UCL

Balancing variable supply with flexible demand

ECEEE Summer Study, 1 June 2017

Dina Subkhankulova

UCL ENERGY INSTITUTE

Prof Mark Barrett
Dr Ed Manley

International Institute for Applied Systems Analysis
IIASA

Dr Artem Baklanov
Dr David McCollum

UCL SECReT
SECURITY SCIENCE DOCTORAL RESEARCH TRAINING CENTRE

Presentation overview

1) Motivation for research
2) Contributions
3) Model description
4) Results & discussion
5) Conclusions and further research

1. Motivation for research

The UK electricity system is changing:

Supply side	Demand-side
• Dispatchable generators replaced by renewables • System storage • Distributed electricity generation	• Small scale renewables • Consumer storage (electric, thermal) • New technology (electric vehicles, heat pumps) • Smart consumption devices

Unpredictable supply + Unpredictable demand = Difficult to balance the grid

1. Motivation for research

Solution?

Demand side management (DSM)

Coordinate consumers to use electricity when renewable energy is abundant

Where are the gaps?

DSM has been considered in idealistic settings,
i.e. identical consumers, isolated system, no market.

1. Motivation for research

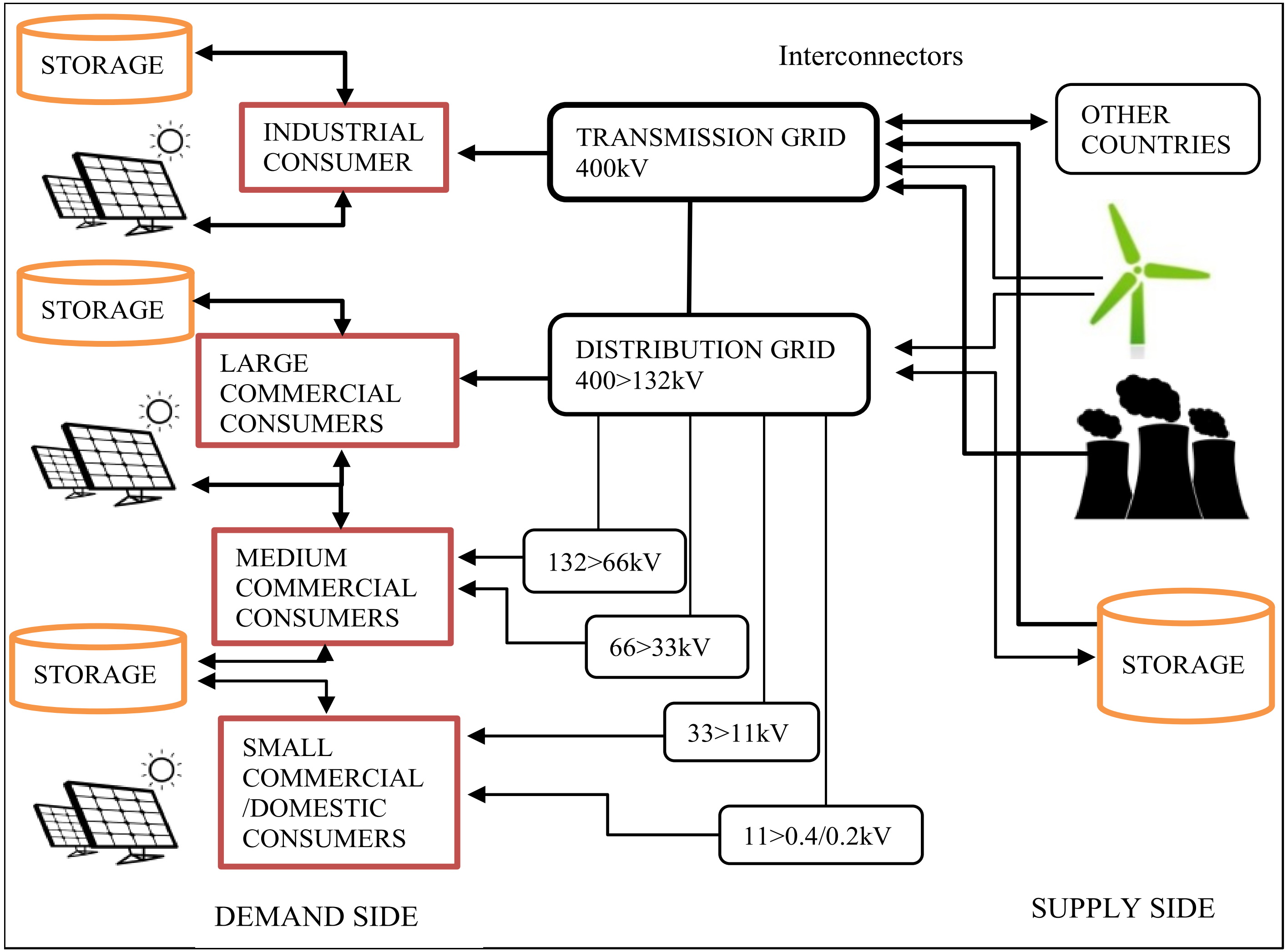


Figure 1: Graphical representation of the electricity flow in the GB electricity grid.

2. Our contributions

Part I – introduce different consumers and DSM regimes

1. What is better **distributed** or **centralised** coordination and for whom?
2. What is the **value** of storage in the future UK electricity system?

Part II – introduce competition for utilities

1. How could DSM influence future **business models** of electricity utilities?
2. Can DSM be **disruptive**? Can utilities use it to gain a competitive advantage while compromising global sustainability goals?

3. Part I – general framework

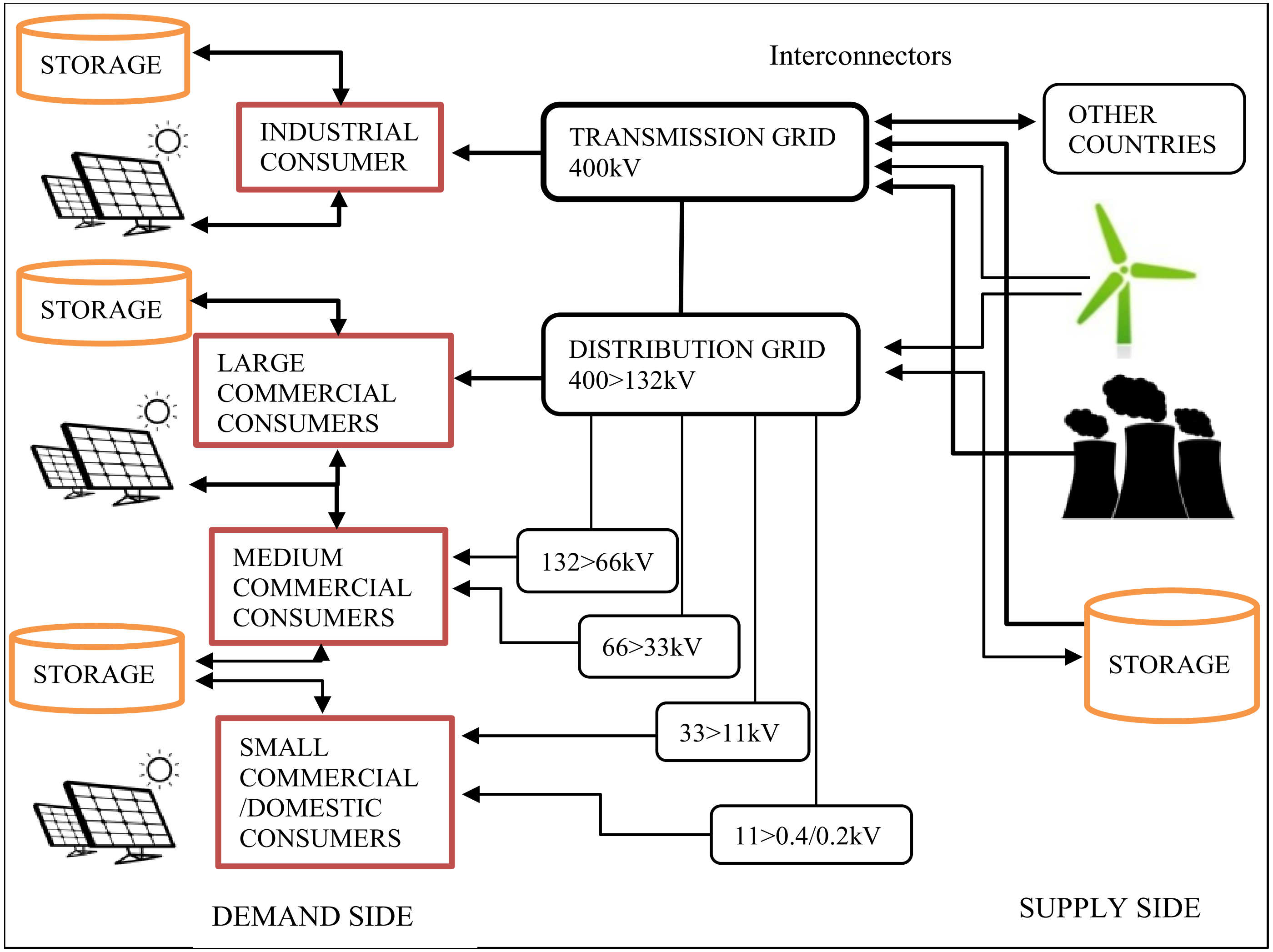
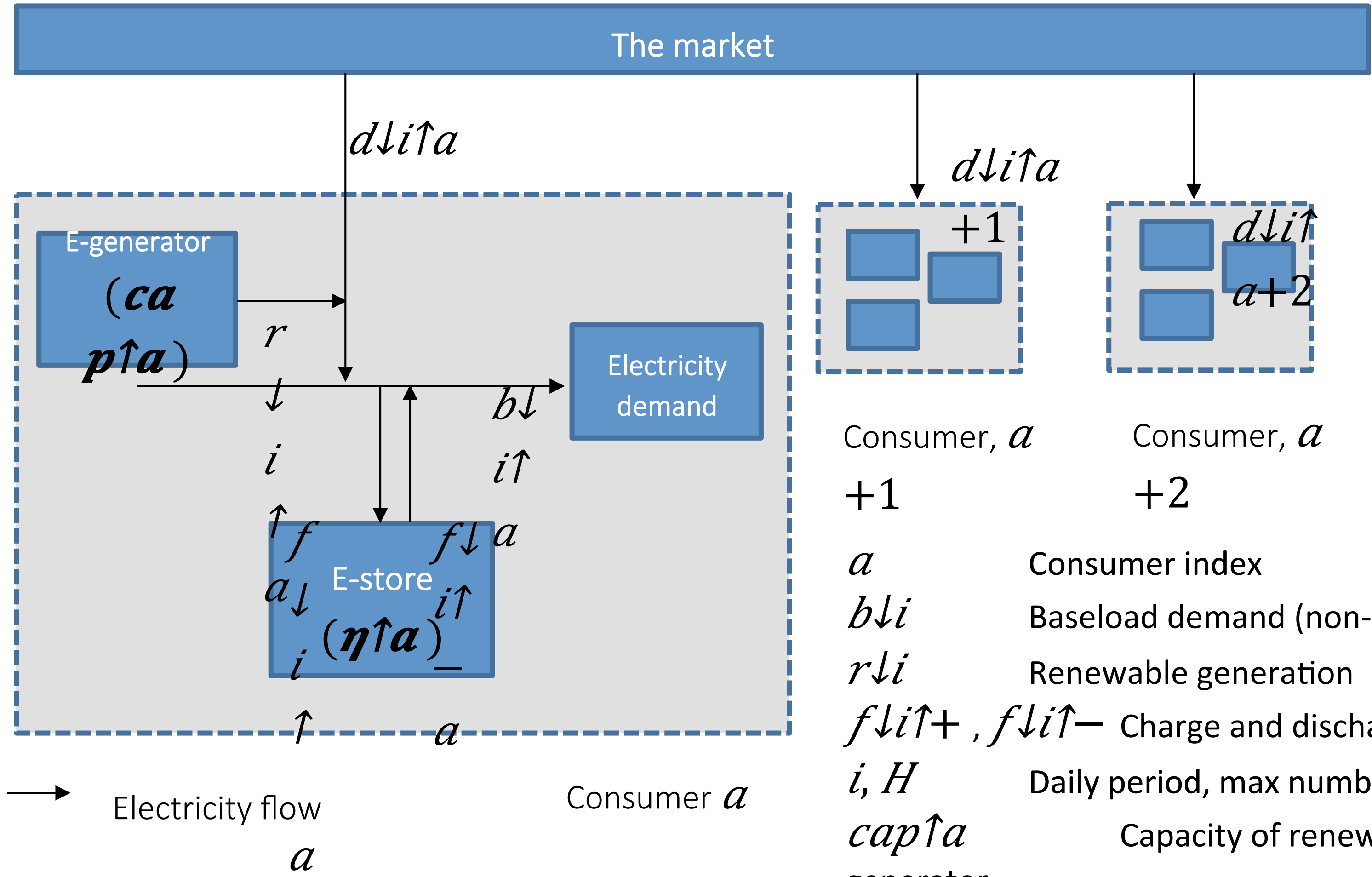


Figure 1: Graphical representation of the electricity flow in the GB electricity grid.

3. Part I – consumer

Figure 2: Graphical representation of consumer resources.



a	Consumer index
b_i	Baseload demand (non-deferrable)
r_i	Renewable generation
f_i^+, f_i^-	Charge and discharge profile
i, H	Daily period, max number of periods
cap^a	Capacity of renewable generator
η^a	Storage efficiency
d_i^a	Net demand (residual)

Net demand: $d_i^a = b_i^a + f_i^{+a} - \eta^a \cdot f_i^{-a} - r_i^a \quad \forall\, i \in [1, H]$

3. Part I – DSM regimes

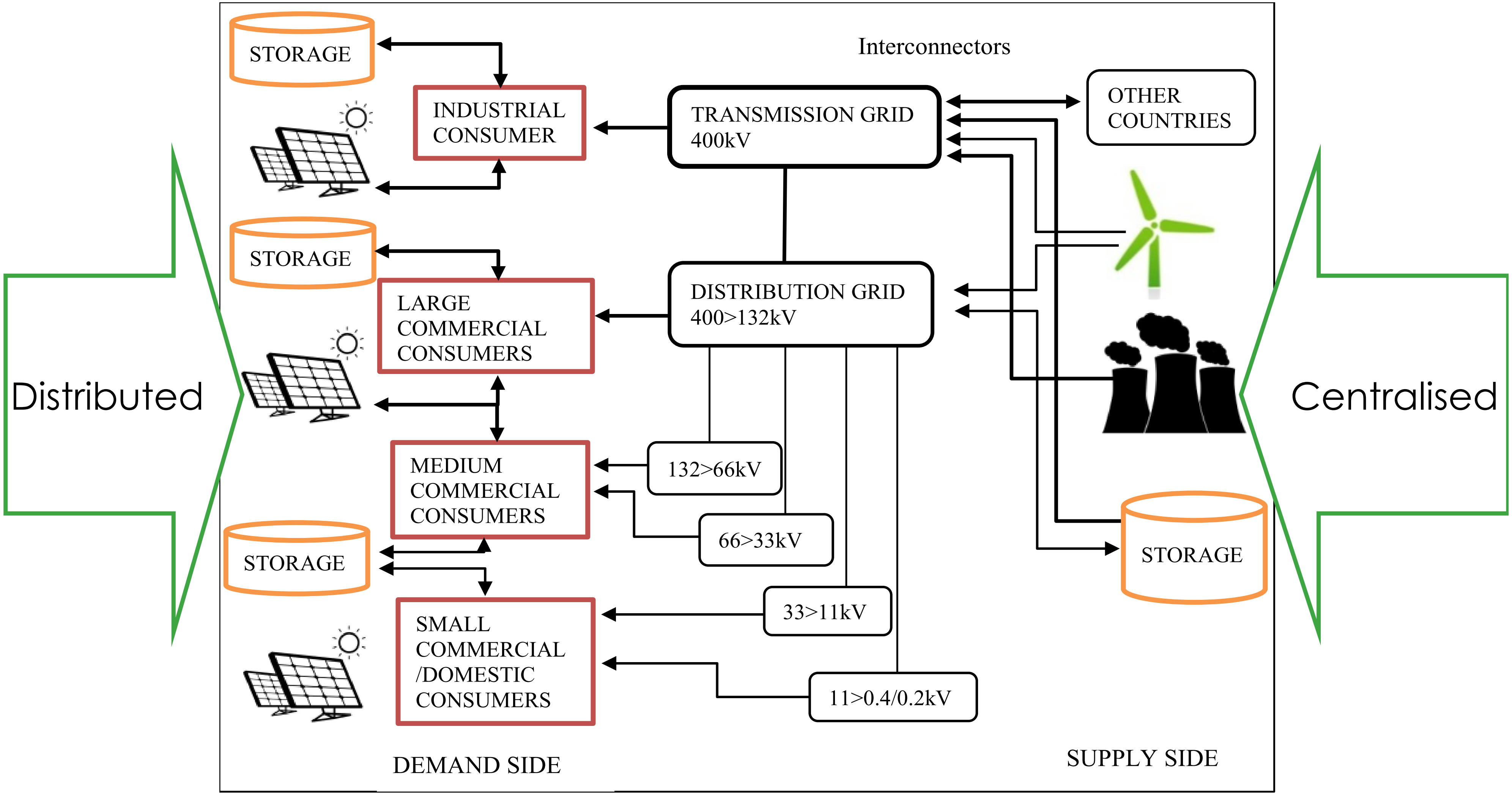
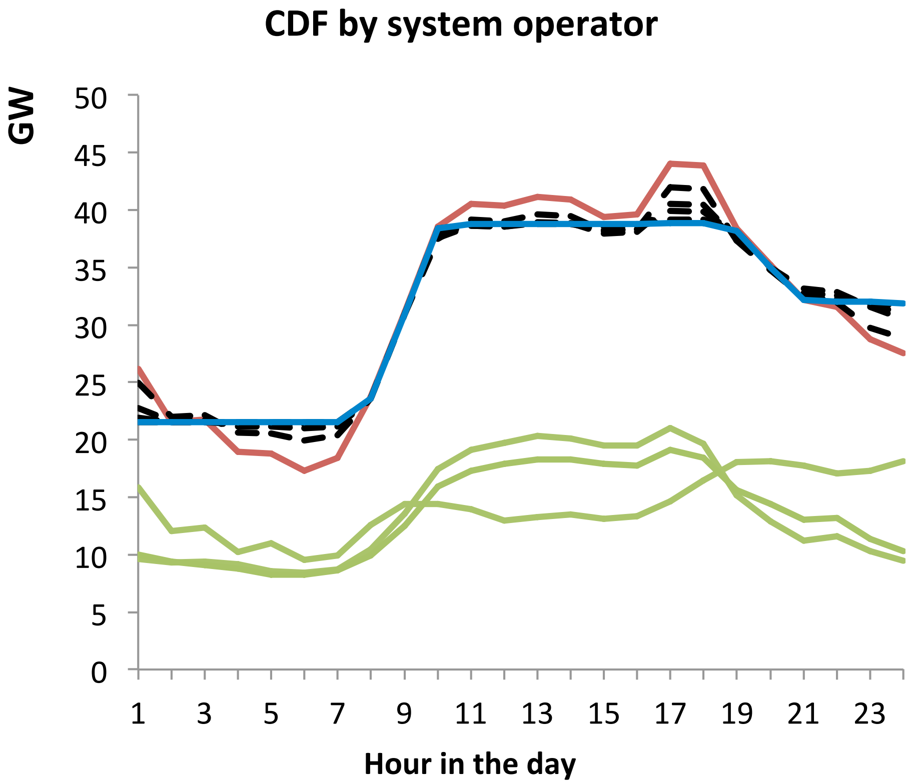


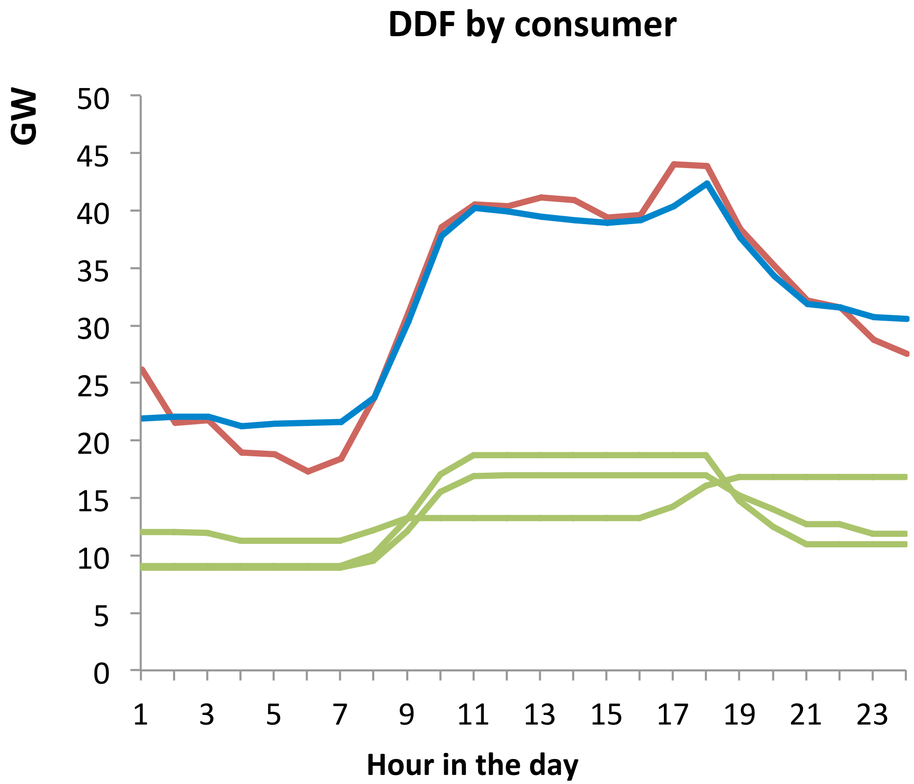
Figure 1: Graphical representation of the electricity flow in the GB electricity grid.

3. Part I – DSM regimes

Centralised with demand flattening (CDF) – the aggregator (supplier or system operator) negotiates the demand profile with a set of consumers

Distributed with demand flattening (DDF) – consumers smooth own residual demand profiles

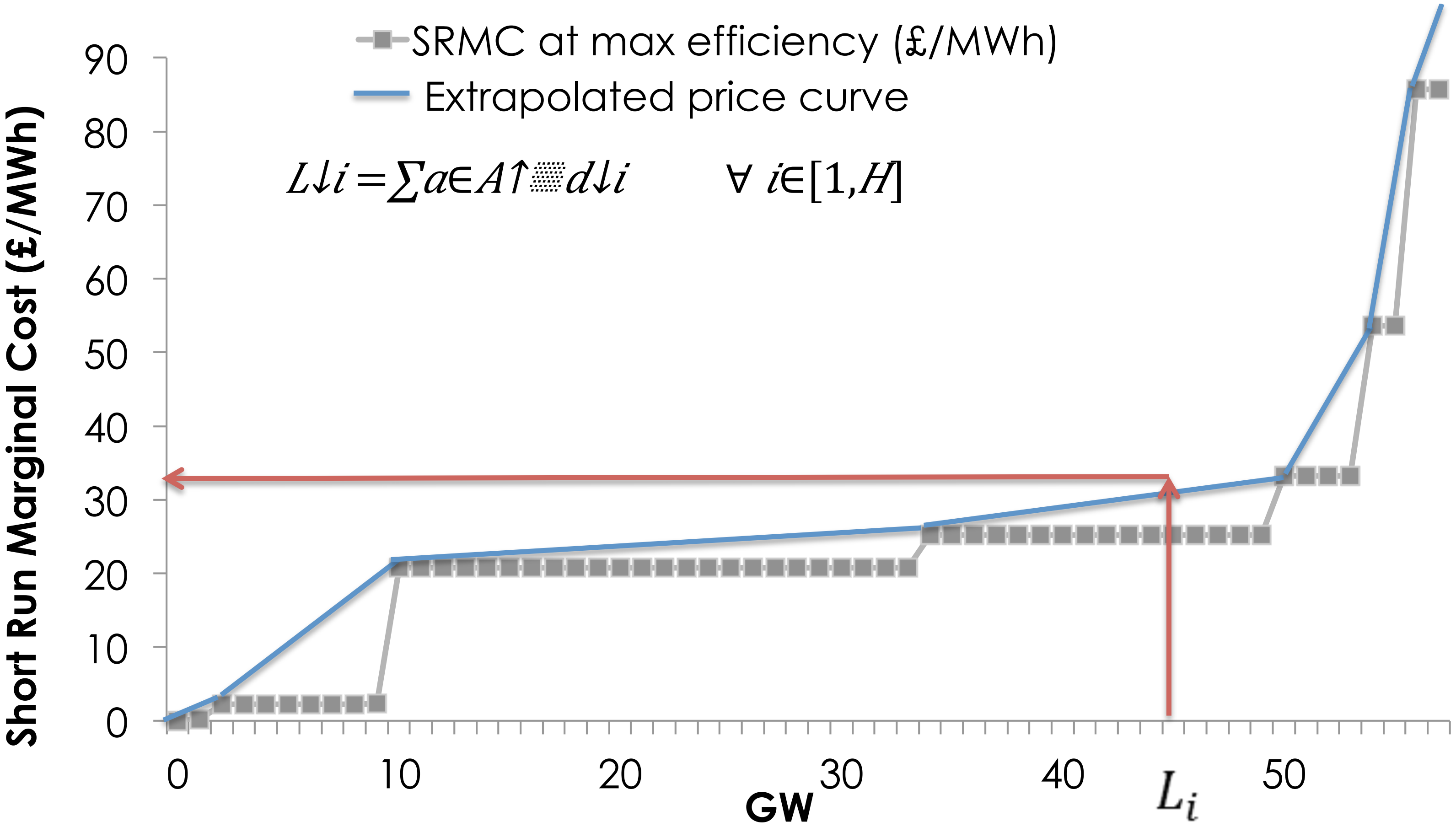




Before coordination — After coordination — Consumer demand

Figure 3: Comparison of DSM regimes. Algorithm adapted from (Gan, L., Wierman, A., Topcu, U., Chen, N., & Low, S. H. , 2013)

3. Part I – The market



$$L_i = \sum_{a \in A} d_i \qquad \forall\ i \in [1, H]$$

$p_i(L_i)$ = average cost of MWh purchased in the market

$\pi_i^a = p_i + uplift^a$ = Retail price per MWh

3. Part I – National scenarios

Consumer Power (CP)	**Gone Green(GG)**
• Market-driven world • High levels of prosperity • High investment and focus on the desires of consumers	• Ambitious policy interventions and innovation • Focus on long-term environmental goals • High levels of prosperity
No progressions (NP)-base case • Business as usual • Focus on affordability above green ambition • Little innovation	**Slow progression (SP)** • Limiting economic conditions • Limited choices for residential consumers and businesses • Slow pace transitions

Source: http://fes.nationalgrid.com/

4. Part I – Simulation scenarios

Reference scenario

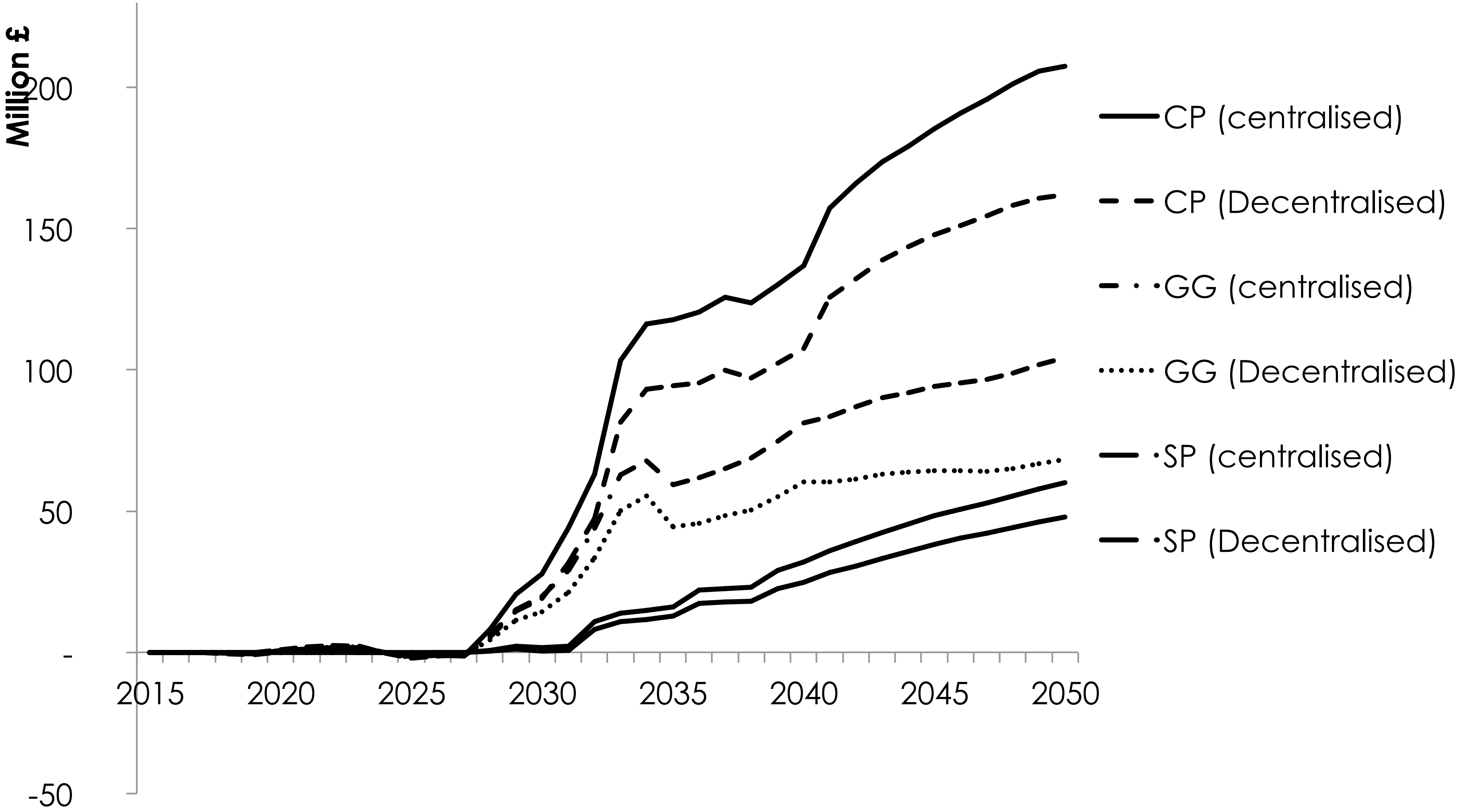
National scenario	Storage scenario			
NP	NP	GG	SP	CP
GG	NP	GG	SP	CP
SP	NP	GG	SP	CP
CP	NP	GG	SP	CP

For each national scenario we calculate the savings arising from integrating storage relative to NP storage scenario

$$Savings = d_i^{GG} \times \pi_i^{GG} - d_i^{NP} \times \pi_i^{NP} \qquad \forall\ i \in [1, H]$$

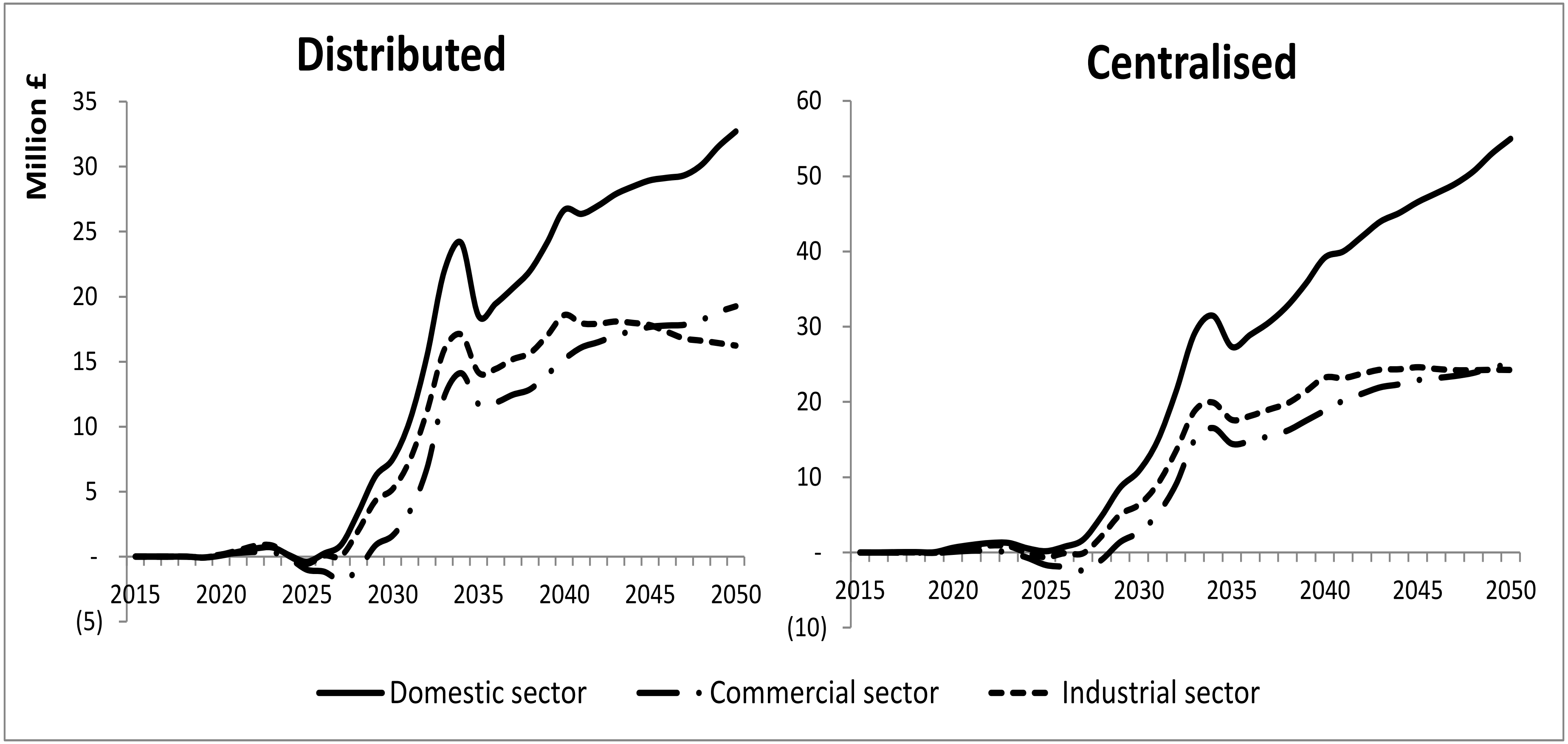
4. Part I – Results

Figure 4: Annual savings by the whole system under different storage scenarios.



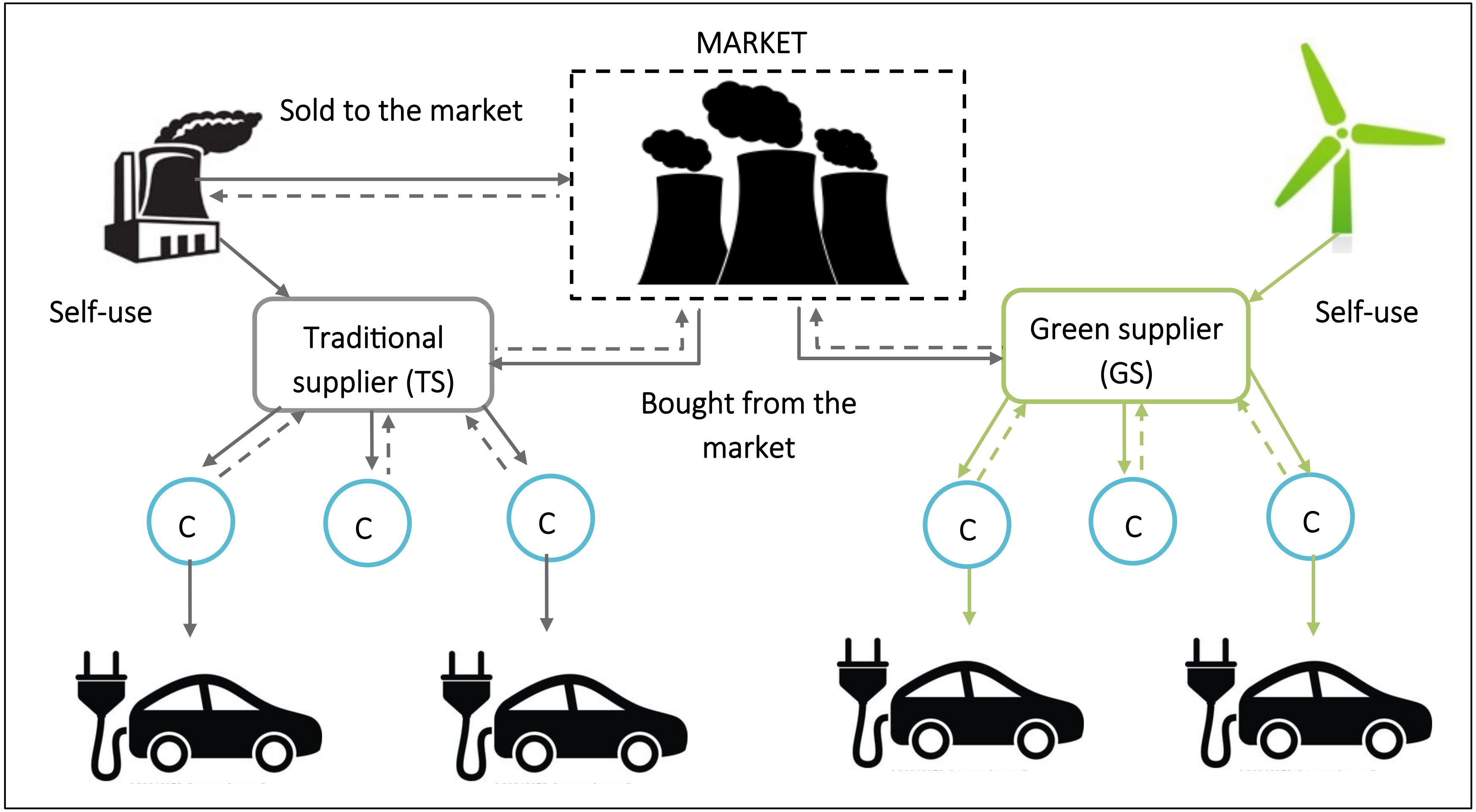
4. Part I – Results

Figure 5: Annual savings under Gone Green scenarios grouped by coordination regime.



3. Part II – General framework

Figure 6: Graphical representation of interactions between market players



Key: C = consumer → = electricity flow - - ▸ = cash flow

3. Part II – Suppliers learning

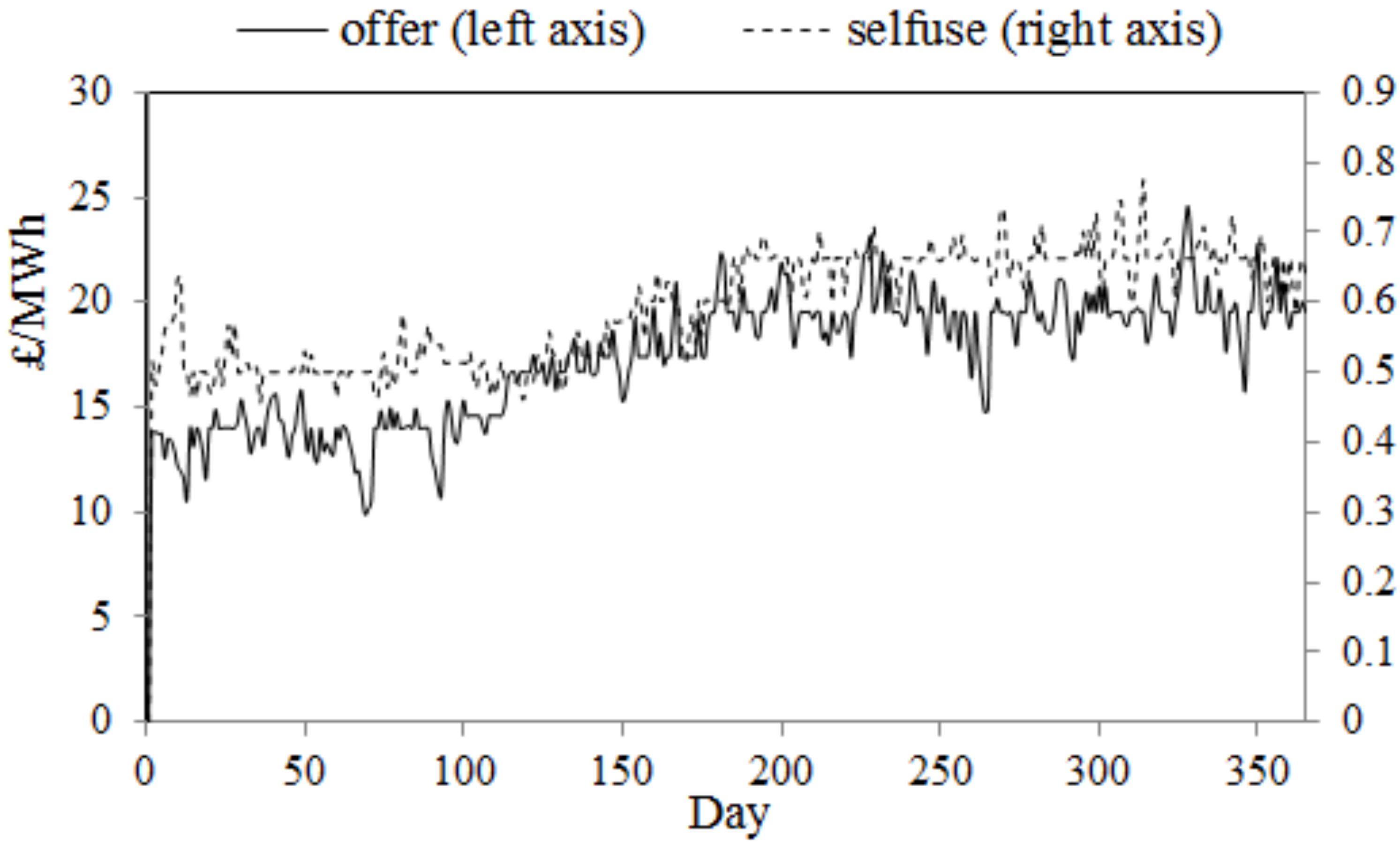
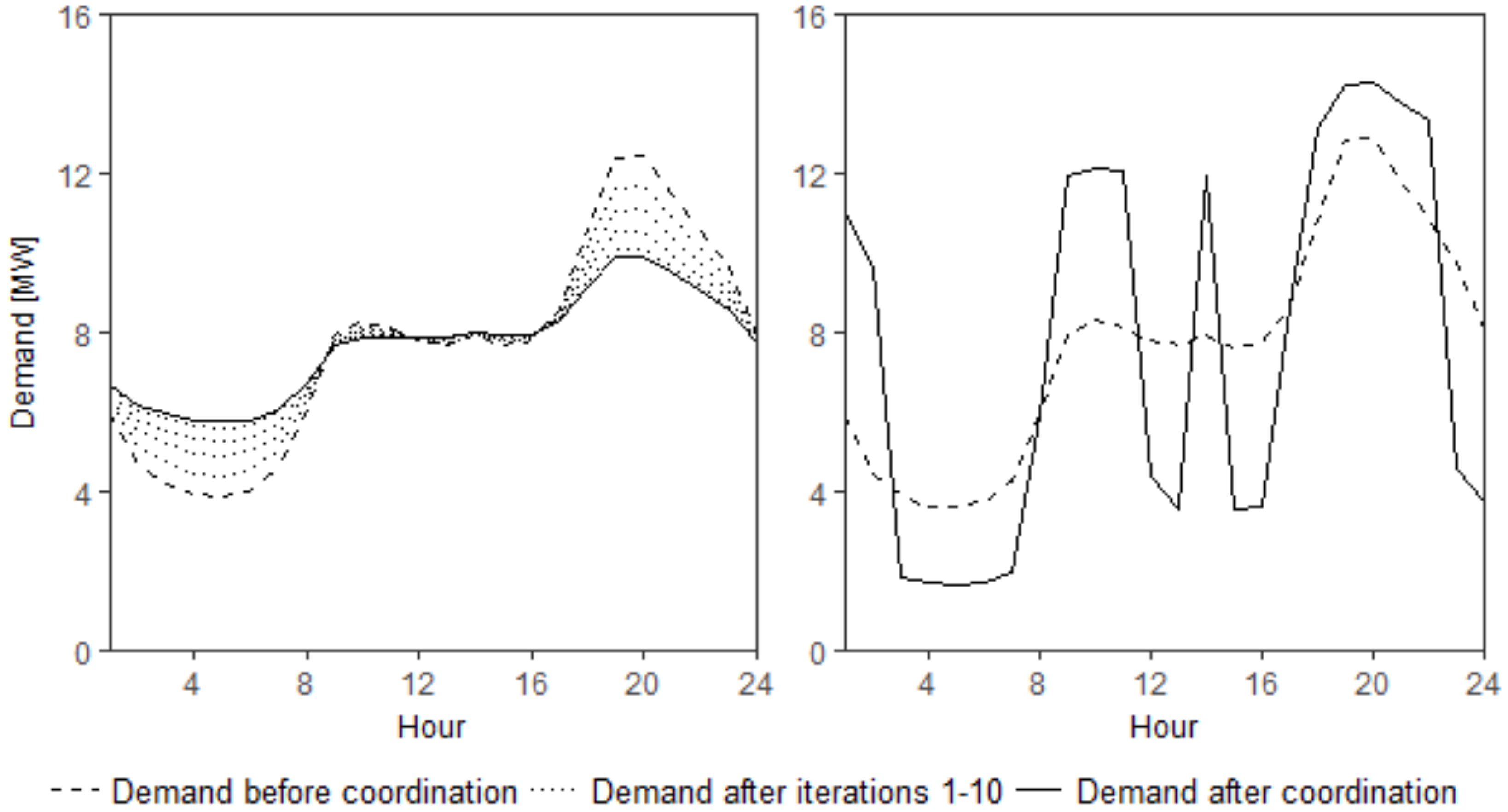


Figure 7: Time series of traditional supplier adjusting offer and self-reserve parameter.

3. Part II – Supplier DSM regimes

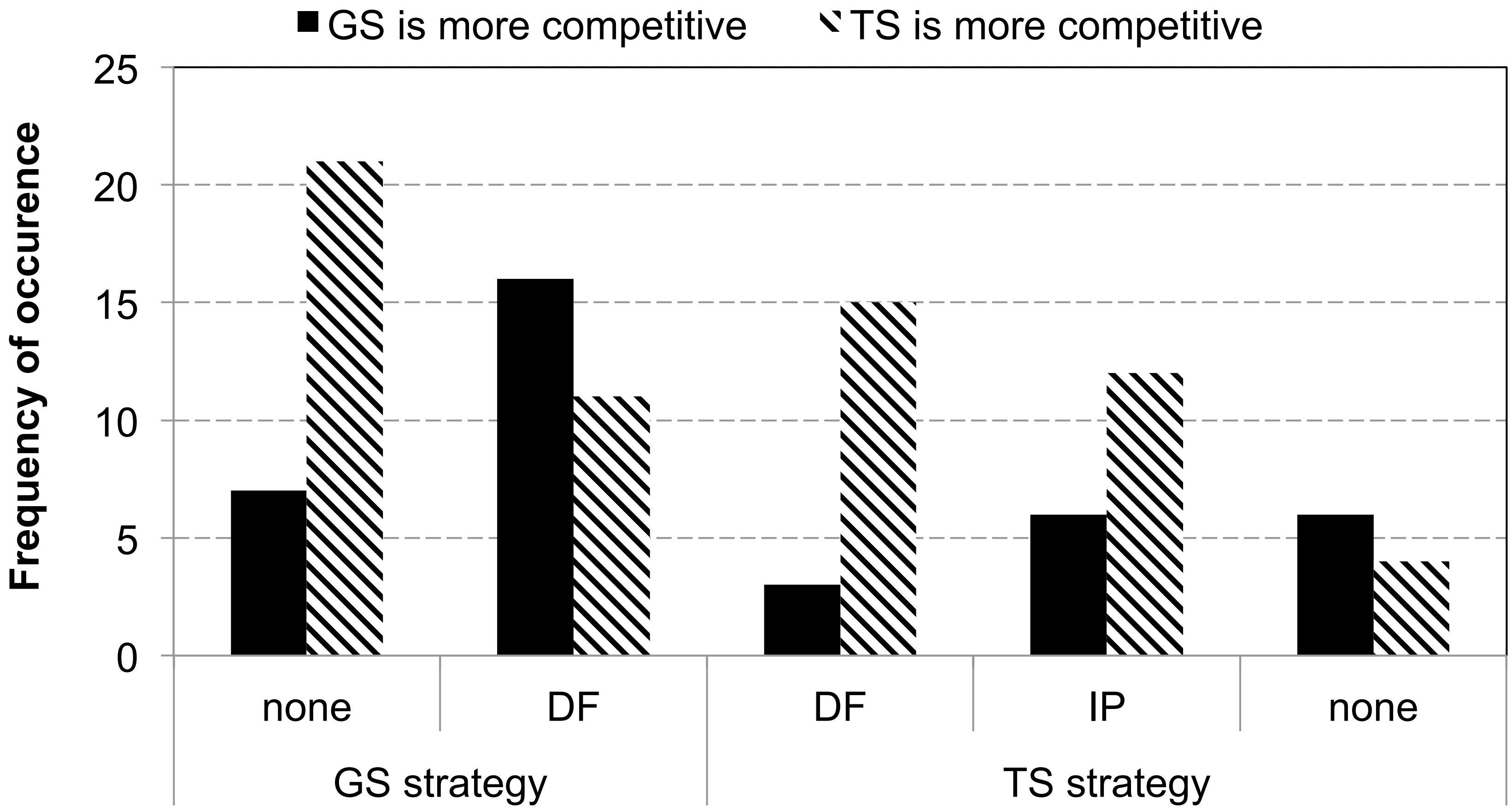
Centralised demand flattening (CDF) Centralised peak increasing(CPI)



Assume that the green supplier does not deploy CPI

4. Part II – Results

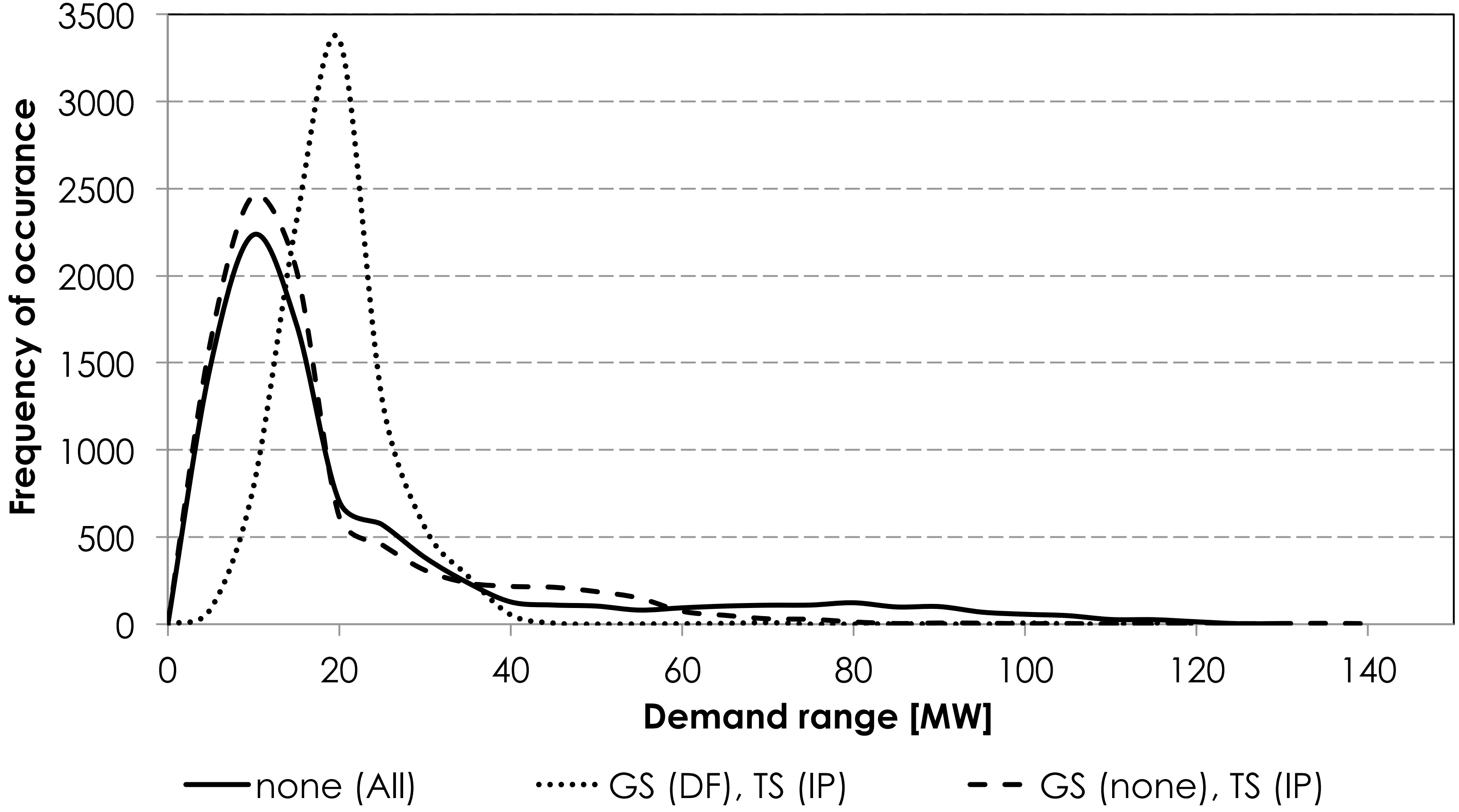
Figure 8: Residual system demand distribution under different supplier coordination regimes.



Key: none=no coordination DF=demand flattening IP=increasing peak

4. Part II – Results

Figure 9: Residual system demand distribution under different supplier coordination regimes.



Key: none=no coordination DF=demand flattening IP=increasing peak

5. Conclusions

- Consumers benefit differently from storage depending on DSM regime → **Should that be regulated? How can we make it fair?**
- DSM used as a tool to compete can lead to higher demand peaks → **Should DSM activities between suppliers and consumers be disclosed?**

Further work…

- Introducing other consumer resources: heat pumps, thermal stores, electric vehicles, resistance heating
- Merging part I and part II into a single model
- Allowing consumers to switch suppliers
- Introducing more advanced learning strategy to suppliers

Thank you

dina.subkhankulova.13@ucl.ac.uk

Questions?

Additional slides

Assumptions

1. Storage is equally distributed between different types of consumers
2. Consumers of the same type are identical => aggregated
3. Ancillary services are excluded from the market
4. Electricity costs are modelled at short run marginal costs (SRMC)
5. Power trading is not modelled
6. The merit order is constructed based on SRMC of generation technology
7. The model is deterministic
8. The transportation sector is not modelled
9. Pump storage is operated last after consumer coordination
10. Suppliers have an equal number of consumers
11. GS does not sell electricity in the market

Storage constraints

C1: Maximum and minimum power constraints

$$0 \le f_i^{a+} \le f_{max}^{a},\ 0 \le f_i^{a-} \le f_{min}^{a},\ \forall\ i \in [1,H],$$

C2: Storage efficiency constraint

$$\sum_{i \in H} f_i^{a-} = \eta^{a} \sum_{i \in H} f_i^{a+}\ ,$$

C3: Energy that can be stored or used at a time slot

$$f_i^{a-} \le \sum_{j=1}^{i-1} \left(\eta^{a} f_j^{a+} - f_j^{a-}\right),\ \forall\ i \in [1,H],$$

$$f_i^{a+} \le e^{a} - \left(\sum_{j=1}^{i-1} \eta^{a} f_j^{a+} - f_j^{a-}\right),\qquad \forall\ i \in [1, H],$$

C4: no-reselling allowed

$$f_i^{a-} \le d_i^{a},\ \forall i \in [1,H].$$

Where,

d_i^{a} - total electricity demand of consumer a in daily period i [MW],

i, j - period of daily simulation,

H - total number of periods in a daily simulation

Storage constraints

For an electric vehicle we have an additional constraint:

C5: the time constraints for charging

$\sum_{i=t_1}^{t_2} f_i^a = (SOC_2 - SOC_1)\cdot e^a$.

Where,

$f_i^a = \eta^a f_i^{a+} - f_i^{a-}$ - is the net charge of the battery in time period i [MWh]

t_1, t_2 – start and finish time of charging (specified by the consumer),

SOC_1, SOC_2 – initial and final states of charge of the battery (as specified by consumer).

Centralised coordination algorithm

Input: The aggregator known the base load, b_i and the number N of consumers. Each consumer $a \in \{1, \ldots, N\}$ knows its flexible demand and constraints. The utility sets K – the number of iterations.

Output: Flexible load schedule $\boldsymbol{f^a} = f_i^{a+} - f_i^{a-} \quad \forall\ i \in [1, H]$

1) Set k=0 and initialise the flexible load schedule as

$$f_i^{a}(0) = 0, \qquad \forall\ i \in [1, H],\ a \in A$$

2) The aggregator calculates the average aggregate load per consumer

$$g_i(k) = \sum_{i=1}^{N} d_i^a / N \qquad i \in [1, H],$$

Where,

$$d_i^a = b_i^a + f_i^a(k) - f_i^a(k)$$

and sends the signal $g_i(k)$ to all consumers.

3) Each consumer solves the following optimisation problem for $\boldsymbol{f^{a+}}, \boldsymbol{f^{a-}}$:

$$\min \sum_{i=1}^{H} g_i(k) d_i^a + 1/2 \left(d_i^a - d_i^a\right)^2 \qquad \text{S.T.C.}$$

Set $f_i^{a+}(k) = f_i^{a+}$ and $f_i^{a+}(k) = f_i^{a+}$

and report new demand profile to utility, d_i^a

4) Set k=k+1. If $k<K$ go to step 2).

Source: http://users.cms.caltech.edu/~adamw/papers/eEnergy2013.pdf

Individual optimisation with storage

Objective of coordination: balance demand with renewable supply, i.e.

Objective function: $\min\left(\frac{1}{H}\sum_{i=1}^{T} d_i - \frac{1}{H}\sum_{\tau=1}^{T} d_\tau\right)^2$

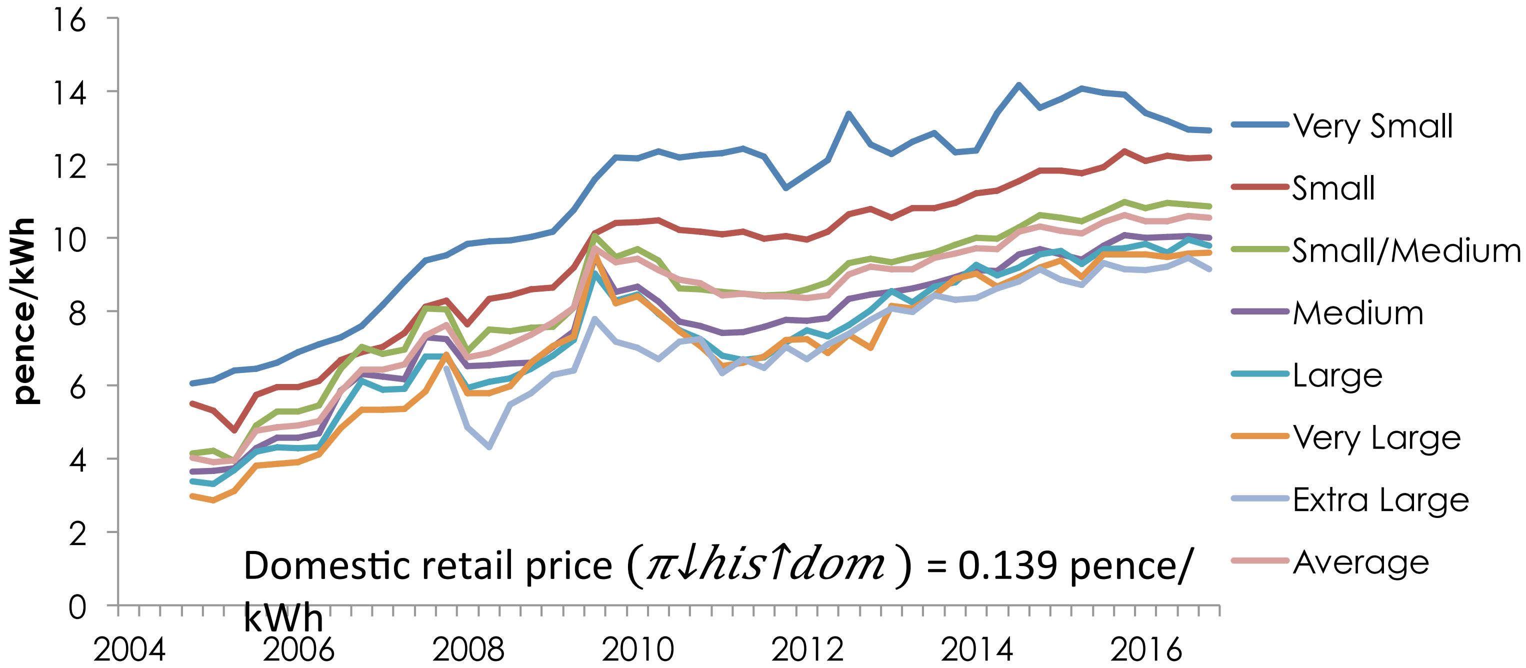
Where, $d_i = b_i - r_i + f_i^{+} - f_i^{-}$

b_i Baseload demand
r_i Renewable generation
f_i^{+}, f_i^{-} Charge and discharge profile
i, τ Daily period
H Total number of period in a day

Subject to storage constraints

Calibrating retail prices

Retail electricity prices for non-domestic consumers



Source: Department of energy and climate change (DECC, 2016)

$\sum_{i=1}^{T} \pi_i^a \times d_i^a / \sum_{i=1}^{T} d_i^a = \pi_{his}^a$ uplift is calibrated a

Cost of generating electricity

The market consists of electricity generators stacked according their short run marginal cost (SRMC), i.e.

$$p_{SRMC}^{S} = c_{varO\&M}^{S} + p_{fuel}^{S}(t)/\eta^{j} + \sigma_{C}^{S} \times p_{C}$$

Where,

$c_{varO\&M}^{s}$ variable operational and maintenance cost for a generator of type s [£/MWh],

p_{fuel}^{s} price of fuel used by an electricity generator of type s [£/MWh],

σ_{C}^{S} the emission factor for generator of type s [g CO_2eq/MWh],

p_{C} carbon price [£/g CO_2eq]

η^{s} efficiency of an electricity generator of type s,

ϵ^{s} the additional cost added by the generator [£/MWh].

Model calibration

Model element	Data used and source	Method
Consumers	• Daily demand profiles (half-hourly resolution) (Elexon, 2017) • Annual energy consumption by sector up to 2040 (FES, 2016)	• Daily profiles were aggregated into yearly profiles for different sector and scaled according to annual energy consumption data per sector
Generation	• Installed generation capacities up to 2040 (FES, 2016) • Fuel and carbon prices up to 2040 (FES, 2016) • Renewable generation profile (renewable.ninja.org) • Generator costs (UK-TIMES, 2016)	• Dispatchable generators – SRMC were calculated for each type of electricity and stacked into a merit order based on installed capacities specified in each scenario • Renewable generators – historical generation profiles were scaled according to installed capacities taken from FES
Storage	• Installed storage capacities for pump and consumer storage up to 2040 (FES, 2016)	• The energy and power constraints were fed into consumer specification and then used in the balancing methods DDF, CDF