Imperial College
London

2nd CES workshop: Intelligence and Flexibility in Future Electricity Markets
Universidad de Chile, Santiago, Chile, 20/11/2017

Decentralised optimisation and game-theoretic approaches for market-based coordination of power systems' operation and planning

Dimitrios Papadaskalopoulos
Research Fellow in Decentralised Energy Systems

Imperial College London: Research on Power Systems

- Imperial College London: #8 in THE World University Rankings
- Department of Electrical and Electronic Engineering, Control and Power group
- Power systems: 6 academics, 3 research fellows, ~15 RAs, ~40 PhD students
- MSc program on Future Power Networks
- Energy Futures Lab: multidisciplinary research on tackling energy challenges
- Research projects: UK EPSRC, EC H2020, UK-China, UK-Korea, UK-India initiatives
- Imperial Consultants: close collaboration with energy industry

energy futures lab

An institute of Imperial College London

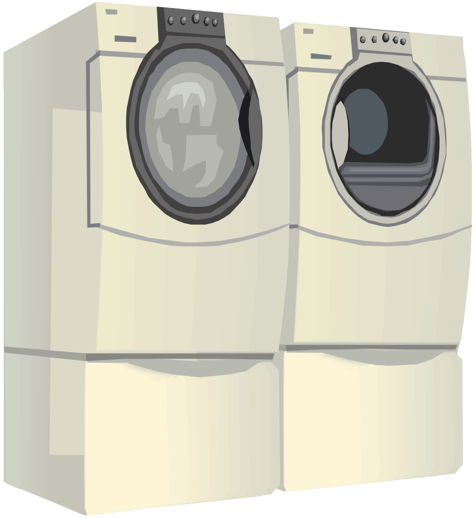
Motivation: Fundamental changes in power systems' operation and planning

- **Smart Grid concept**:
  - ➢Integration of vast number of small-scale flexible demand and energy storage technologies in system operation and planning
  - ➢Cannot be addressed through traditional centralised control approaches, due to scalability and privacy limitations
  - ➢Need for **decentralised optimisation approaches**

- **Deregulation of electricity sector**:
  - ➢Moving away from competitive models optimizing system-wide objectives (maximizing of social welfare)…
  - ➢…to models optimizing objectives (maximizing individual profit) of strategic, price-making players
  - ➢Need for **game-theoretic modeling approaches**

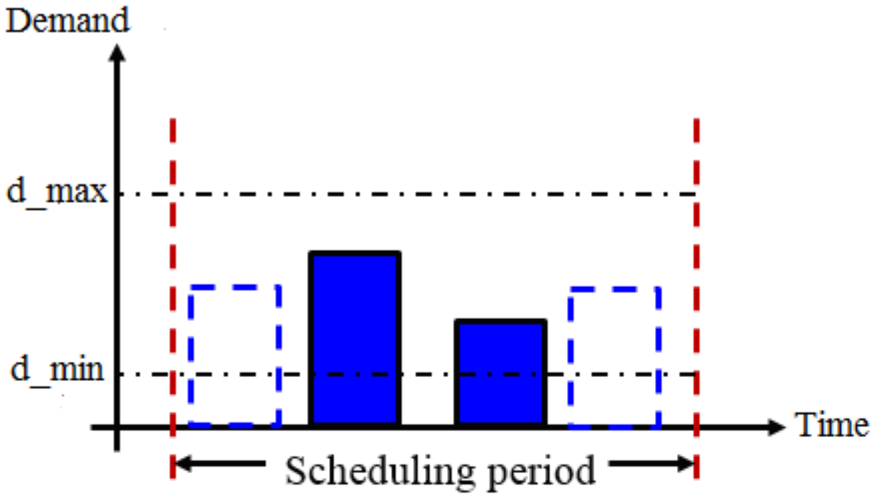
DECENTRALISED COORDINATION OF FLEXIBLE LOADS

Flexible loads



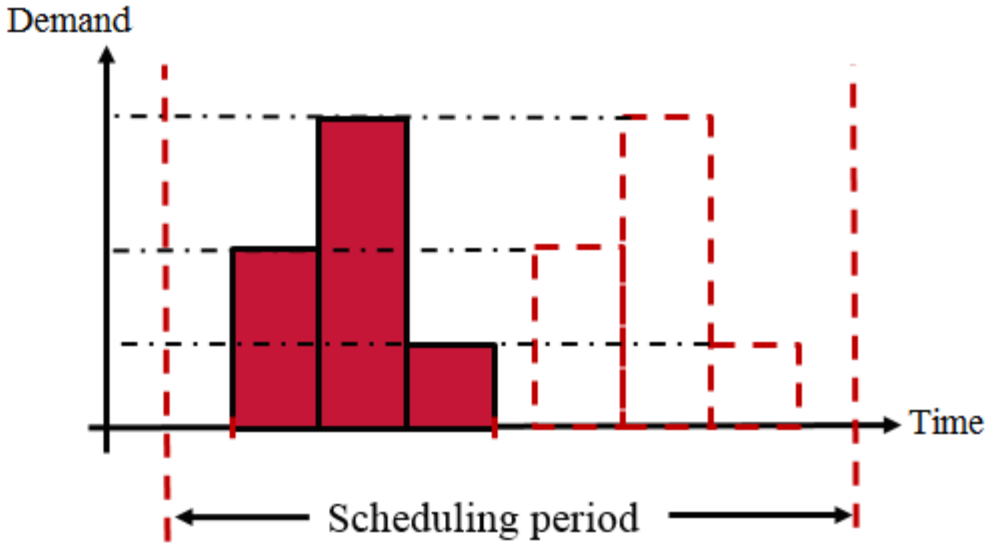
Types of flexible loads

Continuously adjustable power



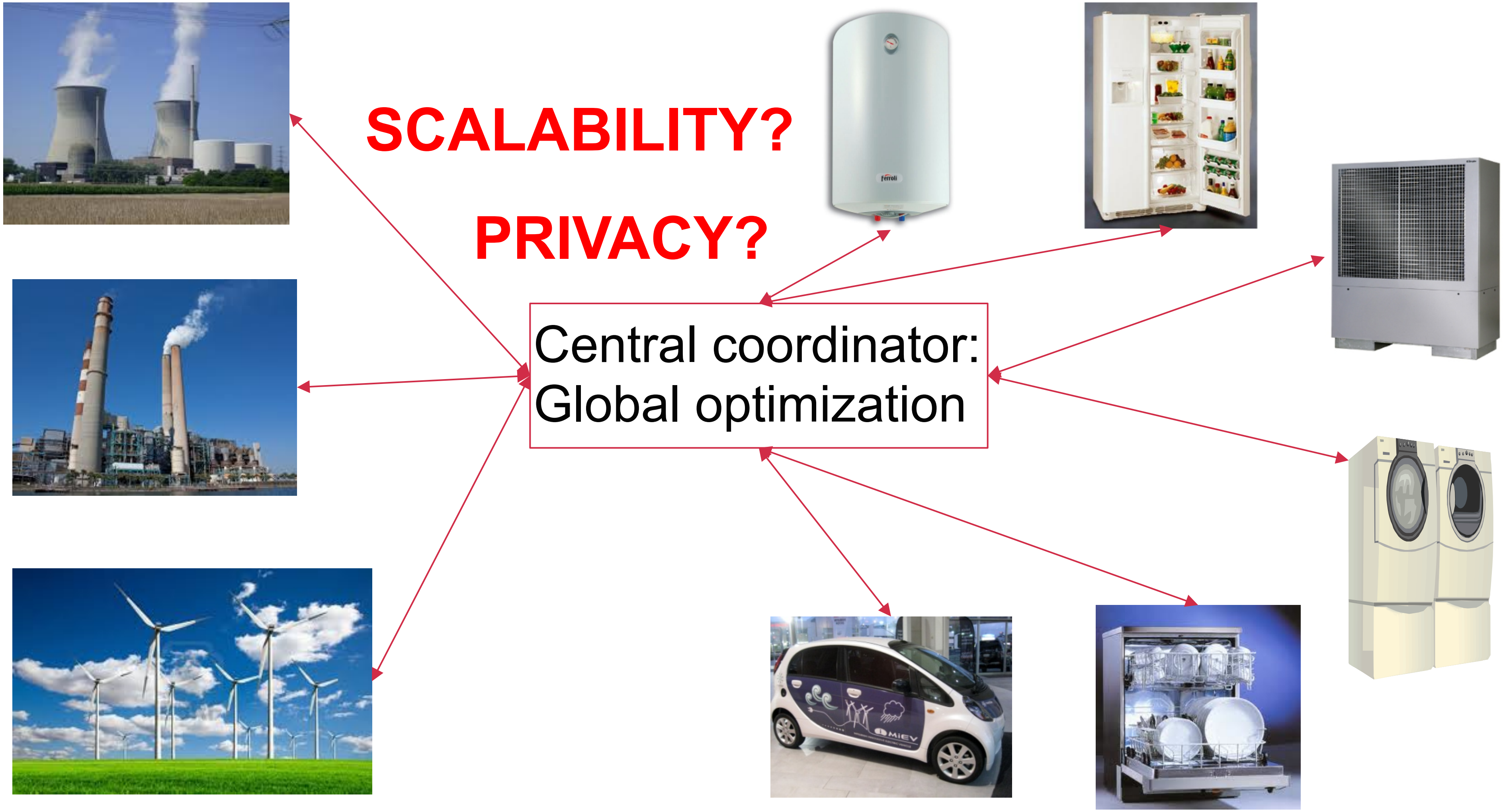
- Flexibility is associated with the maximum instantaneous power limit
- Example: smart-charging electric vehicles

Deferrable cycles



- Flexibility is associated with the maximum cycle delay limit
- Example: dishwashers with delay functionality

Traditional, centralised coordination approach



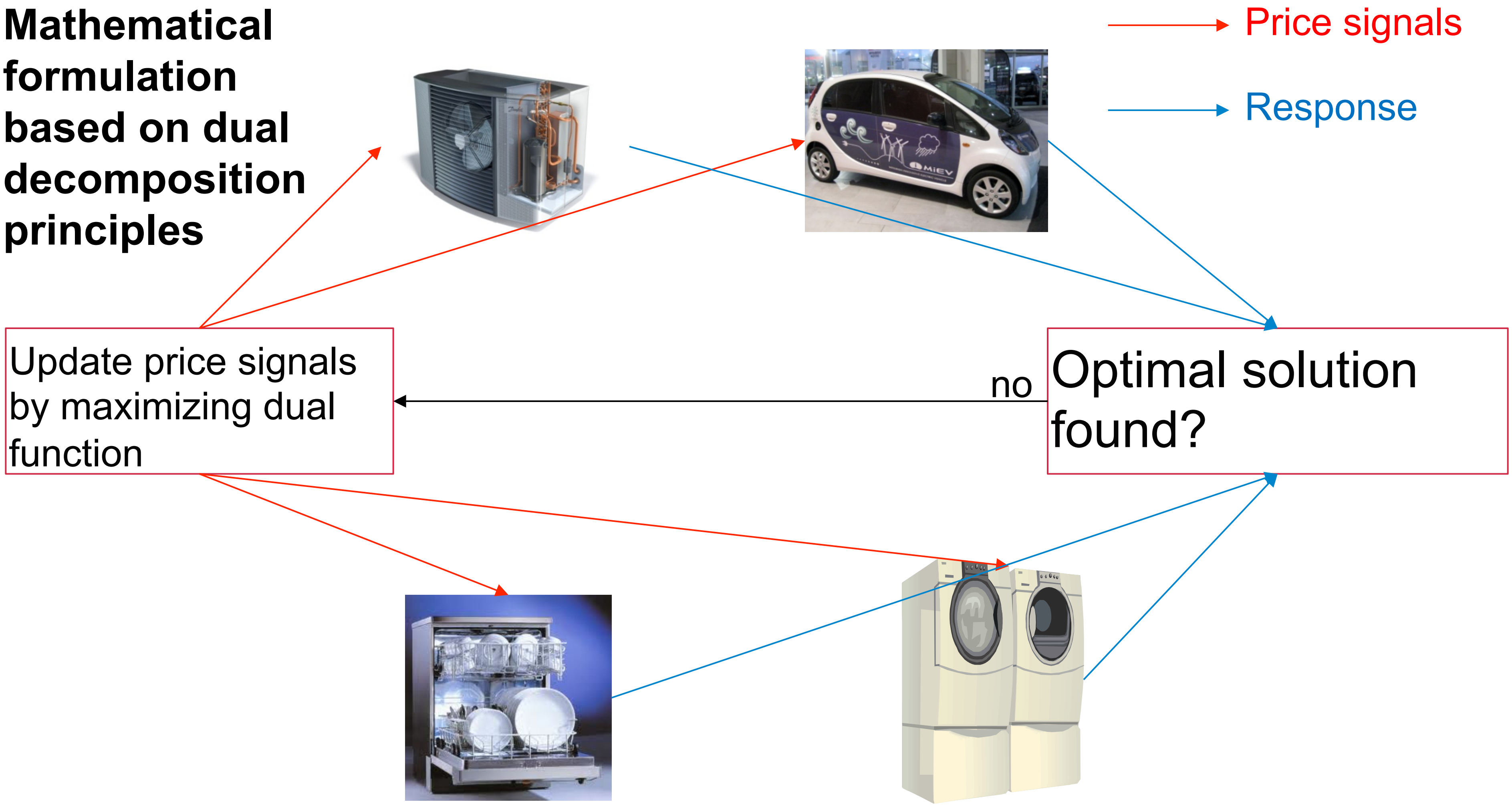
SCALABILITY?

PRIVACY?

Central coordinator:
Global optimization

Decentralised, price-based coordination approach

Mathematical formulation based on dual decomposition principles



Price signals

Response

Update price signals by maximizing dual function

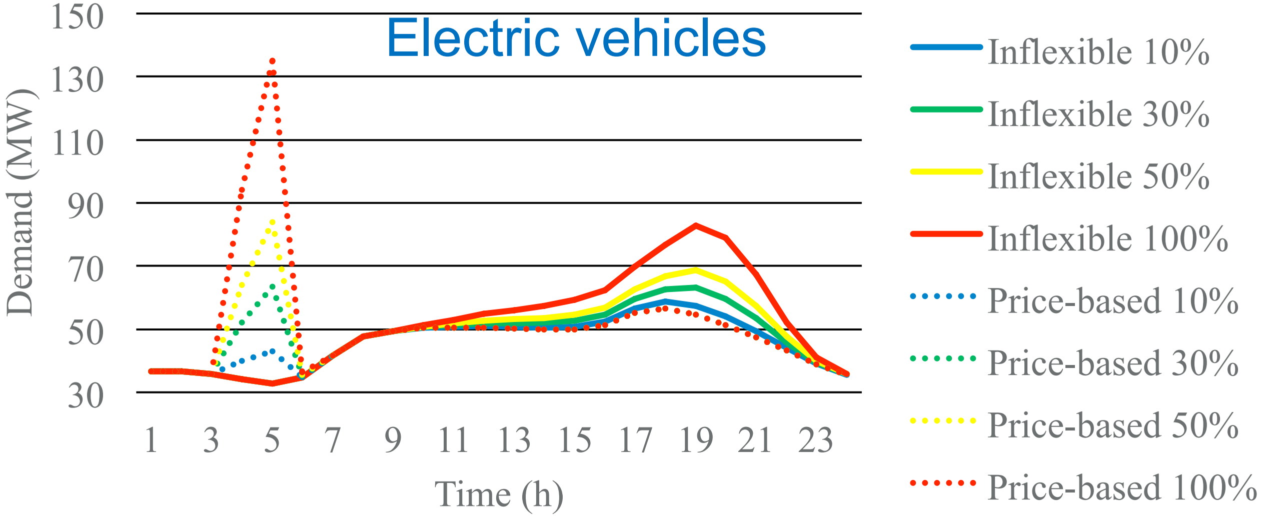
no

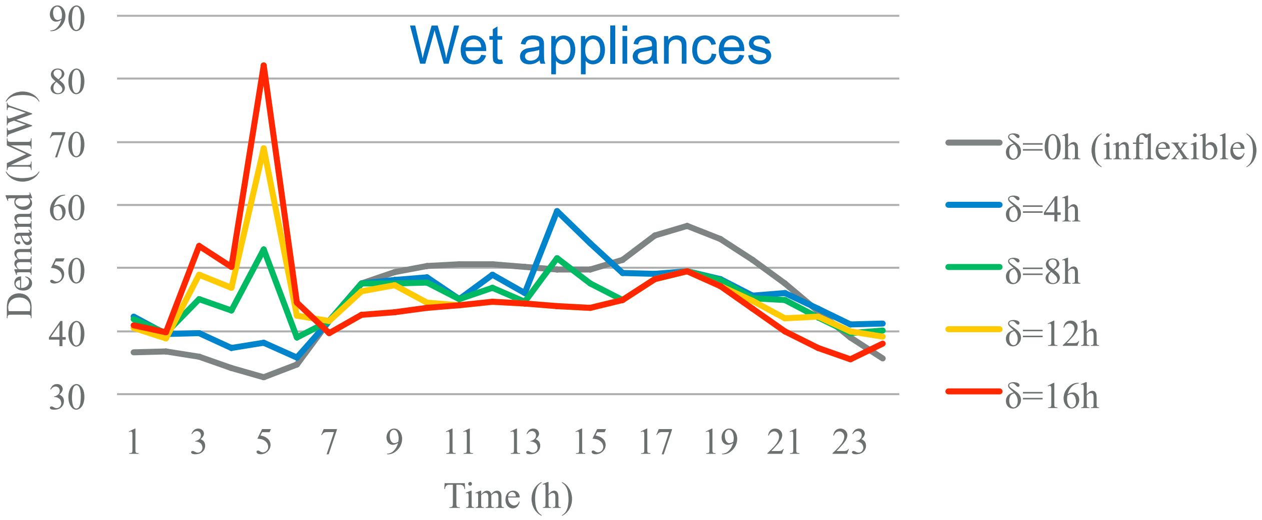
Optimal solution found?

Imperial College London

Demand response concentration effect

- Flexible loads' response is concentrated at the lowest-priced periods
  - ➢New demand peaks, higher costs, higher network losses
  - ➢Concentration effect enhanced with higher number, higher flexibility and lower diversity of flexible loads



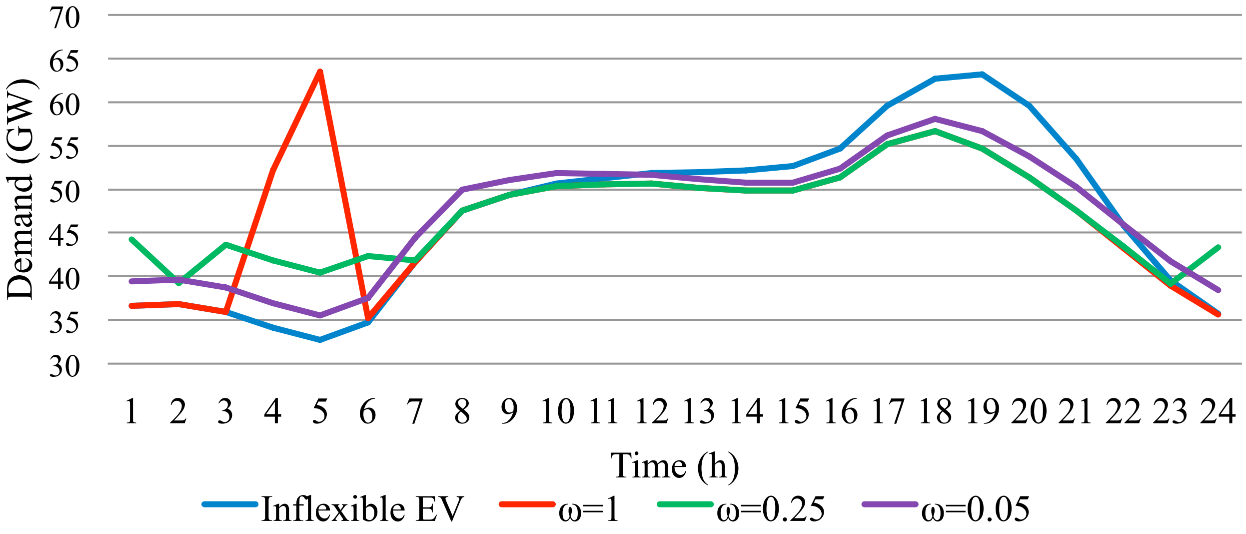


Novel contribution: Strategies against response concentration

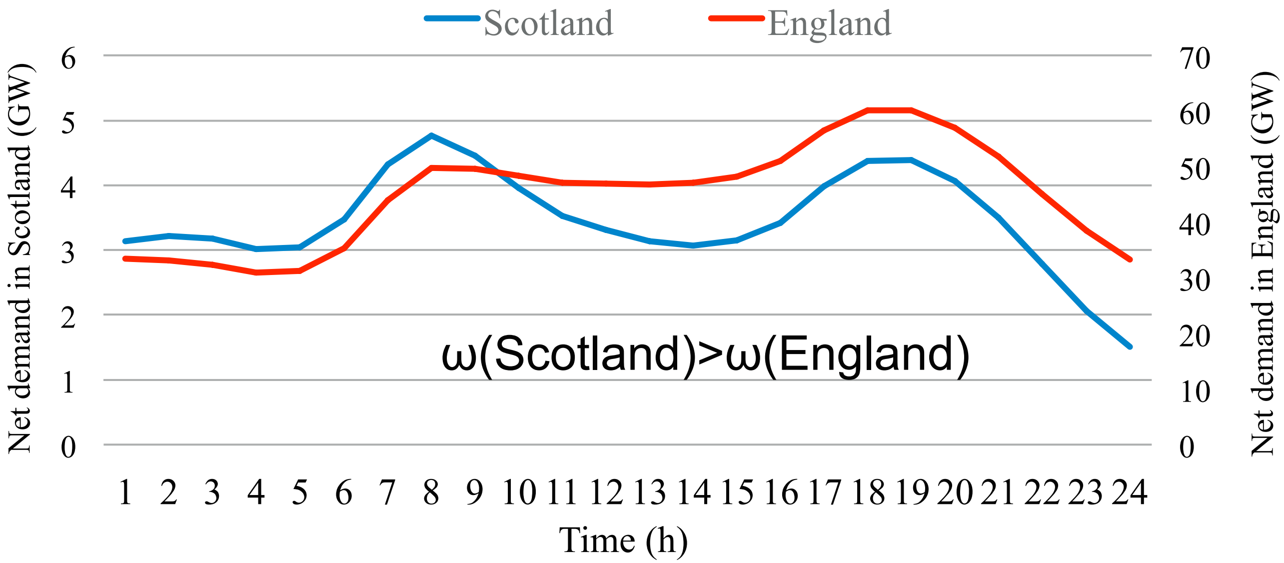
- Impose relative flexibility restriction ω
    - Loads with continuously adjustable power: *maximum power restriction*
    - Loads with deferrable cycles: *maximum cycle delay restriction*
- Apply non-linear / flexibility price α
    - Loads with continuously adjustable power: *penalize square of power*
    - Loads with deferrable cycles: *penalize duration of cycle delay*
- Apply differentiated price signals to different loads
    - Randomise prices following normal distribution (with standard deviation σ)

Tuning strategies' parameters

- Trade-off between:
  - Avoiding demand response concentration
  - Filling the off-peak valleys



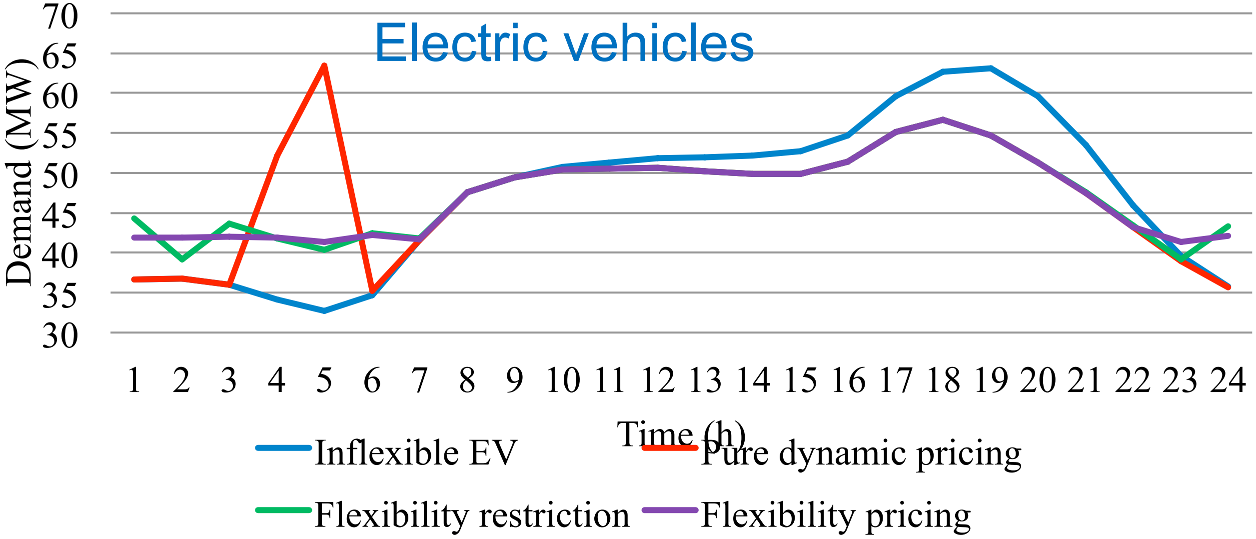
- Network congestion and losses…> location-specific tuning?



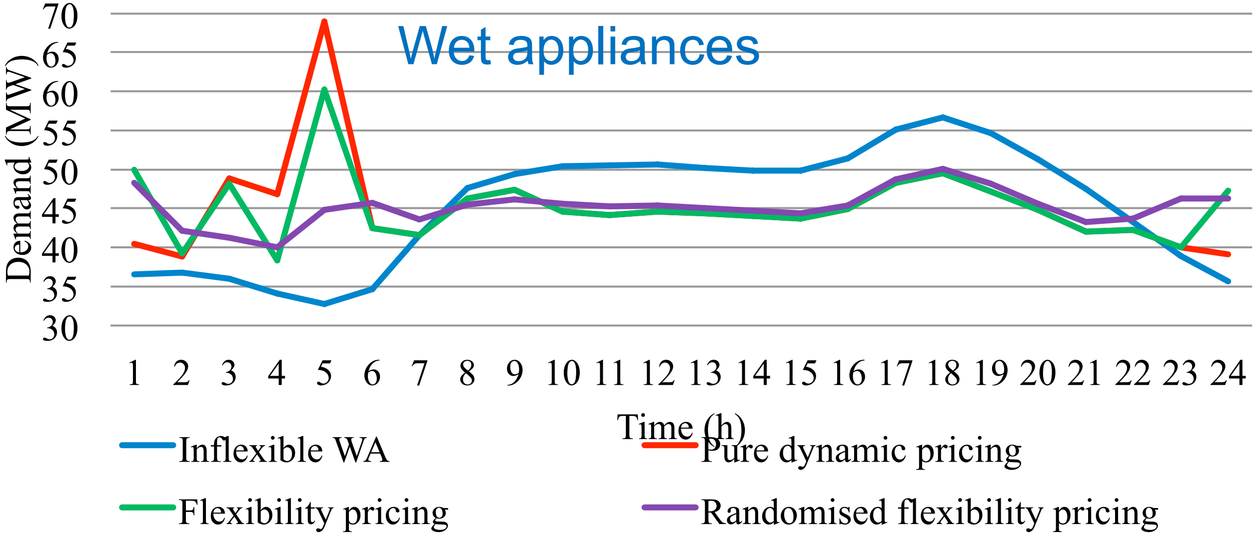
ω(Scotland)>ω(England)

Performance of different measures depends on flexible loads' operational properties

- ➢Flexibility pricing slightly outperforms flexibility restriction
- ➢Randomised pricing does not bring additional benefits



- ➢Flexibility restriction and flexibility pricing have similar performance
- ➢Randomised pricing brings significant additional benefits



Relevant publications

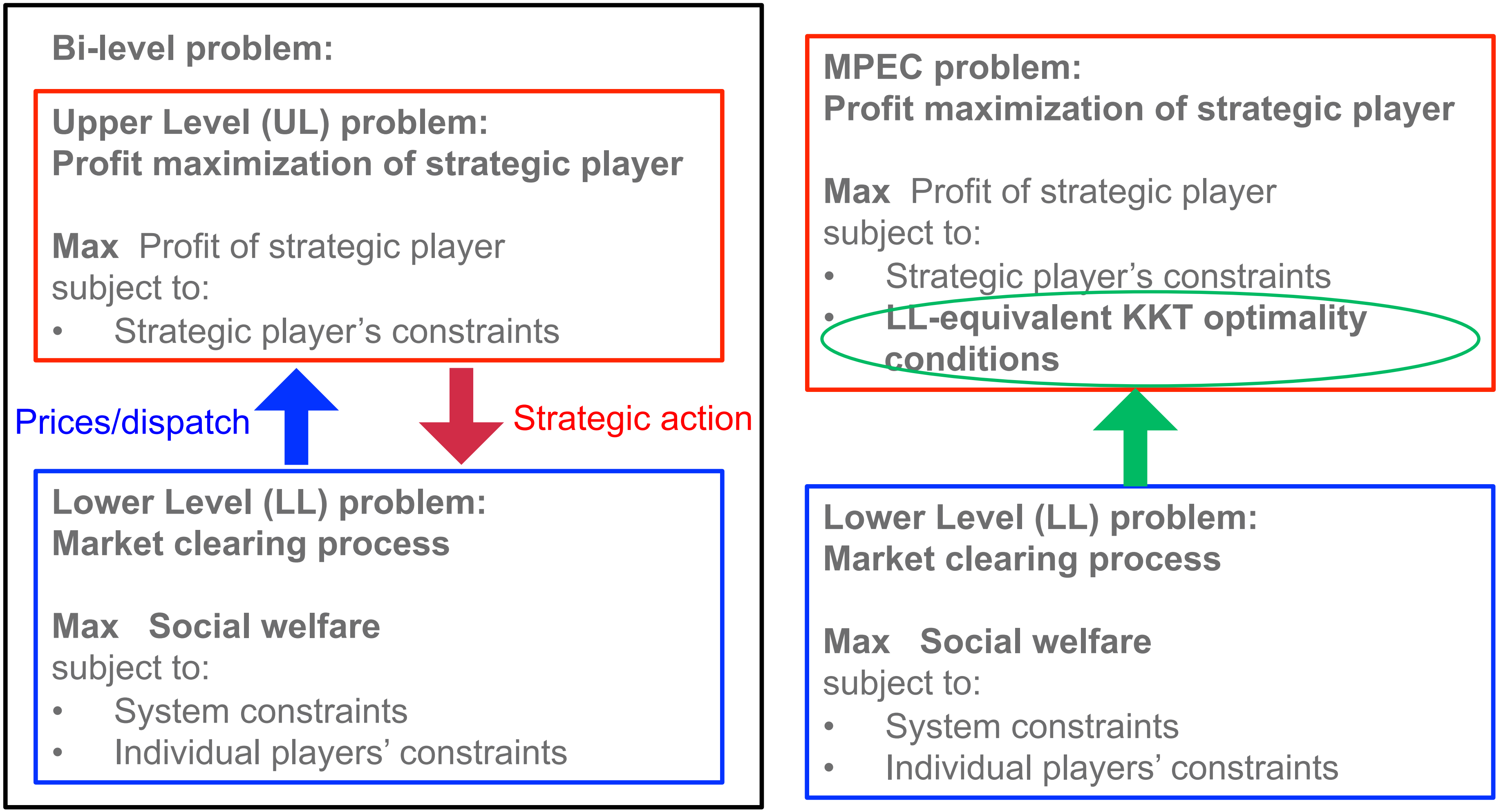
- D. Papadaskalopoulos and G. Strbac, “Decentralized Participation of Flexible Demand in Electricity Markets – Part I: Market Mechanism,” *IEEE Transactions on Power Systems*, November 2013.
- D. Papadaskalopoulos, G. Strbac, P. Mancarella, M. Aunedi and V. Stanojevic, “Decentralized Participation of Flexible Demand in Electricity Markets – Part II: Application with Electric Vehicles and Heat Pump Systems,” *IEEE Transactions on Power Systems*, November 2013.
- D. Papadaskalopoulos, D. Pudjianto and G. Strbac, “Decentralized Coordination of Microgrids with Flexible Demand and Energy Storage,” *IEEE Transactions on Sustainable Energy*, October 2014.
- Y. Ye, D. Papadaskalopoulos and G. Strbac, “Factoring Flexible Demand Non-Convexities in Electricity Markets,” *IEEE Transactions on Power Systems*, July 2015.
- D. Papadaskalopoulos and G. Strbac, “Non-linear and Randomized Pricing for Distributed Management of Flexible Loads,” *IEEE Transactions on Smart Grid,* March 2016.
- D. Papadaskalopoulos and G. Strbac, “Smart price-based scheduling of flexible residential appliances,” book chapter appearing in *Smarter Energy: from Smart Metering to the Smart Grid*, IET, 2016.

GAME-THEORETIC MODELLING OF OPERATION AND PLANNING

Motivation

- Deregulation of the electricity sector
  - ➢Unbundling of vertically integrated utilities
  - ➢Introduction of competition in generation, supply (and maybe network) sectors
- Need to move away from traditional competitive operation and planning models optimizing system-wide objectives (maximizing social welfare)…
- …to models capturing the strategic, price-making objectives of multiple independent energy market players (maximizing profit) and identifying the system conditions emerging from the interaction of these self-interested players
  - ➢Non-cooperative game-theoretic modelling approaches constitute a natural choice

Bi-level optimization model of strategic behaviour



Bi-level problem:

Upper Level (UL) problem:
Profit maximization of strategic player

Max Profit of strategic player
subject to:
- Strategic player's constraints

Lower Level (LL) problem:
Market clearing process

Max Social welfare
subject to:
- System constraints
- Individual players' constraints

MPEC problem:
Profit maximization of strategic player

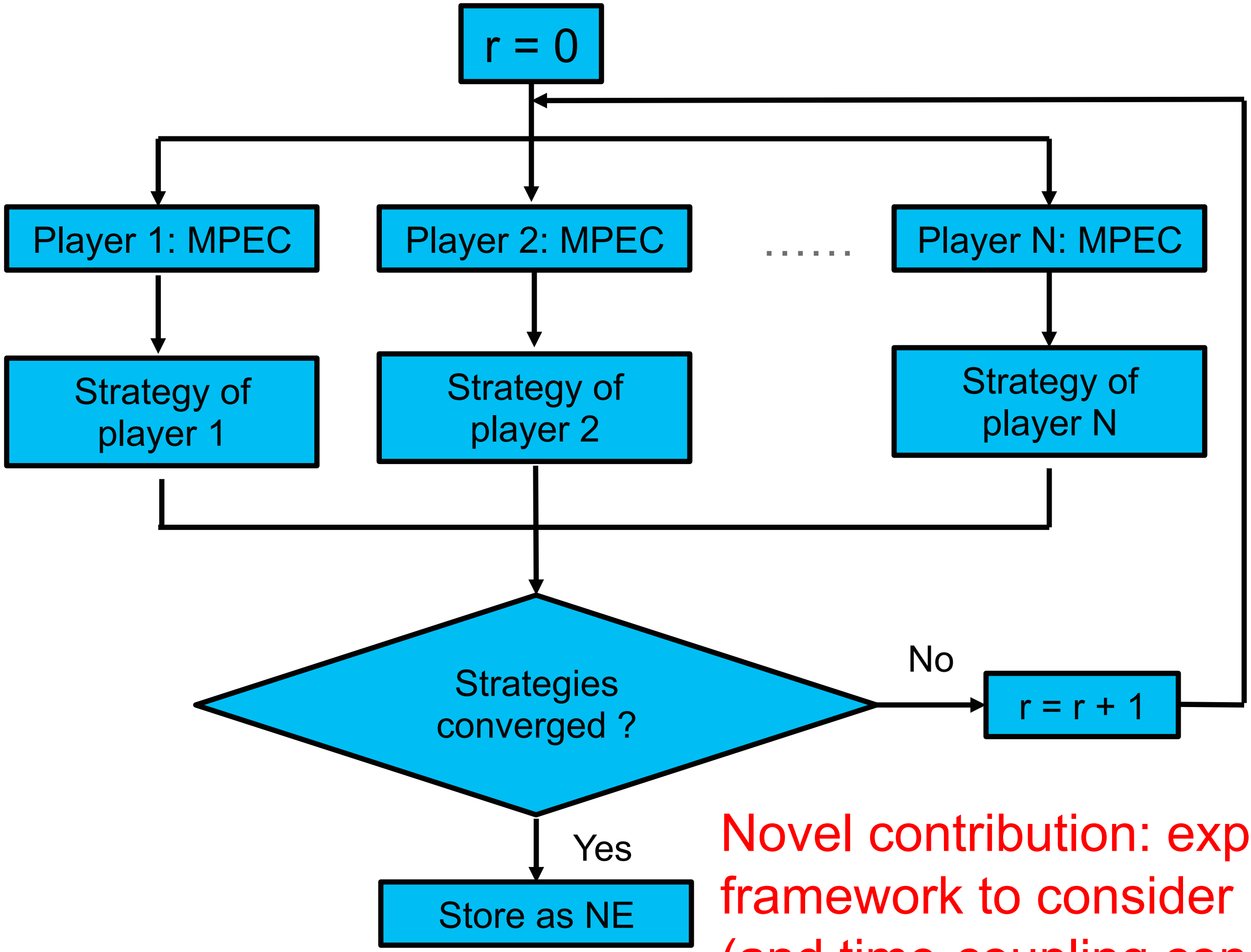
Max Profit of strategic player
subject to:
- Strategic player's constraints
- **LL-equivalent KKT optimality conditions**

Lower Level (LL) problem:
Market clearing process

Max Social welfare
subject to:
- System constraints
- Individual players' constraints

MPEC is complex, highly non-linear > need for linearization / decomposition techniques

Equilibrium programming: Finding Nash Equilibria (NE)



r = 0

Player 1: MPEC

Player 2: MPEC

……

Player N: MPEC

Strategy of player 1

Strategy of player 2

Strategy of player N

Strategies converged ?

No

r = r + 1

Yes

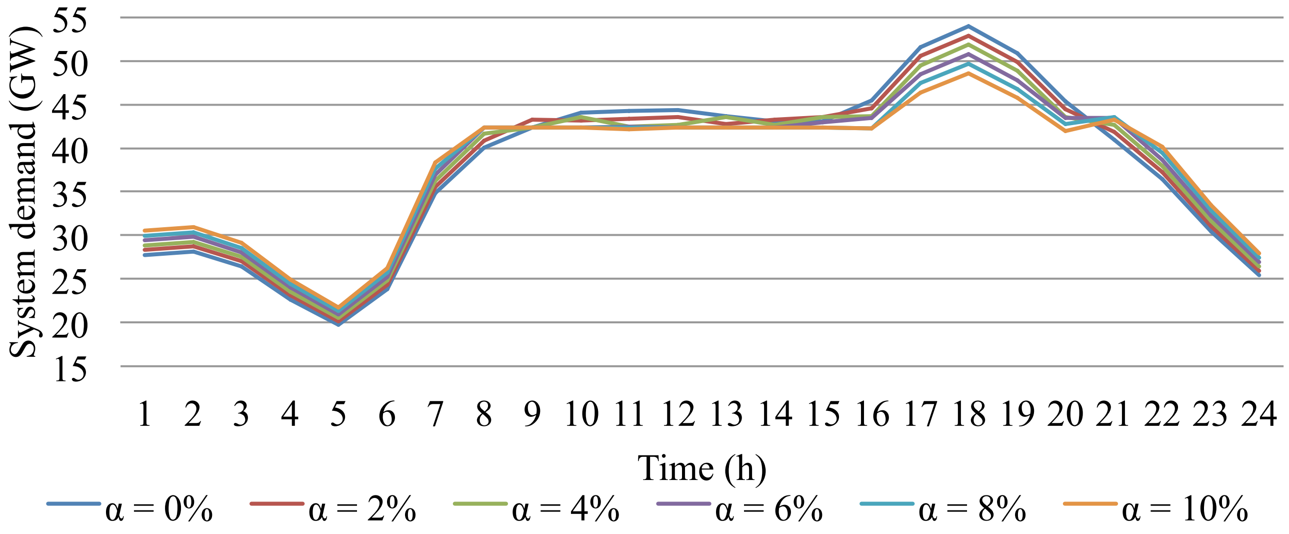
Store as NE

Existence, uniqueness and convergence to NE are not generally guaranteed ! > need for heuristics

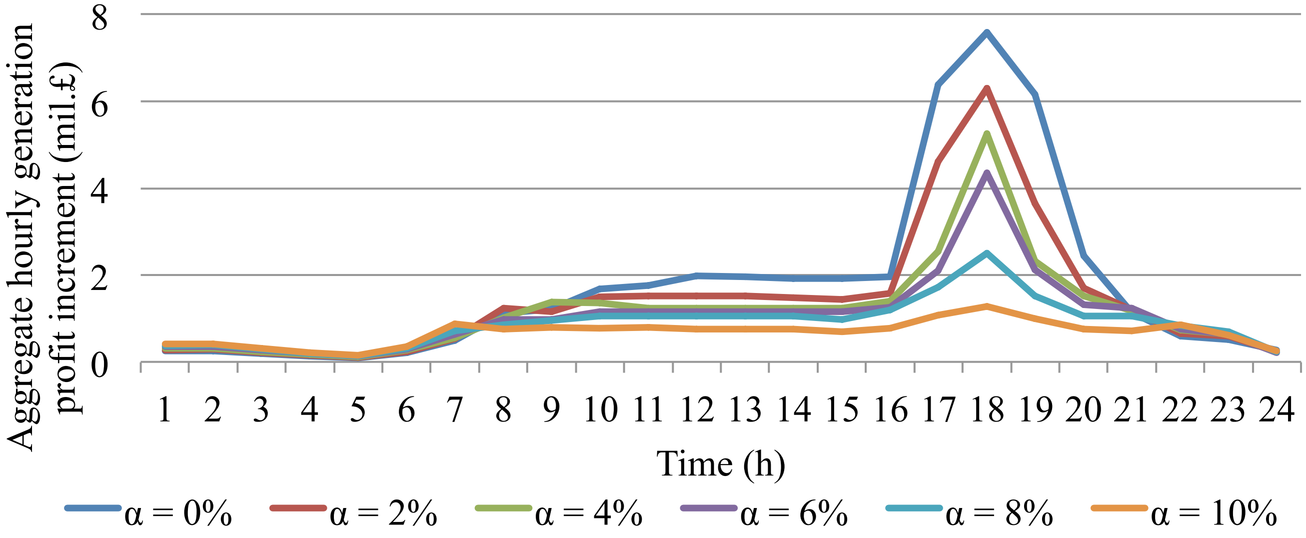
Novel contribution: expand this modelling framework to consider multiple time periods (and time-coupling constraints of demand and storage) as well as network constraints

Impact of flexible demand on producers' market power

- Impact of varying demand flexibility levels on system demand

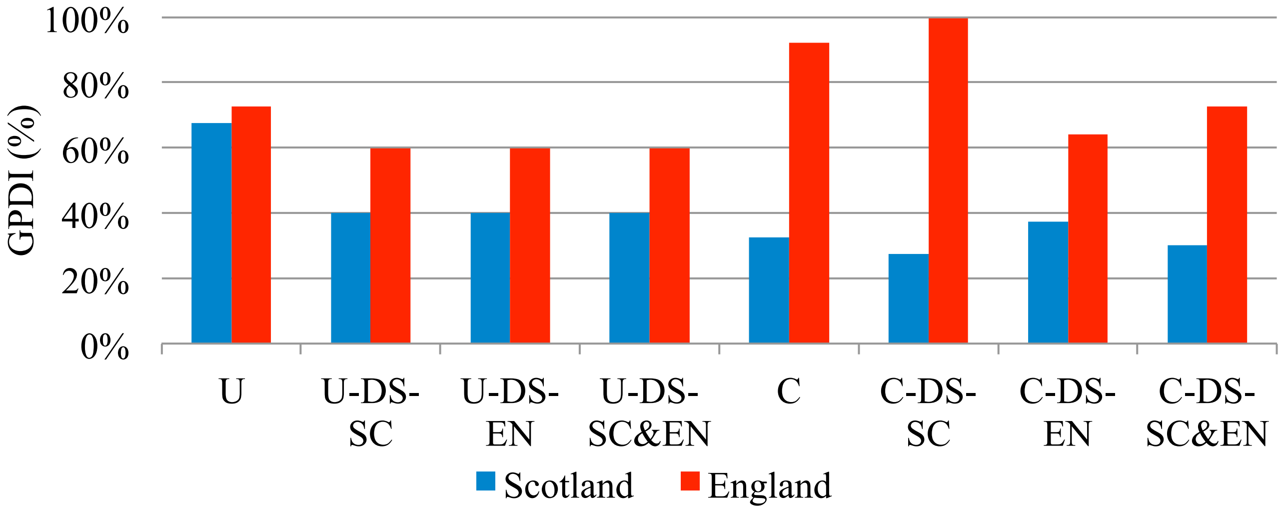


- Impact of varying demand flexibility on producers' market power

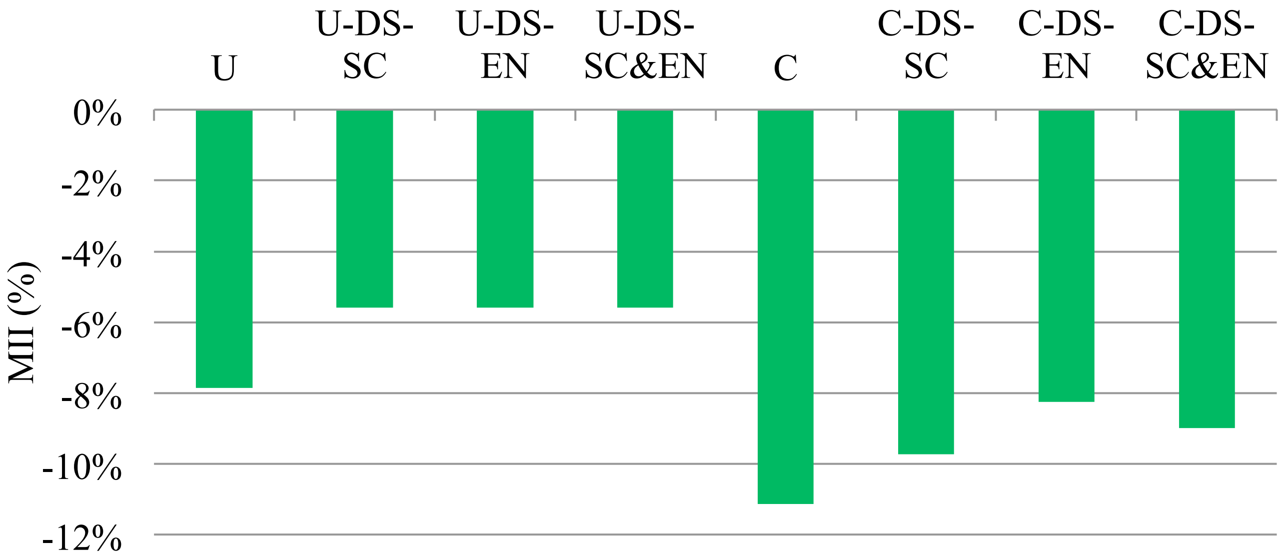


Impact of flexible demand on producers' market power

- Impact of congestion and demand flexibility location on producers' market power

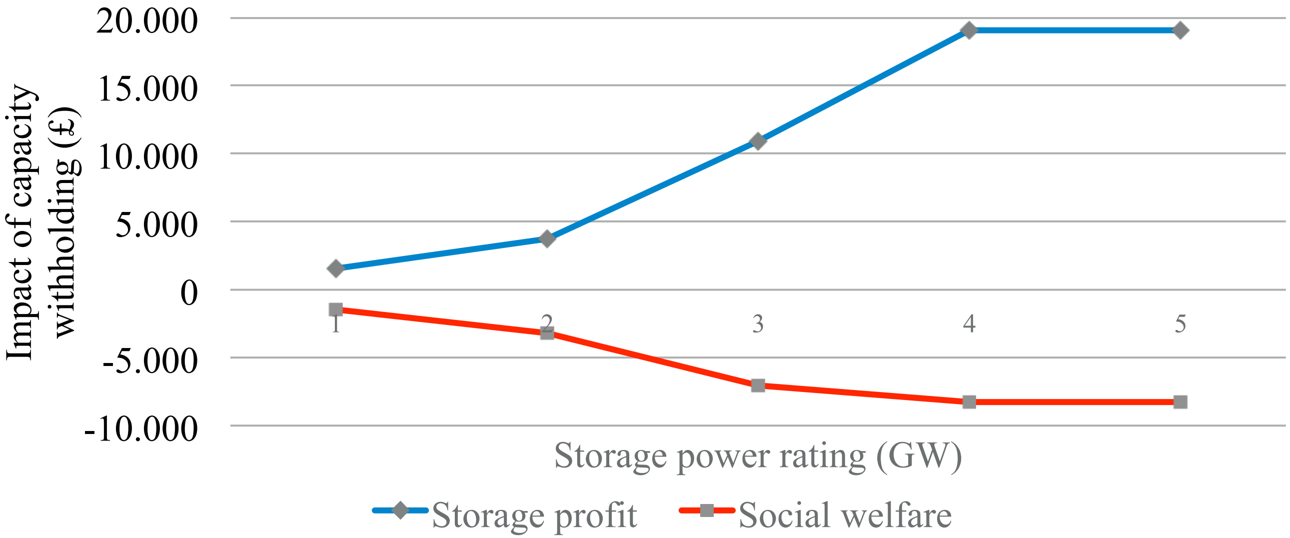


- Impact of congestion and demand flexibility location on market efficiency

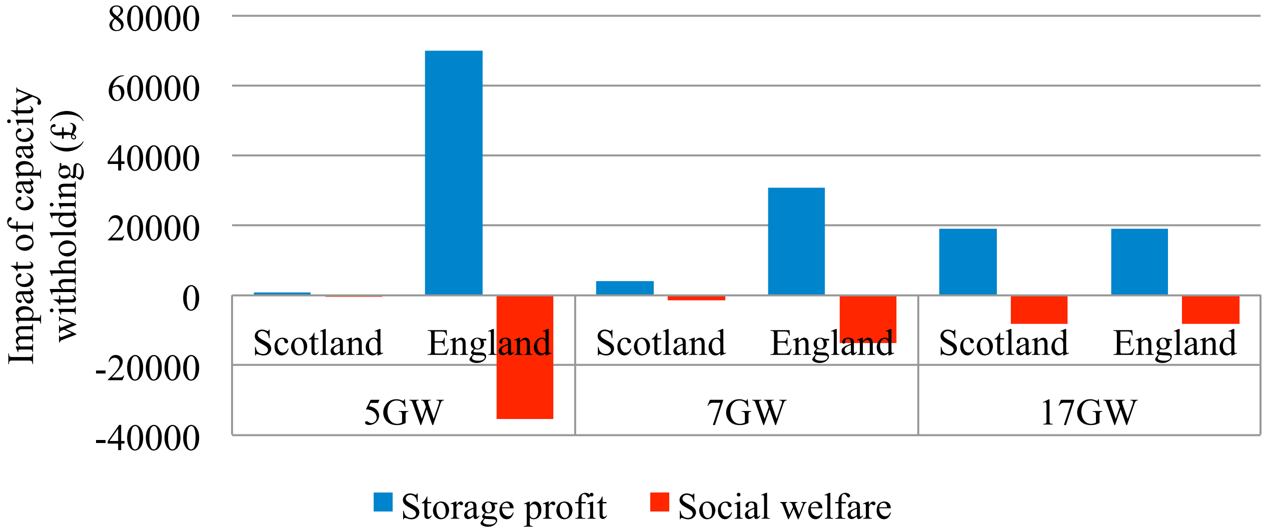


Exercise of market power by strategic storage through capacity withholding

- Impact of storage size on its market power potential

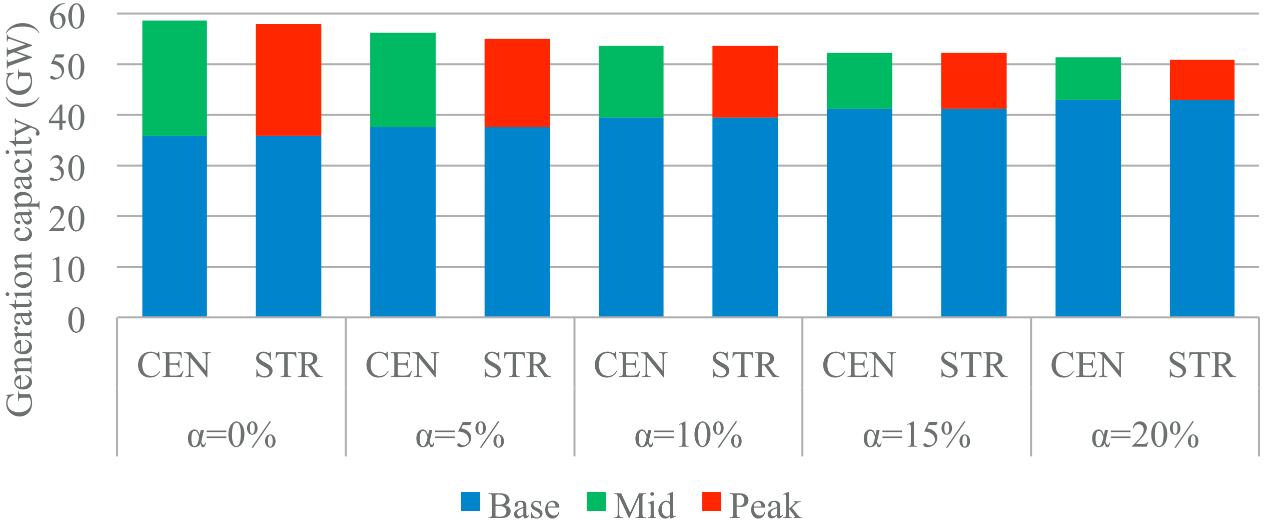


- Impact of storage location on its market power potential

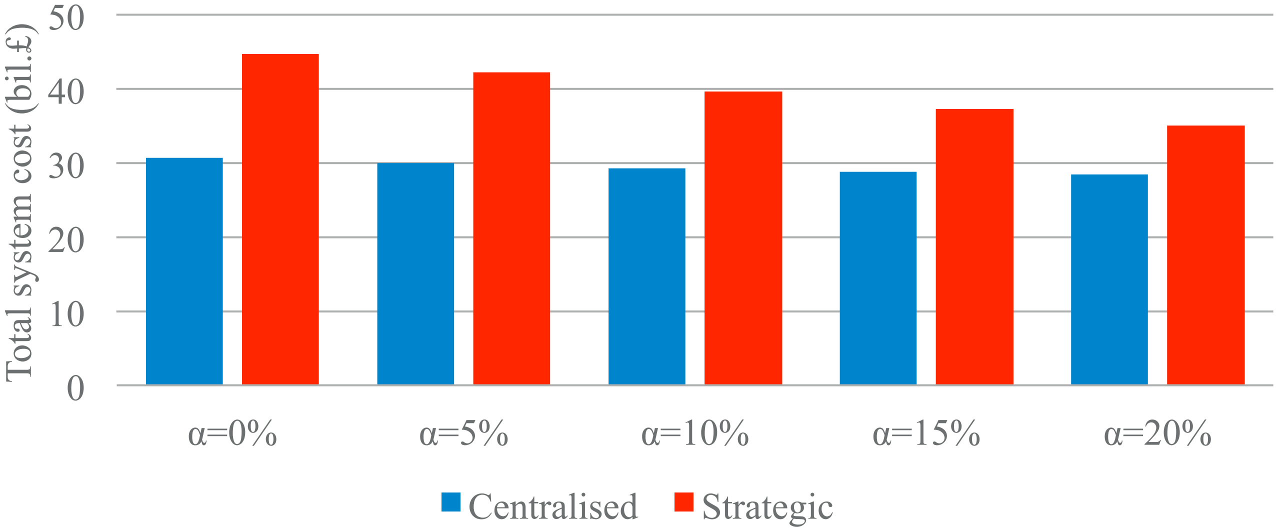


Impact of flexible demand on generation planning

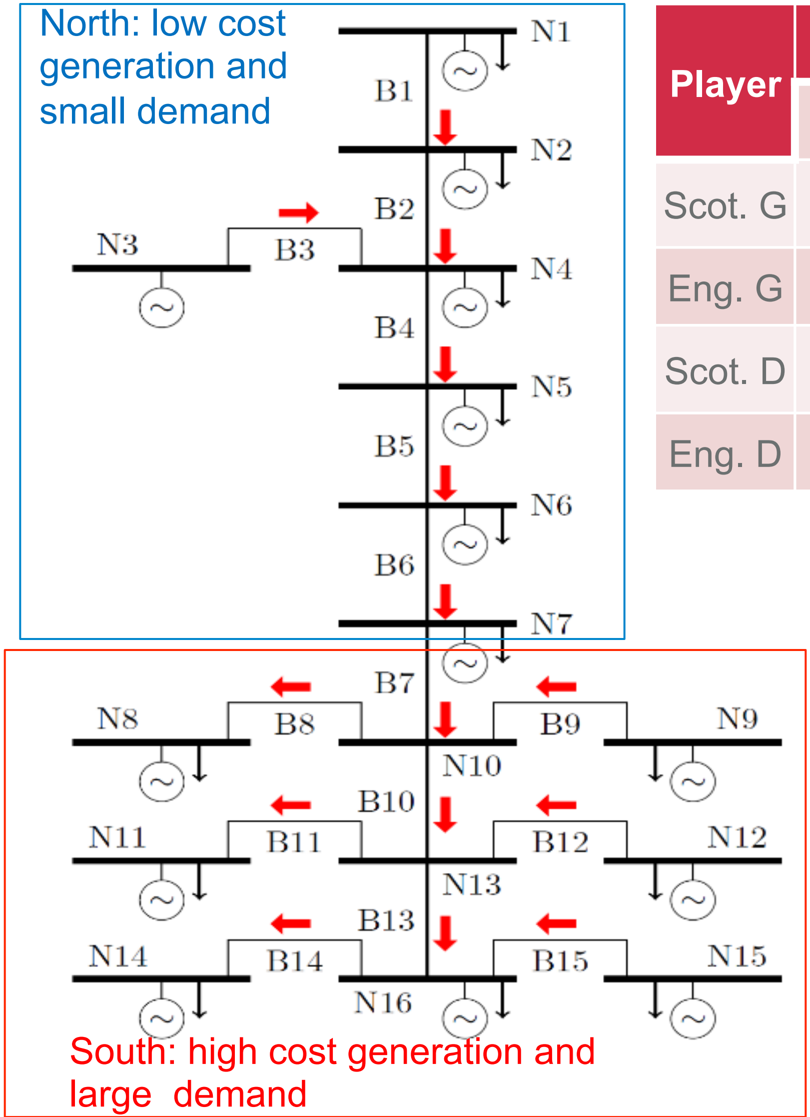
- Impact of varying demand flexibility levels on generation mix



- Impact of varying demand flexibility on total (investment and operation) system cost



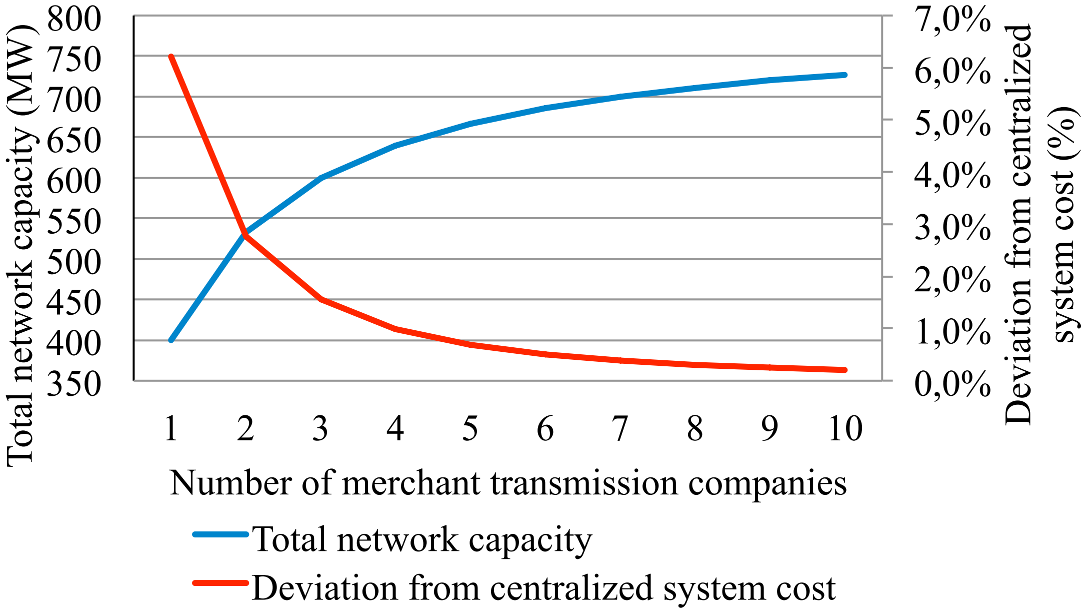
Game-theoretic modelling of decentralised network planning



North: low cost generation and small demand

South: high cost generation and large demand

Player	Players' capacity contribution per branch (MW)							
	B1	B3	B4	B6	B7	B8	B9	B10
Scot. G	220	70	830	2020	2670	420	0	270
Eng. G	0	0	0	0	0	0	0	0
Scot. D	0	0	0	0	0	0	0	0
Eng. D	440	320	10	1150	900	140	3790	3080



Relevant publications

- Y. Ye, D. Papadaskalopoulos and G. Strbac, “Investigating the Impact of Demand Shifting on Electricity Producers’ Market Power,” *IEEE Transactions on Power Systems*, submitted.
- Y. Ye, D. Papadaskalopoulos and G. Strbac, “An MPEC approach for analysing the impact of energy storage in imperfect electricity markets,” *13th International Conference on the European Energy Market*, 2016.
- D. Papadaskalopoulos, Y. Ye, R. Moreira and G. Strbac, “Strategic Capacity Withholding by Energy Storage in Electricity Markets,” *12th PowerTech Conference*, 2017.
- Y. Fan, D. Papadaskalopoulos and G. Strbac, “A game theoretic modeling framework for decentralized transmission planning,” *19th Power Systems Computation Conference (PSCC)*, 2016.
- A. de Paola, D. Papadaskalopoulos and G. Strbac, “Investigating the Social Efficiency of Merchant Transmission Planning through a Non-Cooperative Game-Theoretic Framework,” *IEEE Transactions on Power Systems*, submitted.

Future work directions in market modelling

- Need to consider multiple sectors (generation, transmission, distribution) and timescales (long-term planning to real-time balancing) simultaneously

- Incorporate uncertainties and risk perceptions of strategic players in their decision making problems > need for stochastic / robust reformulations

- Existing models cannot deal with a very large number of strategic players due to computational / convergence challenges > explore games with a continuum of players and mean-field game theory

- Rational behaviour assumption is not always valid > insights from behavioural economics and applied sociology

Imperial College
London

Decentralised optimisation and game-theoretic approaches for market-based coordination of power systems’ operation and planning

Dimitrios Papadaskalopoulos
d.papadaskalopoulos08@imperial.ac.uk