Imperial College London
BUSINESS SCHOOL

Investing for a low-carbon electricity system

Richard Green

9 January 2013

Imperial College London
BUSINESS SCHOOL

Menu

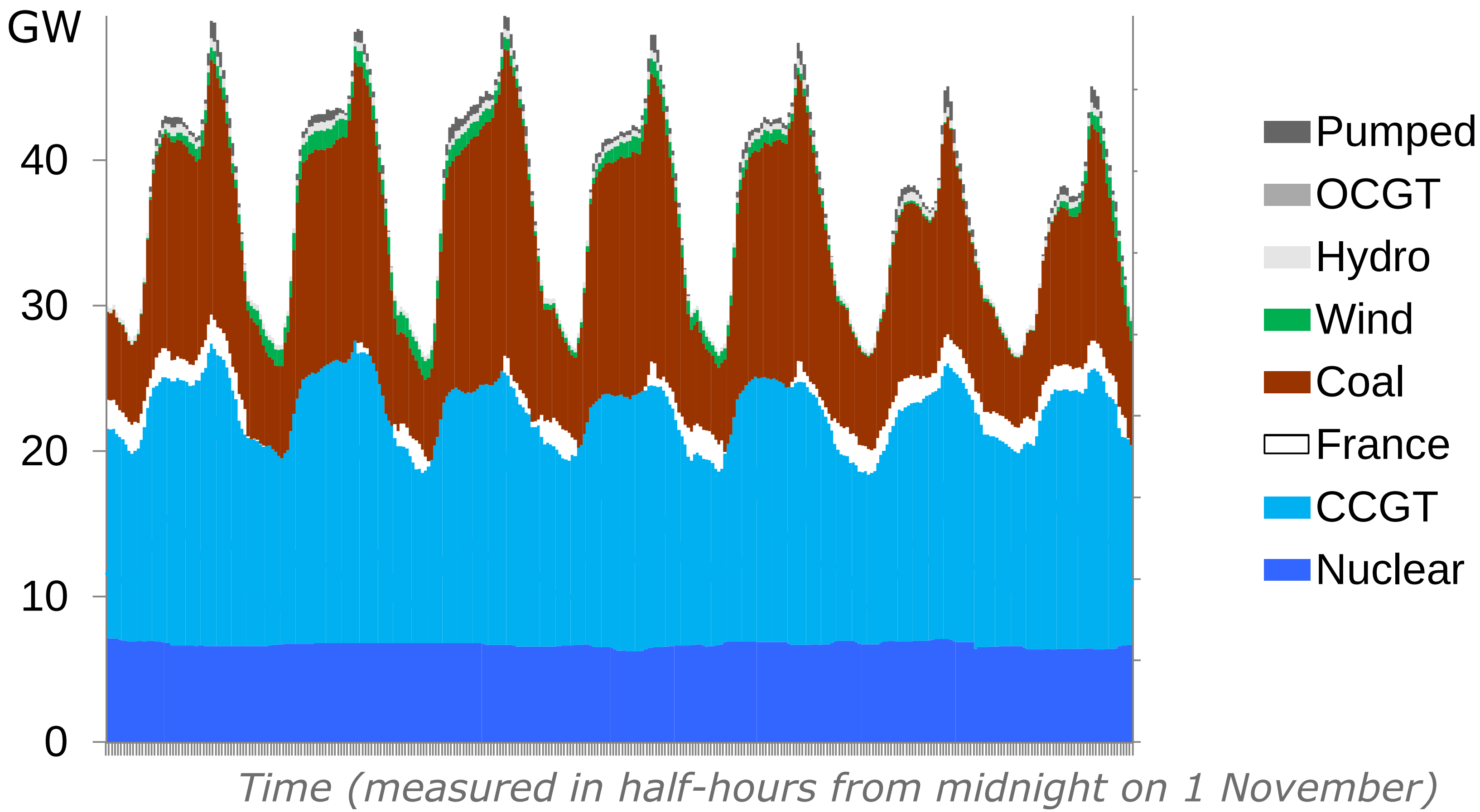
- Characteristics of electricity and wind
- Competitive equilibrium in prices and investment
- Strategic equilbrium in prices and investment
- The impact of simplified modelling
- An optimal portfolio of wind plants
- Policy measures for low-carbon generation in the UK

Main source paper:

- R. Green and N. Vasilakos, ñThe long-term impact of wind power on electricity prices and generation capacityò

Imperial College London BUSINESS SCHOOL

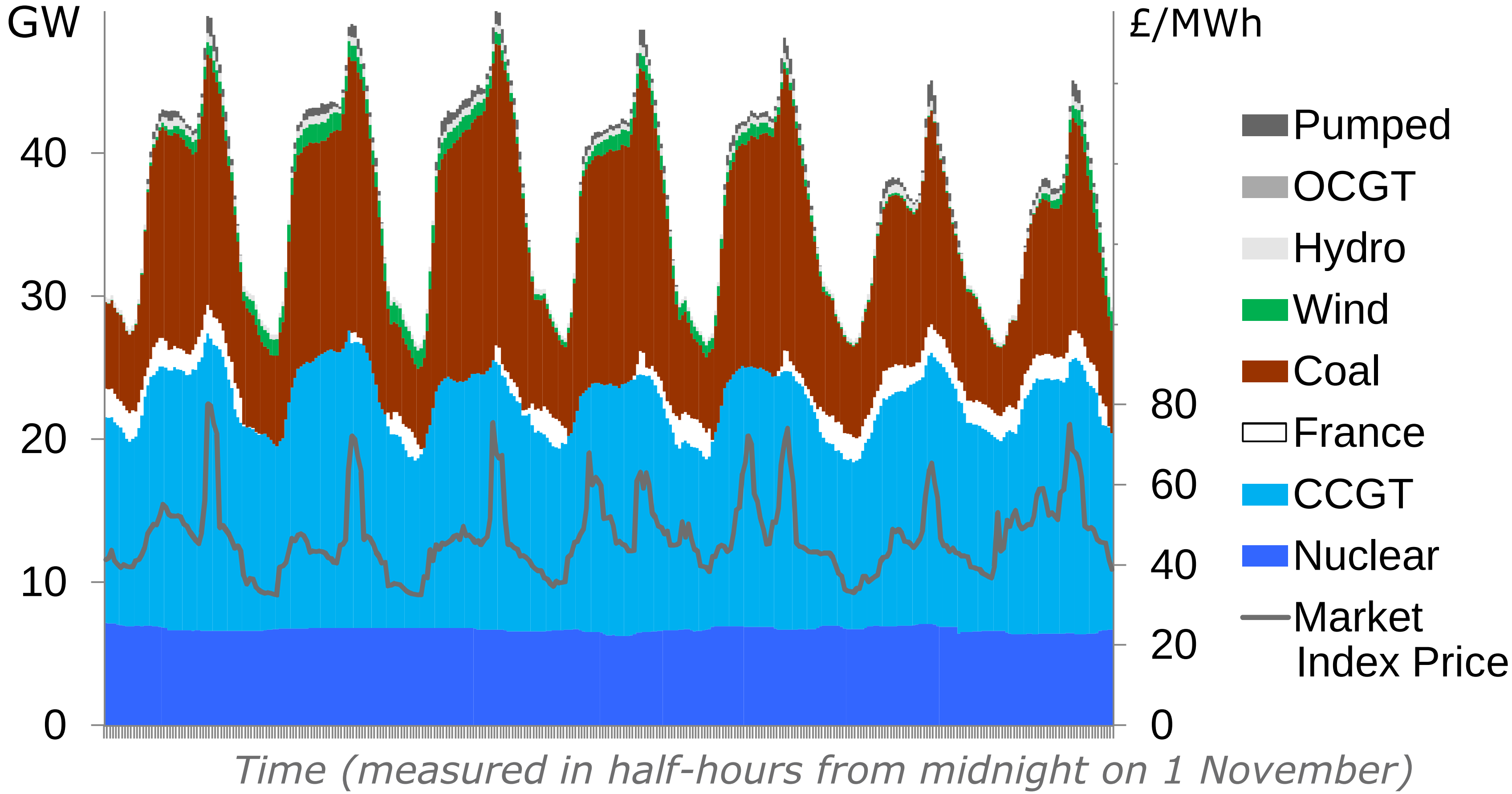
Generation in Great Britain, 1-7 November 2011



Source: Elexon

Imperial College London
BUSINESS SCHOOL

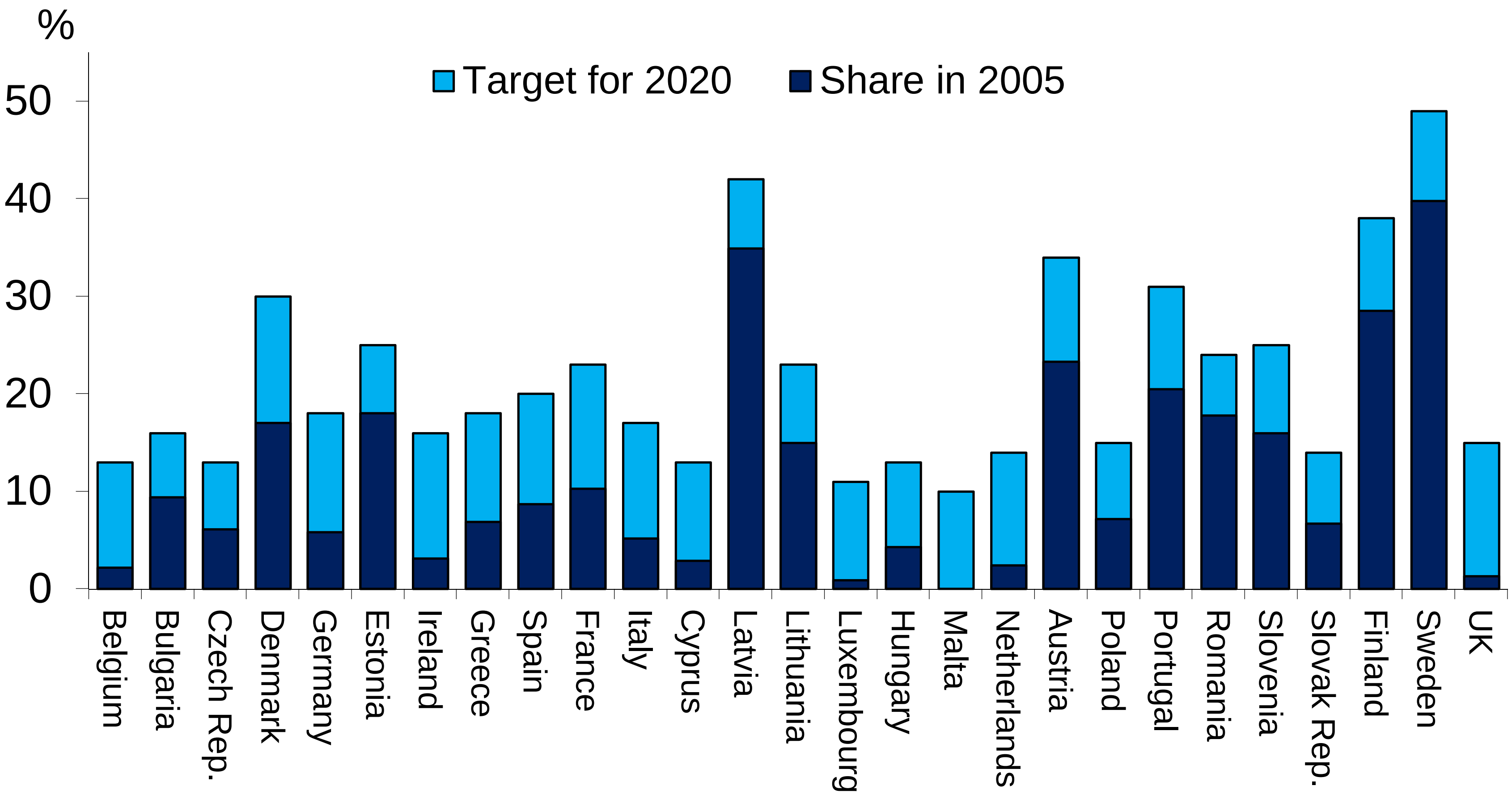
Generation in Great Britain, 1-7 November 2011



Source: Elexon

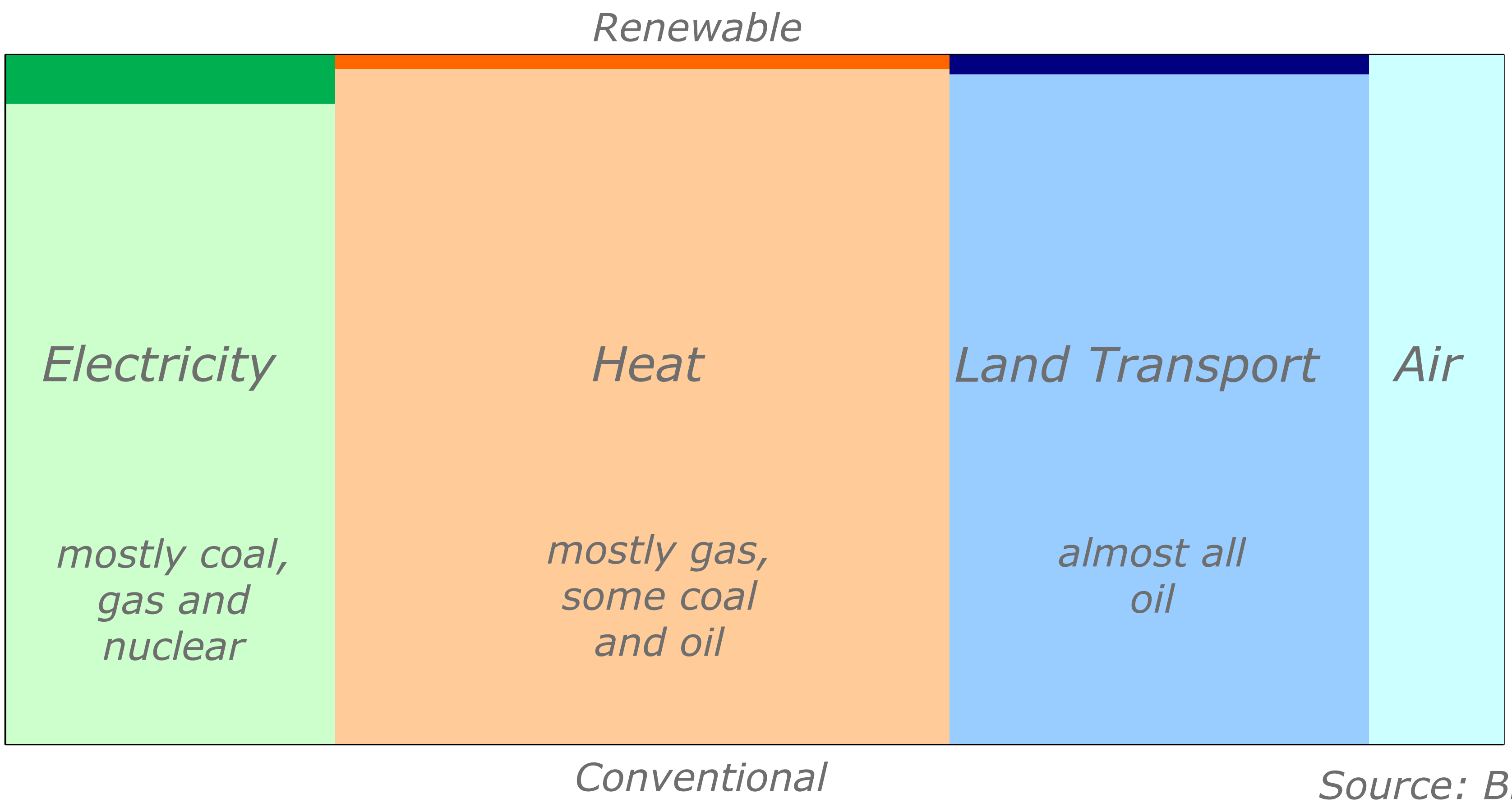
Imperial College London
BUSINESS SCHOOL

The 20-20-20 2020 Targets



Imperial College London
BUSINESS SCHOOL

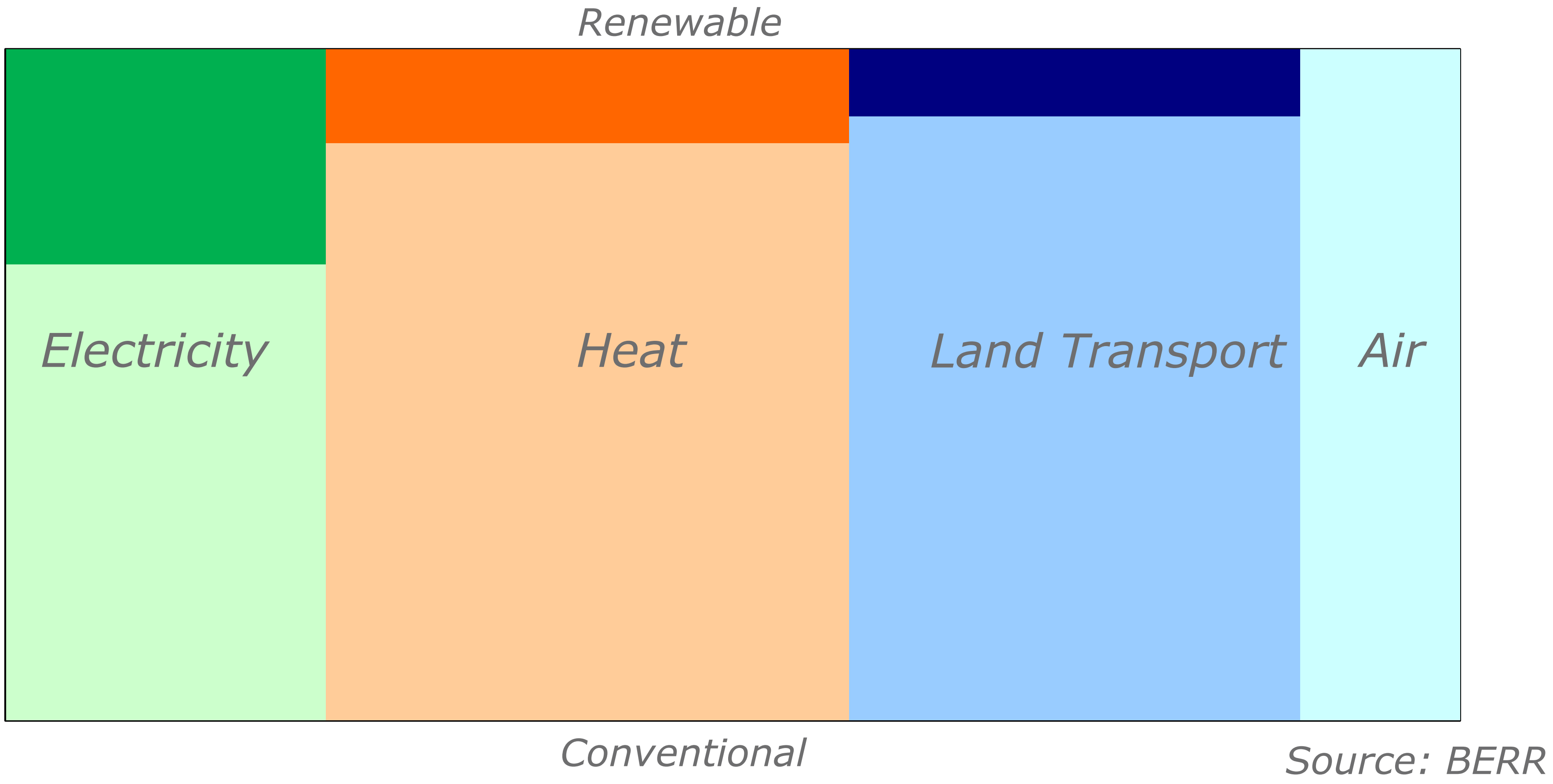
UK Energy in 2010



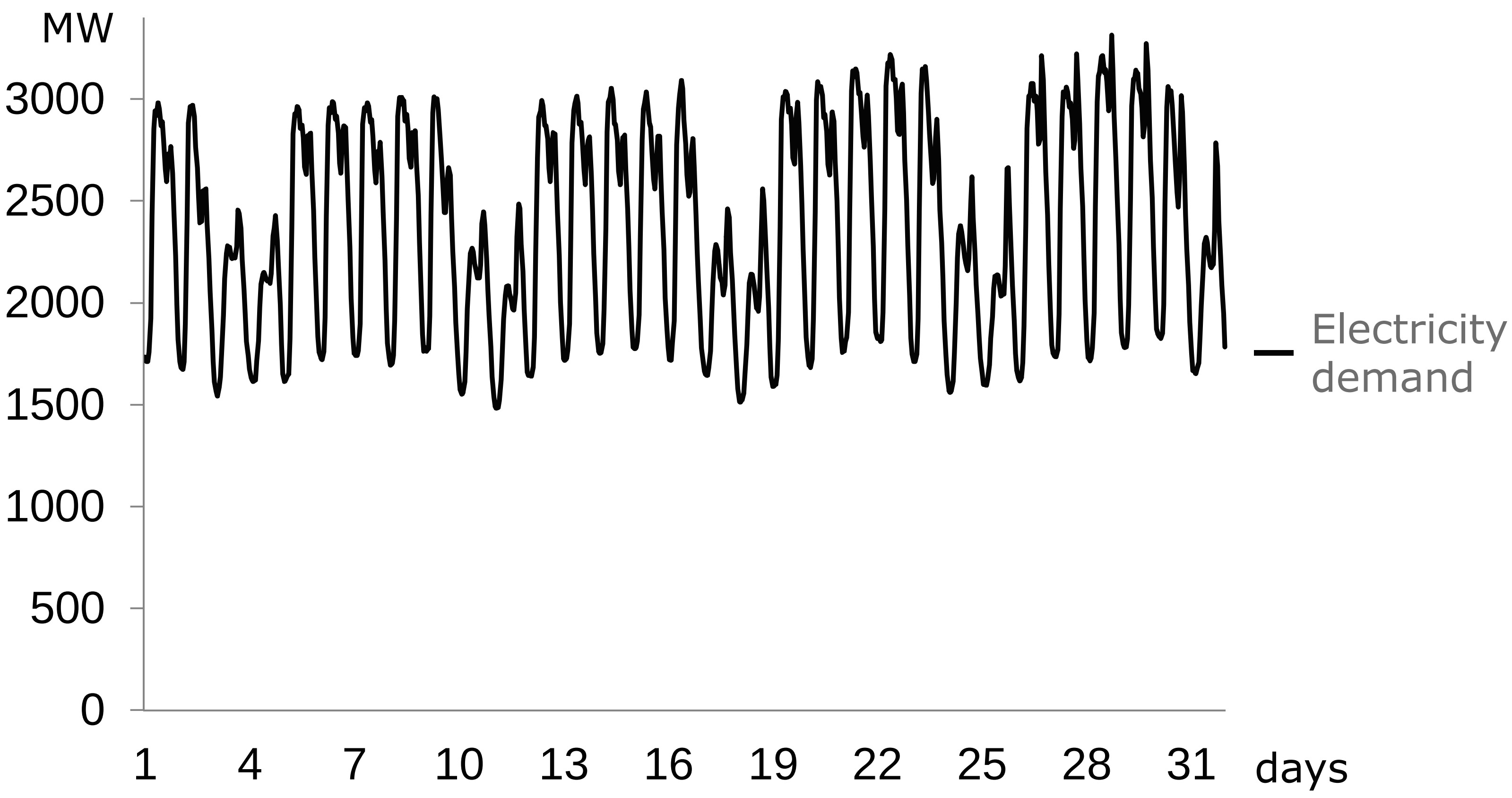
Source: BERR

Imperial College London
BUSINESS SCHOOL

UK Energy in 2020 (?)

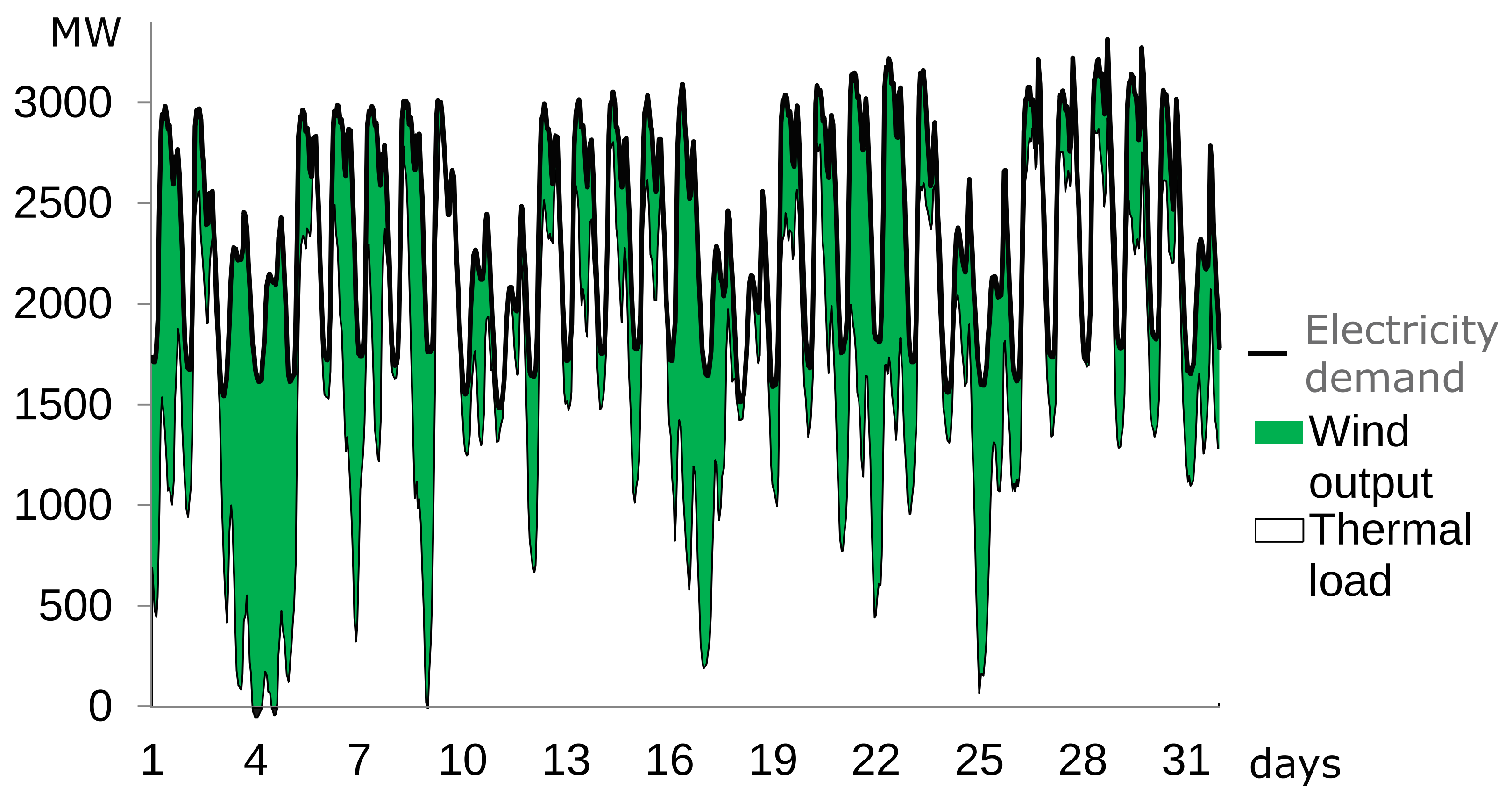


Western Denmark, October 2009

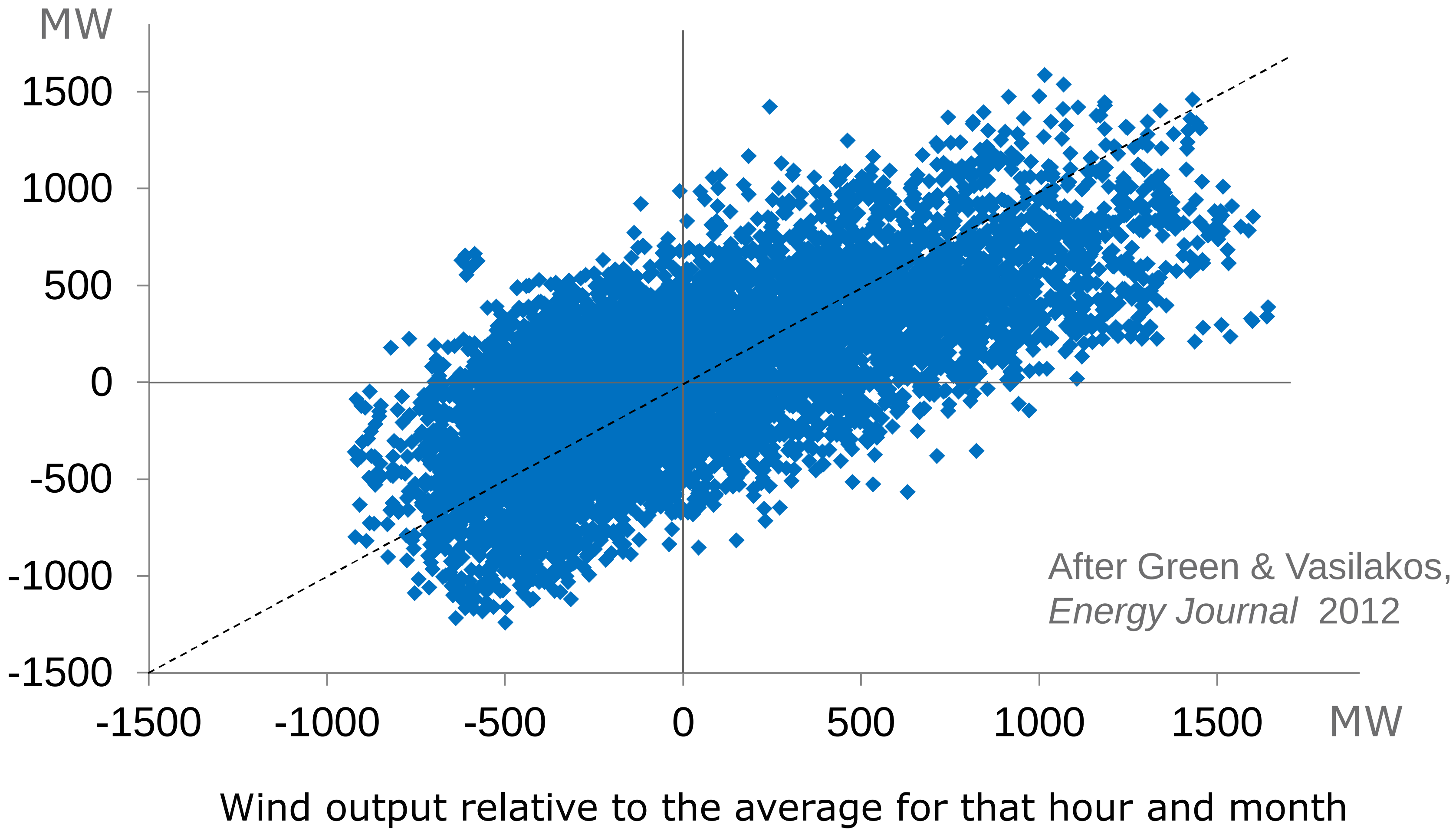


Imperial College London BUSINESS SCHOOL

Western Denmark, October 2009



West Denmark's net electricity exports, relative to average



But what if there isnđt enough transmissioné ?

- Denmark has a peak demand of c. 6 GW and interconnectors totalling c. 5 GW
- Great Britain has a peak demand of c. 60 GW and interconnectors totalling

- What is the optimal mix of generation and transmission investment?
- What price signals can bring it about?

- This paper just looks at generation, howeveré

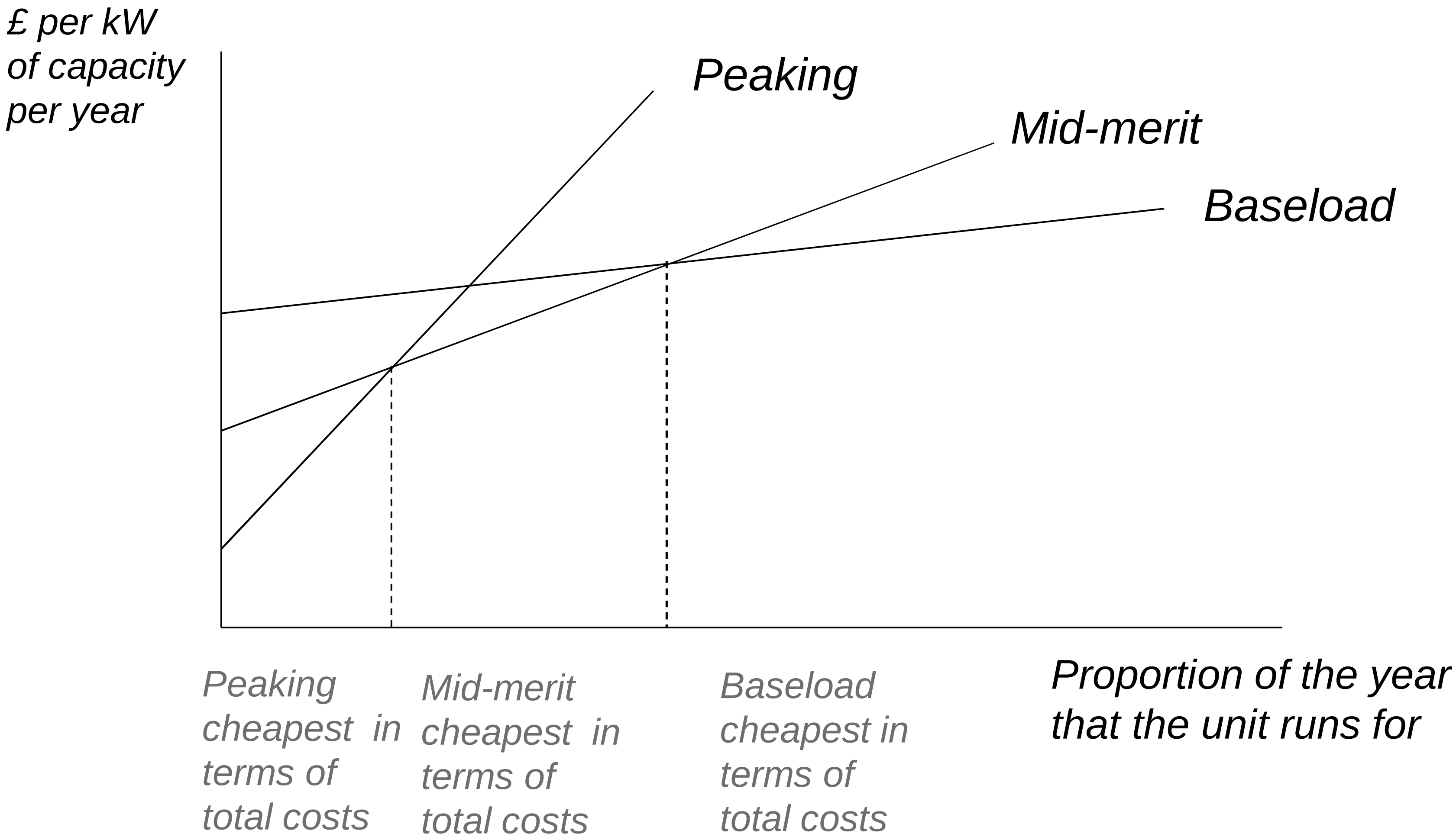
Imperial College London
BUSINESS SCHOOL

How does wind affect prices?

- Volatility linked to output variations
- Additional capacity depresses prices (ñthe merit-order effectò)
  - Sensfuß et al (*Energy Policy,* 2008) ï Germany
  - Sáenz de Miera et al (*Energy Policy,* 2008) ï Spain
- Price patterns affect optimal capacity mix

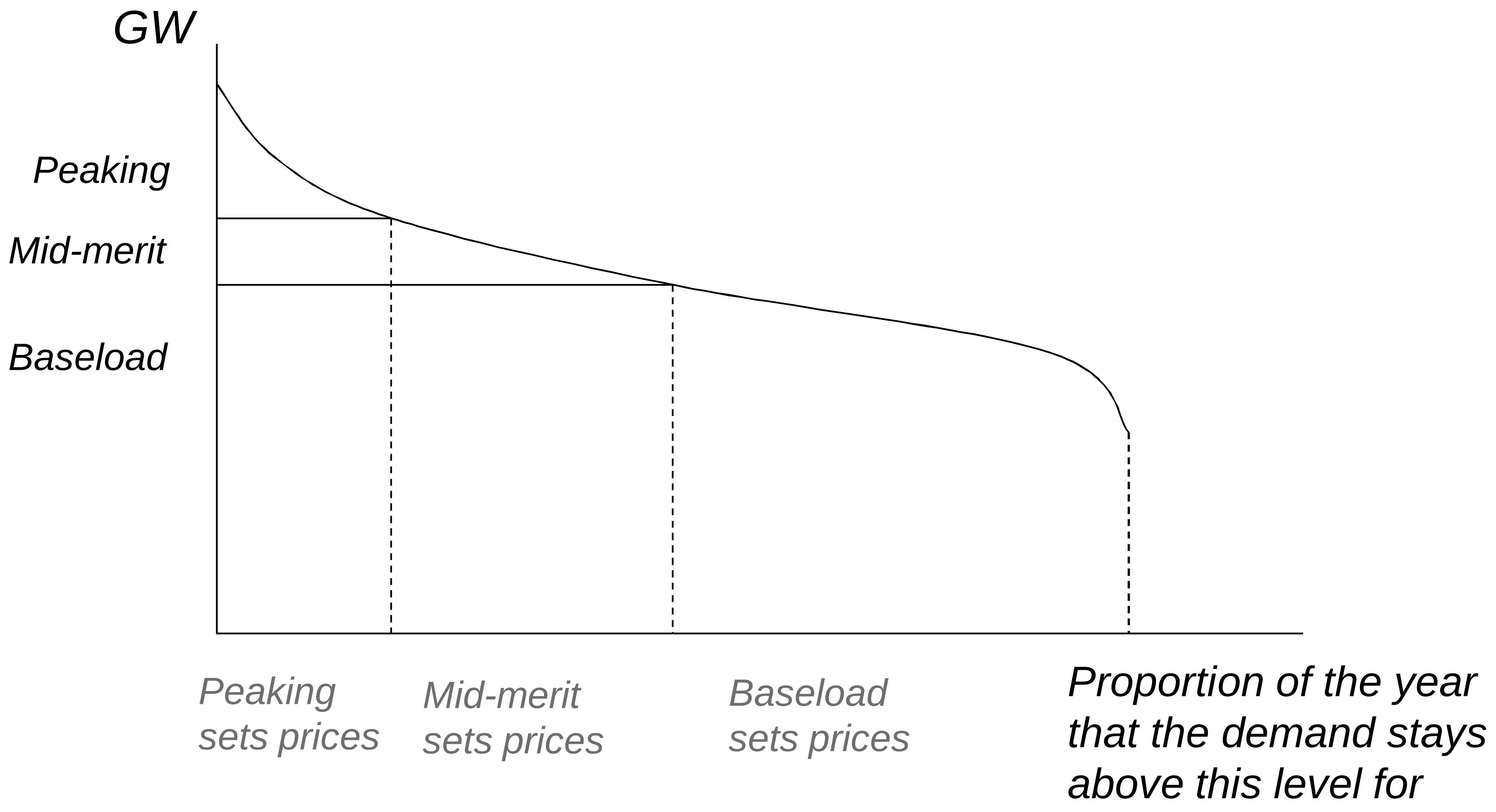
Imperial College London
BUSINESS SCHOOL

Generating technologies and their total costs

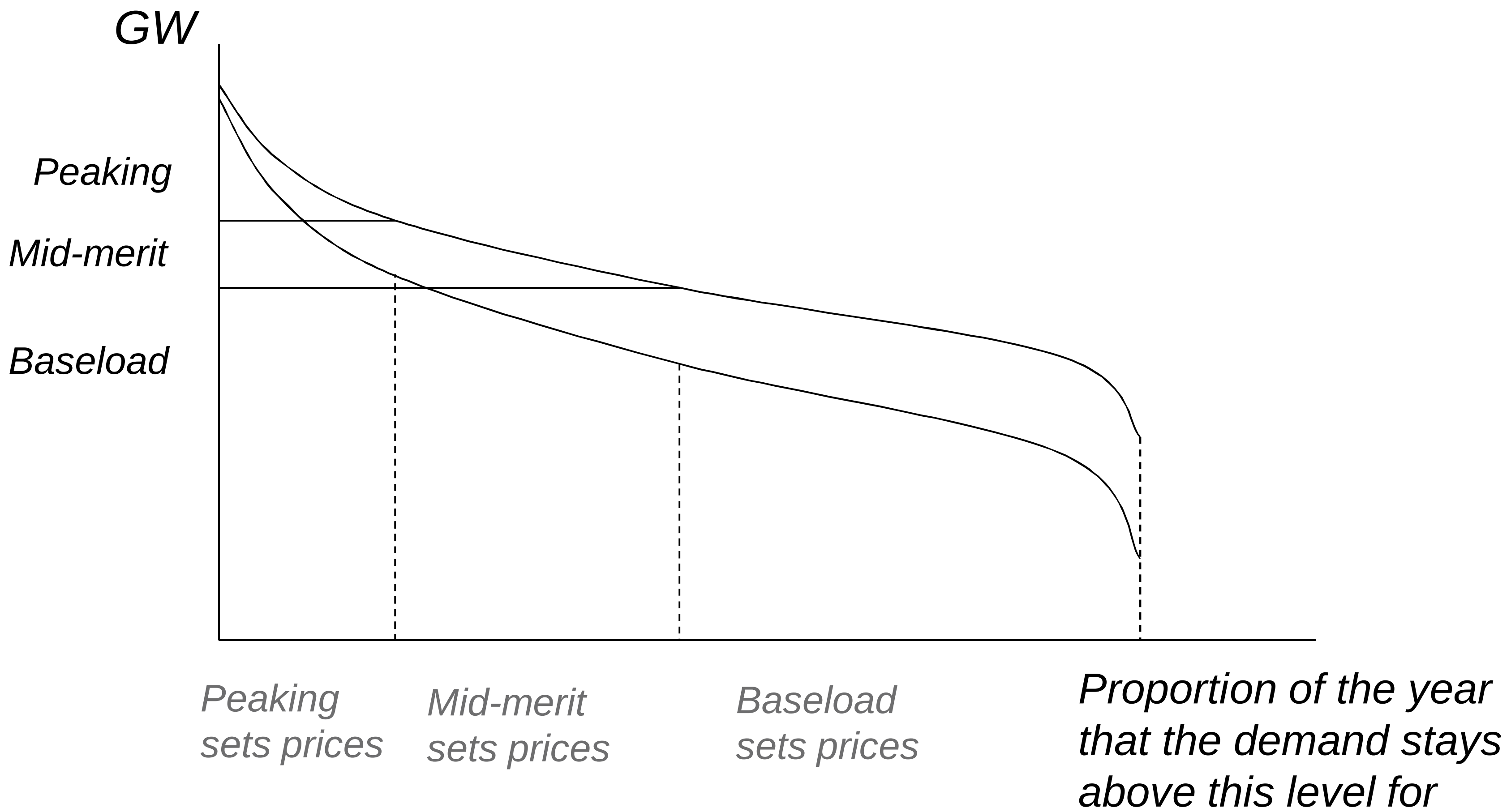


Imperial College London
BUSINESS SCHOOL

Generating capacities: the load-duration curve



Generating capacities: the load-duration curve



Implications

Å The optimal capacity mix changes a lot when wind power is added

Å Time-weighted average prices do not change very much

(wholesale market prices excluding renewable subsidies)

Å The prices in particular hours may well change

Å The demand-weighted price could go up or downé

Imperial College London
BUSINESS SCHOOL

A simulation model

- Demand and wind variation from 12 yearsô historic hourly data for Great Britain
- Demand scaled to (possible) 2020 levels
- Wind output based on 30 GW on- and offshore capacity ï ambition for 2020
- Costs taken from Mott Macdonaldôs report to the Department of Energy and Climate Change
  - Average (discounted) fuel costs over many decades
  - Carbon price averages £70/tonne!
  - Coal is not an equilibrium investment

The model

$$\max_{k_i, q_{it}} W = \sum_{t=1}^{T} \int_0^{Q_t} p_t(q)\,dq - \sum_{i=1}^{I} \left[F_i k_i + \sum_{t=1}^{T} v_i q_{it} \right]$$

Value of output, less capacity (k) cost and output (q) variable costs

$$s.t. \; Q_t \le \sum_{i=1}^{I} q_{it} \qquad \forall t$$

Demand (Q) < output

$$q_{it} \le a_{it} k_i \qquad \forall i, t$$

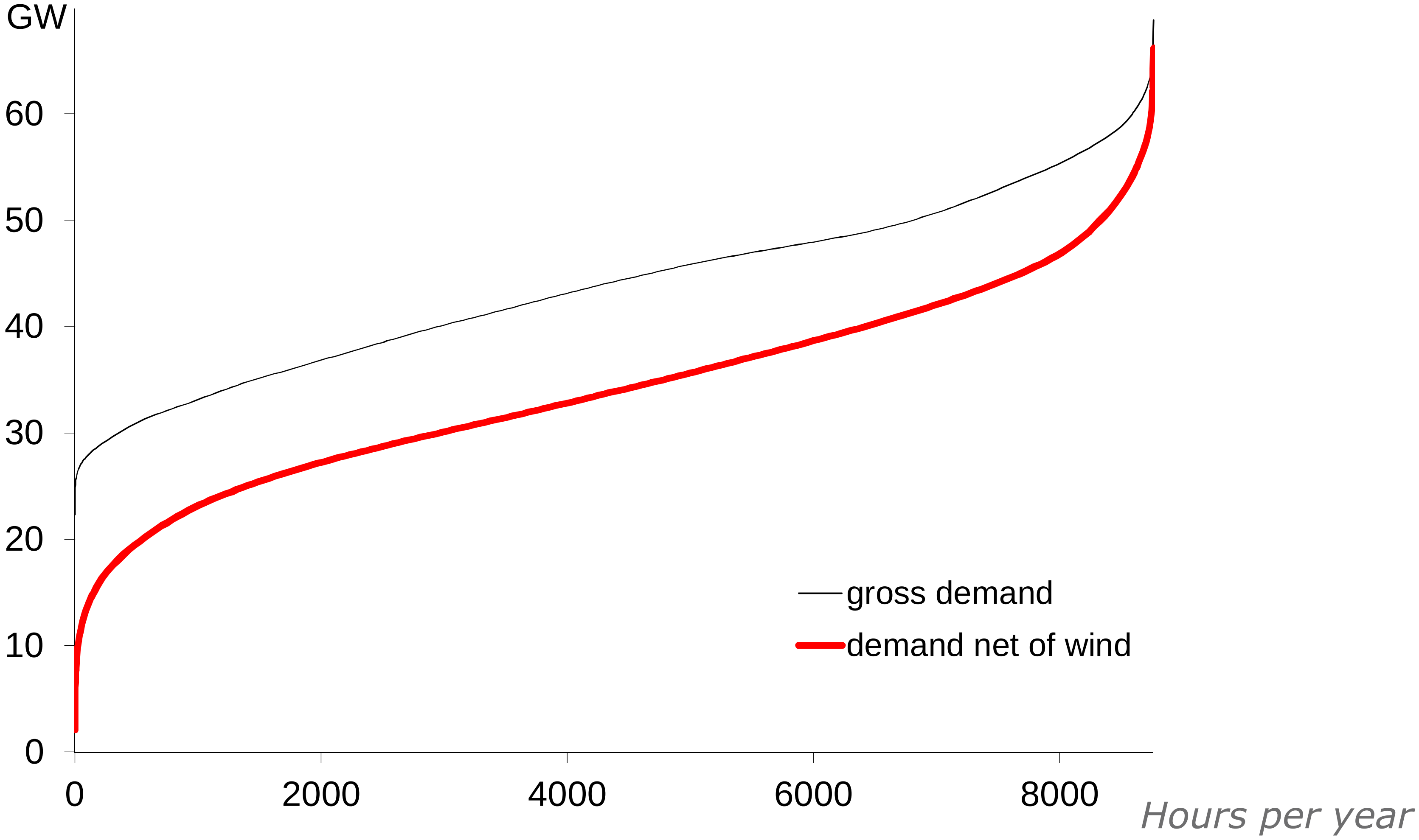
Output < available capacity

$$q_{nt} \ge m a_{nt} k_n \qquad \forall t$$

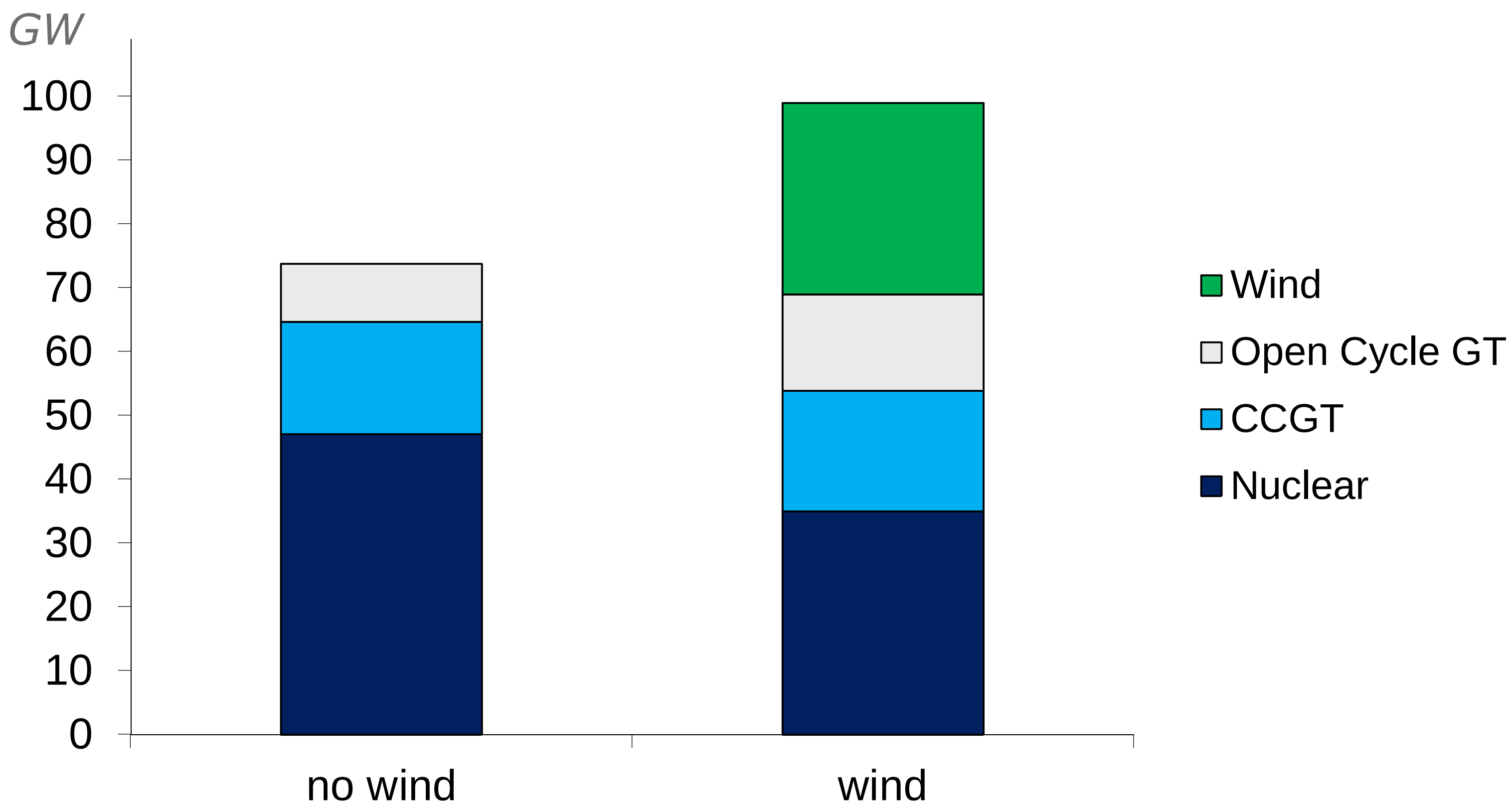
Nuclear output > minimum stable

Imperial College London
BUSINESS SCHOOL

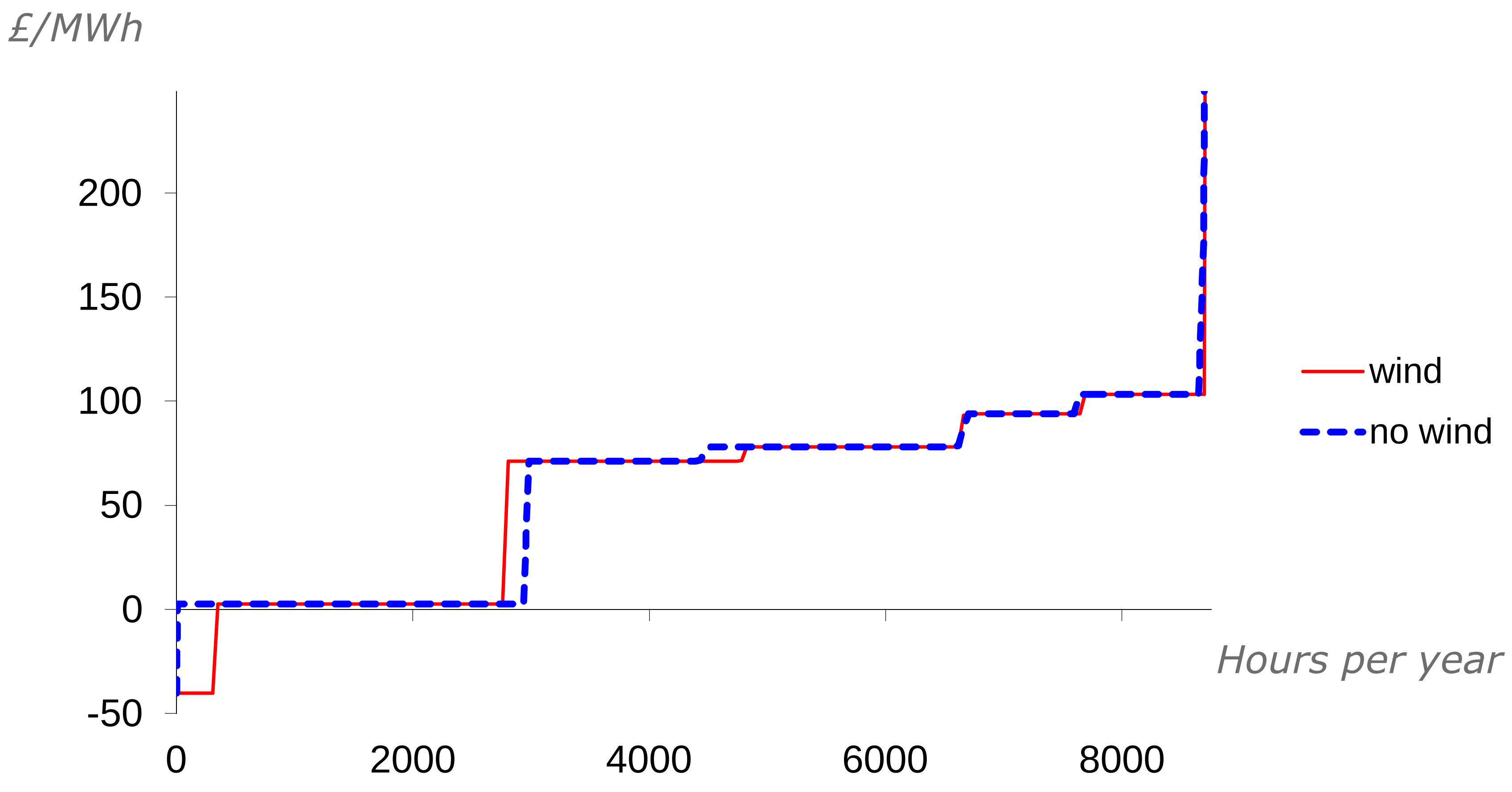
Load-duration curves



Equilibrium capacity mix (base case)

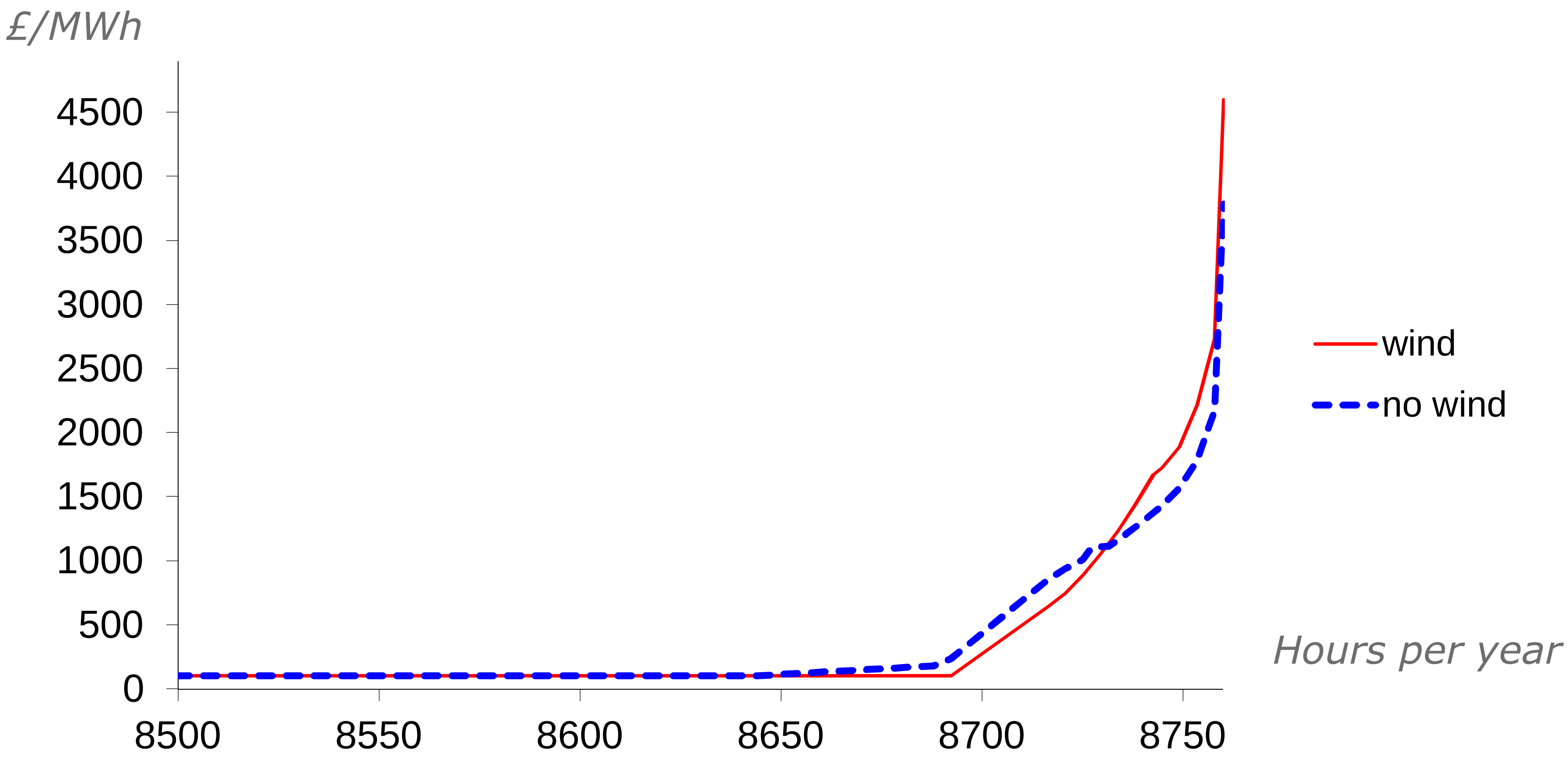


Price duration curves (base case)

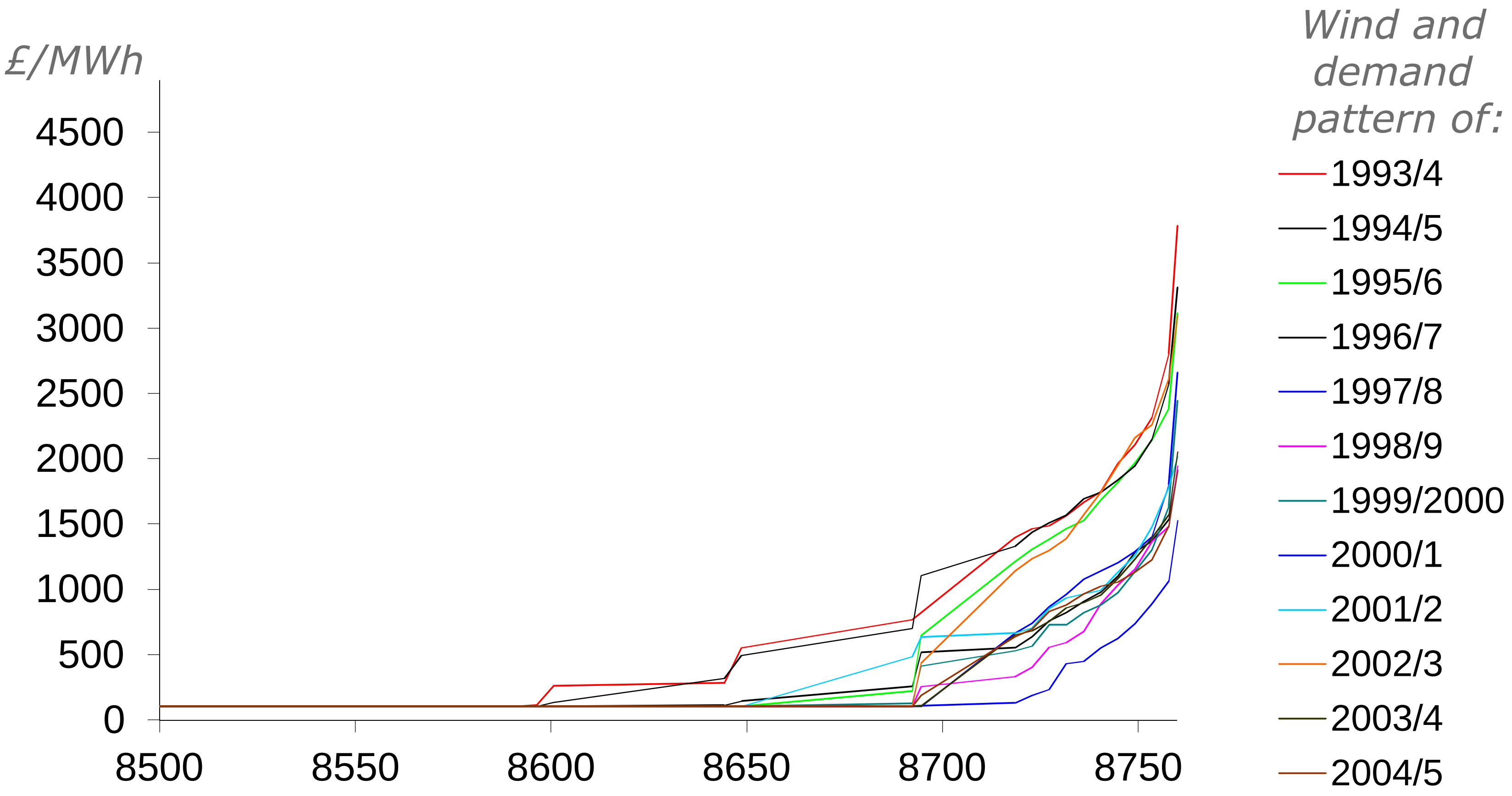


Imperial College London BUSINESS SCHOOL

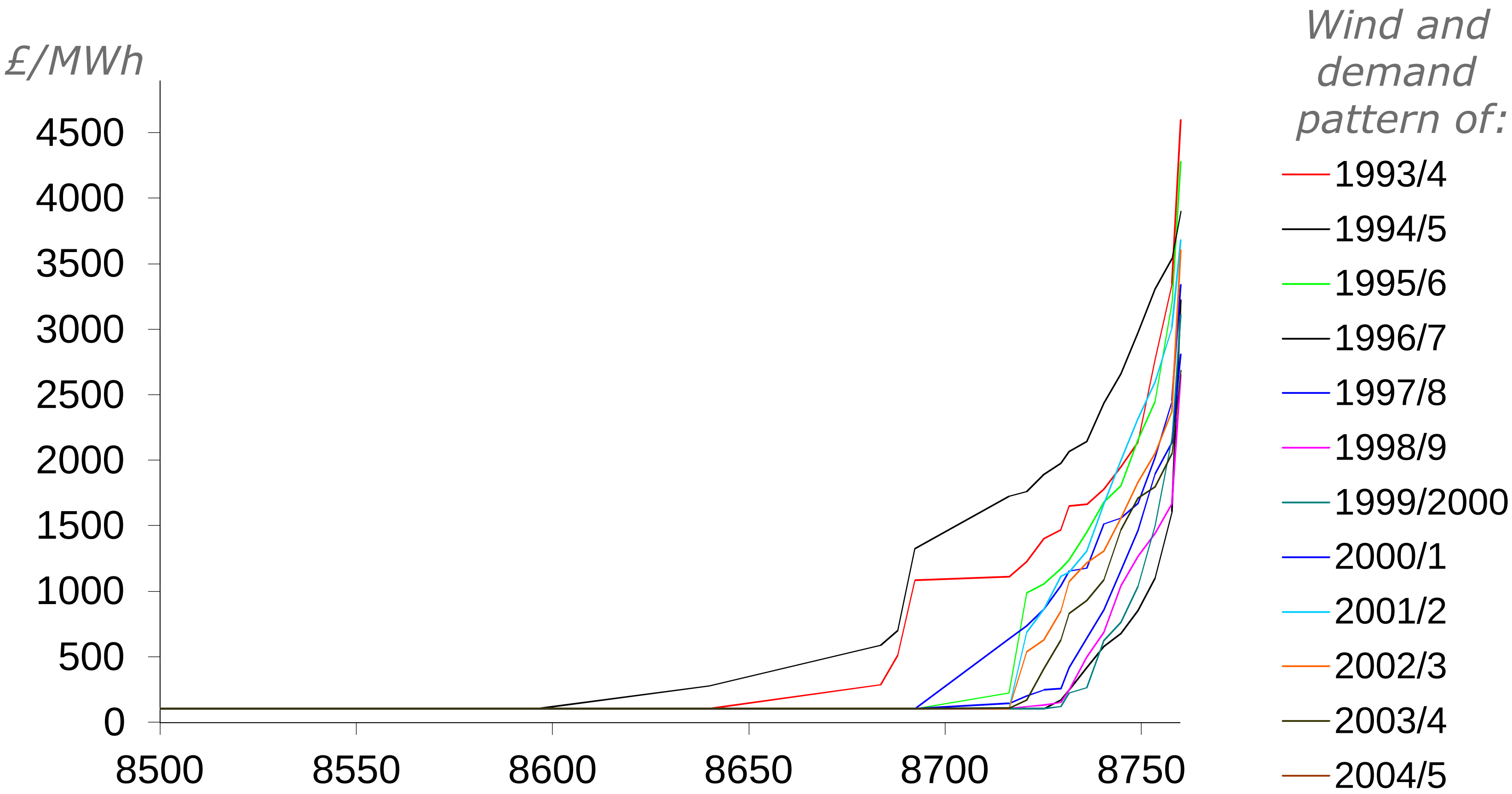
Price duration curves (detail) (base case)



Price duration curve (detail) (no wind)



Price duration curve (detail) (net of wind)



Prices

Average price (£/MWh) for:	No wind	Wind
Base load	66.28	66.24
Thermal output	76.35	84.10
Wind output		*30.97*
Demand	76.35	*73.38*

All the quantitative results in this presentation depend on the particular numbers assumed for costs, but qualitative conclusions should be robust to changes in them…

Imperial College London
BUSINESS SCHOOL

Cost to consumers

Å Consumers pay the demand-weighted price in the wholesale market

ÅFalls slightly as more wind in winter

Å Plus balancing, grid & supply costs

Å< 1p/kWh of intermittent output (CCC, 2011)

Å Plus extra cost of renewable support

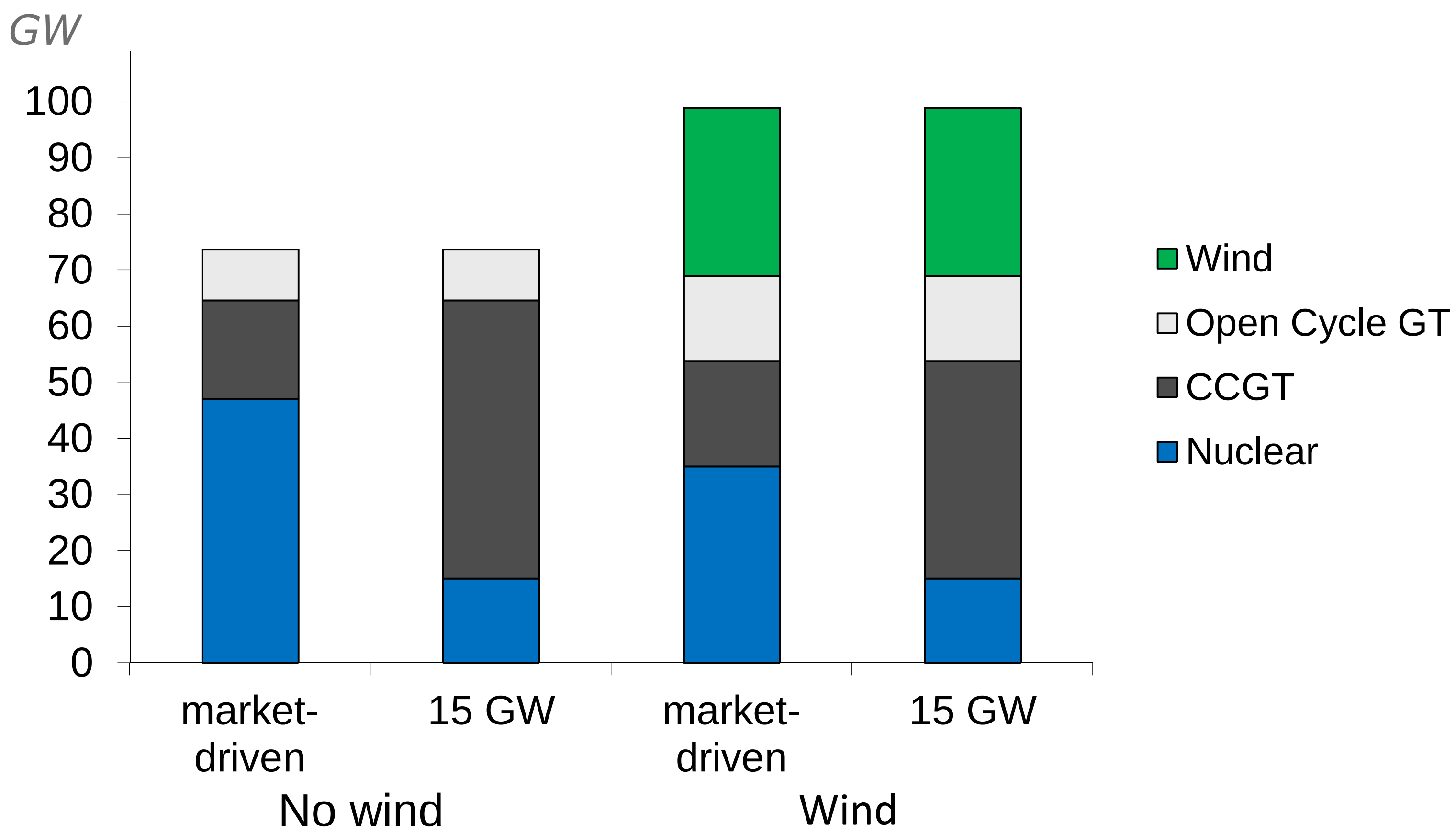
ÅROCs / out-of-the-money part of CfD-FIT

Prices, output and emissions

Average price (£/MWh) for:	No wind	Wind
Base load	66.28	66.24
Thermal output	76.35	84.10
Wind output		*30.97*
Demand	76.35	*73.38*
Thermal output (TWh)	383	299
Wind output (TWh)		83
CO2 (m tonnes)	31.3	35.1

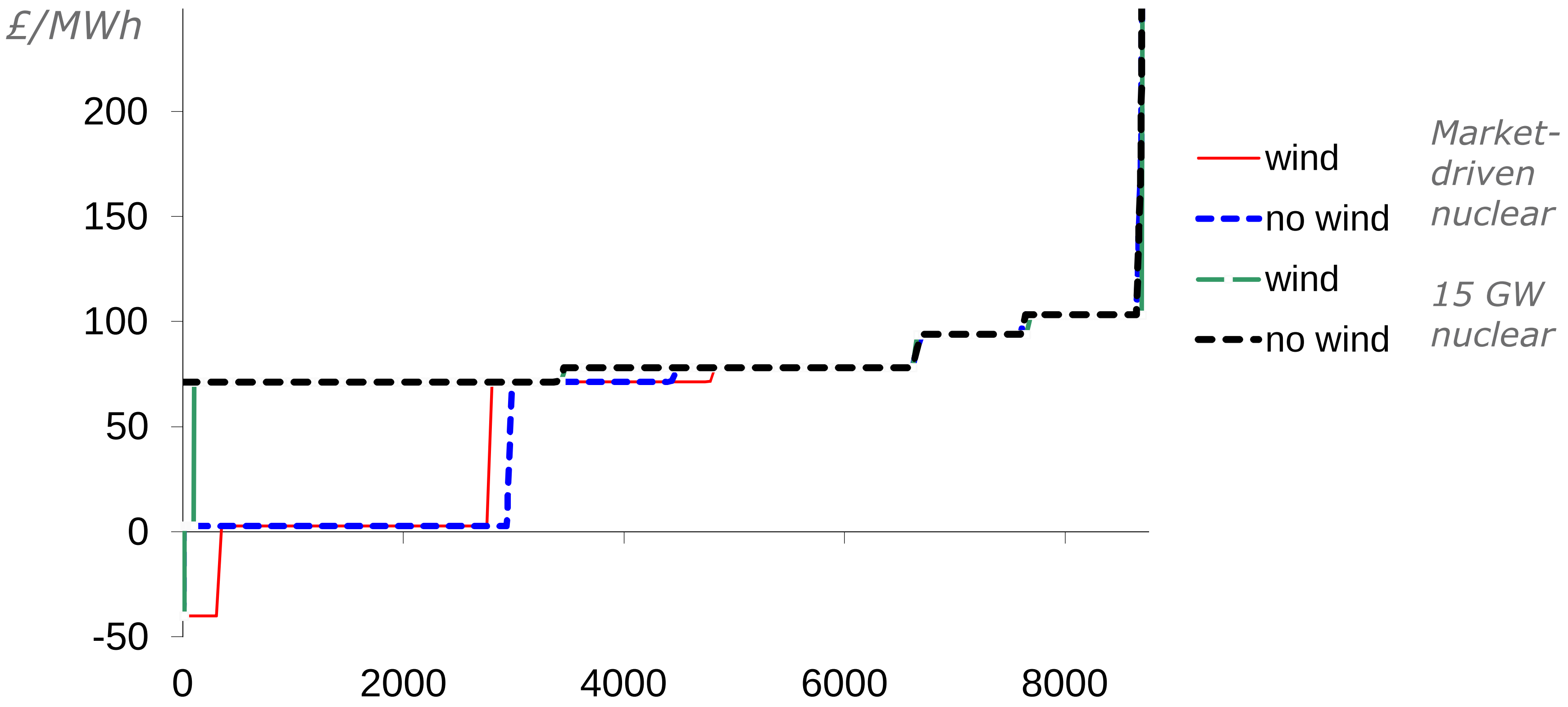
Imperial College London
BUSINESS SCHOOL

Equilibrium capacity mix (varying nuclear)



Imperial College London
BUSINESS SCHOOL

Price duration curves (varying nuclear)



A constraint on nuclear power

Market-driven nuclear:	No wind	Wind
Nuclear capacity (GW)	47.0	35.0
Time-weighted price (£/MWh)	66.28	66.24
Price for wind (£/MWh)		30.97
CO2 (m tonnes)	31.3	35.1
15 GW of nuclear:		
Time-weighted price (£/MWh)	90.07	89.25
Price for wind (£/MWh)		66.19
CO2 (m tonnes)	106.3	79.4

Implications

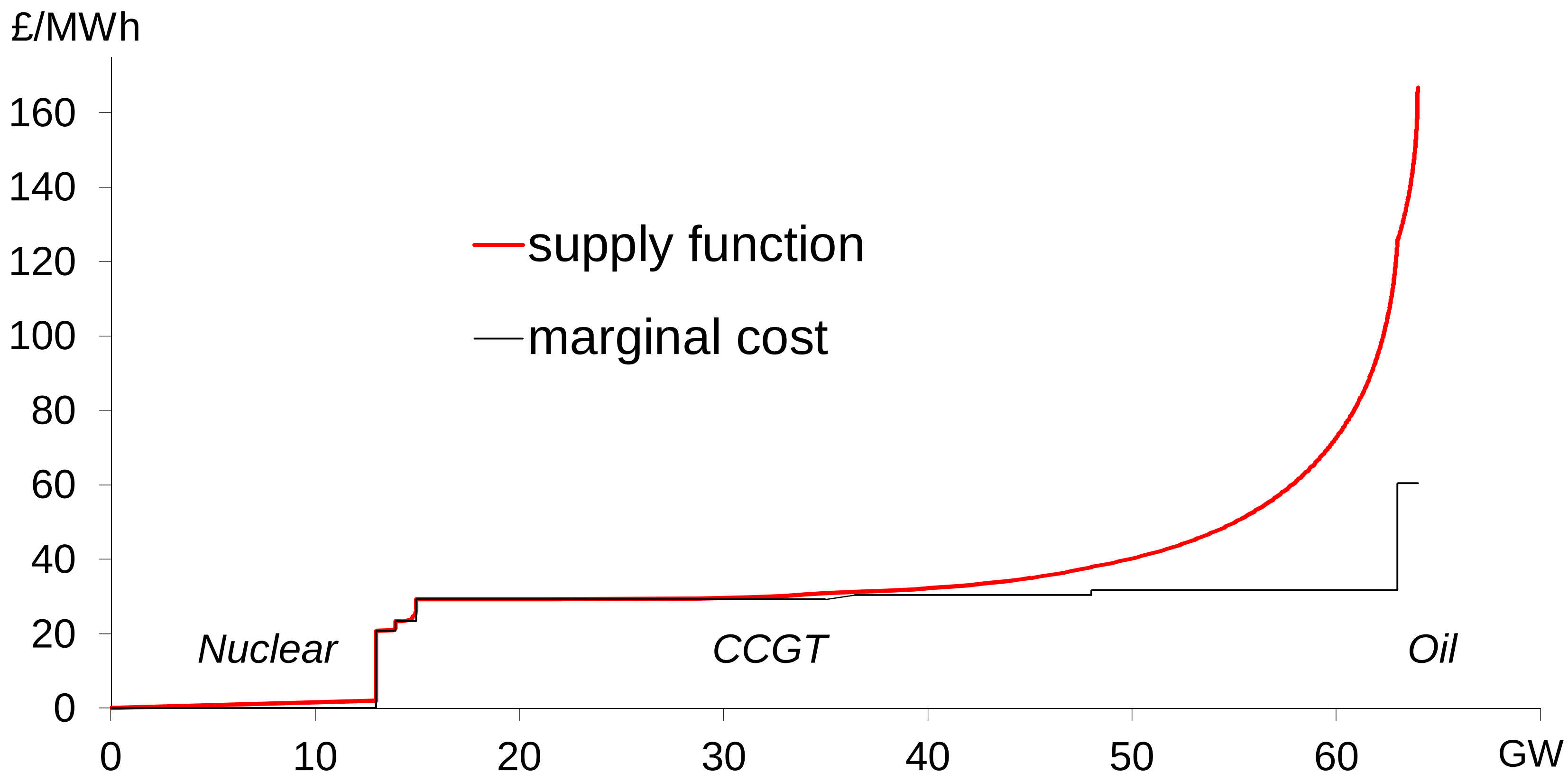
- More capacity will only run for short periods per year
  - Paying for it through an energy market may be a challenge
  - UK government is developing a capacity market to provide extra support for this
- Demand response reduces capacity needs
- Year-to-year wind variations do affect prices and profits
  - But fuel prices may be a bigger risk

Strategic firms

- Use the Supply Function Equilibrium of Klemperer & Meyer (*Econometrica*, 1989) as applied by Green & Newbery (*Journal of Political Economy*, 1992)
- Less popular than Cournot models
- Produces more realistic price levels (?)
- Harder to implement

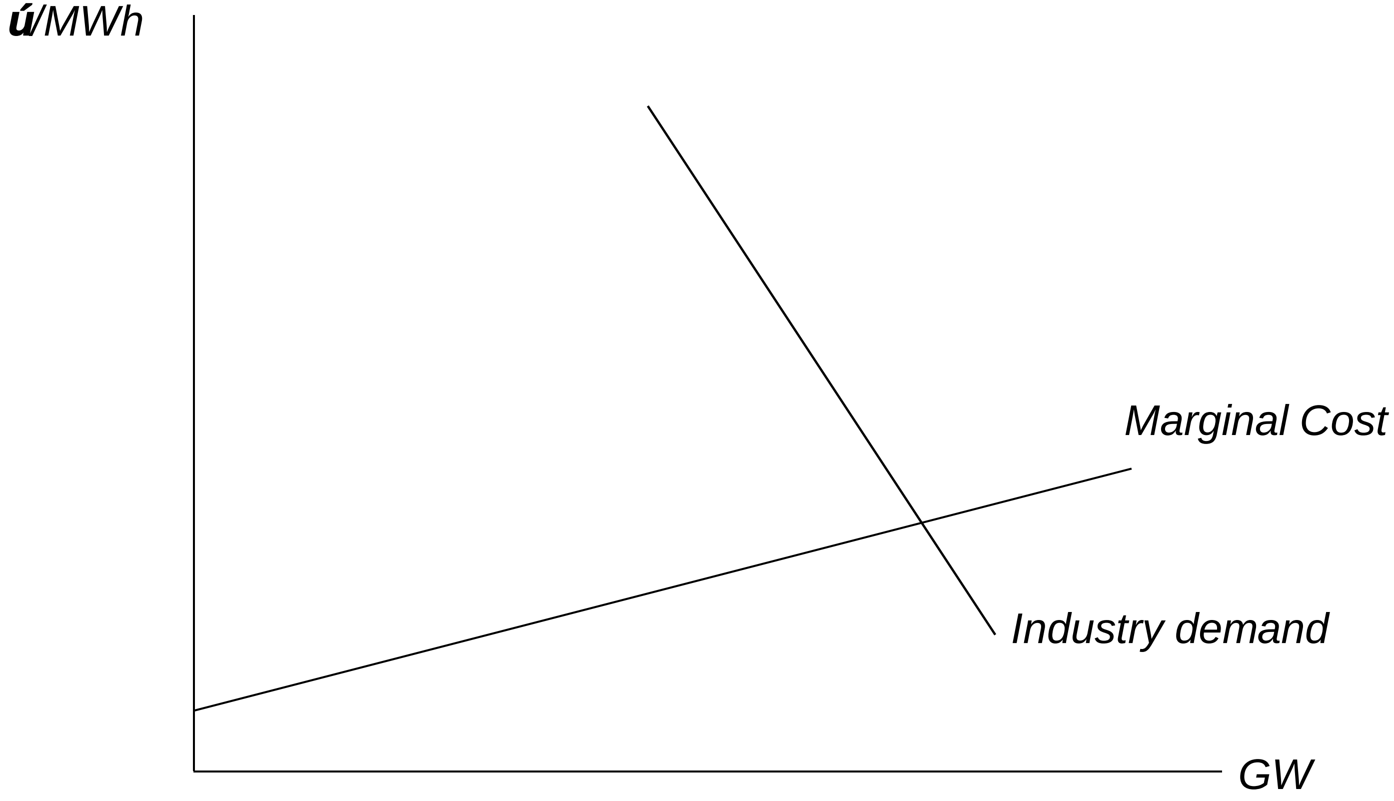
Imperial College London
BUSINESS SCHOOL

Industry supply function (thermal power): 6 firms



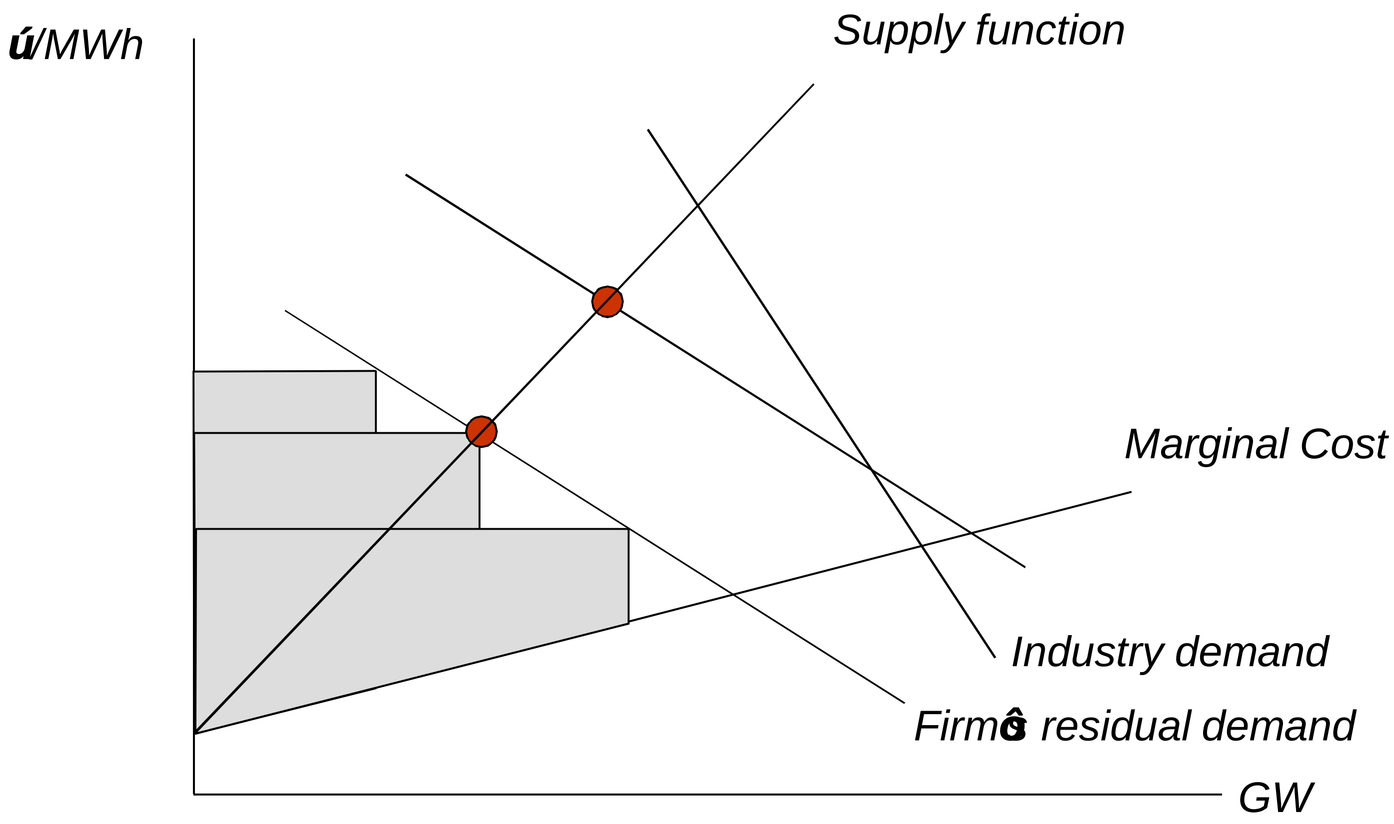
Imperial College London
BUSINESS SCHOOL

A supply function model



Klemperer and Meyer, Econometrica 1989; Green and Newbery, JPE 1992

A supply function model



Klemperer and Meyer, Econometrica 1989; Green and Newbery, JPE 1992

(1) $$D(p^*(t), t) = \sum_i q_i(p^*(t))$$

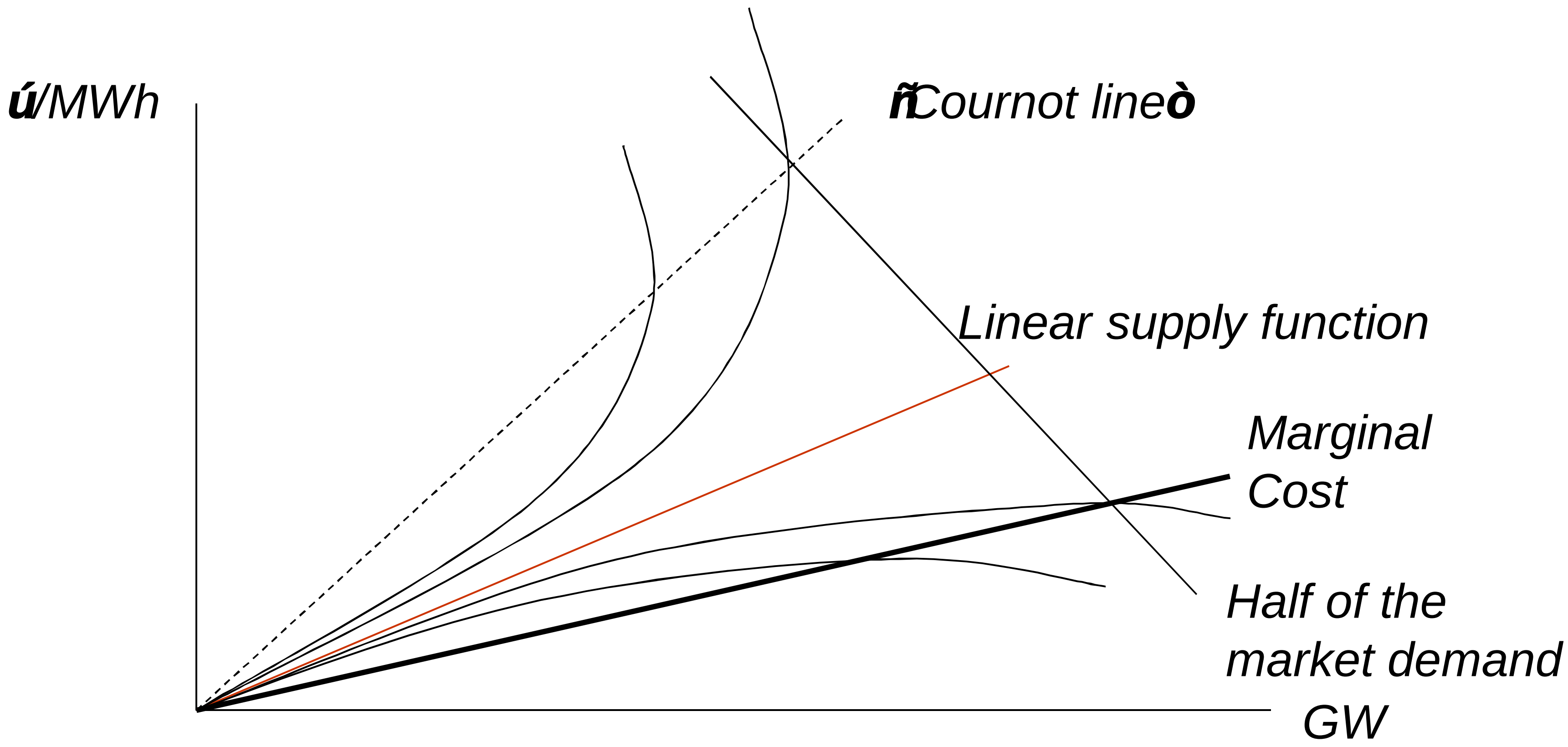
(2) $$\pi_i(p, t) = p\left(D(p, t) - \sum_{j \neq i} q_j(p)\right) - C_i\left(D(p, t) - \sum_{j \neq i} q_j(p)\right)$$

(3) $$\frac{d\pi_i(t)}{dp} = D(p, t) - \sum_{j \neq i} q_j(p) + \left(p - C_i'\left(D(p, t) - \sum_{j \neq i} q_j(p)\right)\right)$$

$$\times\left(\frac{dD(p, t)}{dp} - \sum_{j \neq i} \frac{dq_j}{dp}\right)$$

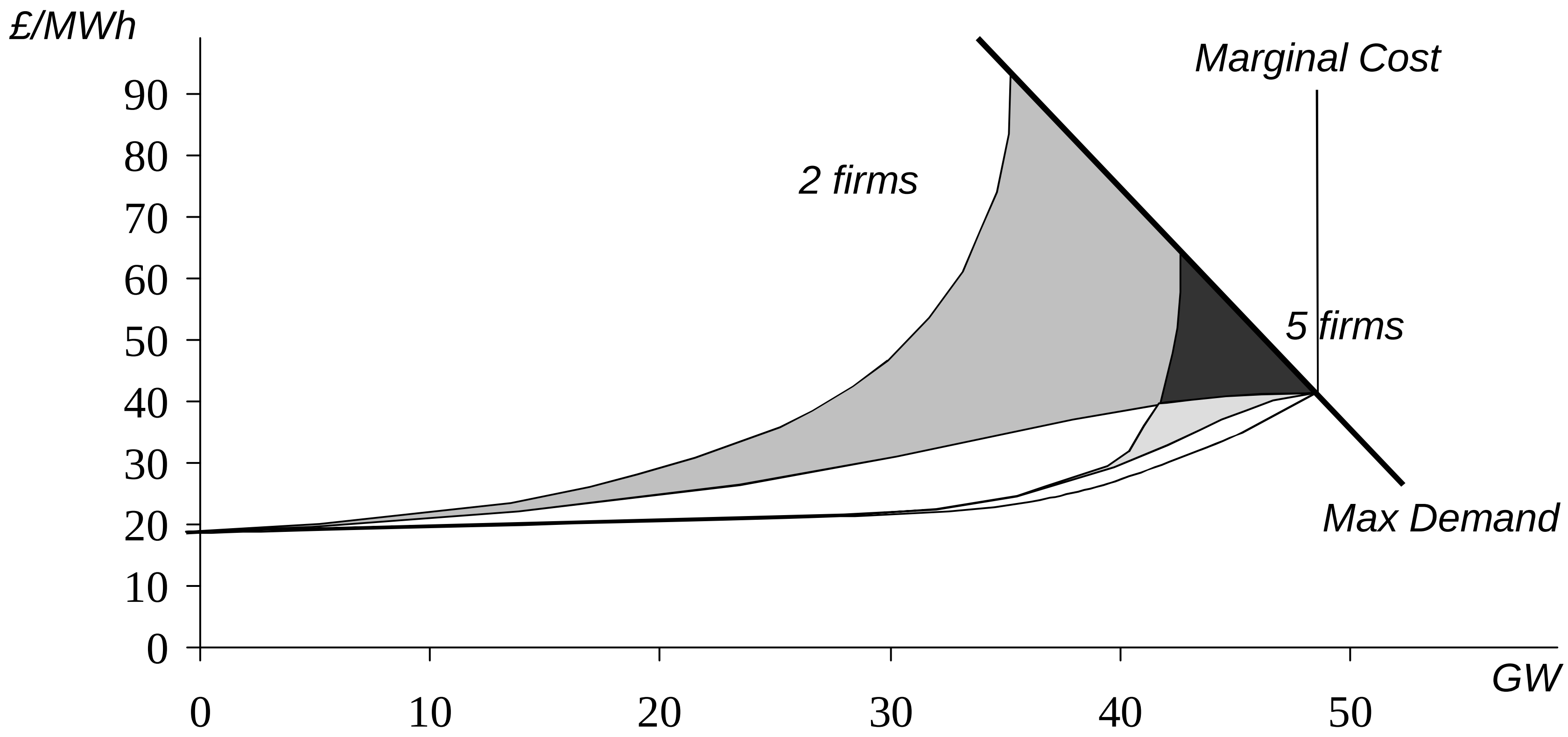
(4) $$q_i(p) = (p - C_i'(q_i(p)))\left(-\frac{dD}{dp} + \sum_{j \neq i} \frac{dq_j}{dp}\right)$$

Symmetric Supply Functions



Imperial College London
BUSINESS SCHOOL

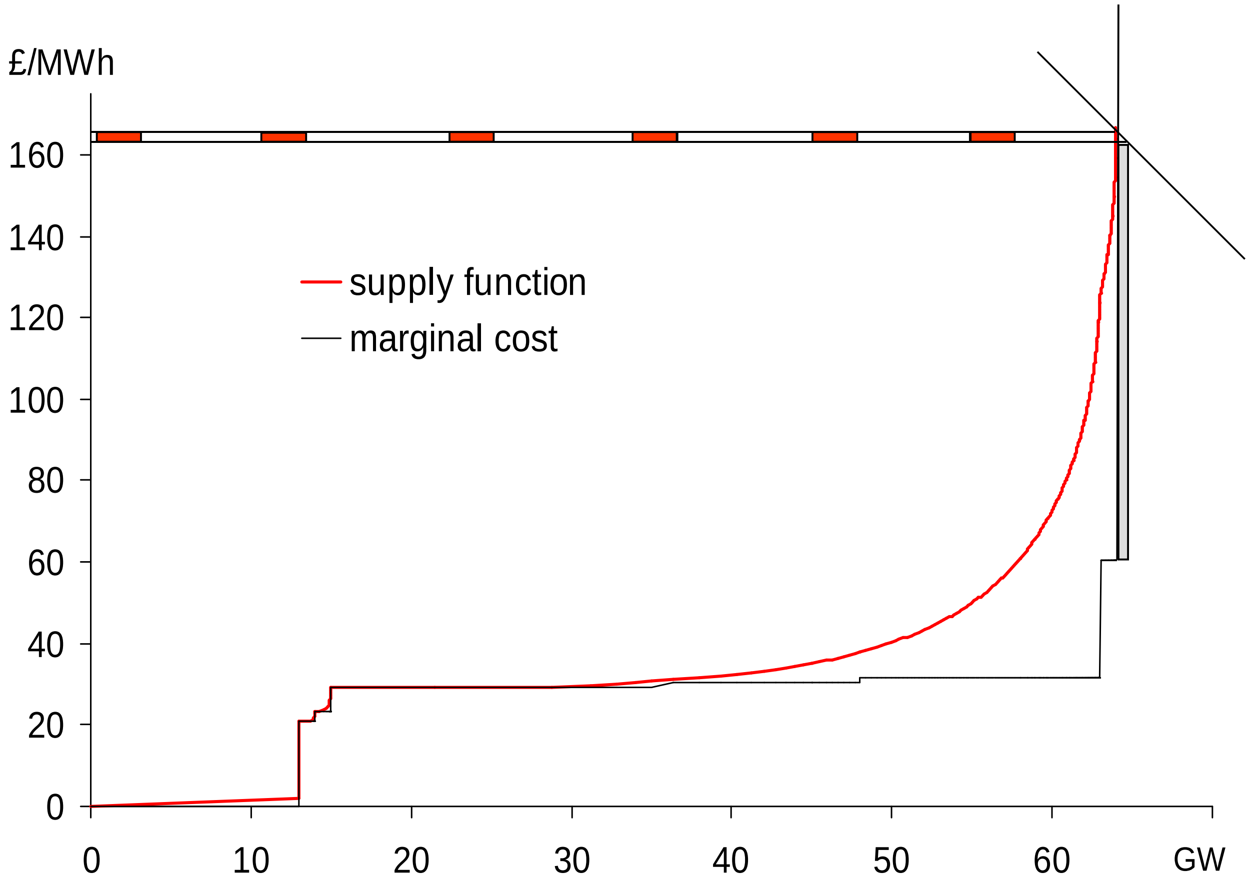
Industry Supply Curves, England and Wales, 1992



Green and Newbery, *Oxrep* 1997, based on Green and Newbery, *JPE* 1992

Imperial College London
BUSINESS SCHOOL

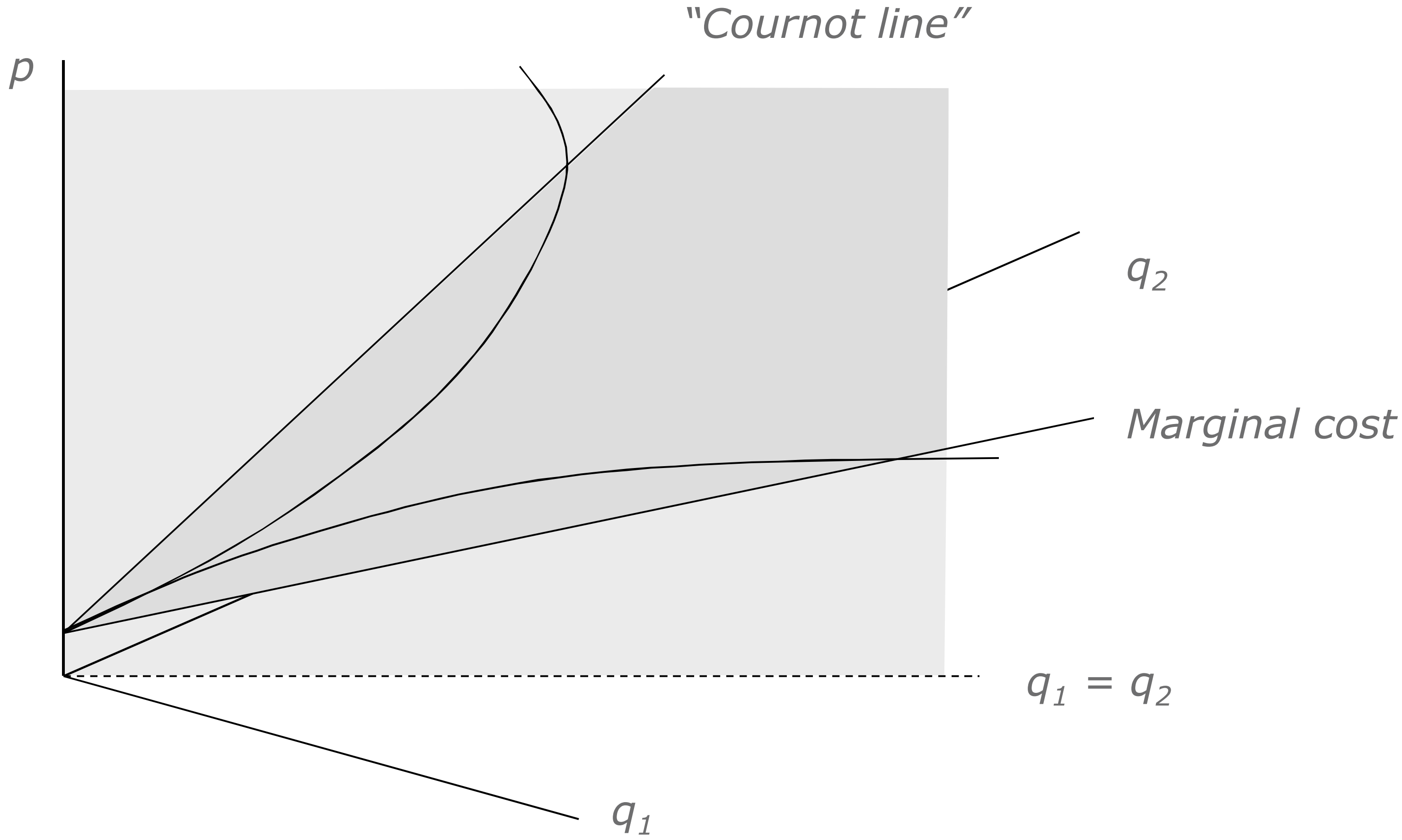
Strategic investment: peaking capacity



Strategic investment: other plant types

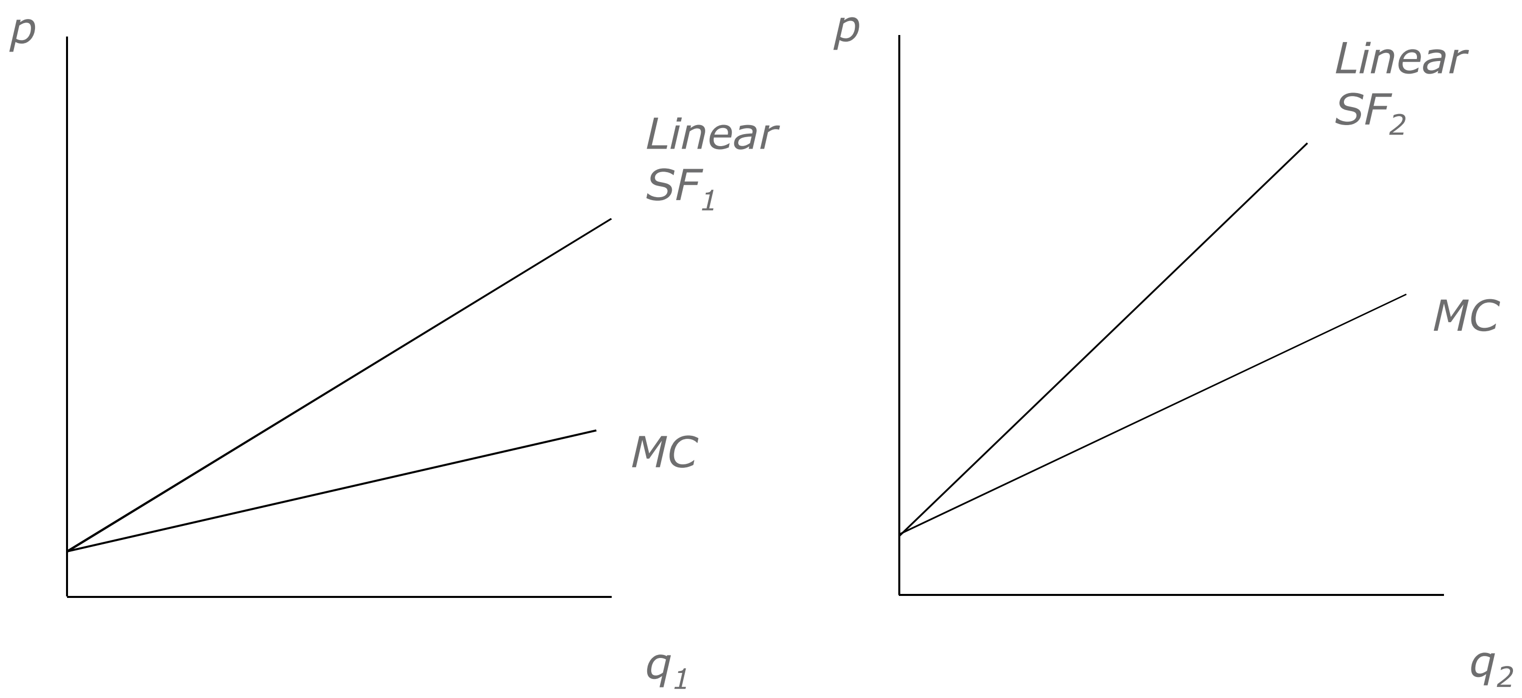
- Replace a small amount of (e.g.) CCGT plant by nuclear:
- Nuclear plant has higher fixed costs
- CCGT plant had higher variable costs
  - Saving depends on the number of running hours
  - This is the same trade-off as with competitive firms
- My optimal supply function would change
  - Envelope theorem implies this does not affect profits
- Other firms' supply functions change in response
  - This will affect my profits
    - Need to model with asymmetric supply functions

Symmetric SFE

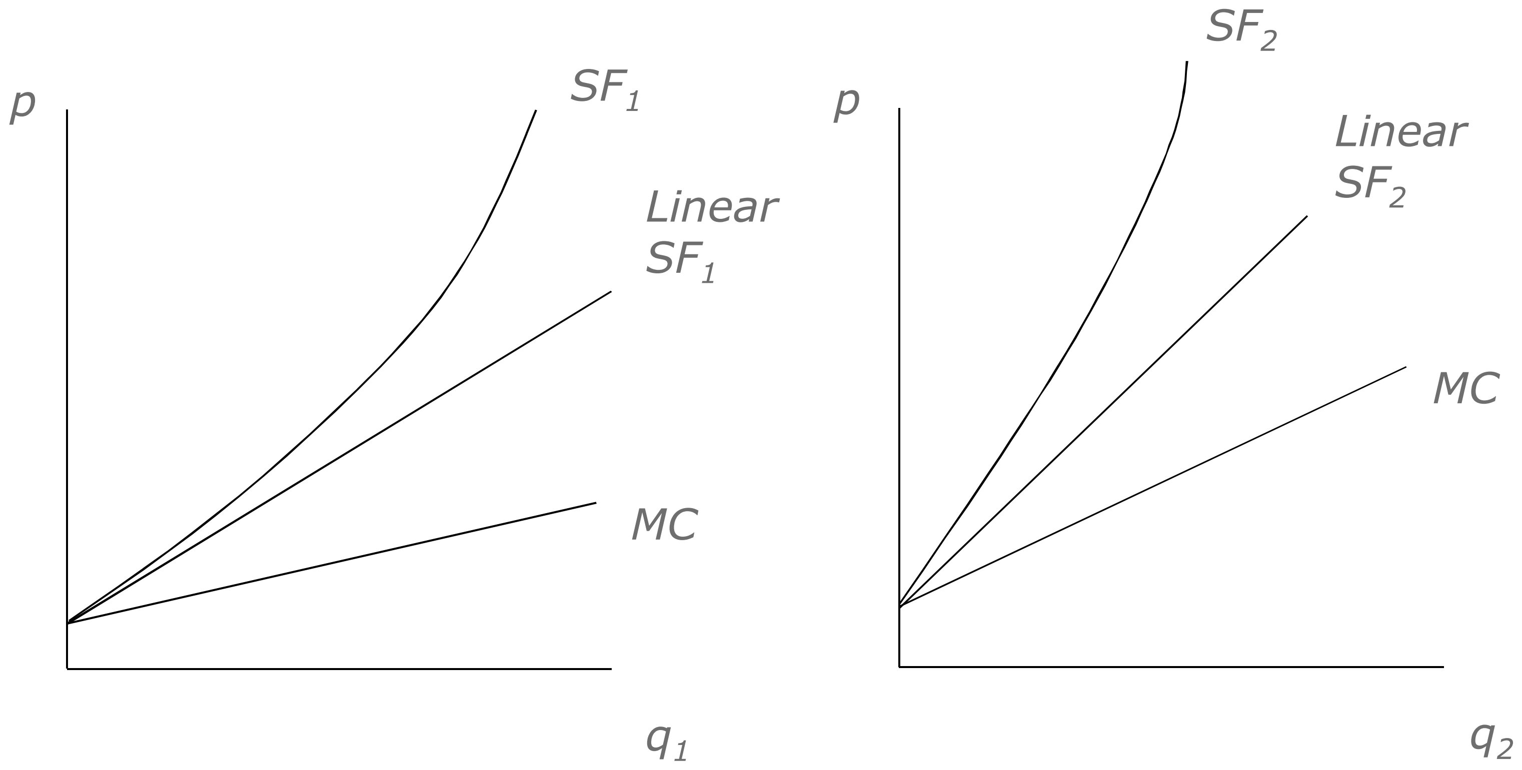


Imperial College London
BUSINESS SCHOOL

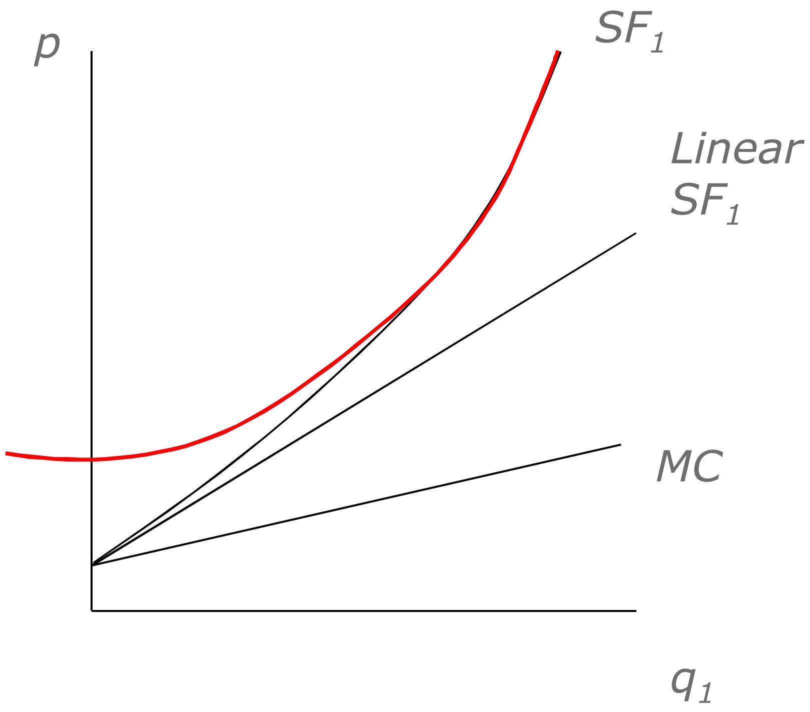
Asymmetric SFE

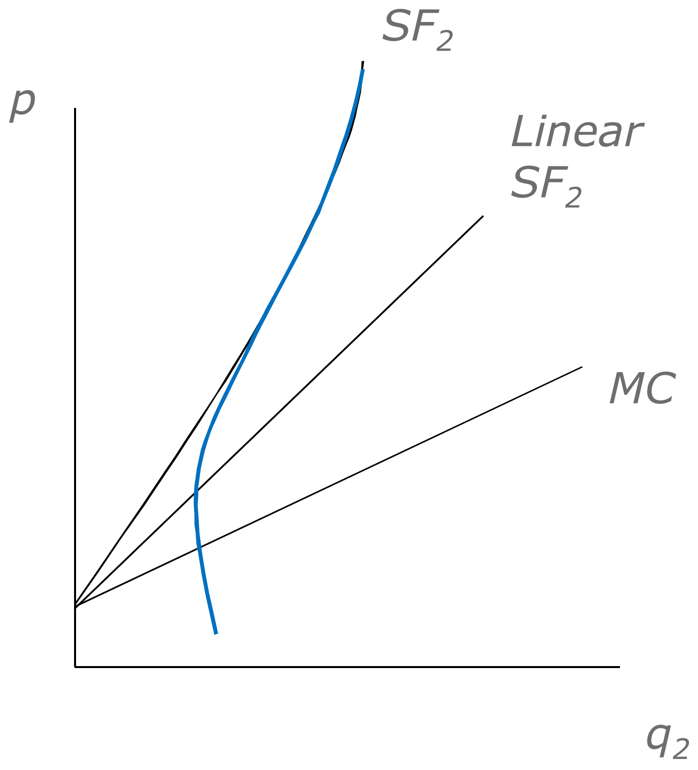


Asymmetric SFE



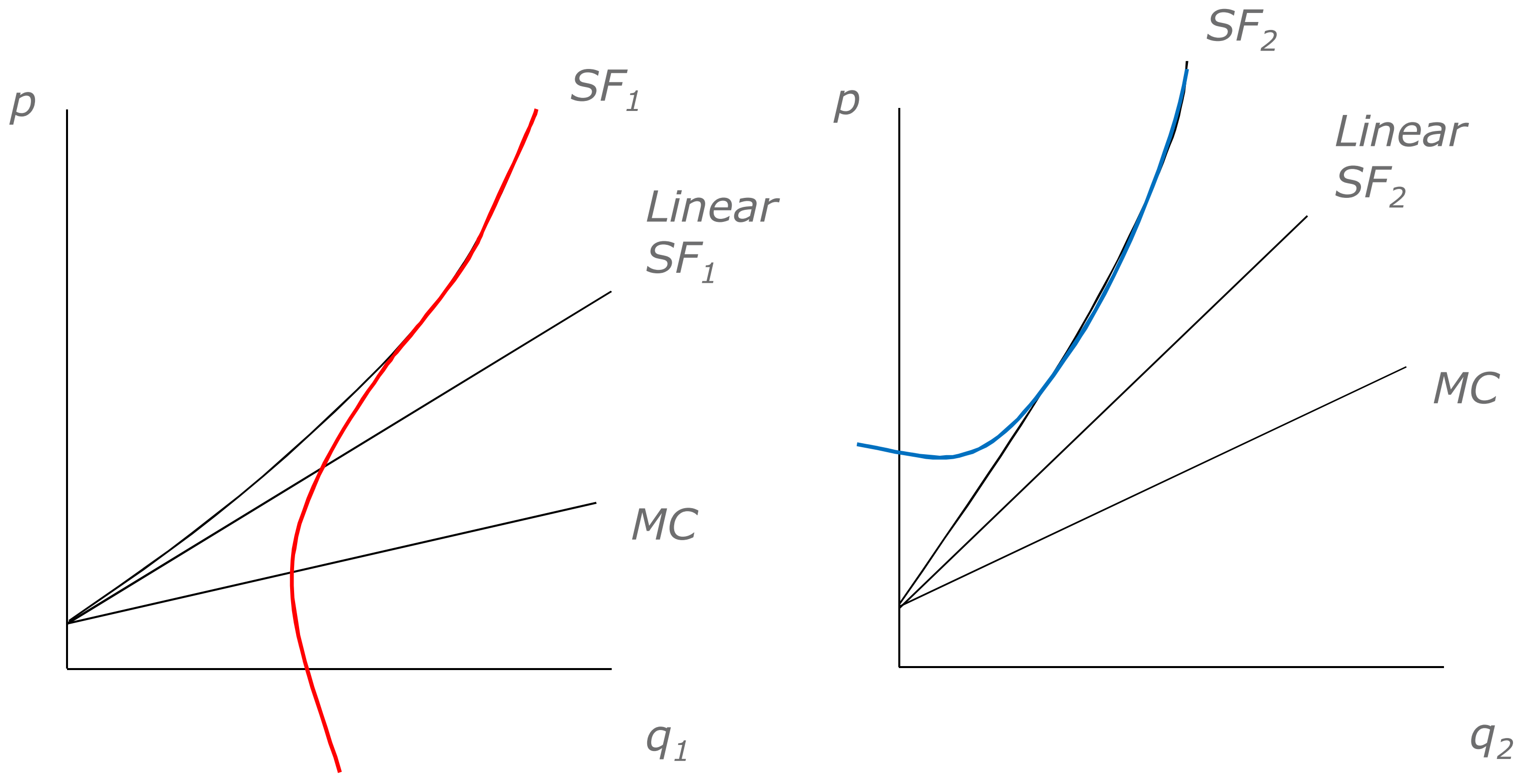
Asymmetric SFE



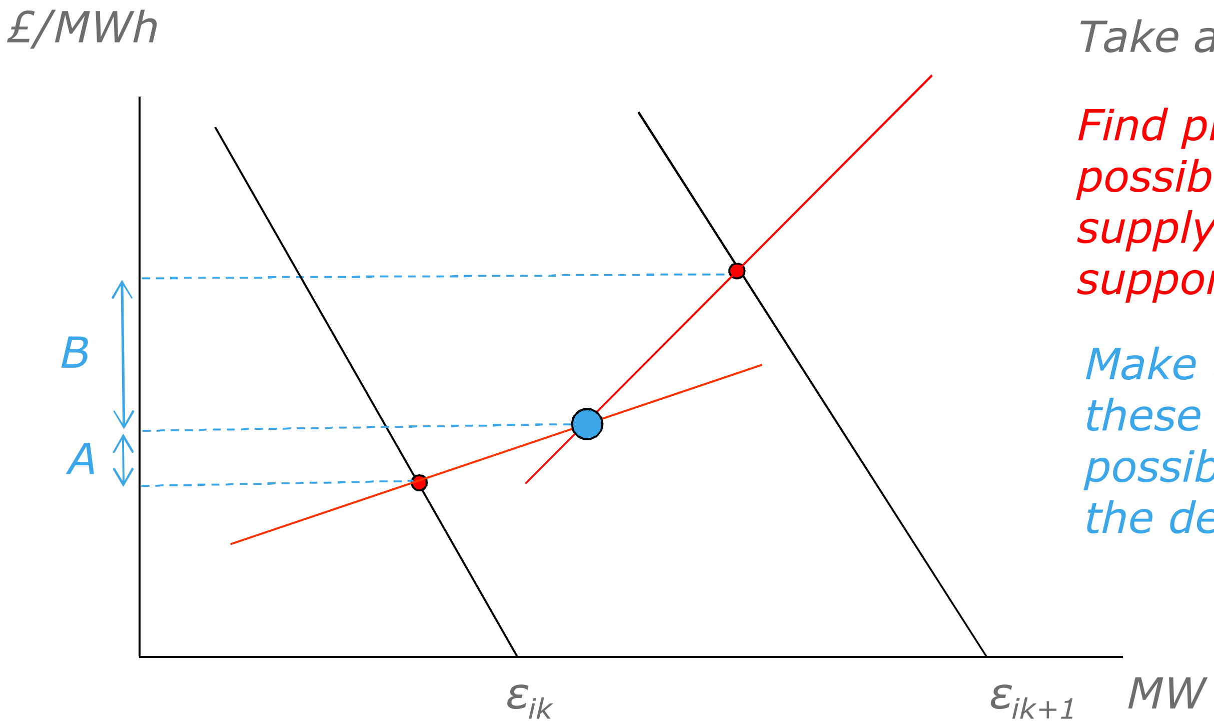


Imperial College London BUSINESS SCHOOL

Asymmetric SFE



Anderson and Hu's algorithm



Take a set of demand shocks

Find price-quantity pairs for a possible equilibrium and the supply function segments supporting them

Make the meeting points of these segments as close as possible to half-way between the demand shocks

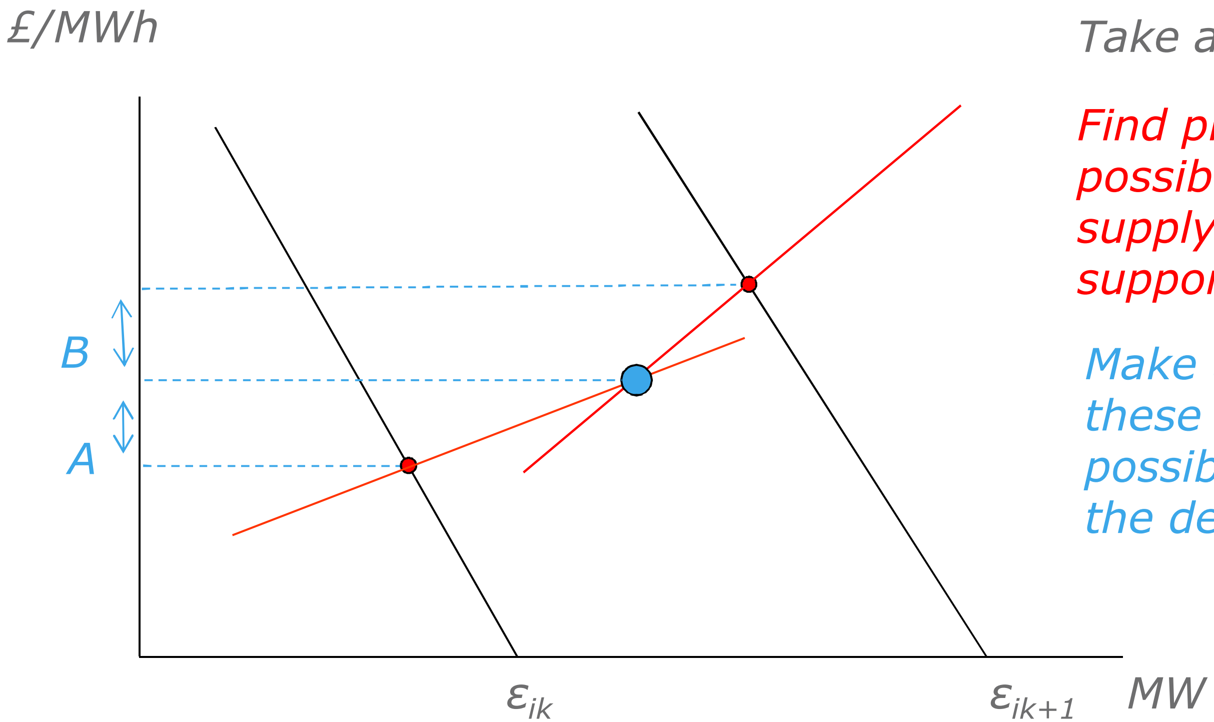
$$\xi_{ik} = A/(A+B)$$

$$\min \sum_{i,k} (\xi_{ik} - 0.5)^2$$

Operations Research, 2008

Imperial College London
BUSINESS SCHOOL

Anderson and Hu's algorithm



Take a set of demand shocks

Find price-quantity pairs for a possible equilibrium and the supply function segments supporting them

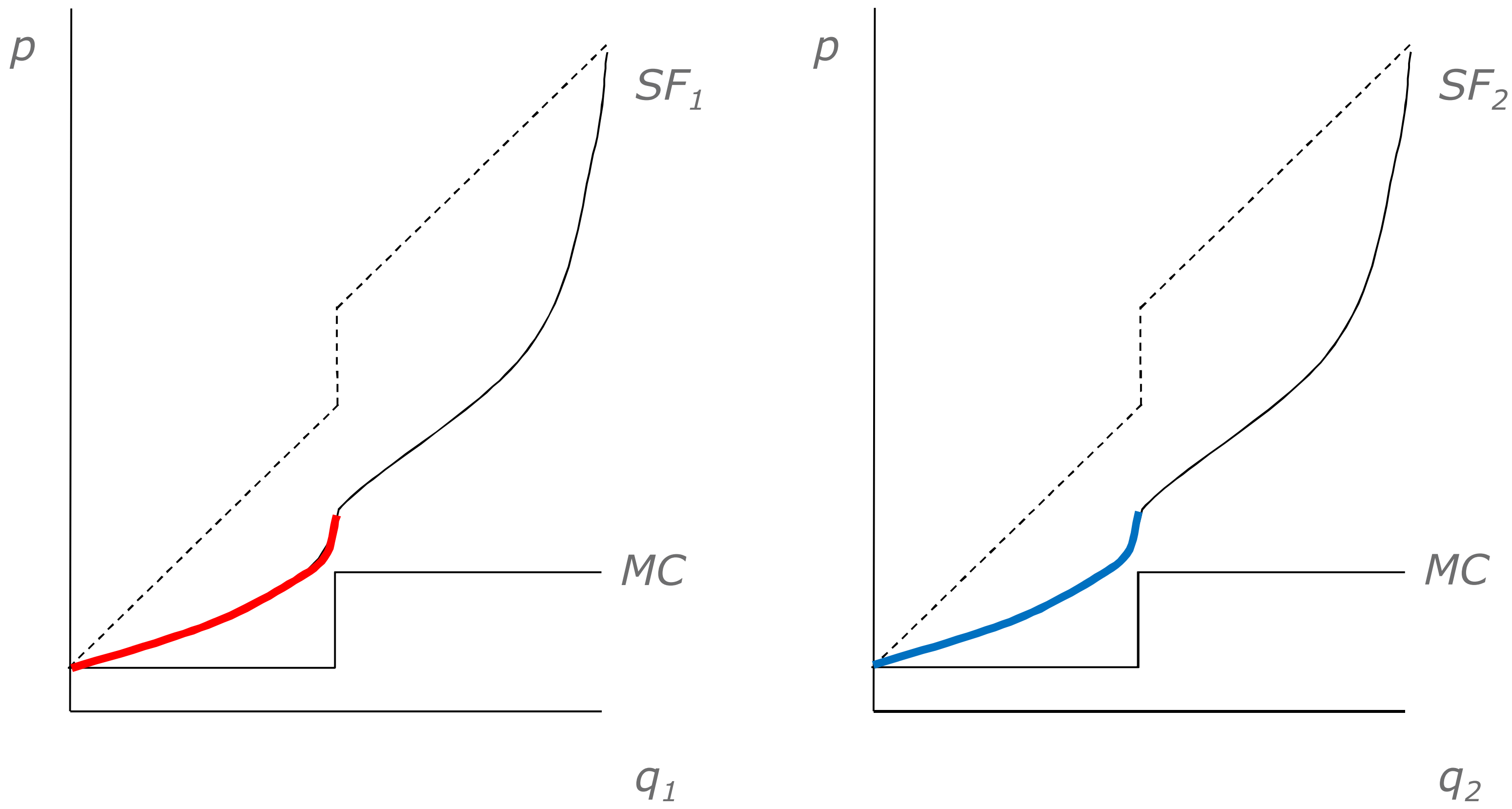
Make the meeting points of these segments as close as possible to half-way between the demand shocks

$$\xi_{ik} = A/(A+B)$$

$$\min \sum_{i,k} (\xi_{ik} - 0.5)^2$$

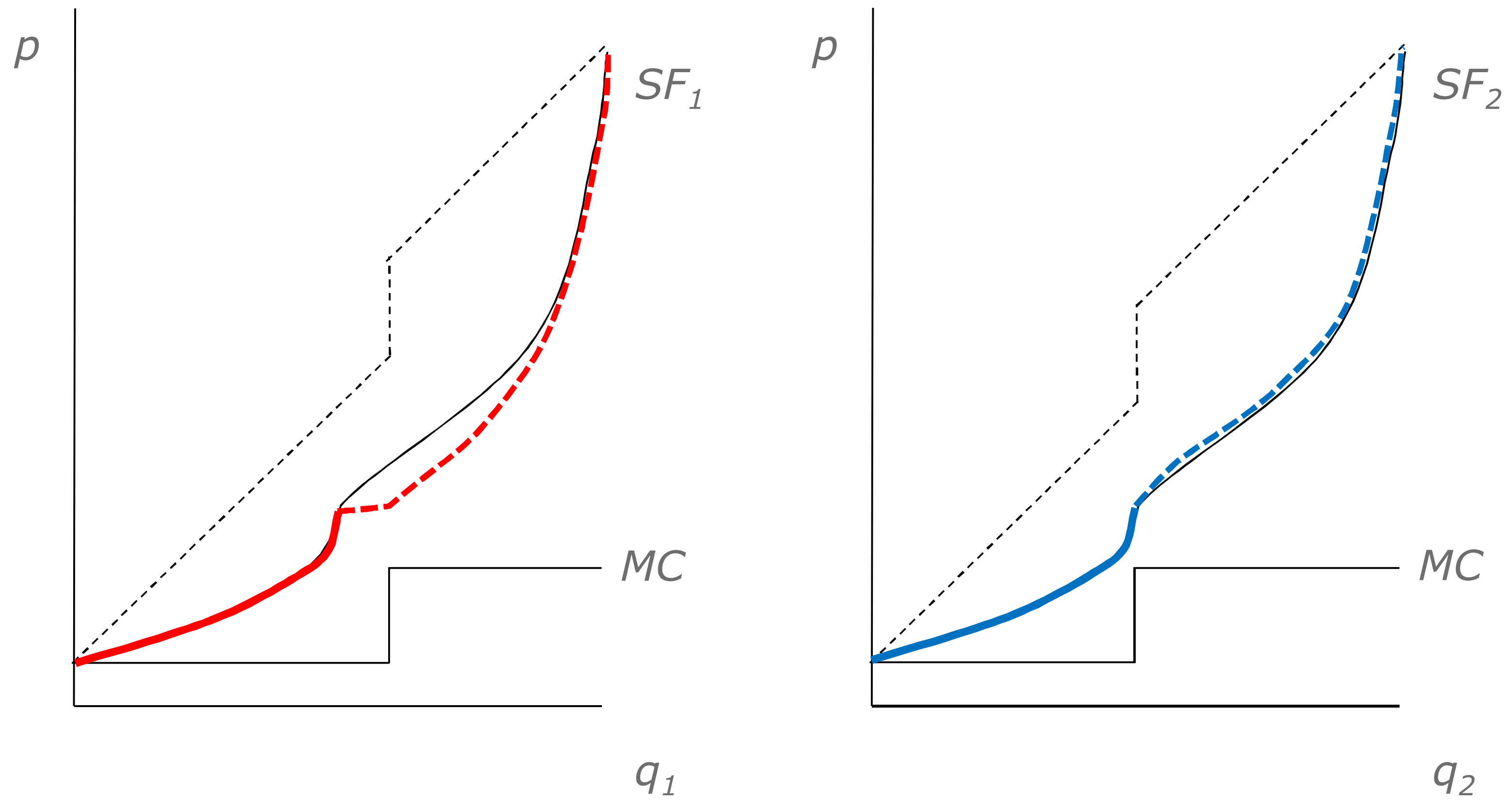
Operations Research, 2008

Asymmetric SFE



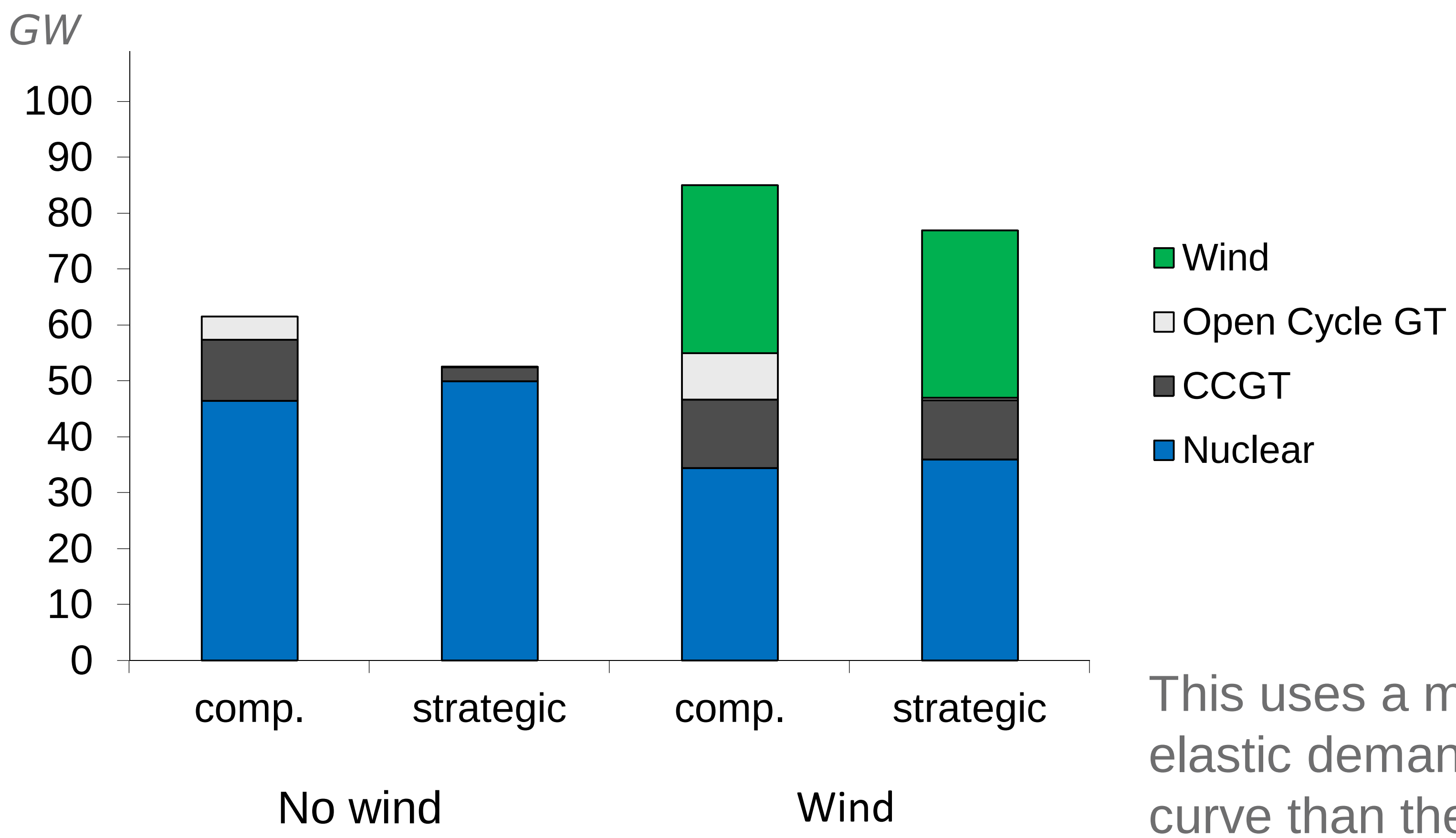
Imperial College London BUSINESS SCHOOL

Asymmetric SFE



Imperial College London
BUSINESS SCHOOL

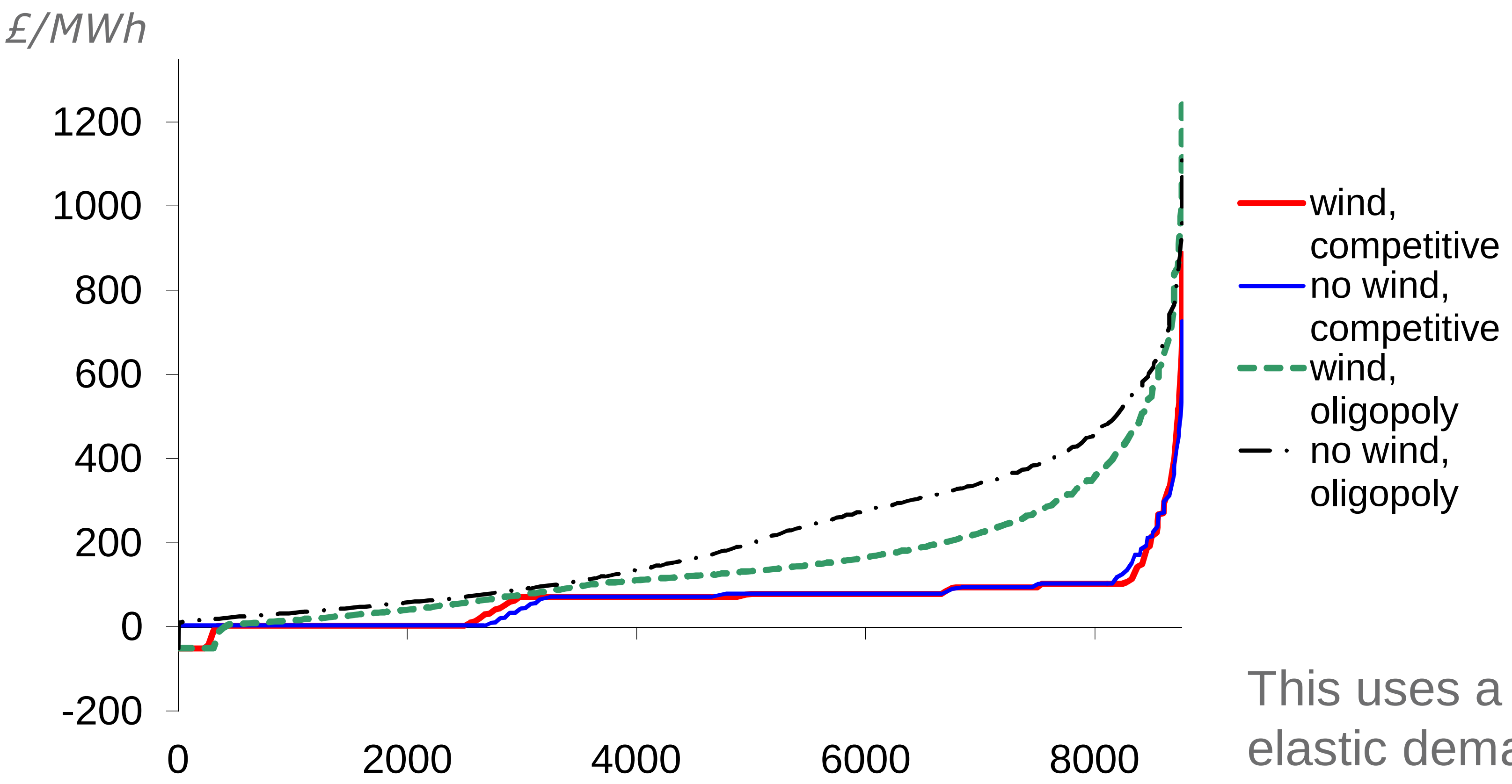
Equilibrium capacity mix (competitive and strategic)



This uses a more elastic demand curve than the earlier slides

Imperial College London BUSINESS SCHOOL

Price duration curves (varying market structure)



This uses a more elastic demand curve than the earlier slides

Imperial College London BUSINESS SCHOOL

Prices

Average price (£/MWh) for:	No wind	Wind
Competitive firms:		
Base load	66.12	65.99
Wind output		42.69
Demand	74.45	71.09
Strategic firms:		
Base load	208.34	152.49
Wind output		96.27
Demand	226.36	159.96

Conclusions

- With competitive behaviour, wind capacity affects the equilibrium thermal capacity mix much more than prices
- Strategic investment implies too little capacity in total, and too much capacity with low variable costs
- If wind capacity is not paid the wholesale price, incentives to raise this are lower

Imperial College
London
BUSINESS SCHOOL