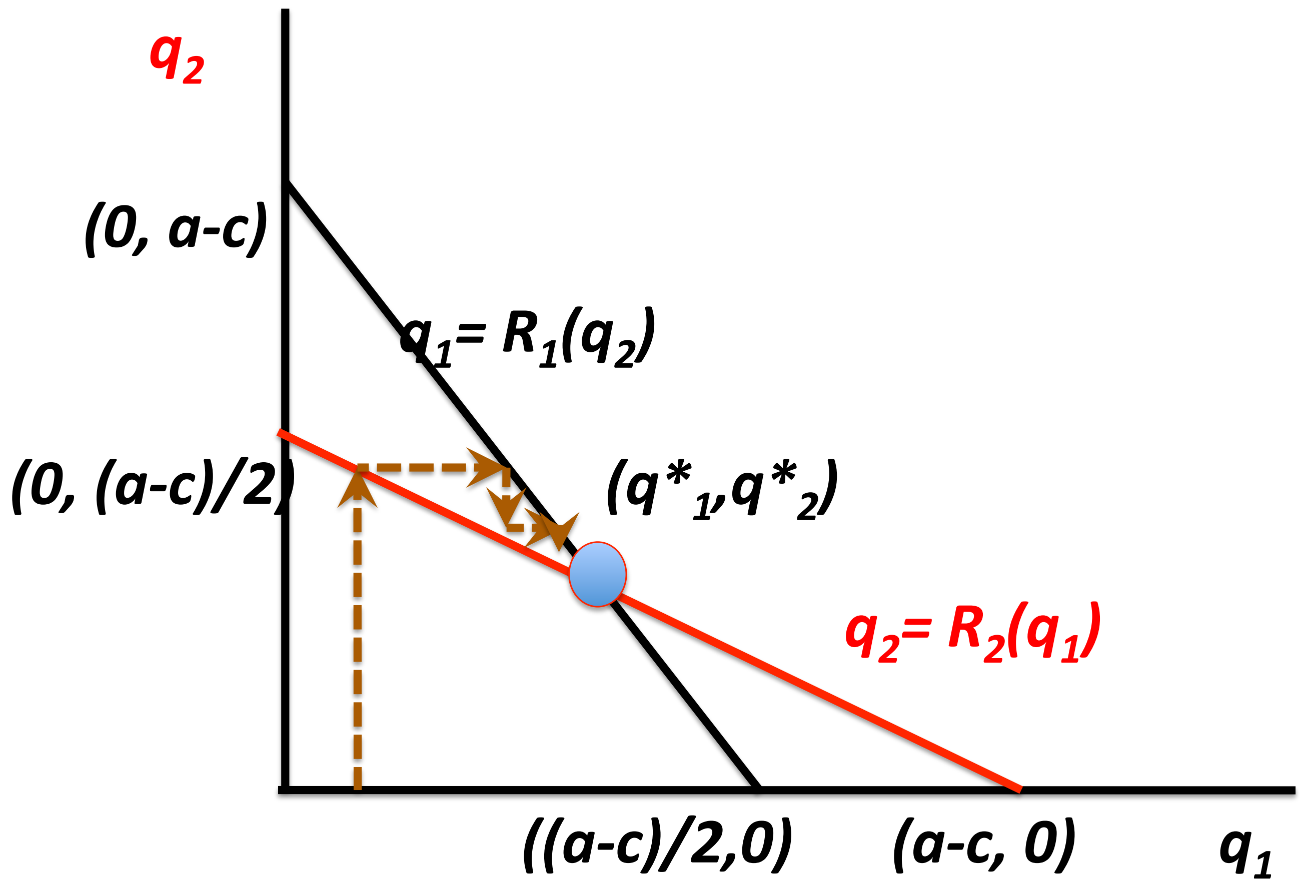
To find each $i$'s optimal strategy, we solve for $\frac{\partial \pi_i(q_i^*, q_j^*)}{\partial q_i} = 0$

$$q_i(q_j) = \tfrac{1}{2}(a - q_j - c) \text{ and } q_j(q_i) = \tfrac{1}{2}(a - q_i - c)$$

# Solving a duopoly (2 firms) game



# Solving a duopoly (2 firms) game



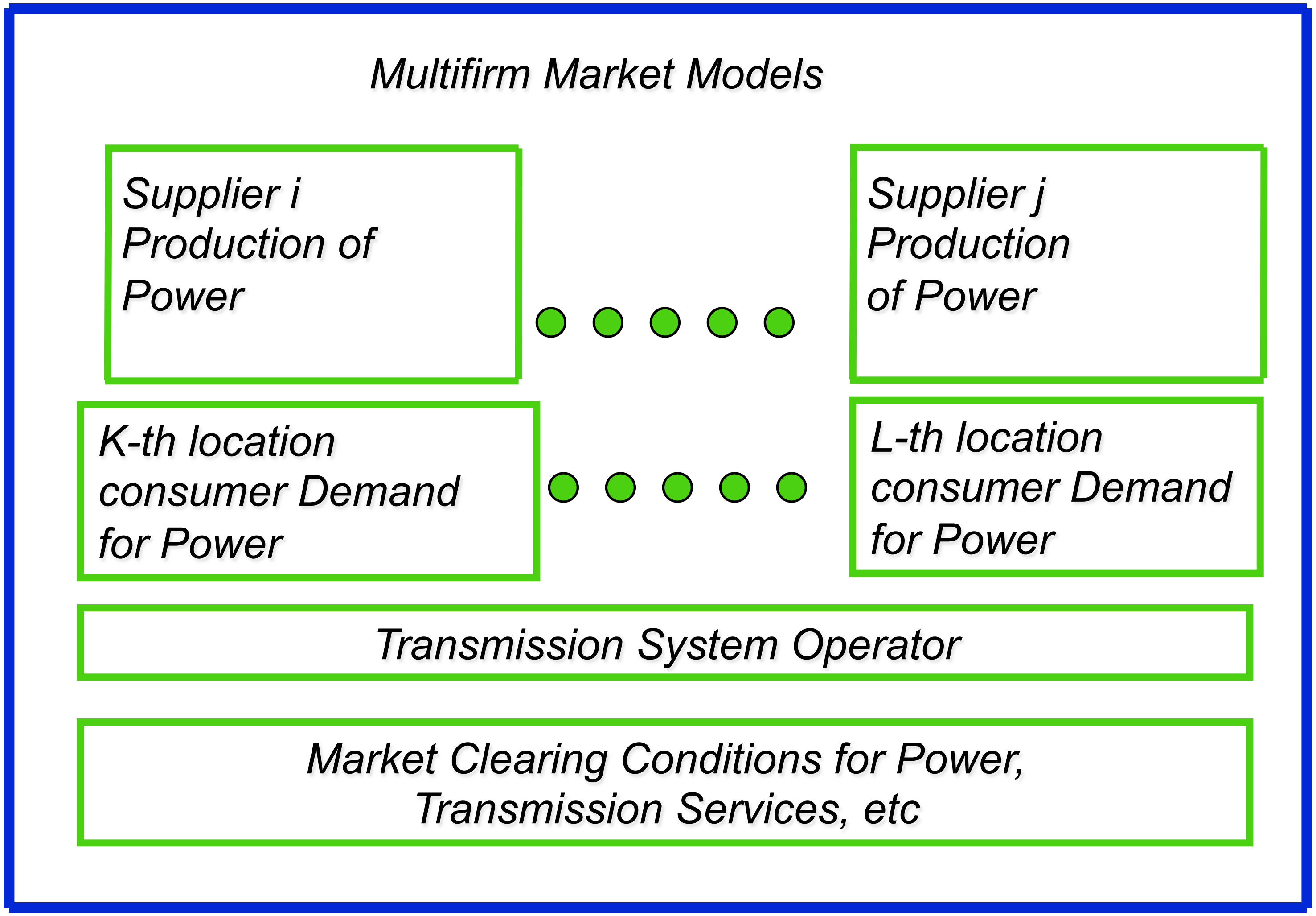
# Solving a duopoly (2 firms) game

Find cell such that $\pi_A$ is highest in column (Firm A maximizes its profit given $y_B$) and $\pi_B$ is highest in row (Firm B maximizes its profit given $y_A$). In the below table, ***Bold italics*** represents Firm A's best response to $y_B$, while **Bold** represents Firm B's best response to $y_A$. The format of the table is:

| $y_A \setminus y_B$: | B's $y$ |
|---|---|
| A's $y$ | $\pi_A$ / $\pi_B$ |

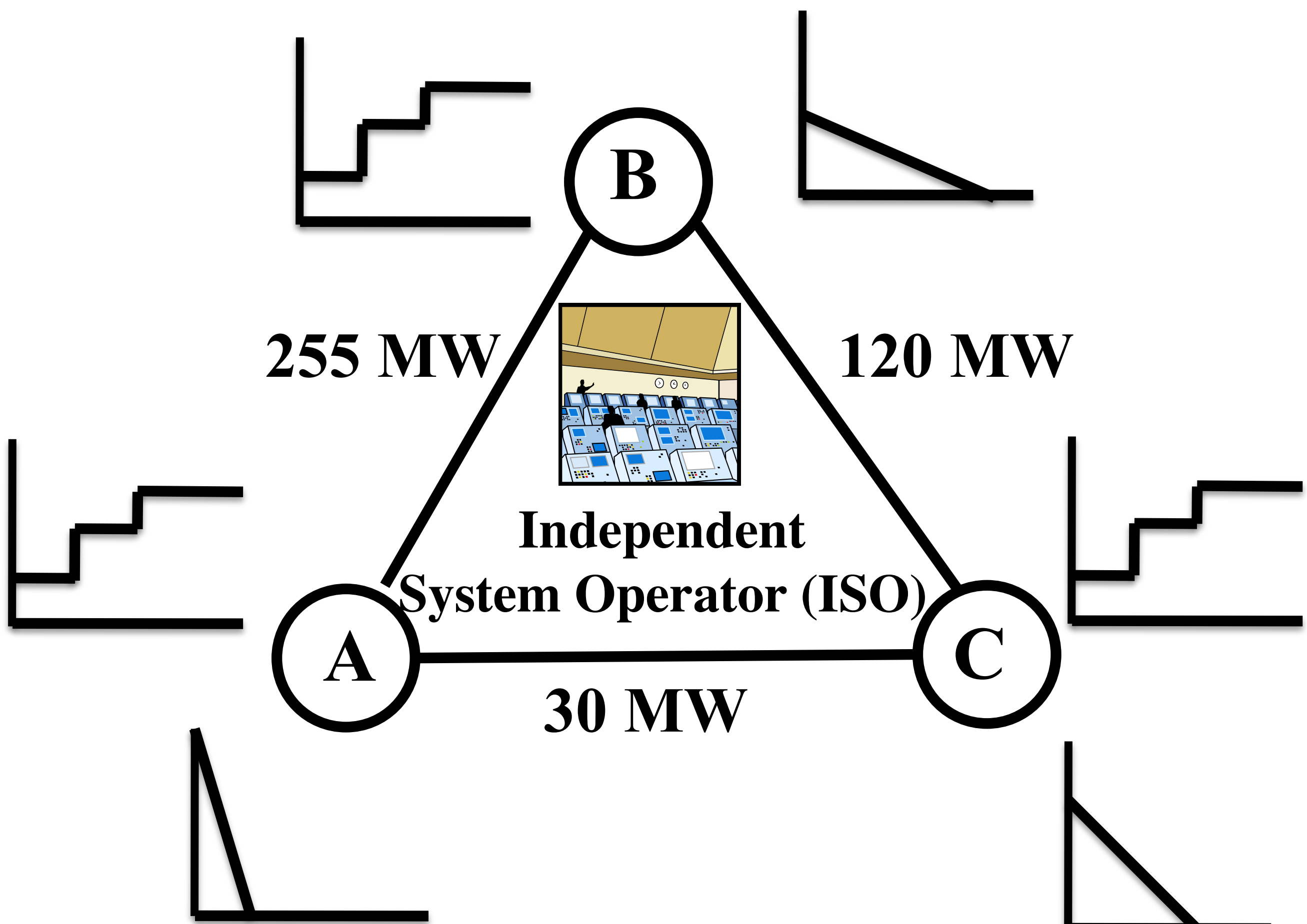
| $y_A \setminus y_B$: | 30 | 32 | 34 | 36 | 38 | 40 | 42 | 44 | 46 | 48 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 | [illegible] / 1650 | [illegible] / 1696 | 1590 / 1734 | 1560 / 1764 | 1530 / 1786 | 1500 / 1800 | 1470 / **[illegible]** | 1440 / 1804 | 1410 / 1794 | 1380 / 1776 | 1350 / 1750 |
| 32 | 1696 / 1620 | 1664 / 1664 | 1632 / 1700 | 1600 / 1728 | 1568 / 1748 | 1536 / 1760 | 1504 / **1764** | 1472 / 1760 | 1440 / 1748 | 1408 / 1728 | 1376 / 1700 |
| 34 | 1734 / 1590 | 1700 / 1632 | 1666 / 1666 | 1632 / 1692 | 1598 / 1710 | 1564 / 1720 | 1530 / **1722** | 1496 / 1716 | 1462 / 1702 | 1428 / 1680 | 1394 / 1650 |
| 36 | 1764 / 1560 | 1728 / 1600 | 1692 / 1632 | 1656 / 1656 | 1620 / 1672 | 1584 / **1680** | 1548 / **1680** | 1512 / 1672 | 1476 / 1656 | 1440 / 1632 | 1404 / 1600 |
| 38 | 1786 / 1530 | 1748 / 1568 | 1710 / 1598 | 1672 / 1620 | 1634 / 1634 | 1596 / **[illegible]** | [illegible] / 1638 | ***1520*** / 1628 | ***1482*** / 1610 | ***1444*** / 1584 | ***1406*** / 1550 |
| 40 | 1800 / 1500 | 1760 / 1536 | 1720 / 1564 | ***1680*** / 1584 | ***1640*** / 1596 | ***1600*** / **[illegible]** | ***[illegible]*** / 1596 | ***1520*** / 1584 | 1480 / 1564 | 1440 / 1536 | 1400 / 1500 |
| 42 | ***1806*** / 1470 | ***1764*** / 1504 | ***1722*** / 1530 | ***1680*** / 1548 | 1638 / 1558 | 1596 / **1560** | 1554 / 1554 | 1512 / 1540 | 1470 / 1518 | 1428 / 1488 | 1386 / 1450 |
| 44 | 1804 / 1440 | 1760 / 1472 | 1716 / 1496 | 1672 / 1512 | 1628 / **1520** | 1584 / **1520** | 1540 / 1512 | 1496 / 1496 | 1452 / 1472 | 1408 / 1440 | 1364 / 1400 |
| 46 | 1794 / 1410 | 1748 / 1440 | 1702 / 1462 | 1656 / 1476 | 1610 / **1482** | 1564 / 1480 | 1518 / 1470 | 1472 / 1452 | 1426 / 1426 | 1380 / 1392 | 1334 / 1350 |
| 48 | 1776 / 1380 | 1728 / 1408 | 1680 / 1428 | 1632 / 1440 | 1584 / **1444** | 1536 / 1440 | 1488 / 1428 | 1440 / 1408 | 1392 / 1380 | 1344 / 1344 | 1296 / 1300 |
| 50 | 1750 / 1350 | 1700 / 1376 | 1650 / 1394 | 1600 / 1404 | 1550 / **1406** | 1500 / 1400 | 1450 / 1386 | 1400 / 1364 | 1350 / 1334 | 1300 / 1296 | 1250 / 1250 |

# Model Structure




**Equilibrium calculation: Solve *n* conditions for *n* unknowns**

# Electricity Markets

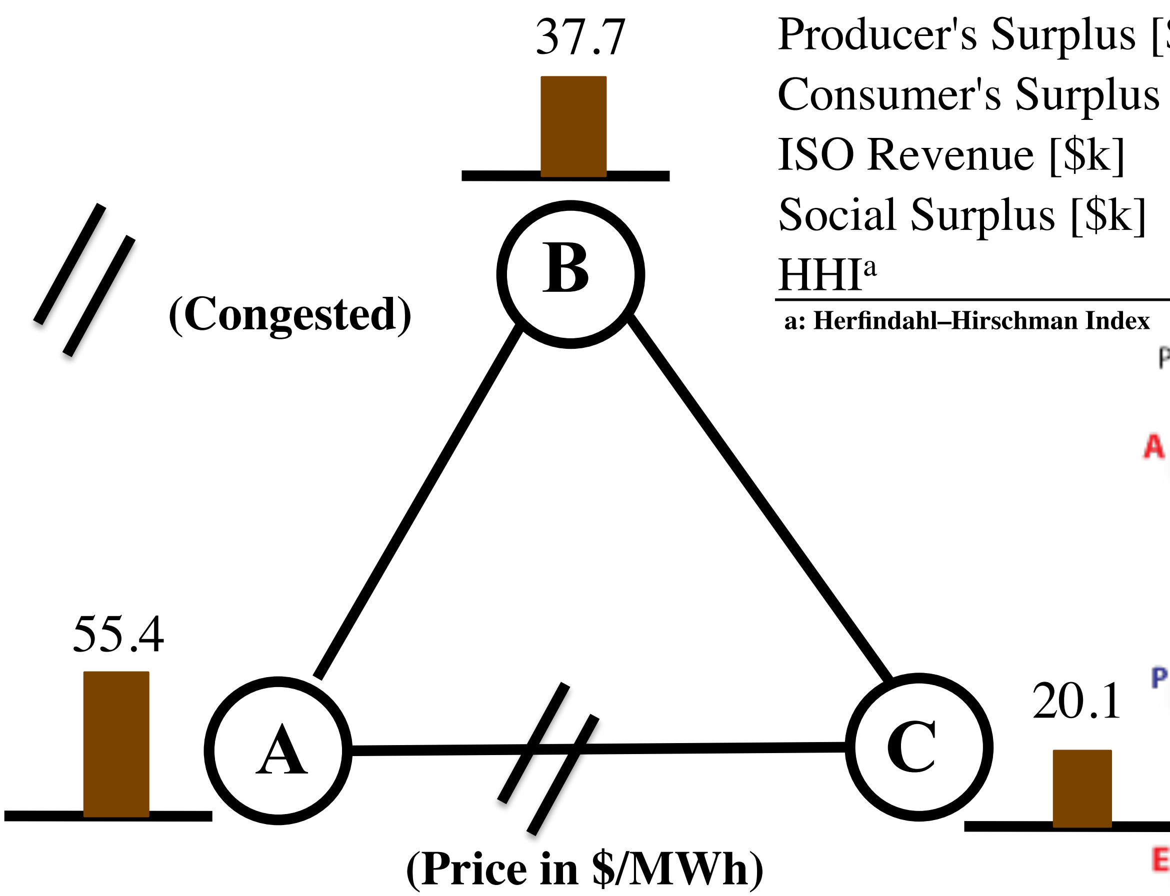



( 10 Facilities, 3 producers)

# Case Analysis

- **Case 1: Perfect Competition**
- **Case 2: Oligopoly Competition (Cournot)**
- **Case 3: Duopoly Competition (Merger)**
- **Case 4: Monopoly Competition**
- **Case 5: Transmission Investment (A-C: 30 → 430 MW)**

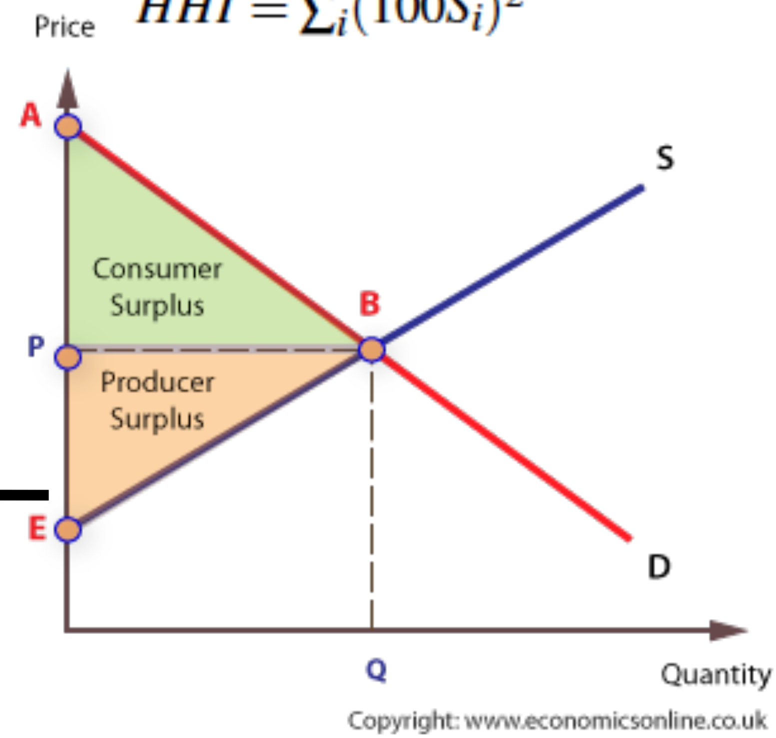
# Results: Competitive Market



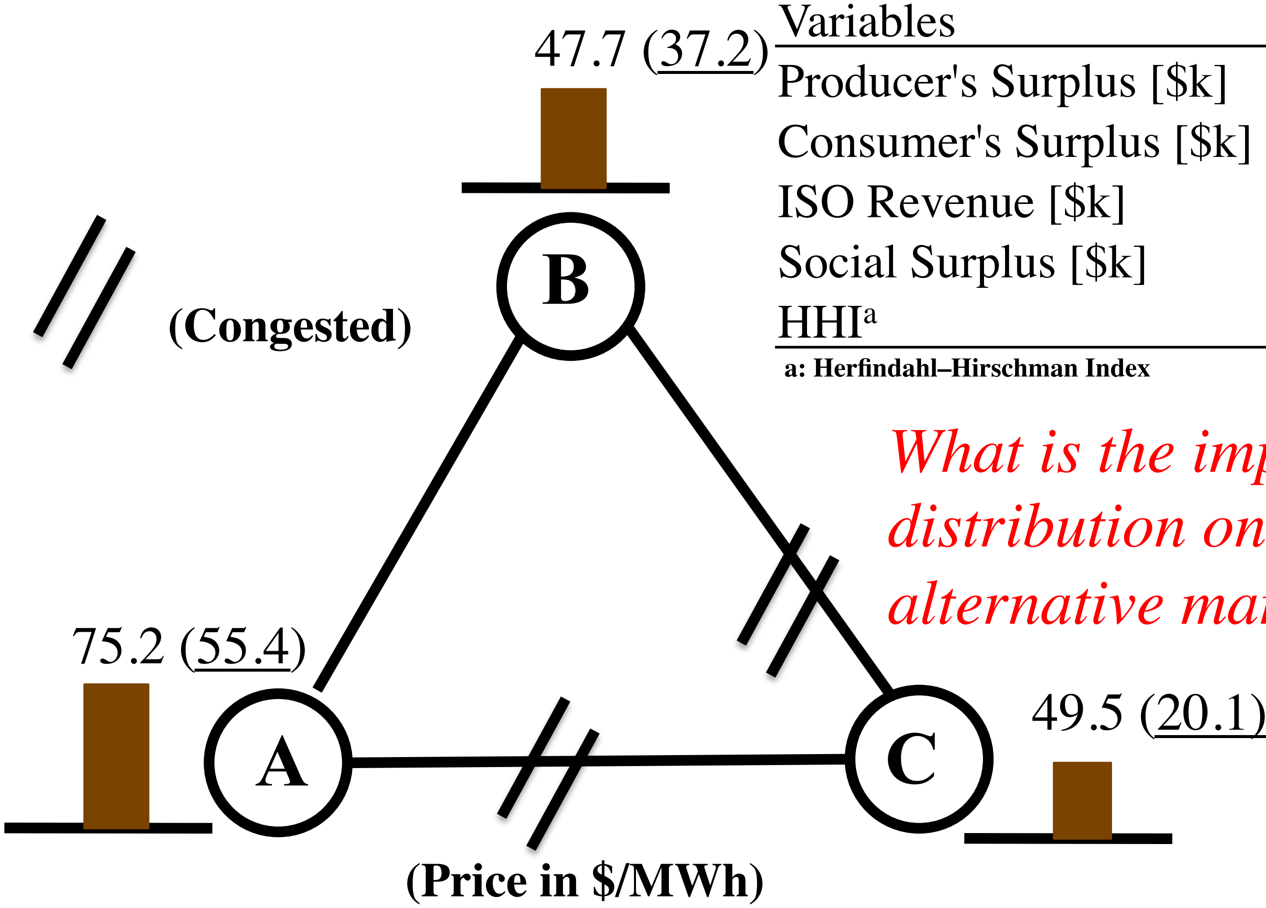

| Variables | Firm 1 | Firm 2 | Firm 3 |
|---|---|---|---|
| Producer's Surplus [$k] | 5.9 | 3.8 | 1.1 |
| Consumer's Surplus [$k] | | | 131.8 |
| ISO Revenue [$k] | | | 1.6 |
| Social Surplus [$k] | | | 153.7 |
| HHI[a] | | | 3500 |

**a: Herfindahl–Hirschman Index**

$$HHI = \sum_i (100 S_i)^2$$



# Results: Oligopoly Cournot Markets

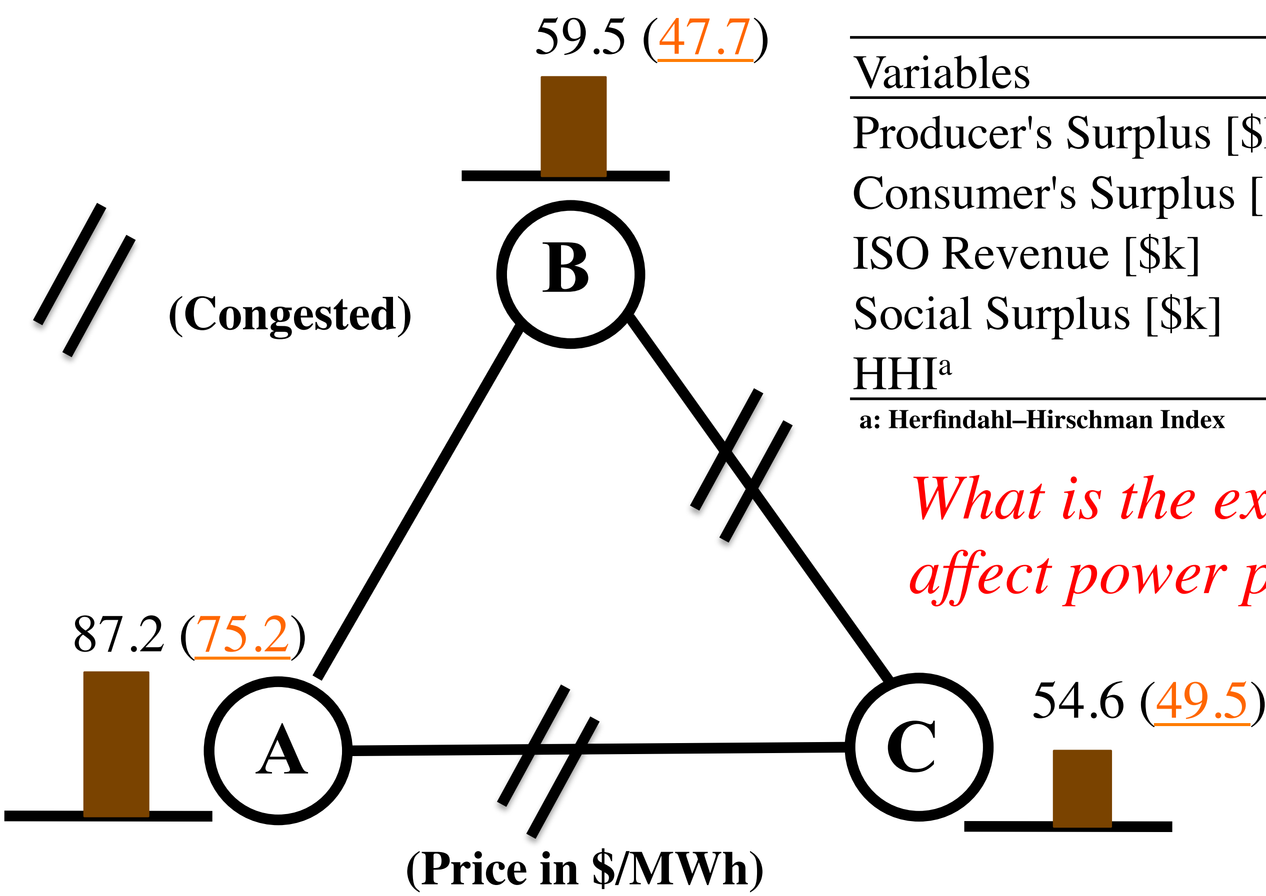



| Variables | Firm 1 | Firm 2 | Firm 3 |
|---|---|---|---|
| Producer's Surplus [$k] | 19.0 (5.9) | 13.5(3.8) | 20.7(1.1) |
| Consumer's Surplus [$k] | | | 92.1 (131.8) |
| ISO Revenue [$k] | | | 5.1 (1.6) |
| Social Surplus [$k] | | | 150.5 (153.7) |
| HHI[a] | | | 3350 (3500) |

**a: Herfindahl–Hirschman Index**

*What is the impact on power prices & distribution on surplus under an alternative market structure?*

# Results: Duopoly Markets (Merger Analysis)

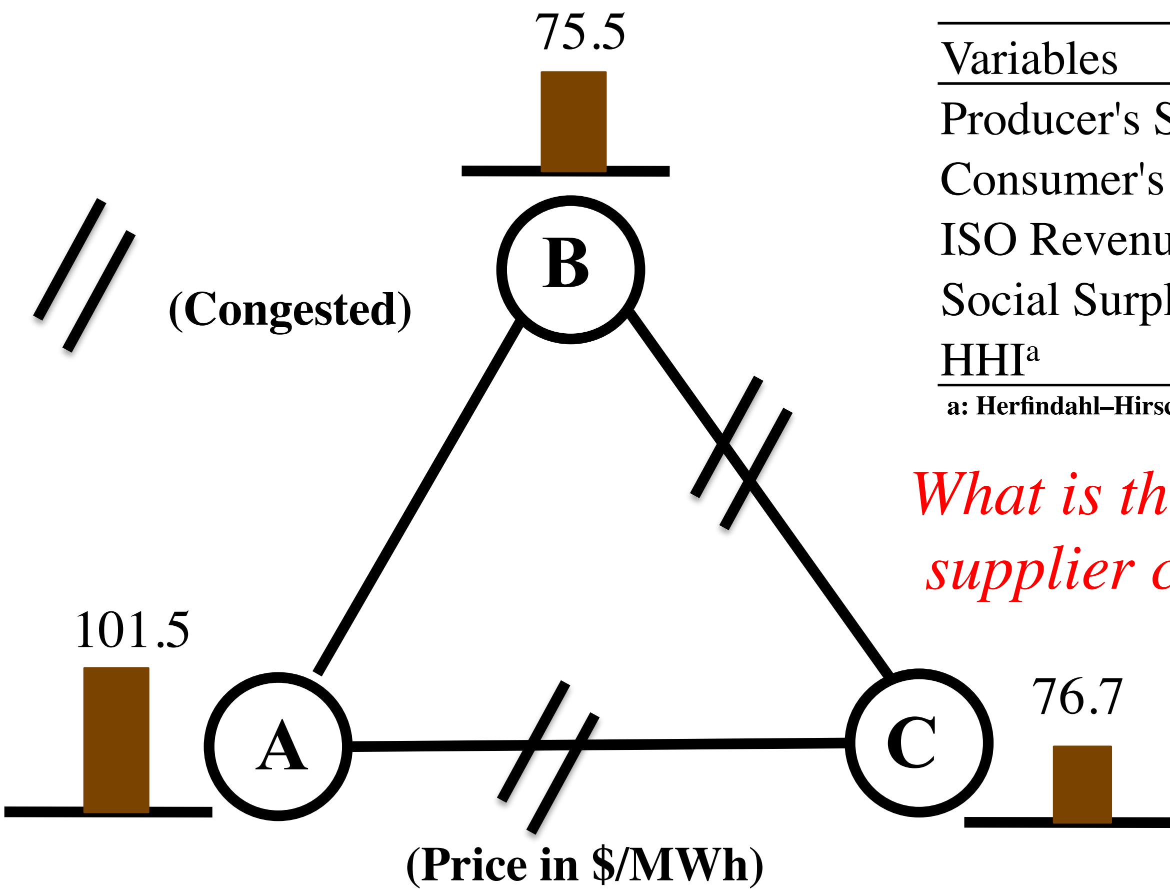



| Variables | Firm 1 | Firm 2 |
|---|---|---|
| Producer's Surplus [$k] | 27.5 | 37.2 |
| Consumer's Surplus [$k] | | 76.3 (92.1) |
| ISO Revenue [$k] | | 5.1 (5.1) |
| Social Surplus [$k] | | 145.6 (150.5) |
| HHI[a] | | 5030 (3350) |

a: Herfindahl–Hirschman Index

*What is the extent that a merge might affect power prices?*

# Results: Monopoly Markets

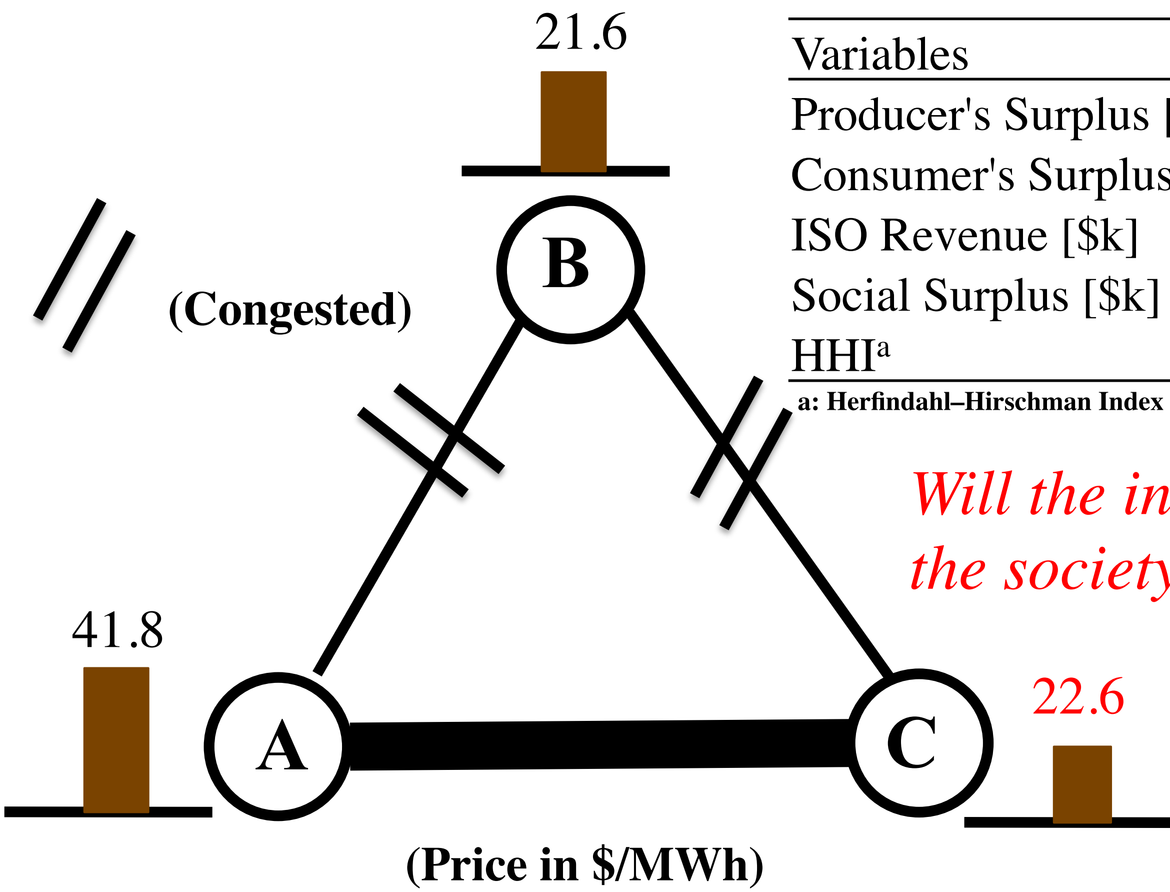



| Variables | Firm 1 |
|---|---|
| Producer's Surplus [$k] | 70.5 |
| Consumer's Surplus [$k] | 54.6 |
| ISO Revenue [$k] | 4.8 |
| Social Surplus [$k] | 129.9 |
| HHI[a] | 10000 |

**a: Herfindahl–Hirschman Index**

*What is the extent that a single supplier can exercise market power?*

# Results: Transmission Investment

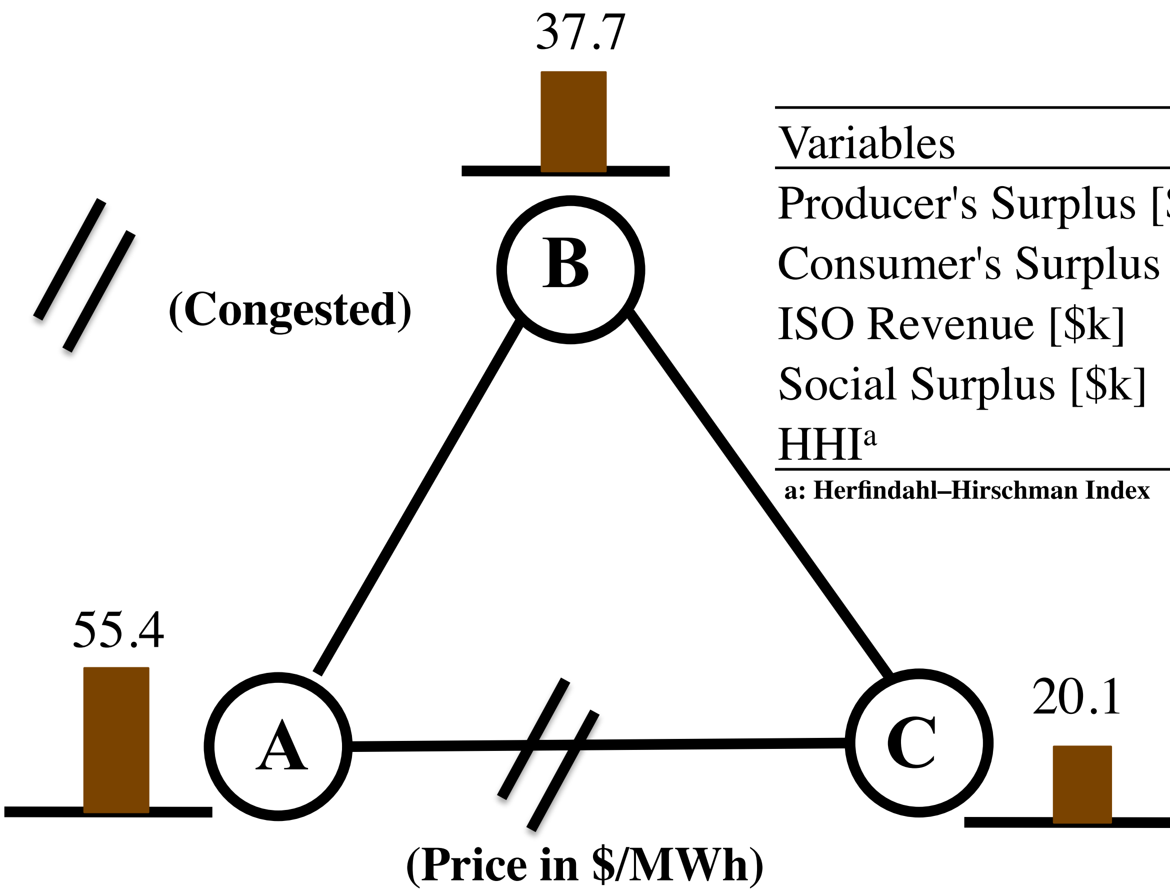



| Variables | Firm 1 | Firm 2 | Firm 3 |
|---|---|---|---|
| Producer's Surplus [$k] | 1.5 | 0.3 | 4.3 |
| Consumer's Surplus [$k] | | | 151.1 |
| ISO Revenue [$k] | | | 12.2 |
| Social Surplus [$k] | | | 153.7 |
| HHI[a] | | | 43 |

**a: Herfindahl–Hirschman Index**

*Will the investment be justified from the society's perspective?*

# Results: Competitive Market




| Variables | Firm 1 | Firm 2 | Firm 3 |
|---|---|---|---|
| Producer's Surplus [$k] | 5.9 | 3.8 | 10.6 |
| Consumer's Surplus [$k] | | | 131.8 |
| ISO Revenue [$k] | | | 1.6 |
| Social Surplus [$k] | | | 153.7 |
| HHI[a] | | | 3500 |

**a: Herfindahl–Hirschman Index**

$$HHI = \sum_i (100S_i)^2$$

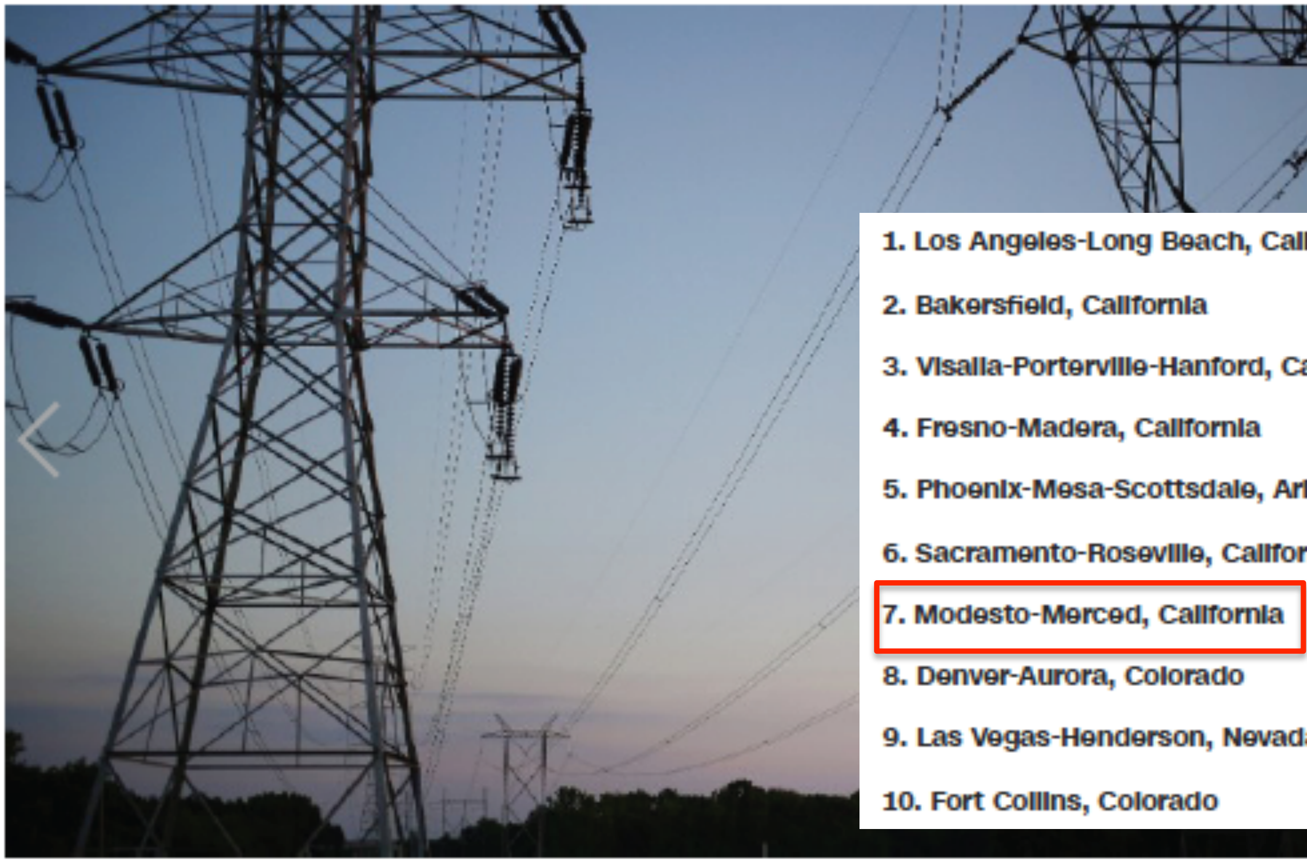
# Advantages of Process Models for Policy & Markets Analysis

- **Explicitness:**
  - assumptions can be laid bare
  - changes in technology, policies, prices, objectives can be modeled by altering:
    - decision variables
    - objective function coefficients
    - constraints
- **Descriptive uses:**
  - show detailed cost, emission, technology choice impacts of policy changes
  - show changes in market prices, consumer welfare
- **Normative:**
  - identify better solutions through use of economic models
  - show tradeoffs among policy objectives

# Other Research:
# Air Pollution & Public Transportation

## Cities with most air pollution revealed

By Jareen Imam, CNN
Updated 4:59 PM ET, Wed April 20, 2016




10 photos: What's causing climate change? Meet the top 10 villains

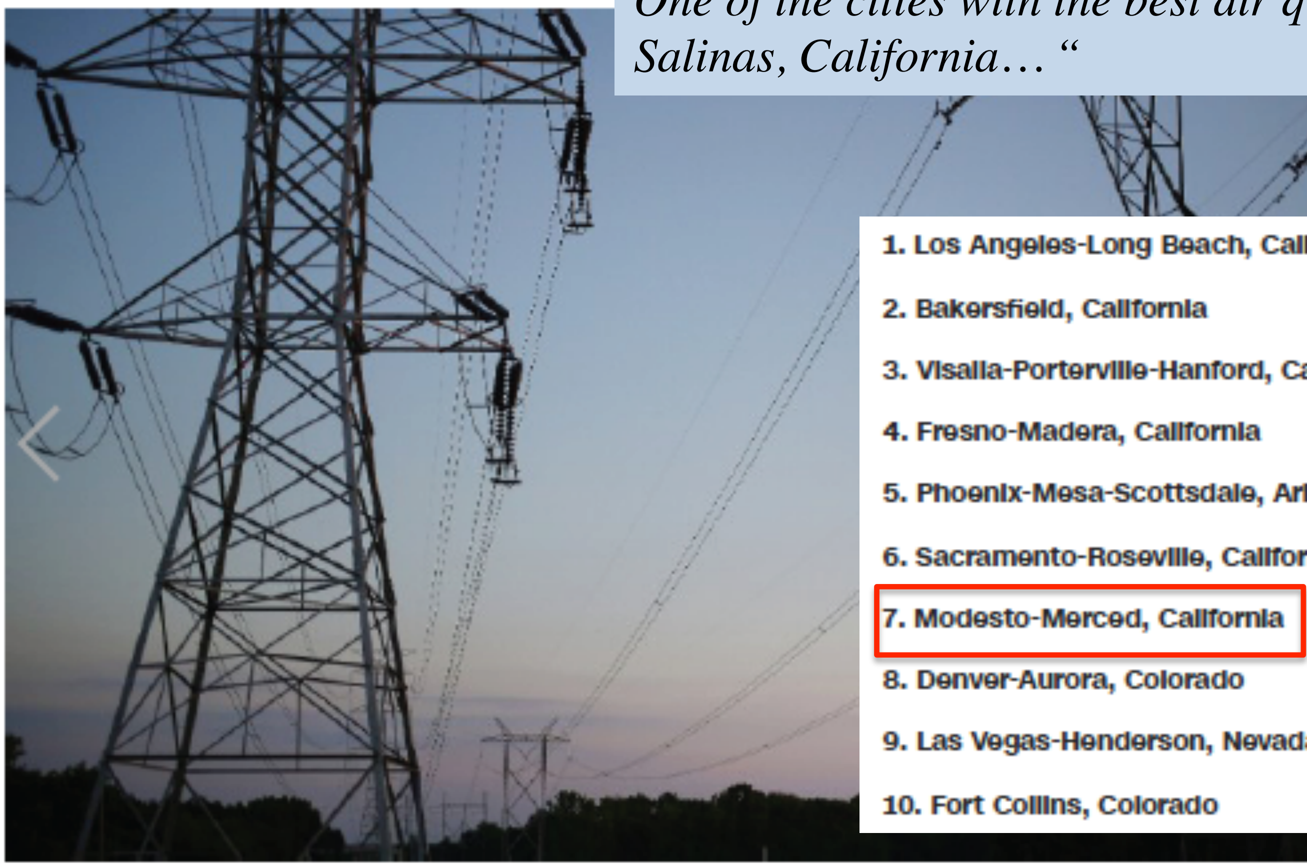
http://www.cnn.com/2016/04/20/health/air-pollution-report-irpt/index.html

# Other Research:
# Air Pollution & Public Transportation

## Cities with most air pollution revealed

By Jareen Imam, CNN
Updated 4:59 PM ET, Wed April 20, 2016

*George Thurston, professor of Environmental Medicine at New York University stated " … One of the cities with the best air quality is Salinas, California… "*



1. Los Angeles-Long Beach, California
2. Bakersfield, California
3. Visalia-Porterville-Hanford, California
4. Fresno-Madera, California
5. Phoenix-Mesa-Scottsdale, Arizona
6. Sacramento-Roseville, California
7. Modesto-Merced, California
8. Denver-Aurora, Colorado
9. Las Vegas-Henderson, Nevada
10. Fort Collins, Colorado

10 photos: What's causing climate change? Meet the top 10 villains

http://www.cnn.com/2016/04/20/health/air-pollution-report-irpt/index.html

# Other Research:
# Air Pollution & Public Transportation

*American Economic Journal: Economic Policy 2012, 4(1): 58–97*
*http://dx.doi.org/10.1257/pol.4.1.58*

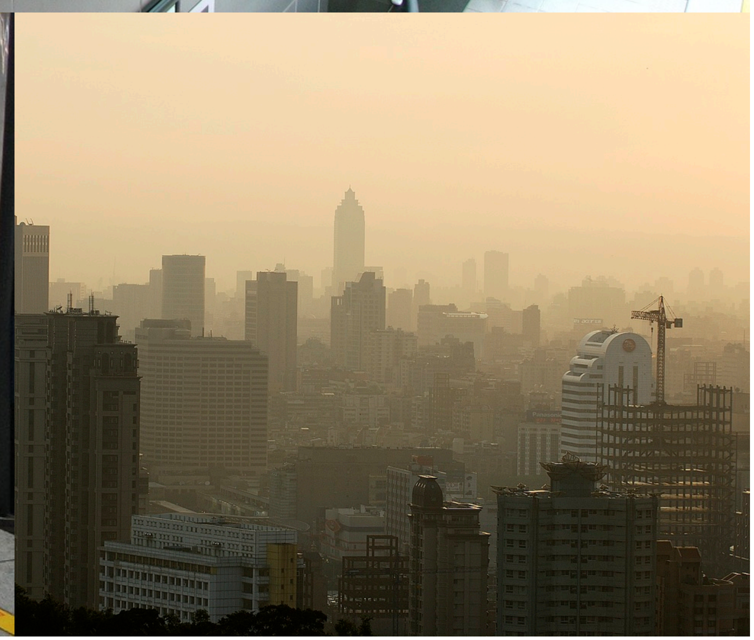
## Green Infrastructure: The Effects of Urban Rail Transit on Air Quality†

*By* Yihsu Chen and Alexander Whalley*

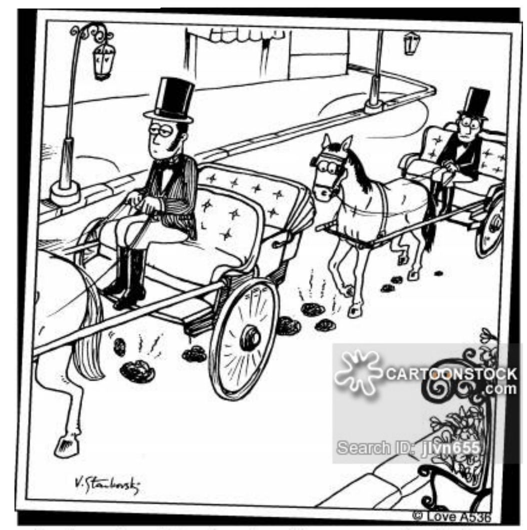
*The transportation sector is a major source of air pollution worldwide, yet little is known about the effects of transportation infrastructure on air quality. This paper quantifies the effects of one major type of transportation infrastructure—urban rail transit—on air quality using the sharp discontinuity in ridership on opening day of a new rail transit system in Taipei. We find that the opening of the Metro reduced air pollution from one key tailpipe pollutant, carbon monoxide, by 5 to 15 percent. Little evidence that the opening of the Metro affected ground level ozone pollution is found however.* (*JEL* L92, Q53, R41, R53)


652
421-AB
888-FA


劇魅影捷運1 17:47



# Motivation



And you thought exhaust problems were bad today.

- Mass Transit sector is very large and growing:
  - 155 million people ride mass transit everyday in 110 cities.
  - 25 mass transit systems are currently under expansion or construction worldwide
  - Since 2000 – 37 new systems have opened.
  - Seen as potential 'Green' Policy: Beijing to become 'Public transit city'
- Travel by mass transit produces significantly less pollution than private vehicle travel per mile.
- We know little about the impact of of urban mass transit on air pollution, as the size of two key elasticities is not clear:
  - Substitution towards low-emissions travel
  - Substitution towards total travel

# Research Questions

- Does urban mass transit infrastructure effect air quality?

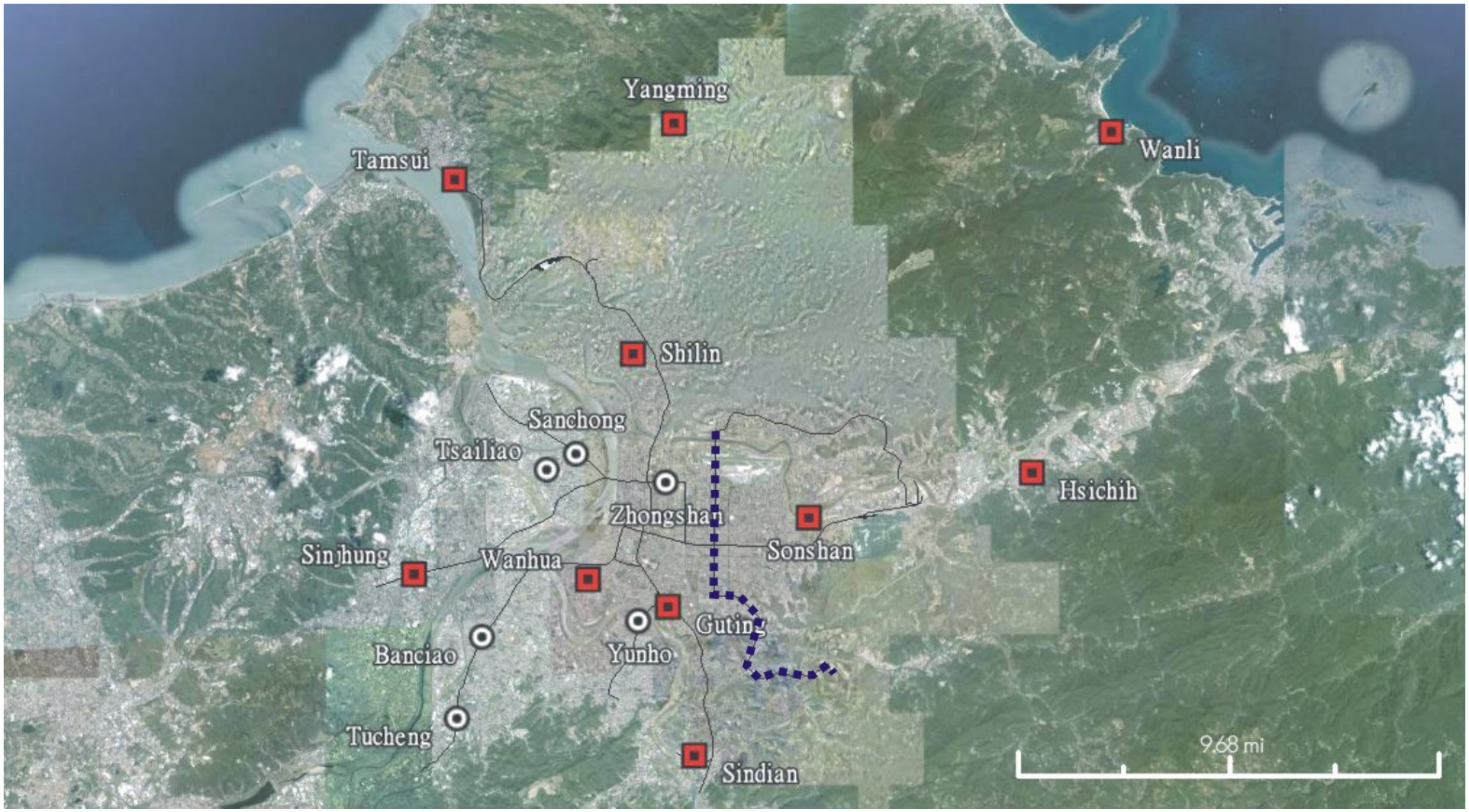
- How do tailpipe and indirect pollutants respond?

- How big are the effects and their economic benefits?

# What We Do

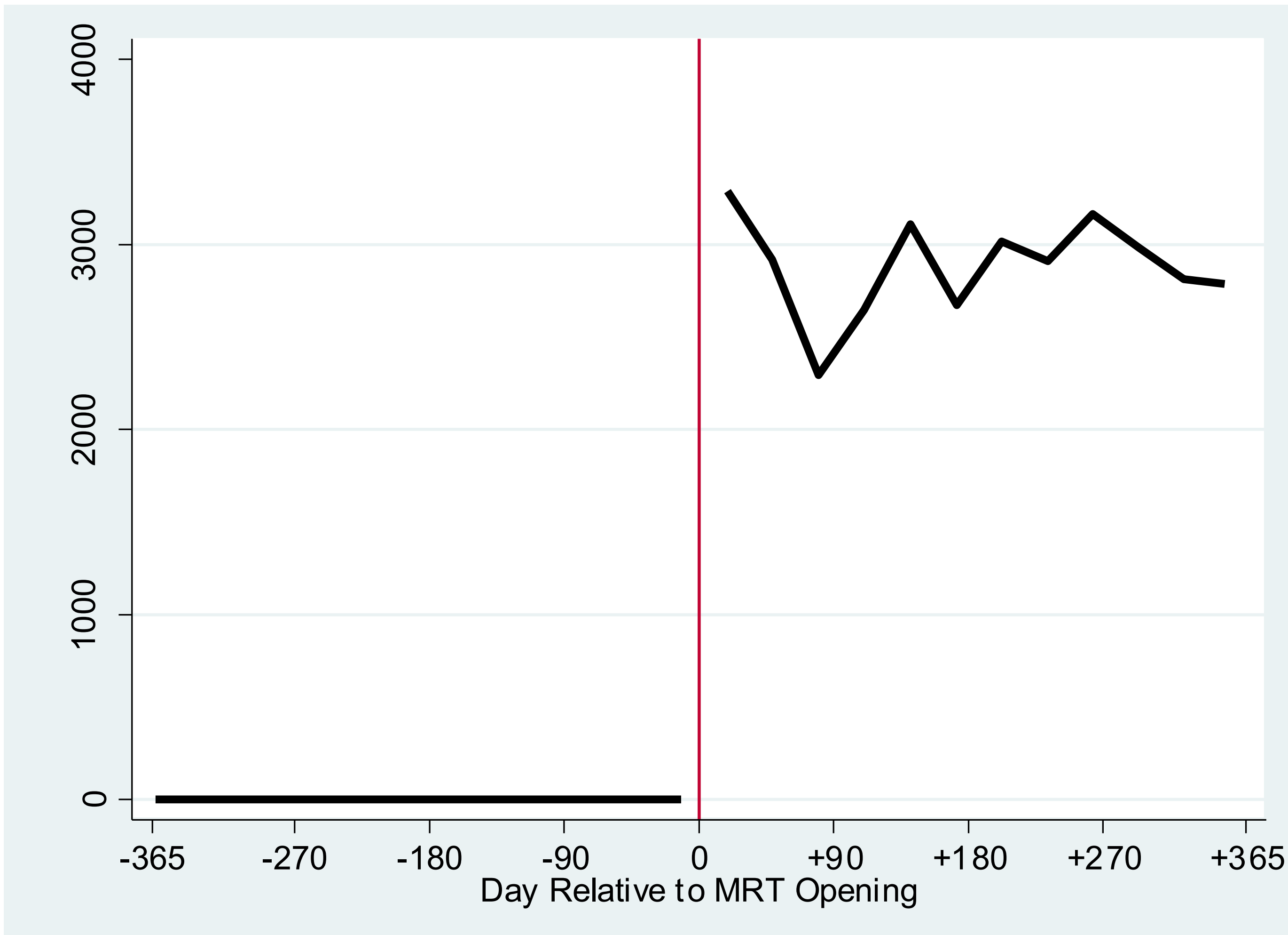
- Study the effects of the opening of the Metropolitan Rapid Transit (MRT) system in 1996 in Taipei
- Quantify the effects of the opening of the MRT on air quality

# Map of Monitoring Stations and Metropolitan Rapid Transit System in Taipei



# Map of Metropolitan Rapid Transit System in Taipei

# Other Research:
# Air Pollution & Public Transportation



# Empirical Approach

Regression Discontinuity Based Specification:

$$y_t = \delta_0 + \delta_1 MetroOpen_t + \delta_2 \mathbf{x}_t + \delta_3 \mathbf{P(t)} + \delta_4 \mathbf{P(t)} \times MetroOpen_t + e_t$$

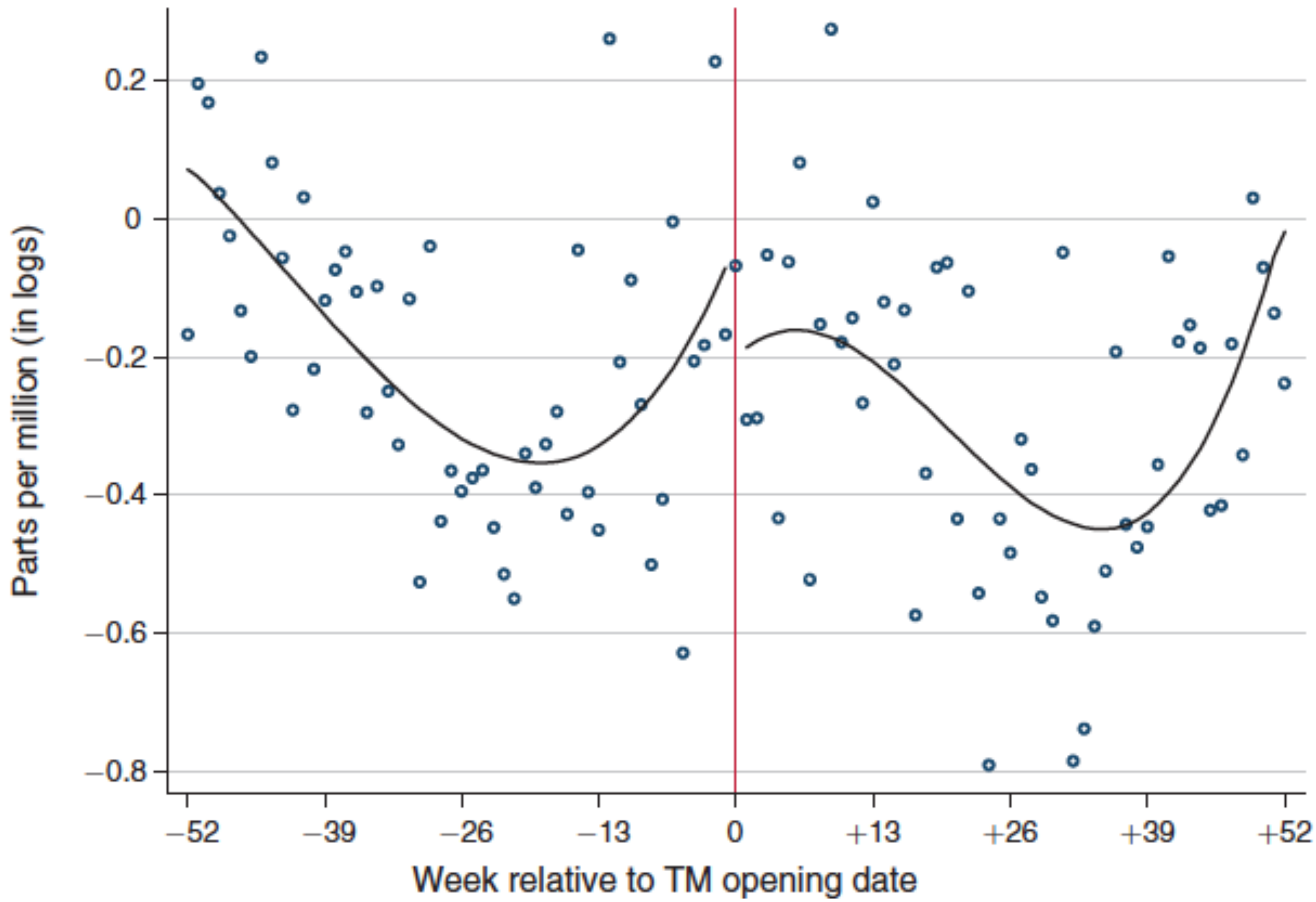
$y_t$ = pollution outcome in log scale
$MetroOpen_t$ = MRT open
$x_t$ = regulation, humidity, wind and temperature controls
$P(t)$ = 3rd Order Polynomial time trend

- cluster standard errors at 5 week level

# Results: Main Regressions

| Dependent variable: | Log(CO) | Log($NO_x$) | Log($O_3$) |
|---|---|---|---|
| Model: | DB-OLS | DB-OLS | DB-OLS |
| | (1) | 2) | (3) |
| Taipei Metro Open | −0.156** (0.059) | −0.083 (0.052) | −0.037 (0.063) |
| Observations | 17,076 | 16,466 | 17,070 |

# CO Mean Daily Pollution Level in Taipei, Polynomial Time Trend



# Results: Falsification Tests

| City: | Taipei | East coast | Kaohsiung |
|---|---|---|---|
| Model: | DB-OLS | DB-OLS | DB-OLS |
| | (1) | (2) | (3) |
| *Dependent variable =* | | | |
| Log(PM10) | 0.041 | | |
| | (0.141) | | |
| Log($SO_2$) | –0.249 | | |
| | (0.199) | | |
| Log(CO) | | 0.088 | –0.037 |
| | | (0.096) | (0.052) |
| Log($NO_x$) | | 0.062 | –0.085 |
| | | (0.058) | (0.057) |
| Log($O_3$) | | 0.165 | 0.056 |
| | | (0.225) | (0.221) |

# MRT Health Benefits

MRT leads health effects valued at $85 million USD the first year

1) CO↓ 1ppm, infant mortality ↓2.5% (Currie, et *al*., 2008)
2) Value per life: 1.2 million USD (Liu and Hammit 1999)

➔1.7 infant lives saved, $8.6 million USD

(=0.834ppm×0.156×0.025×0.00666×77029)

➔(speculative) 58 elderly lives saved, $76.4 million USD

3) Total benefits = $85 million USD
4) Per passenger-mile benefit ($) $\frac{8.6M}{40,000 \times 365 \times 9.3} = 0.063$

# Other Research:
# Biofuel -- Environment & Economics

nature climate change

LETTERS

PUBLISHED ONLINE: 11 DECEMBER 2011 | DOI: 10.1038/NCLIMATE1325

## Increased estimates of air-pollution emission from Brazilian sugar-cane ethanol

C-C. Tsao[1], J. E. Campbell[1]*, M. Mena-Carrasco[2], S. N. Spak[3], G. R. Carmichael[3] and Y. Chen

**Accelerating biofuel production has been promoted as an opportunity to enhance energy security, offset greenhouse-gas emissions and support rural economies. However, large uncertainties remain in the impacts of biofuels on air quality and climate[1,2]. Sugar-cane ethanol is one of the most widely used biofuels, and Brazil is its largest producer[3]. Here we use a life-cycle approach to produce spatially and temporally explicit estimates of air-pollutant emissions over the whole life cycle of sugar-cane ethanol in Brazil. We show that even in regions where pre-harvest field burning has been eliminated on half the croplands, regional emissions of air pollutants continue to increase owing to the expansion of sugar-cane growing areas, and burning continues to be the dominant life-cycle stage for emissions. Comparison of our estimates of burning-phase emissions with satellite estimates of burning in São Paulo state suggests that sugar-cane field burning is not fully accounted for in satellite-based inventories, owing to the small spatial scale of individual fires. Accounting for this effect leads to revised regional estimates of burned area that are four times greater than some previous estimates. Our revised emissions maps thus suggest that biofuels may have larger impacts on regional climate forcing and human health than previously thought.**

Air-pollutant emissions from biofuel production and combustion may have significant impacts on climate and air quality. The change in vehicle emissions that would result from a large-scale conversion from gasoline to E85 (a blend of up to 85% ethanol with gasoline or another hydrocarbon) in the United States could have significant health consequences, by increasing tropospheric ozone concentrations[4], for example. Monetizing the health and climate impacts of US ethanol emissions (fuel production and

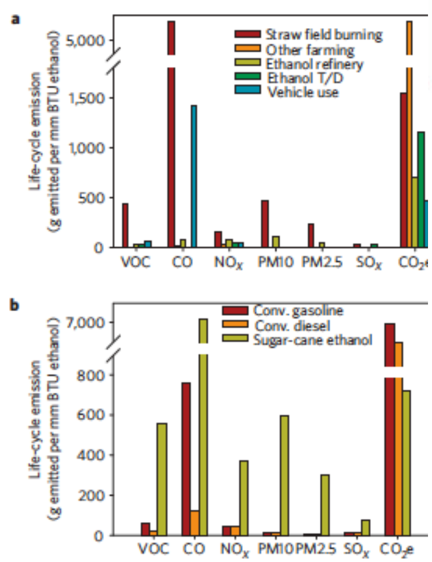
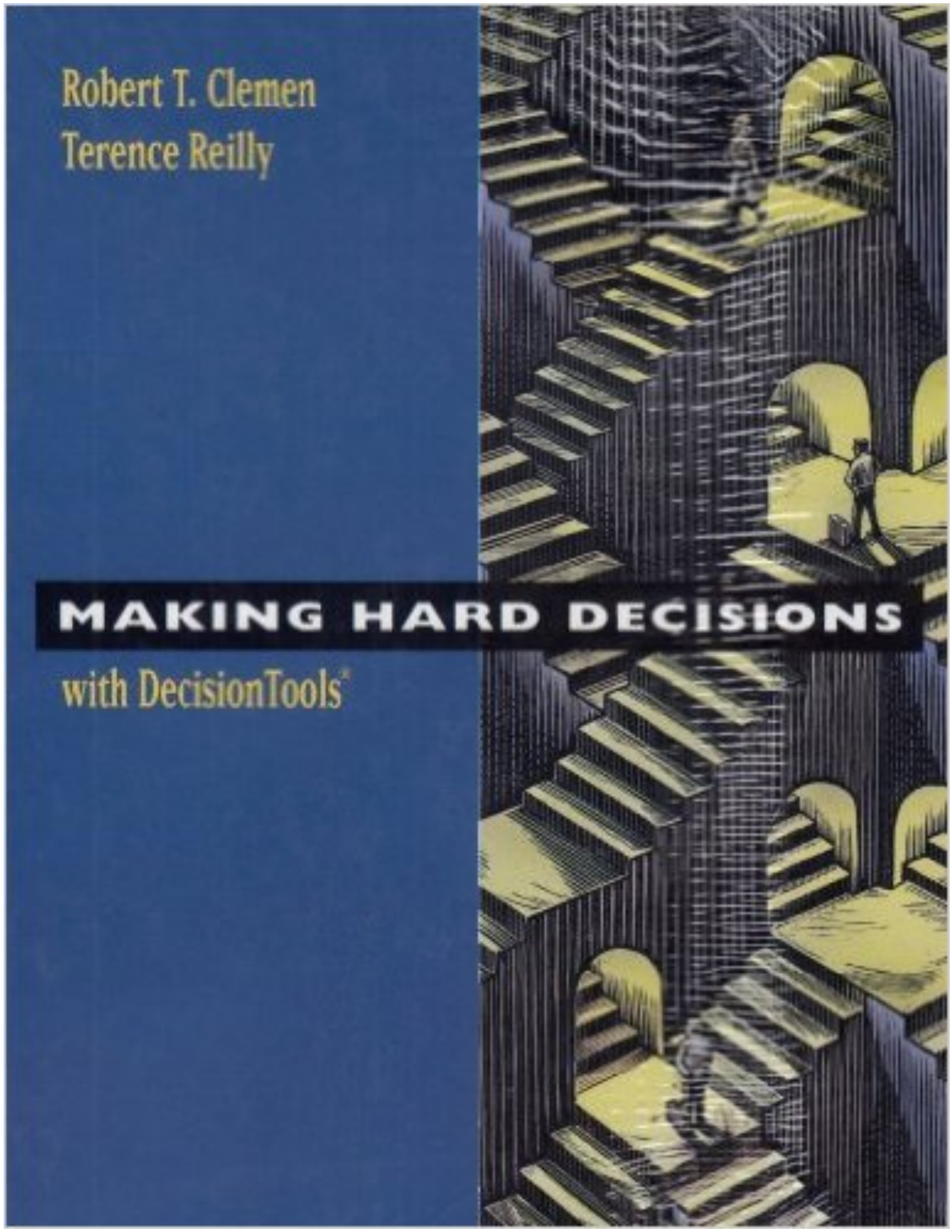



**Figure 1 | Comparisons of life-cycle emissions for sugar-ca[ne] Brazil and conventional liquid fuels. a,** Life-cycle emissions per unit energy of sugar-cane ethanol produced within five life-cycle phases. Although our life-cycle emissions account for a mix of sugar-cane fields where the burning practice is used and not used, the burning-phase emissions shown

Biofuels Supply Chain


| Feedstock production | Feedstock logistics | Conversion | Distribution | End use |
|---|---|---|---|---|
| • Agricultural crops<br>• Agricultural residues<br>• Energy crops<br>• Forest residues<br>• Wastes | Harvesting and Collection<br>Storage<br>Preprocessing<br>Transportation | **Biochemical conversion**<br>-Acid hydrolysis<br>-Pretreatment and enzymatic hydrolysis<br>-Fermentation<br>**Thermochemical Conversion**<br>-Gasification<br>-Pyrolysis<br>-Hydrothermal depolymerisation<br>**Chemical -**<br>Transesterification | **Transporation-**<br>Truck, Rail, Pipeline<br>**Storage-**<br>Blending terminals<br>**Dispensing-**<br>Dedicated pumps, Blending pumps | • Light duty vehicles<br>• Light duty trucks<br>• Heavy duty trucks<br>• Off road vehicles<br>• Locomotives<br>• Airplanes<br>• Jets<br>• Boats<br>• Ships etc. |




# TIM 165

# Decision Analysis

Coming soon in UCSC
Fall, 2016


**Thank you!**

**Yihsu Chen, Ph.D.**
**Email: yihsuchen@ucsc.edu**