FLEXIBILITY IN INTEGRATED ENERGY SYSTEMS AND VIRTUAL STORAGE

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Energy Systems Integration Facility, NREL, Golden, USA – 06/08/2015

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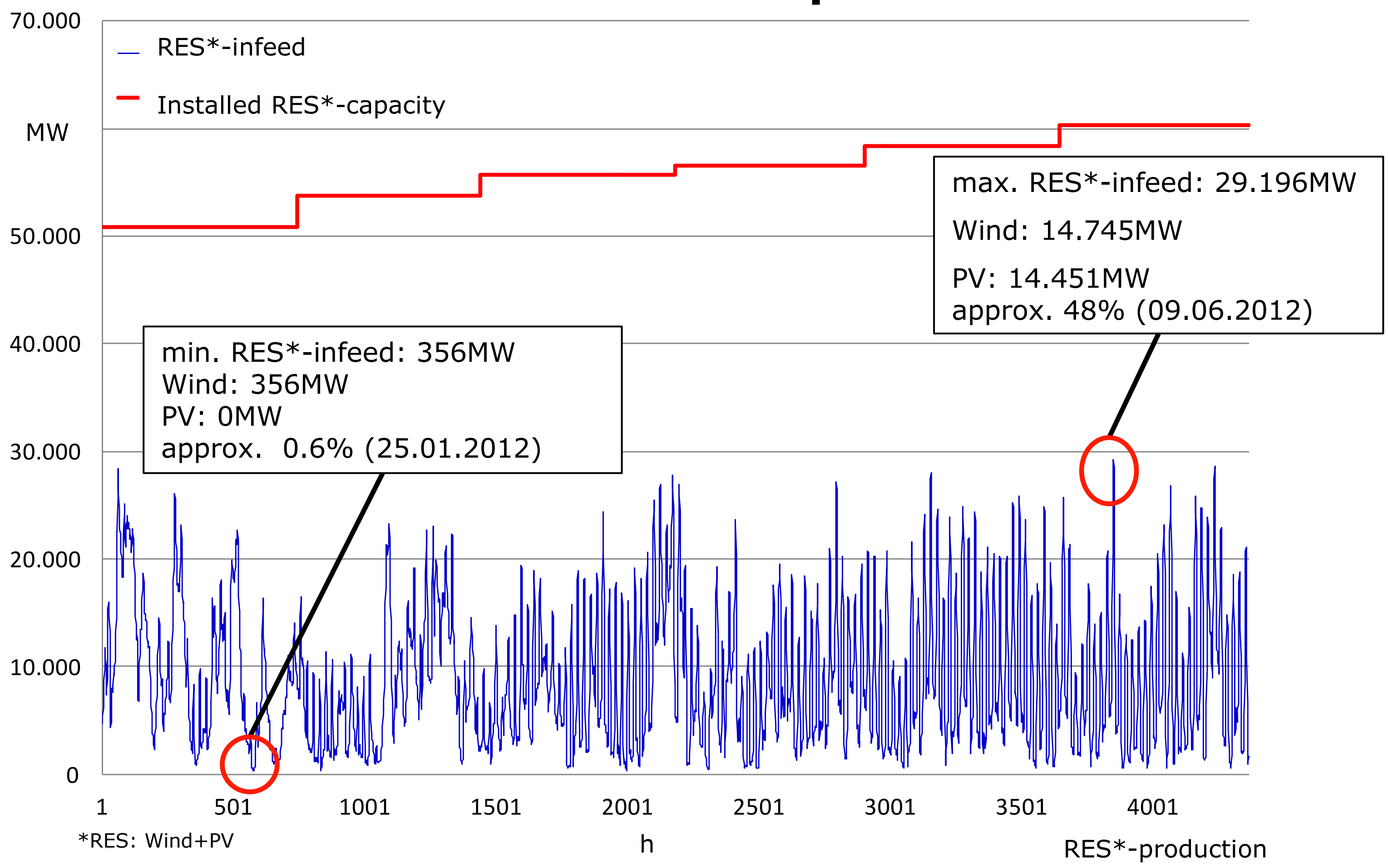
The challenging of system balance with volatile and variable renewable

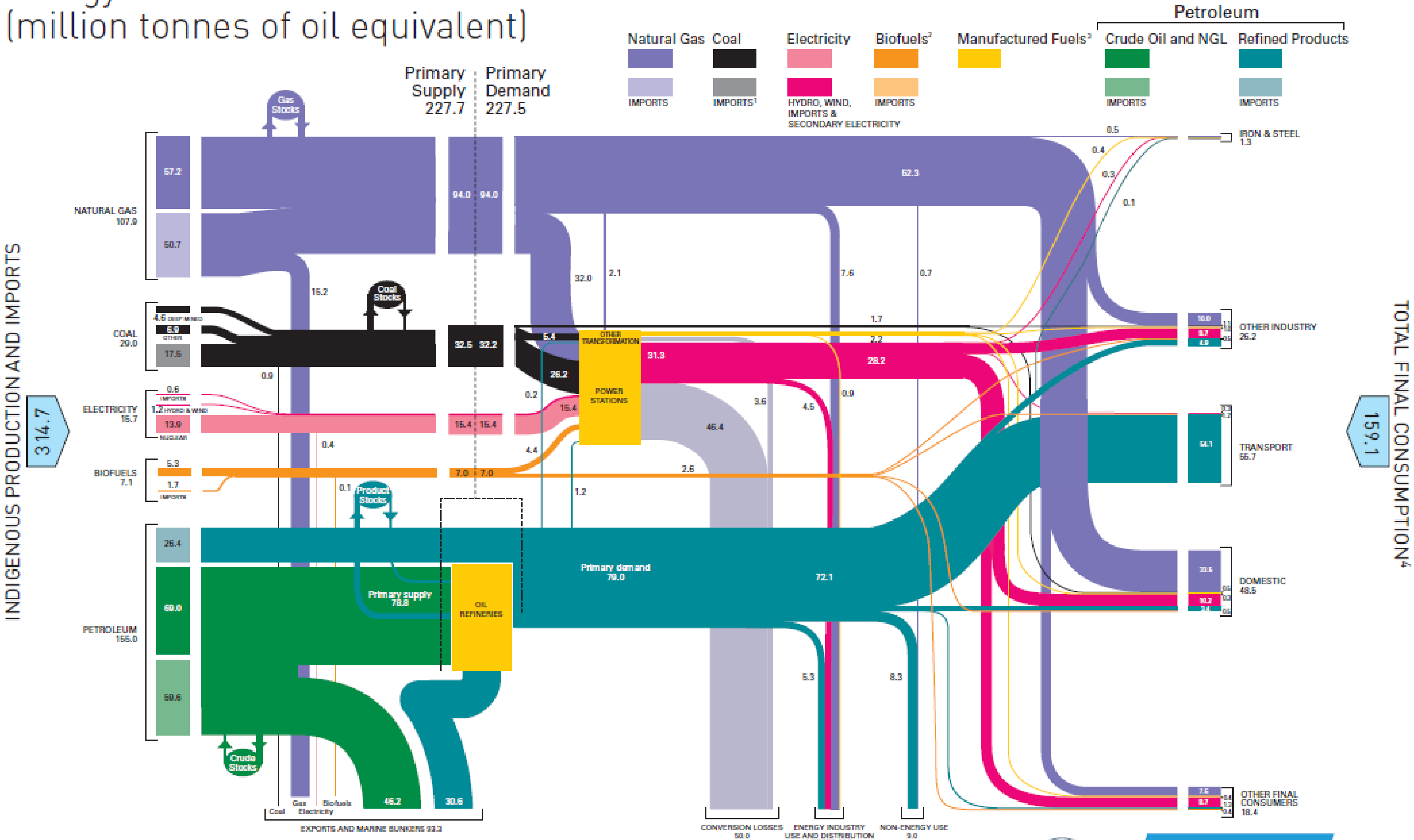
German example



Courtesy of J. Vanzetta (Amprion) and M. Paolone (EPFL)

It’s not only about electricity

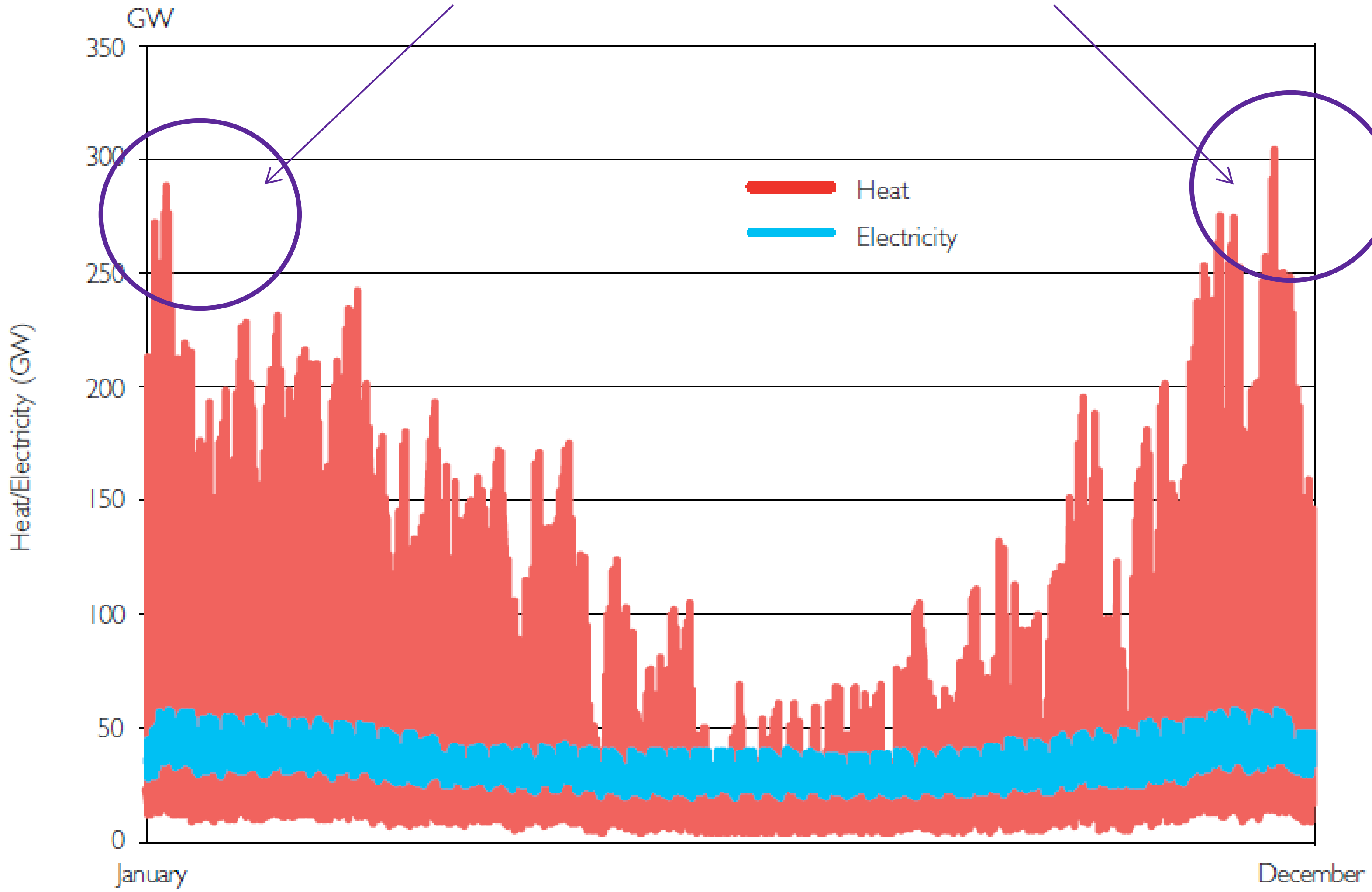
Energy Flow Chart 2010
(million tonnes of oil equivalent)



FOOTNOTES:
1. Coal imports include imports of manufactured fuels, which accounted for 0.1 million tonnes of oil equivalent in 2010.
2. Includes wastes.
3. Includes heat sold.
4. Includes non-energy use.

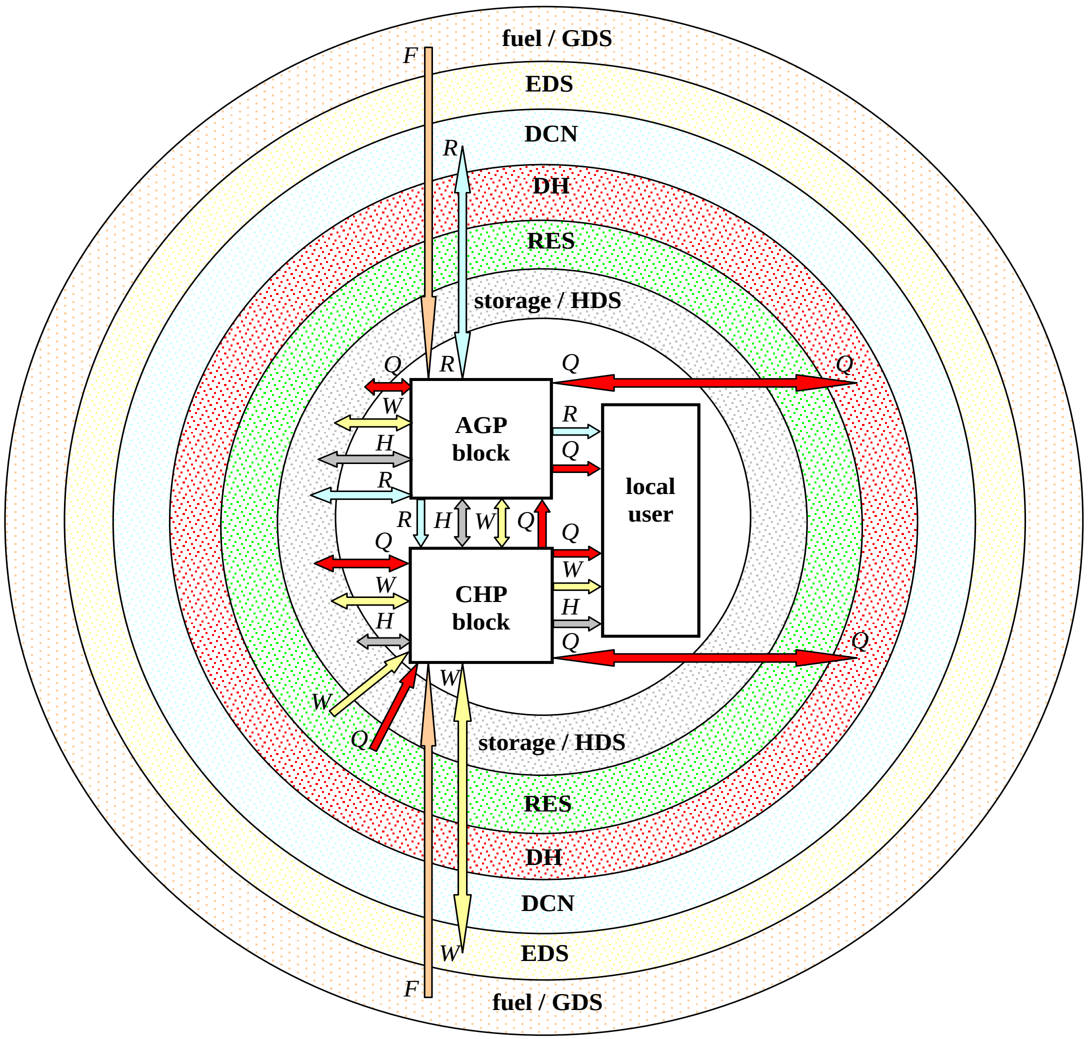
This flowchart has been produced using the style of balance and figures in the 2011 Digest of UK Energy Statistics, Table 1.1.

A glance into the future: Electrification



Source: Courtesy of Imperial College. For illustrative purposes only and based on actual half-hourly electricity demand from National Grid and an estimate of half hourly heat demand.

A Smart Multi-energy Grid vision



AGP – Additional Generation Block

CHP – Combined Heat and Power

DCN – District Cooling Network

DH – District Heating

EDS – Electricity Distribution System

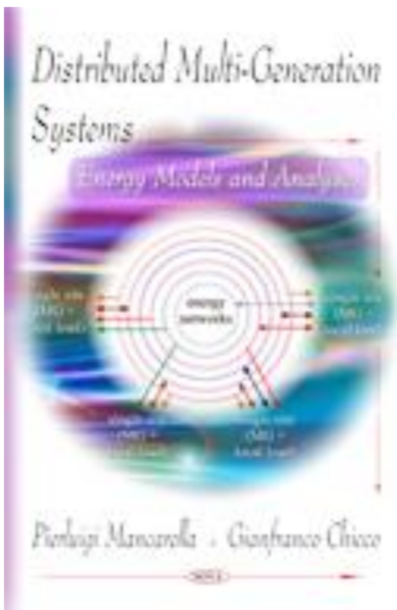
GDS – Gas Distribution System

HDS – Hydrogen Distribution Network

MG – Multi-Generation

W – electricity, Q – heat, R – cooling

H – hydrogen, F - Fuel



P.Mancarella, Multi-energy systems: an overview of models and evaluation concepts, Energy, Vol. 65, 2014, 1-17, *Invited paper*

P. Mancarella, G. Chicco, Distributed Multi-Generation Systems: Energy Models and Analyses, Nova, 2009

Rethinking the energy system: The Smart Multi-energy Grid Vision

- *Integration* as opposed to *Electrification*
- Heat recovery, alternative means for cooling production at the distributed level
- *Flexibility* from energy vector switching
- Economy of scale if coupled to district energy systems
- Can we rethink the overall energy system from a multi-energy perspective and enhance environmental and economic performance, and system flexibility and reliability?
- Distributed multi-energy systems, including Microgrids and District Energy Systems, offer an ideal opportunity for energy infrastructure and ESI at a decentralized level

P.Mancarella, Multi-energy systems: an overview of models and evaluation concepts, Energy, *Invited paper*, Jan 2014

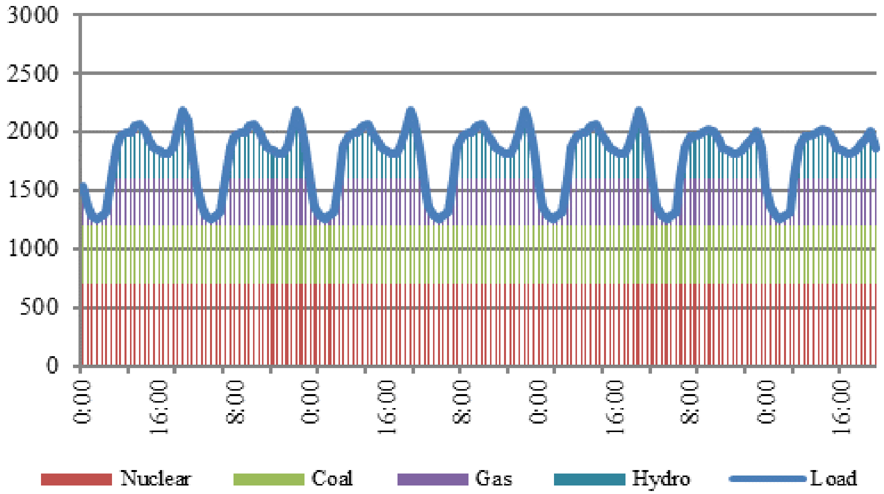
P. Mancarella, G. Chicco, Distributed Multi-Generation Systems: Energy Models and Analyses, Nova, 2009

What is flexibility?

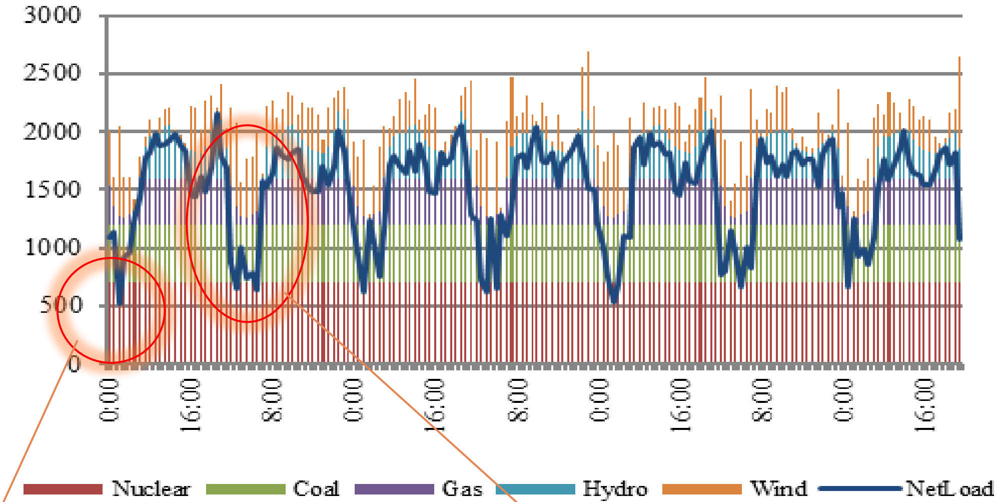
- Flexibility describes the system ability to cope with events that may cause imbalances between supply and demand at different time frames while maintaining the system reliability in a cost effective manner
- Flexibility has always been present in power systems, but its operational requirements will increase in the future with more renewables, CCS and nuclear
- More flexibility will also be needed for networks in order to maximise asset utilisation in a Smart Grid framework
- New sources of flexibility are needed

What are the flexibility issues?

System dispatch with no wind



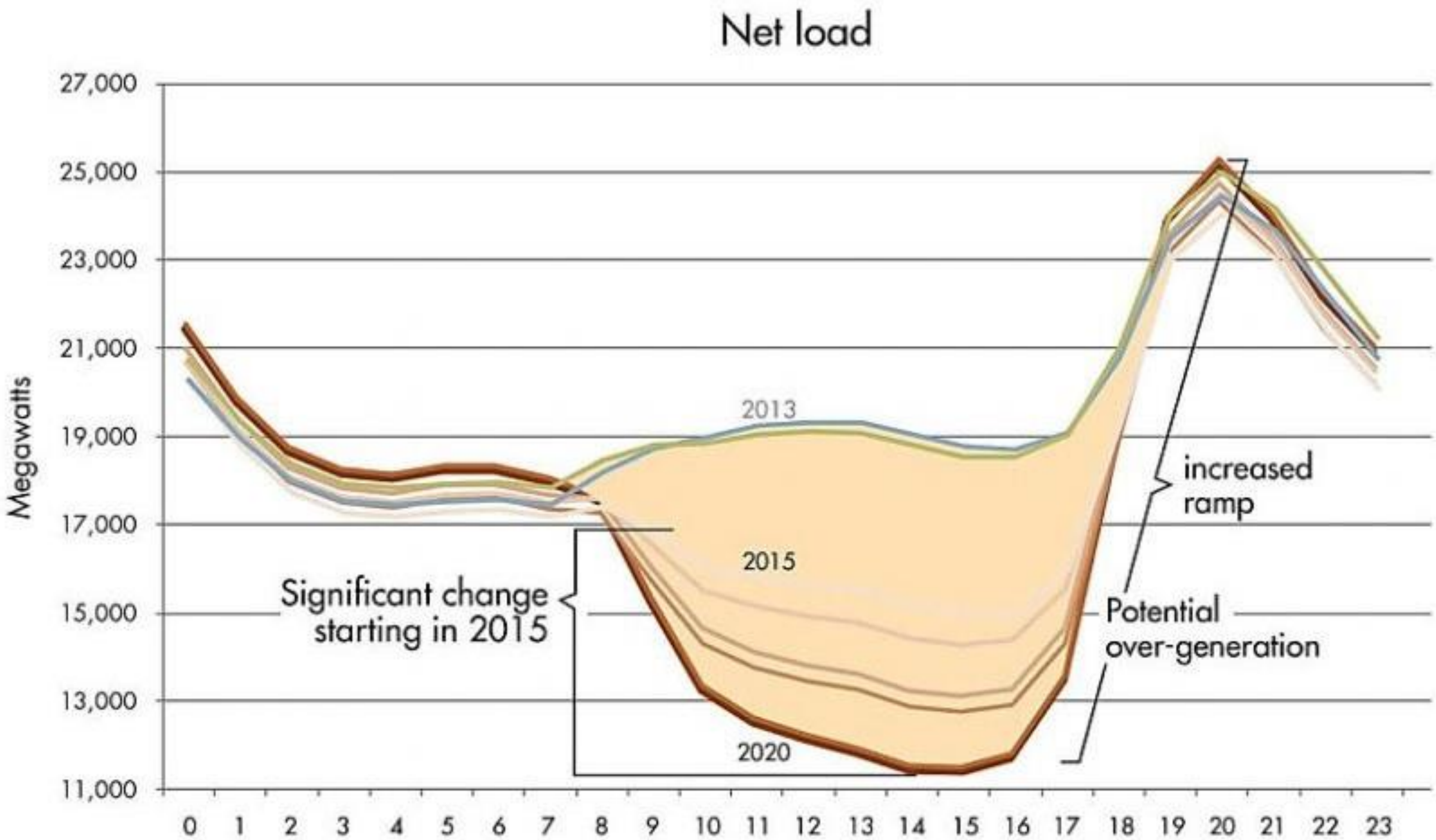
Ideal system dispatch with wind



Minimum-load issue

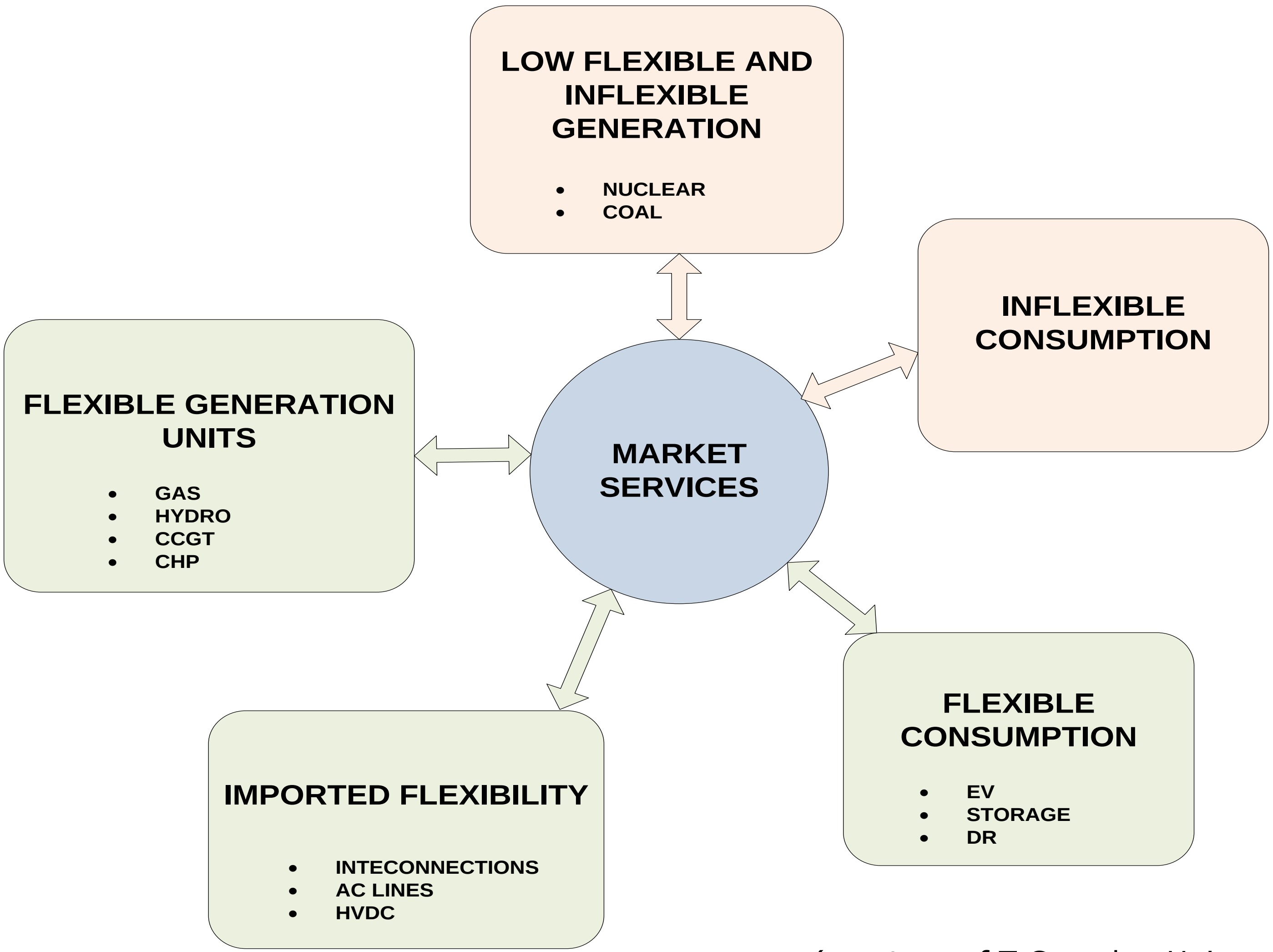
Steep down and up ramps

Another example of flexibility issues: the infamous “*duck* curve”



“Duck curve” elaborating on increasing flexibility requirements due to PV in California by 2020 (source: CAISO)

Flexibility providers

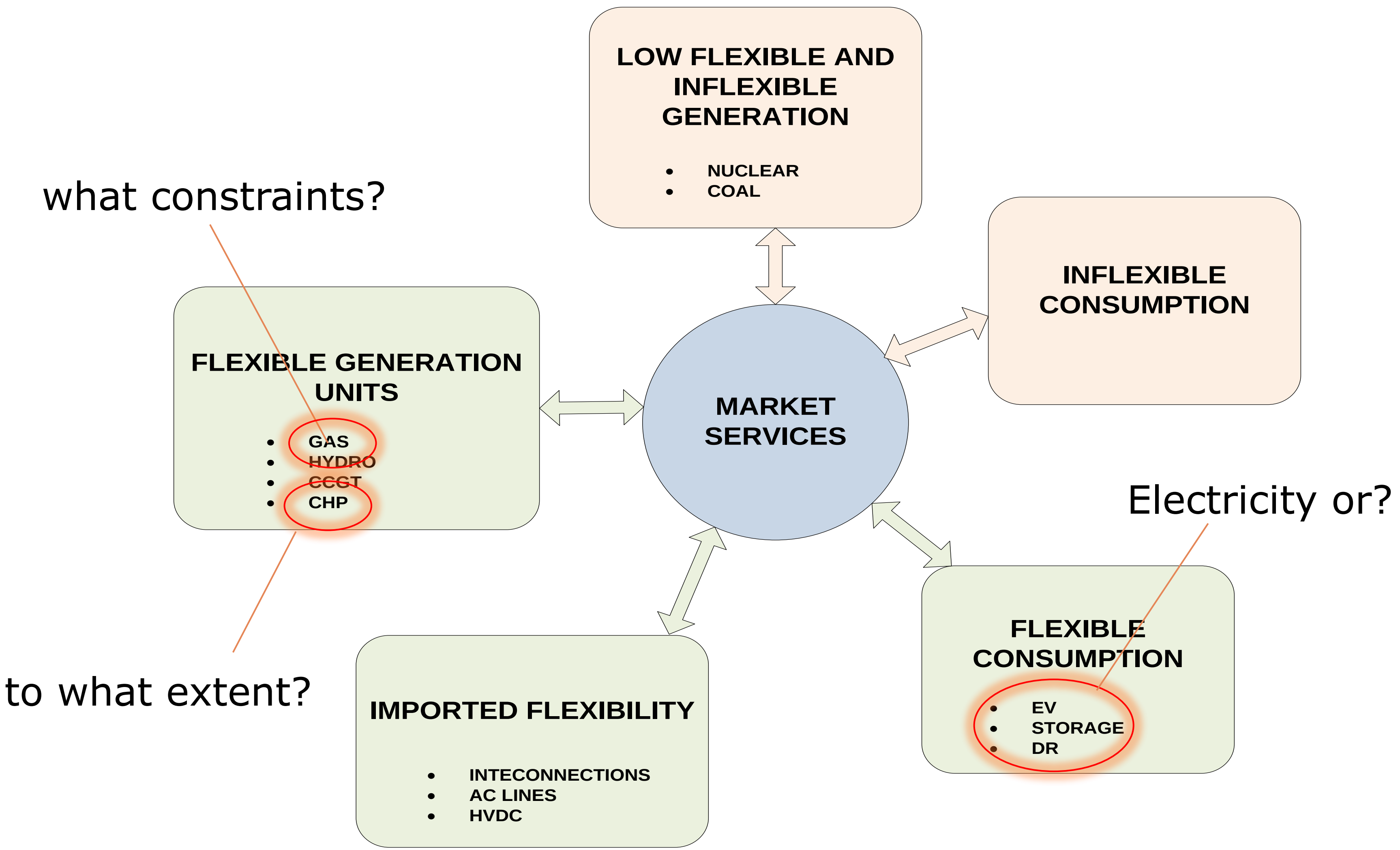


(courtesy of T Capuder, University of Zagreb)

What is flexibility in Energy Systems Integration (ESI) terms?

- Can other energy systems/vectors provide flexibility to the electrical power system (= ability to provide supply and demand balance "quickly")?
- Can flexibility in other energy systems constrain the electrical power system?

Flexibility providers



(courtesy of T Capuder, University of Zagreb)

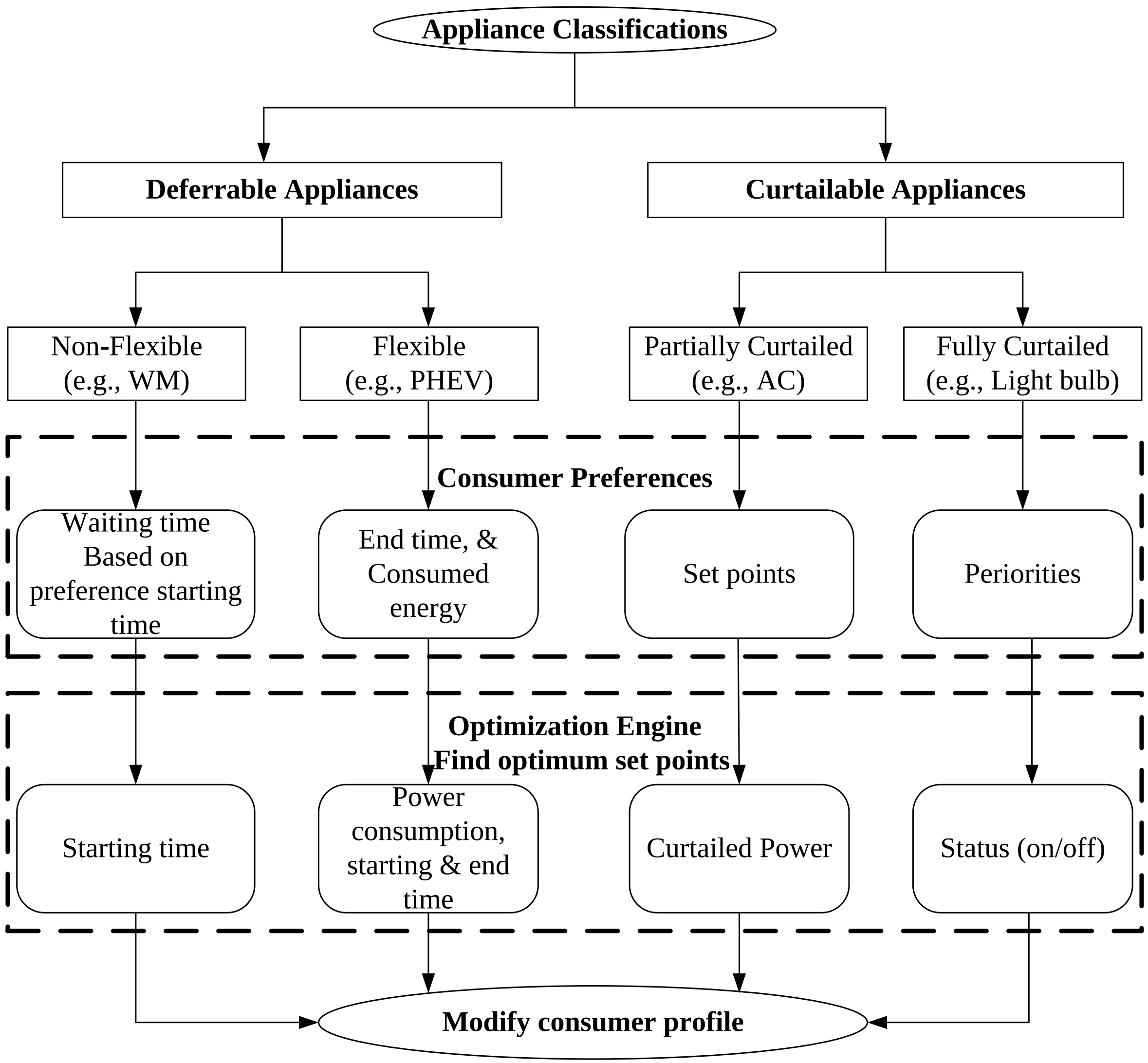
Demand Response, ESI and "Virtual Storage"

- How different is DR from storage?
  - Philosophical question or not?

- How much DR is actually provided by "virtual storage" and other (energy) services?

Y. Zhou, P. Mancarella and J. Mutale, A framework for capacity credit assessment of electrical energy storage and demand response, *submitted to IET Generation, Transmission and Distribution, March 2015, under second review*.

Home appliances and DR



S. Altaher, P. Mancarella, and J. Mutale, Automated Demand Response from Home Energy Management System under Dynamic Pricing and Power and Comfort Constraints, IEEE Transactions on Smart Grid, accepted for publication, January 2015.

A possible classification of home appliances

- **Deferrable** load may be classified into:
  → *Non-flexible* load such as Washing Machine (WM), which has a predefined profile that cannot be altered during operation time

  → *Flexible* load such as Electrical Vehicle (EV)
- **Curtailable** load may be classified into:
  → *Partially curtailable* load such as Air Conditioning (AC), whose power consumption can be controlled according to its temperature set point

  → *Fully curtailable*, according to the consumer priorities, meaning that these appliances can be switched off without the need of re-turned them on later (for example, light bulbs)

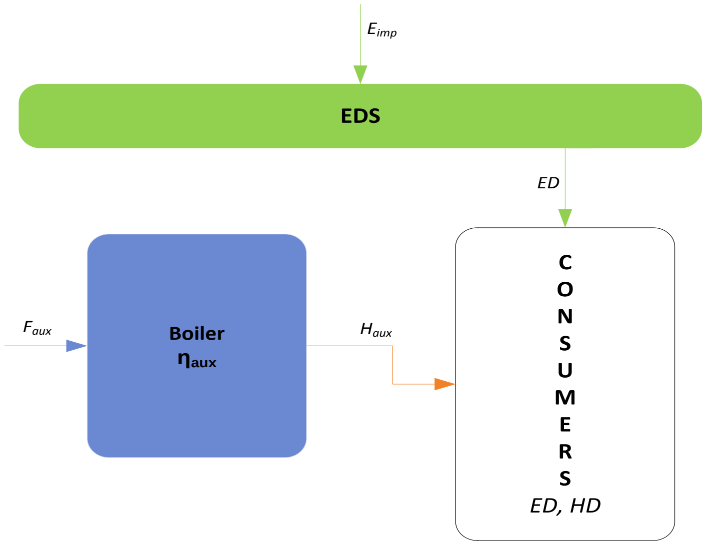
S. Altaher, P. Mancarella, and J. Mutale, Automated Demand Response from Home Energy Management System under Dynamic Pricing and Power and Comfort Constraints, IEEE Transactions on Smart Grid, accepted for publication, January 2015.

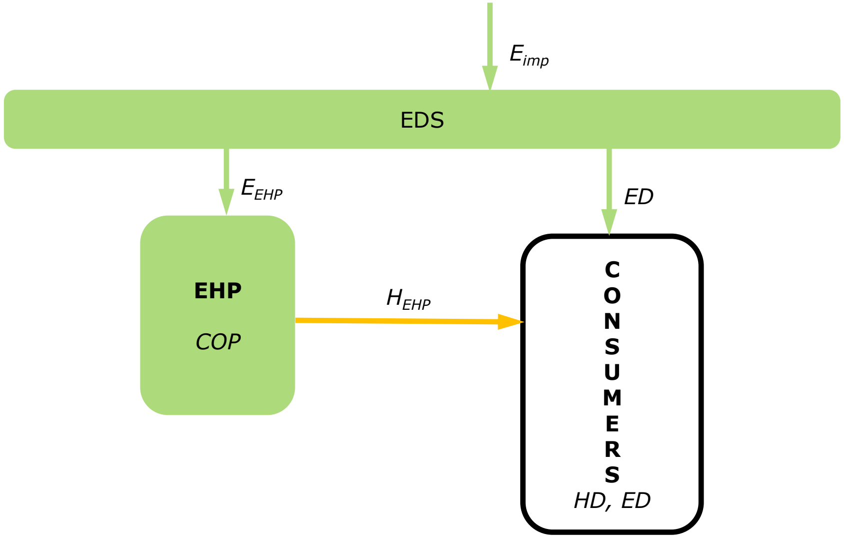
Multi-energy flexibility from arbitrage between energy vectors and services

- *Hic et nunc*
  - Energy shifting
  - Comfort level (reliability) arbitrage
  - Energy to power arbitrage
  - Power to energy arbitrage
- In time
  - (Virtual) Storage
  - Comfort level (reliability) arbitrage
- In space
  - Network arbitrage

- Up- and down-flexibility (generation reference)

How much flexibility?





EDS = Electricity Distribution System

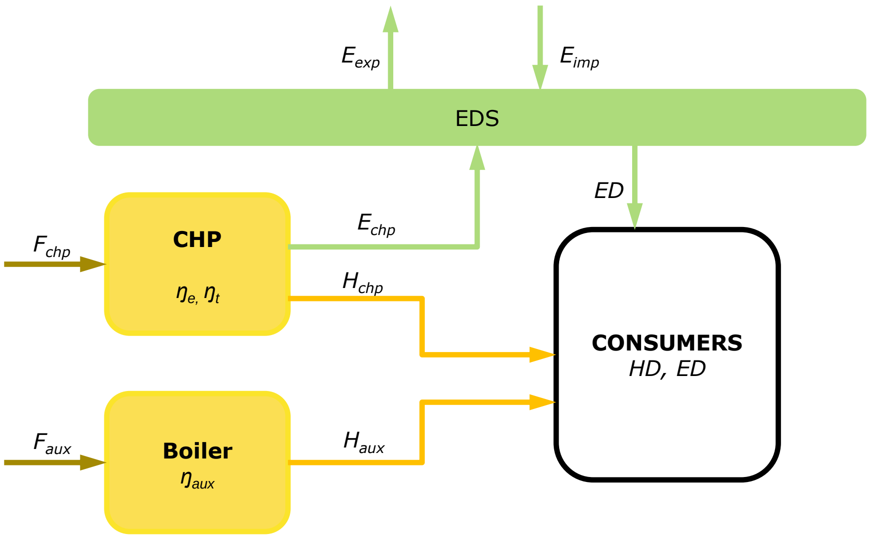
ED = Electricity Demand

HD = Heat Demand

T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

Multi-energy flexibility from energy vector arbitrage

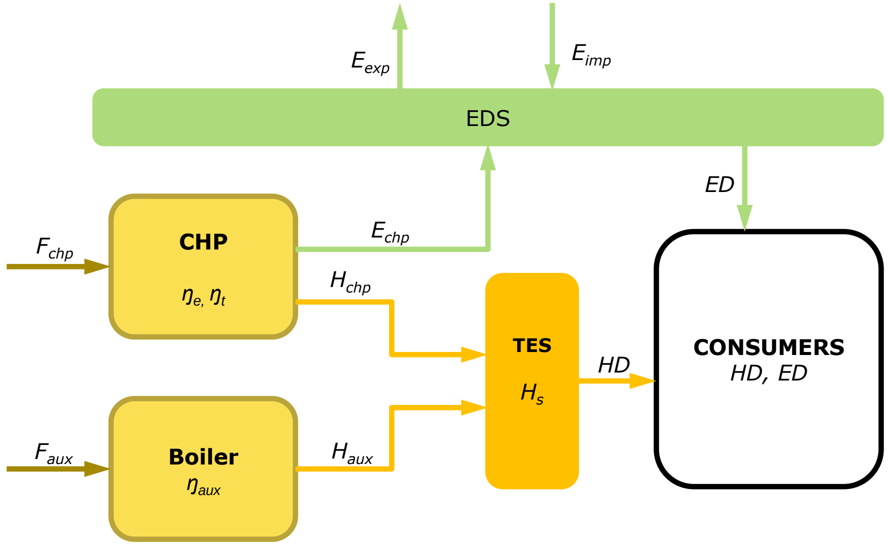
- *Energy shifting "hic et nunc"*
- *Down-flexibility*



T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

Multi-energy flexibility from energy vector arbitrage

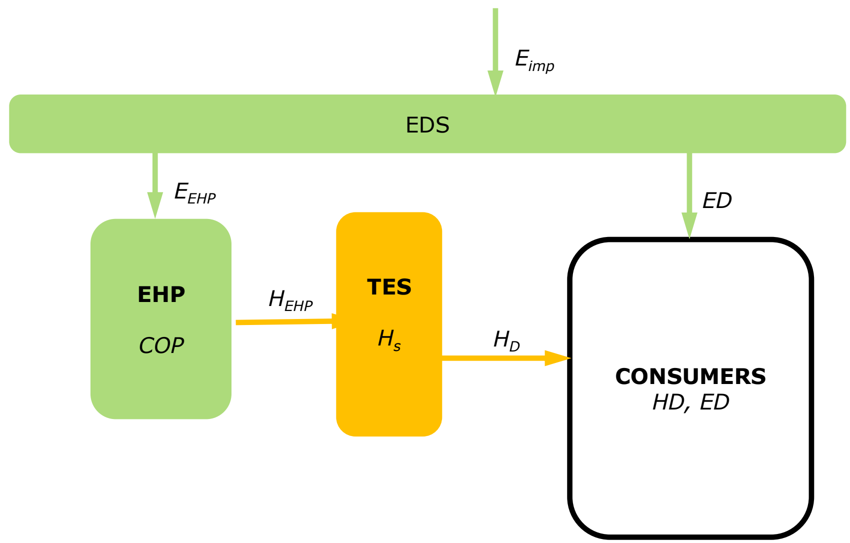
- *Energy shifting*
- *Up- and down-flexibility*
- *(Virtual) storage*



T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

Energy to power and power to energy arbitrage

- *Up- and down-flexibility*
- *(Virtual) storage*



EHP = Electric Heat Pump

COP = Coefficient of Performance

T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

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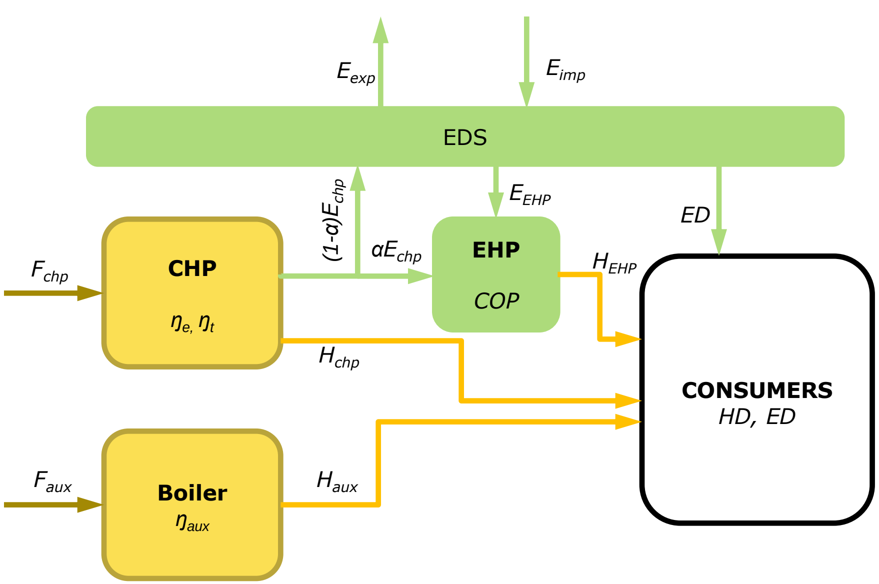
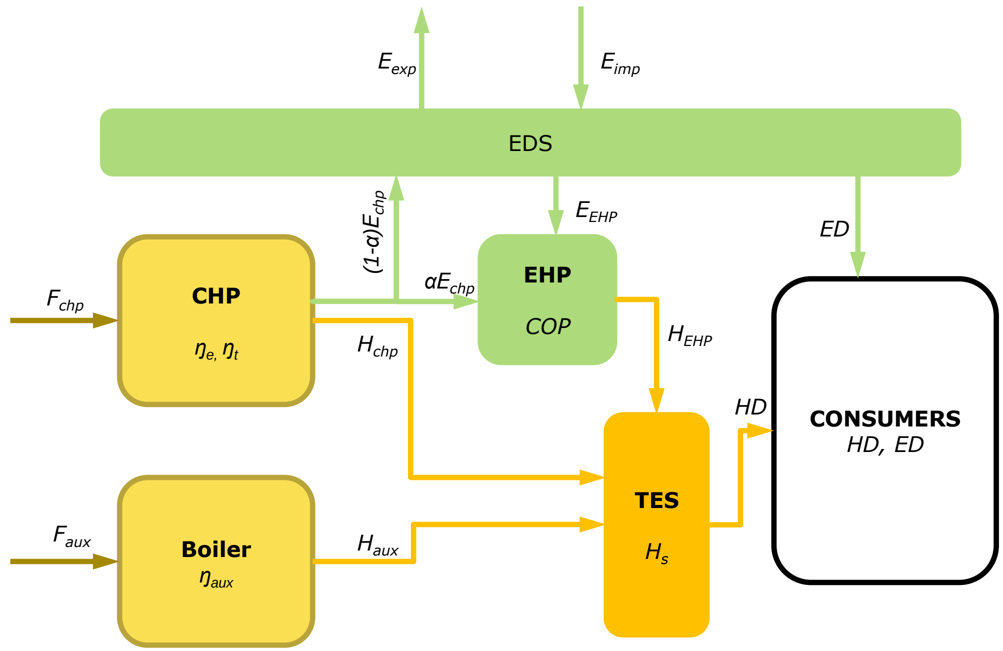
Fully flexible multi-energy system

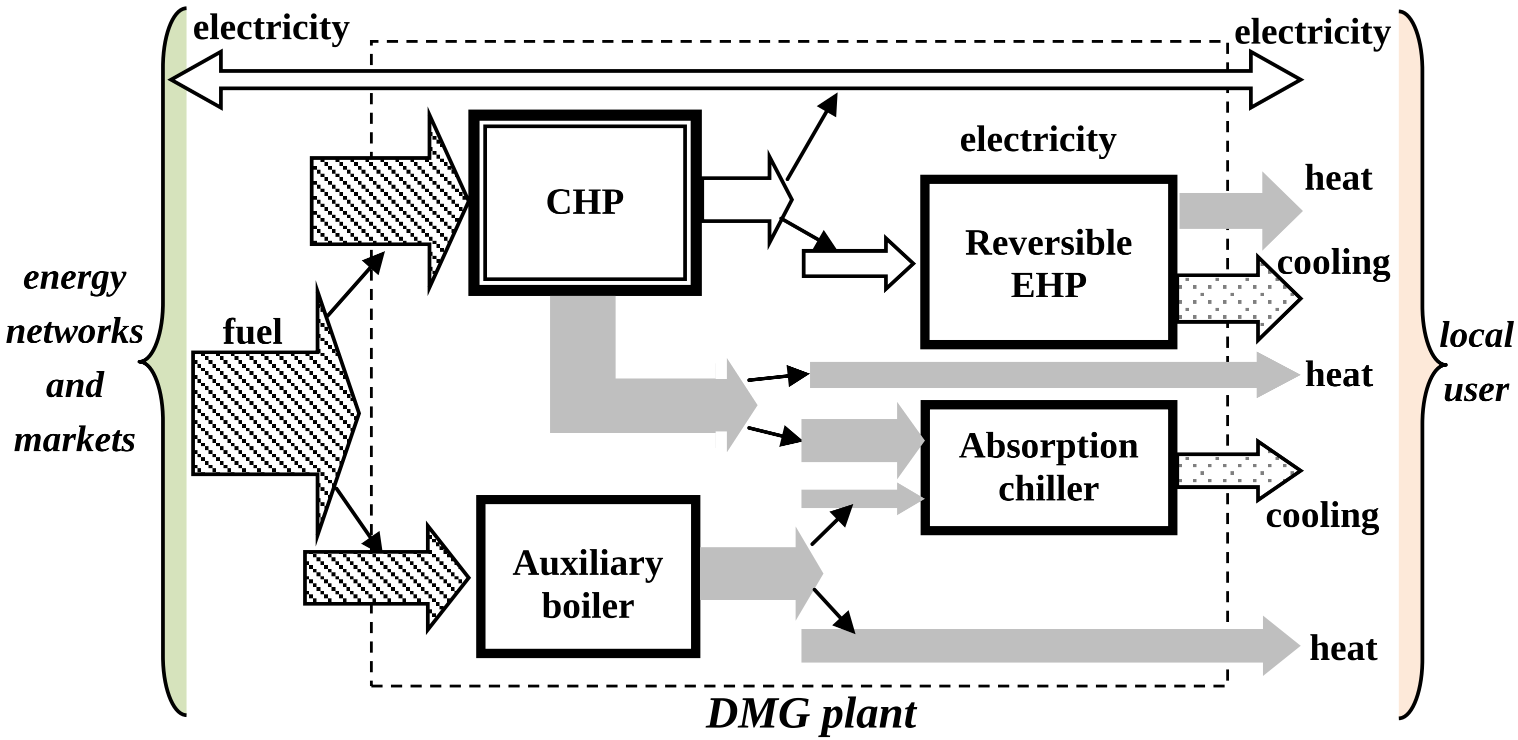
– Operational flexibility
– Real-time control and response
– Shifting between different energy vectors
– Virtual storage, Power-to-heat





T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

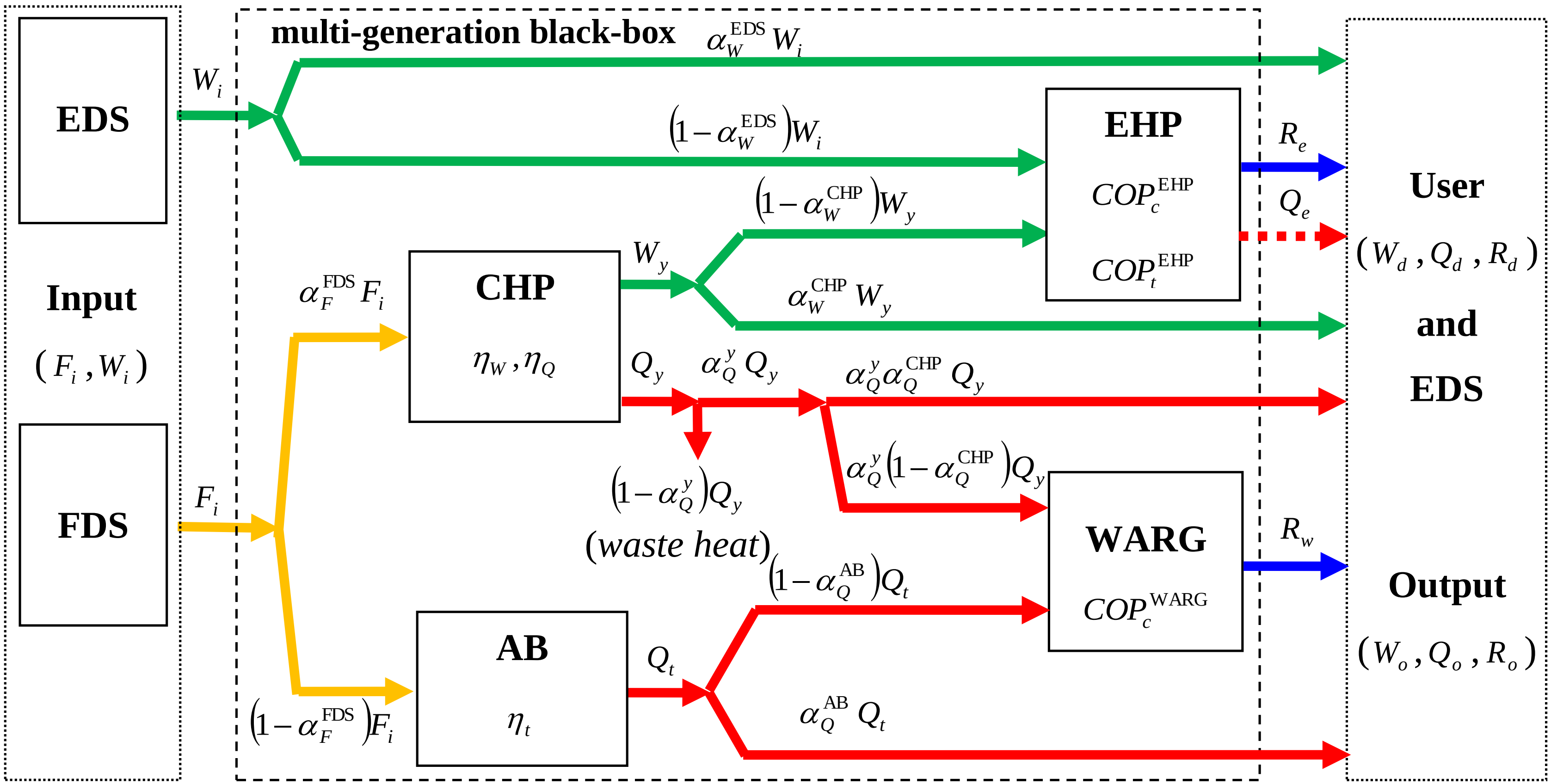
An example from multi-generation



Generic black box "energy hub" model -> buildings, districts, cities, …

Source: P. Mancarella and G.Chicco, Real time Demand Response from Distributed Multi-Generation, *IEEE Trans. on Smart Grid, 2013*

Energy optimization: baseline



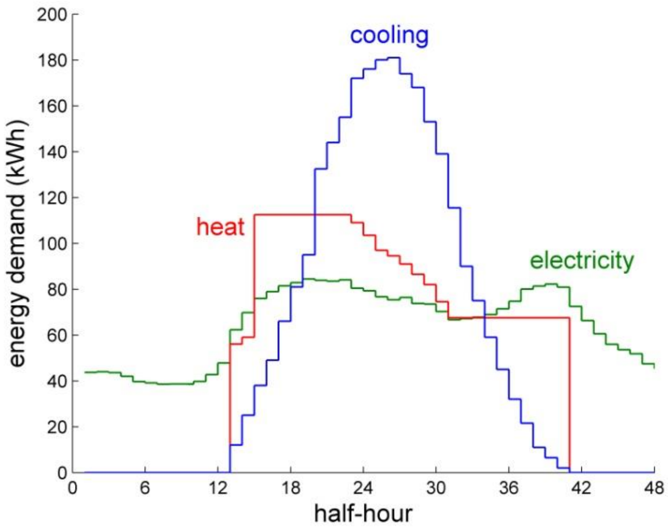
Source: G.Chicco and P.Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, Energy, Volume 34, No. 3, March 2009, Pages 261-273.

Baseline optimization

- $\min\left\{\rho_f^{\mathrm{FDS}} F_i + \rho_i^{\mathrm{EDS}} \max\{W_i, 0\} + \rho_o^{\mathrm{EDS}} \min\{W_i, 0\}\right\}$

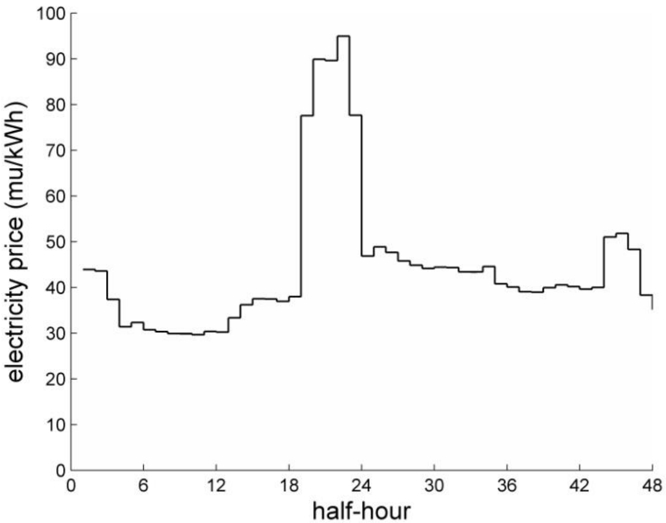
s.t.

- $\mathbf{f}(\mathbf{x}) = \mathbf{0}$ (equality constraints)
- $\mathbf{g}(\mathbf{x}) \le \mathbf{0}$ (inequality constraints)



- Decision variables $\mathbf{x} = \left[F_i, W_i, \boldsymbol{\alpha}^{\mathrm{T}}, W_y, Q_y, Q_t, R_e, R_w\right]^{\mathrm{T}}$

- NLP problem, solved with SQP in Matlab



Source: G.Chicco and P.Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, Energy, Volume 34, No. 3, March 2009, Pages 261-273.

Flexibility from energy vector switching

- *Energy-shifting* possibility, internal to the plant from one form of energy to another (*multi-energy arbitrage* - generalisation of the *fuel substitution* concept)
- *Electricity shifting potential:* the time-dependent maximum reduction in the electricity input from the network starting from a given initial operational state:

1. By switching heat/cooling loads from the electric heat pump (EHP) onto the auxiliary boiler (AB)/absorption chiller (WARG)
2. By increasing the CHP generation set point (if there is headroom for that) owing to the twofold effect of:
   - increasing the local electricity production; *and*
   - increasing the thermal production for heating/cooling purposes (which in case also displaces heat/cooling previously produced through electricity in the EHP operating in heating/cooling mode, respectively)

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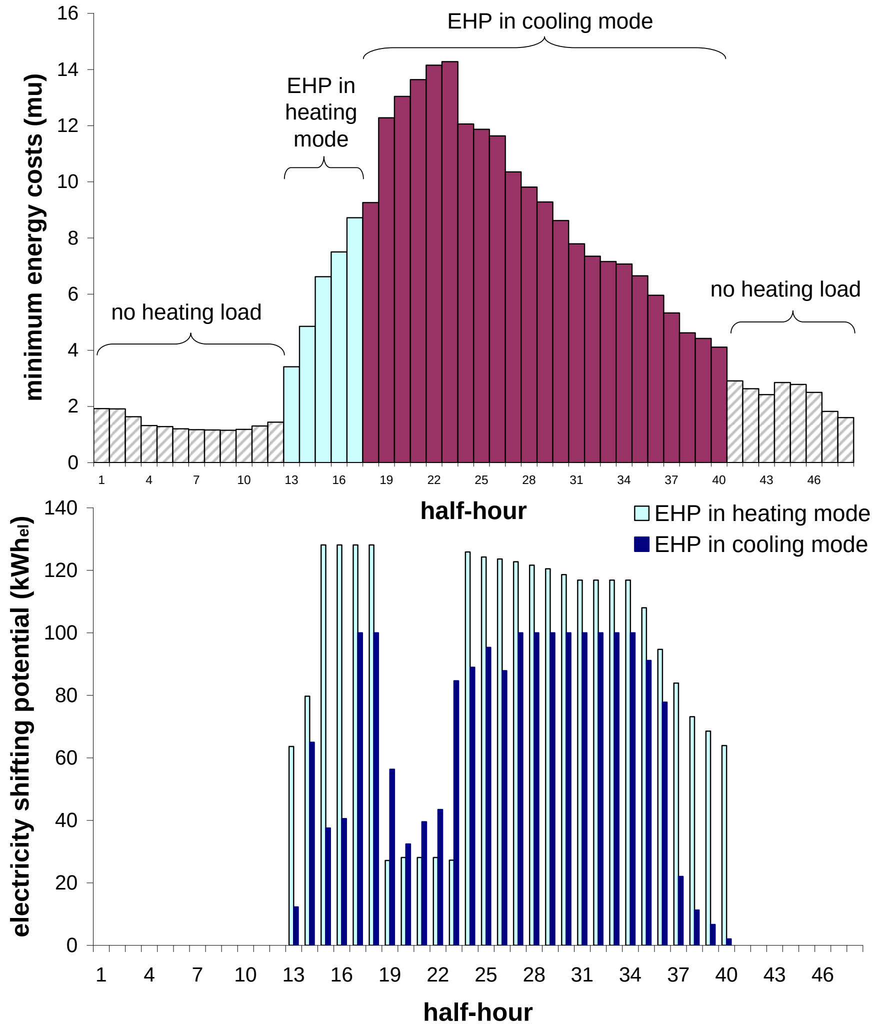
Techno-economic flexibility



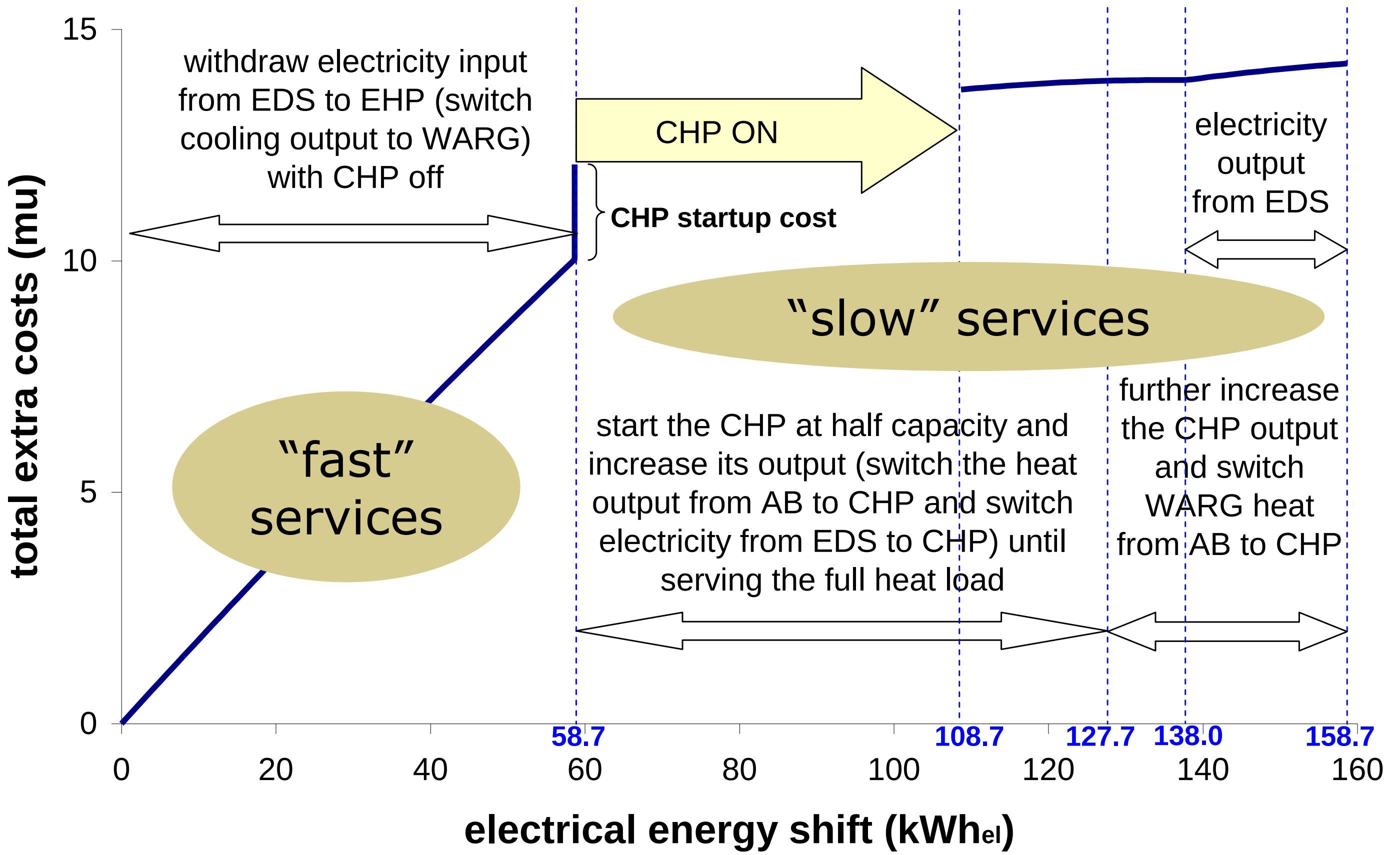
Optimal baseline cost solution for the EHP operation in the Summer day

Electricity shifting potential in the Summer day

- EHP operated in heating mode or in cooling mode

Source: P. Mancarella and G.Chicco, Real time Demand Response from Distributed Multi-Generation, *IEEE Trans. on Smart Grid, 2013*

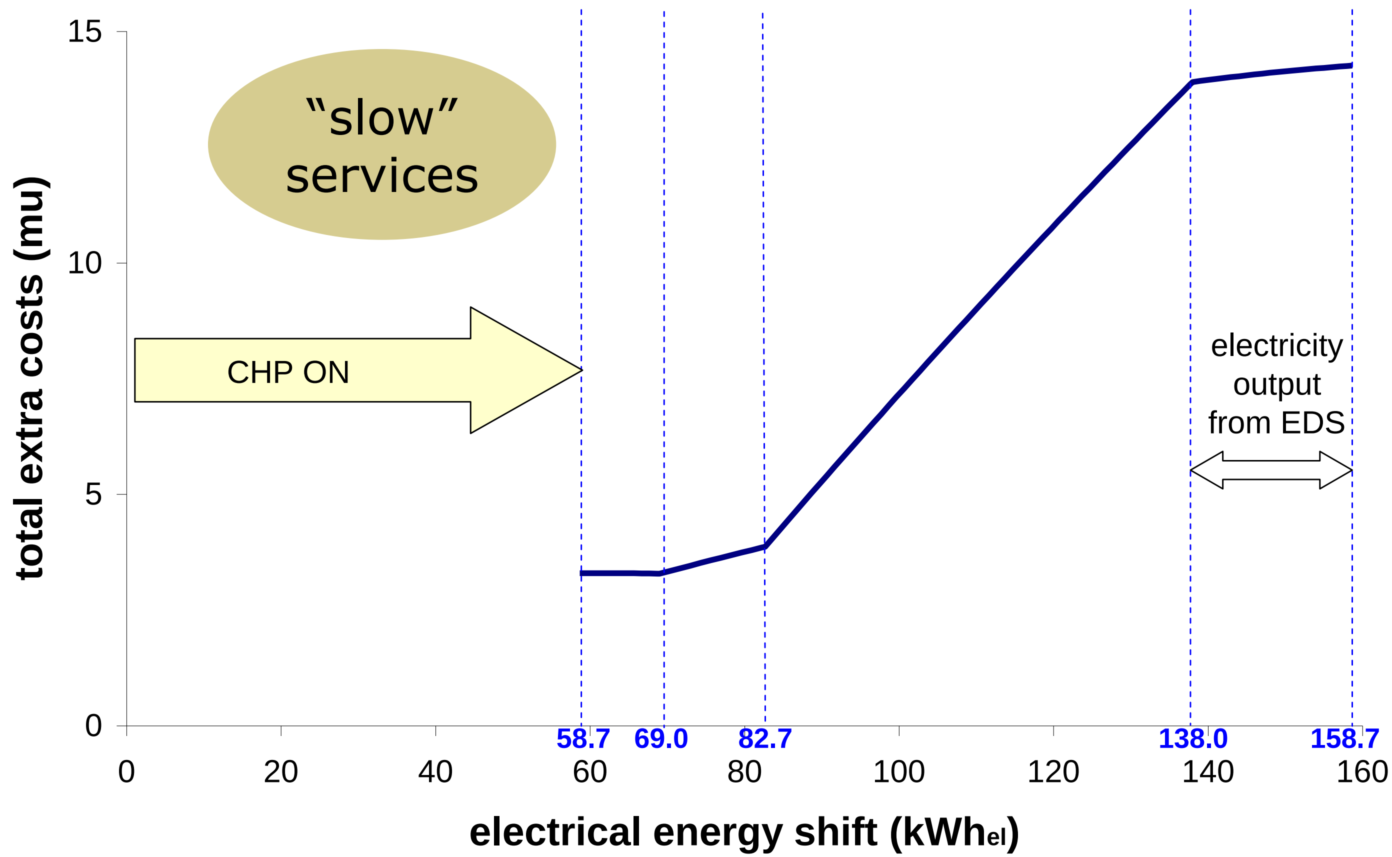
Provision of flexibility: Speed and cost



Total extra costs for shifting energy outside the optimal point

P. Mancarella and G.Chicco, Integrated energy and ancillary services provision in multi-energy systems, Proceedings of the IREP 2013, Rethymnon, Crete, Greece, 25-30 August 2013

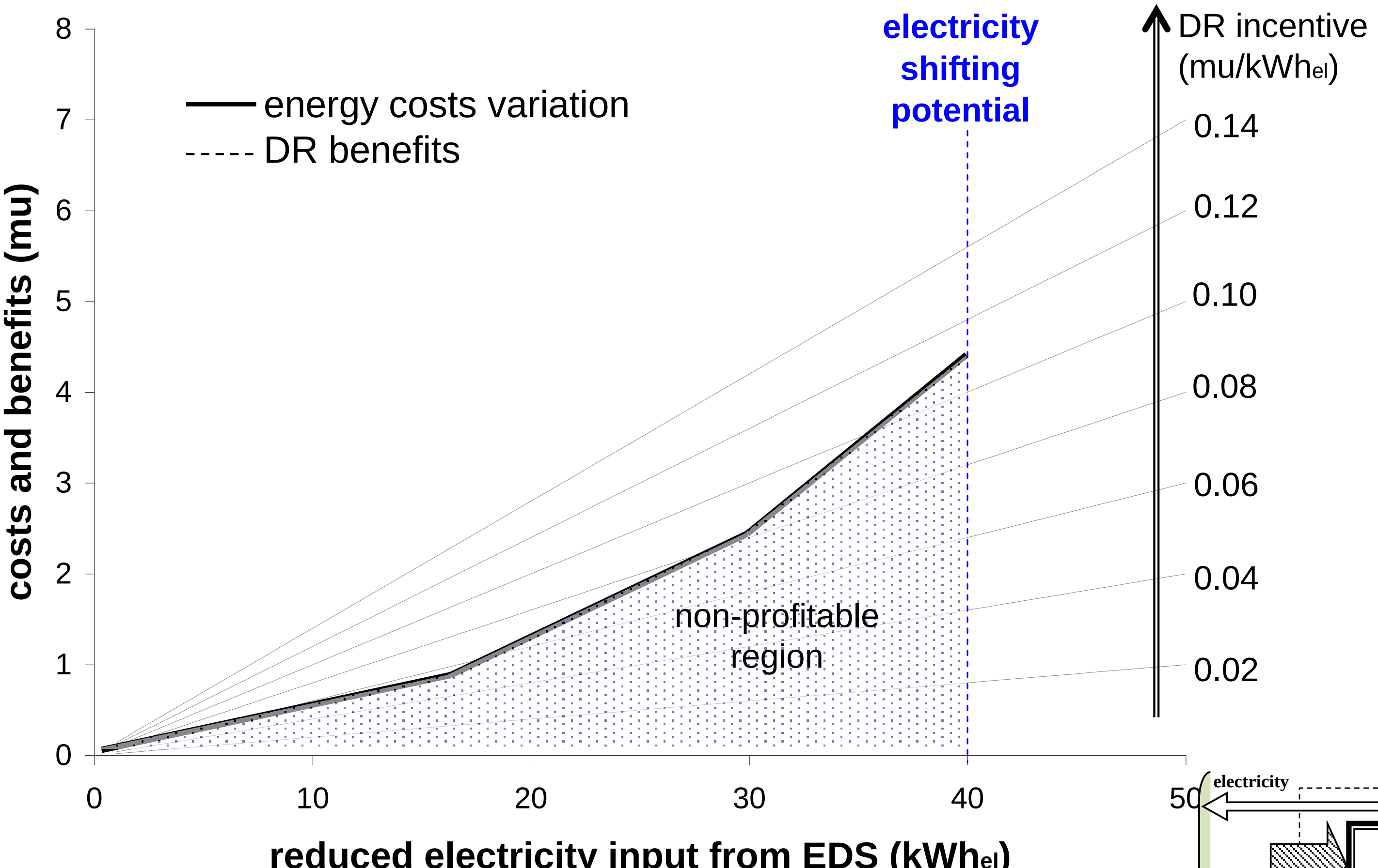
Provision of flexibility: Speed and cost

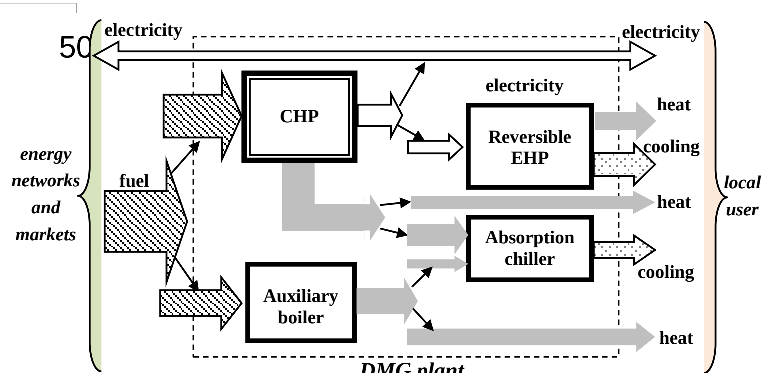


Total extra costs for shifting energy outside the optimal point

P. Mancarella and G.Chicco, Integrated energy and ancillary services provision in multi-energy systems, Proceedings of the IREP 2013, Rethymnon, Crete, Greece, 25-30 August 2013

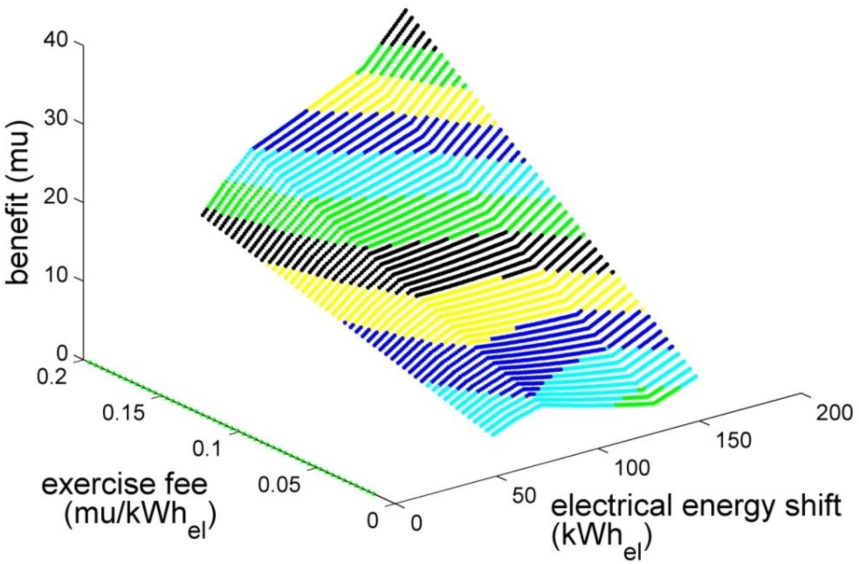
Business case for flexibility



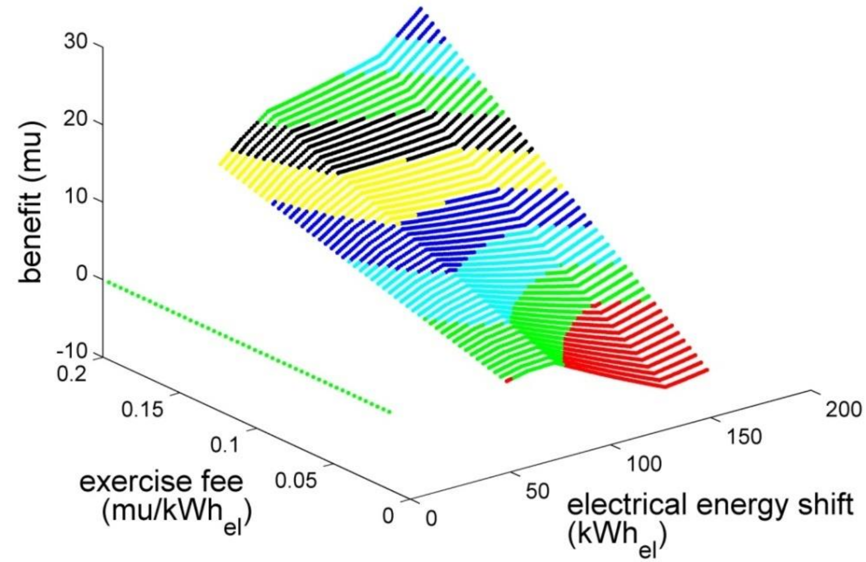


Source: P. Mancarella and G.Chicco, Real time Demand Response from Distributed Multi-Generation, *IEEE Trans. on Smart Grid, 2013*

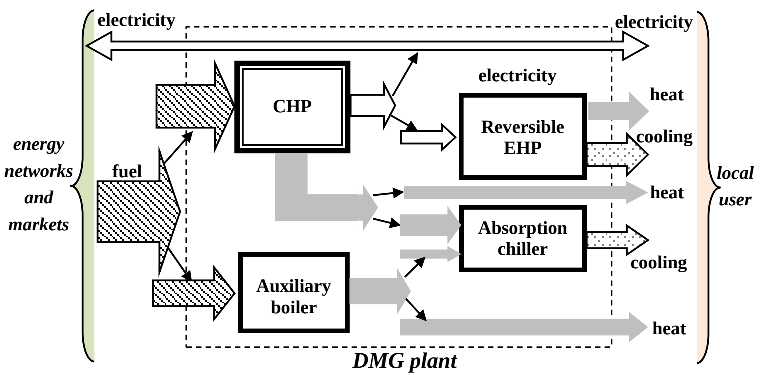
Flexibility profitability maps



availability fee 0.05 mu/kW/halfhour



availability fee 0.02 mu/kW/halfhour



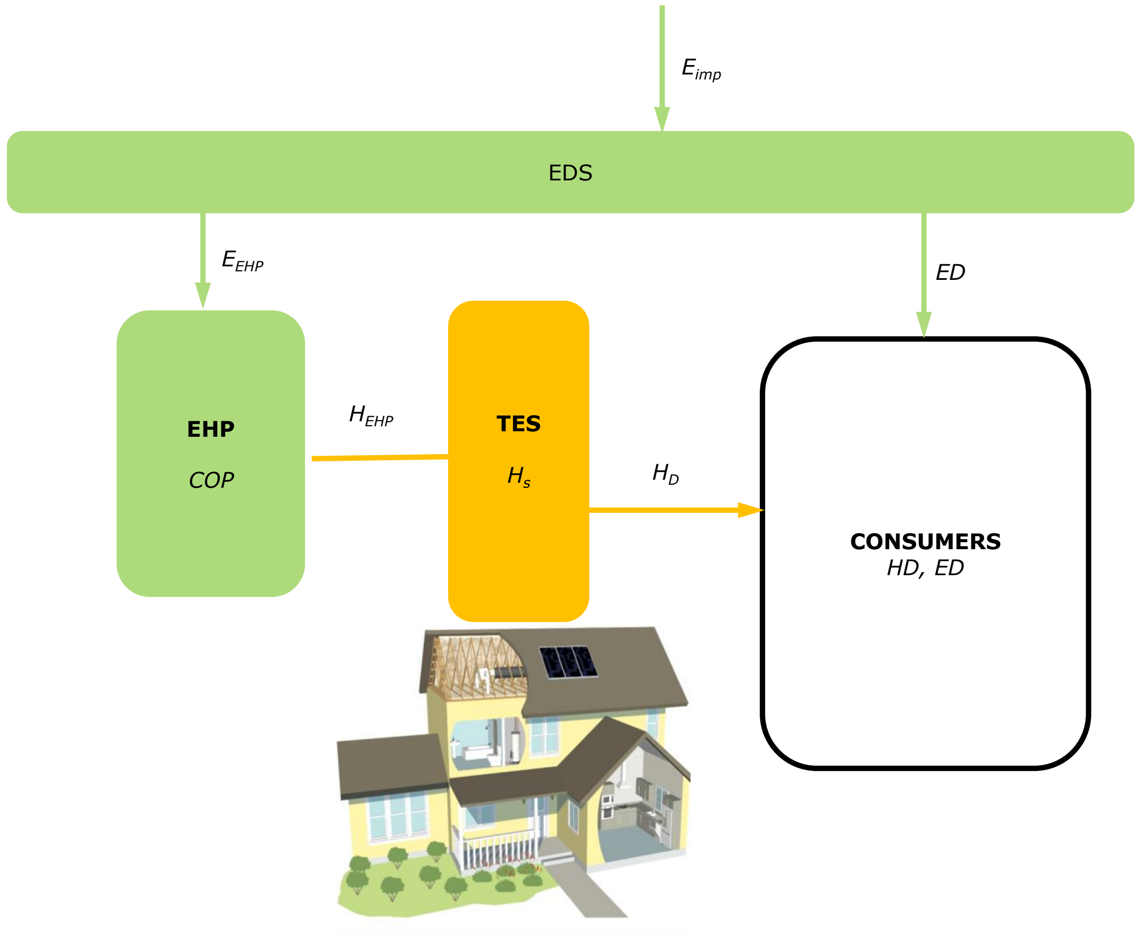
P. Mancarella and G.Chicco, Integrated energy and ancillary services provision in multi-energy systems, Proceedings of the IREP 2013, Rethymnon, Crete, Greece, 25-30 August 2013

Some considerations

- Optimal capacity offer is a function of:
  - Initial operational point cost
  - Out-of-optimal costs (including start-up costs)
  - Availability fee
  - Exercise fee
  - Service speed and plant constraints
- It is not possible to generalize the optimal strategy (for instance, always offer the electricity shifting potential)
- A suitable operational optimization model is needed to take into account all the complexity, including off-design operation models for all equipment
- The customer’s comfort level is not affected!

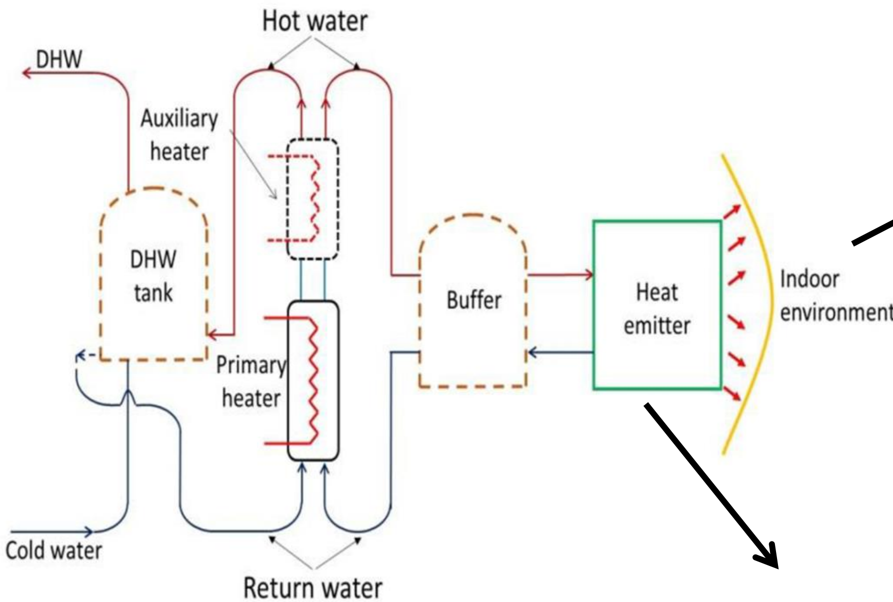
P. Mancarella and G.Chicco, Integrated energy and ancillary services provision in multi-energy systems, Proceedings of the IREP 2013, Rethymnon, Crete, Greece, 25-30 August 2013

Comfort-to-power arbitrage and virtual storage in buildings

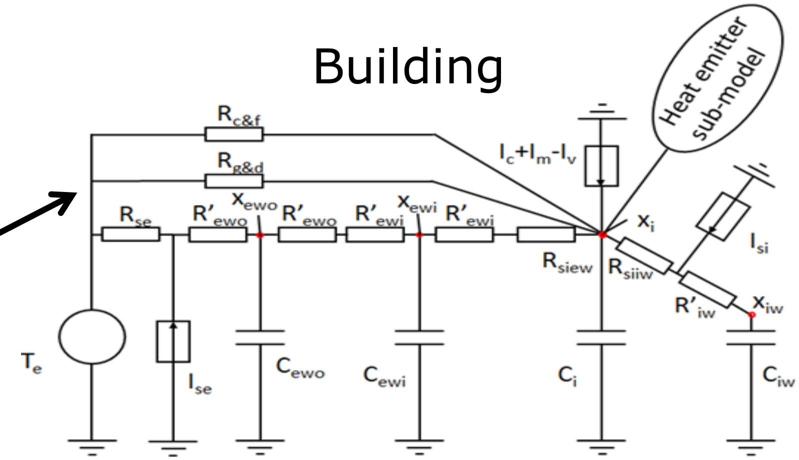


Electro-thermal modelling

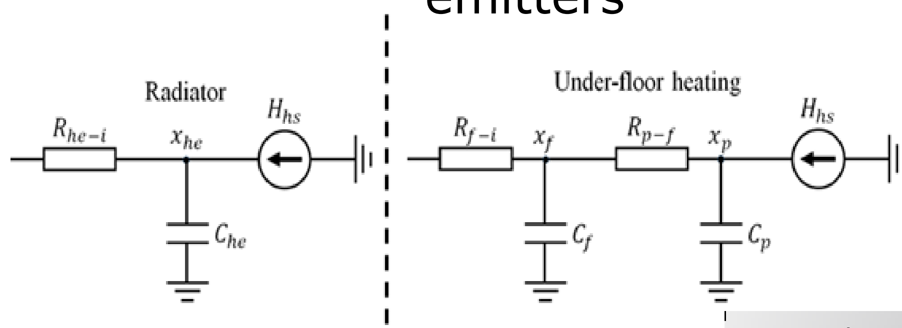
Supply



Building

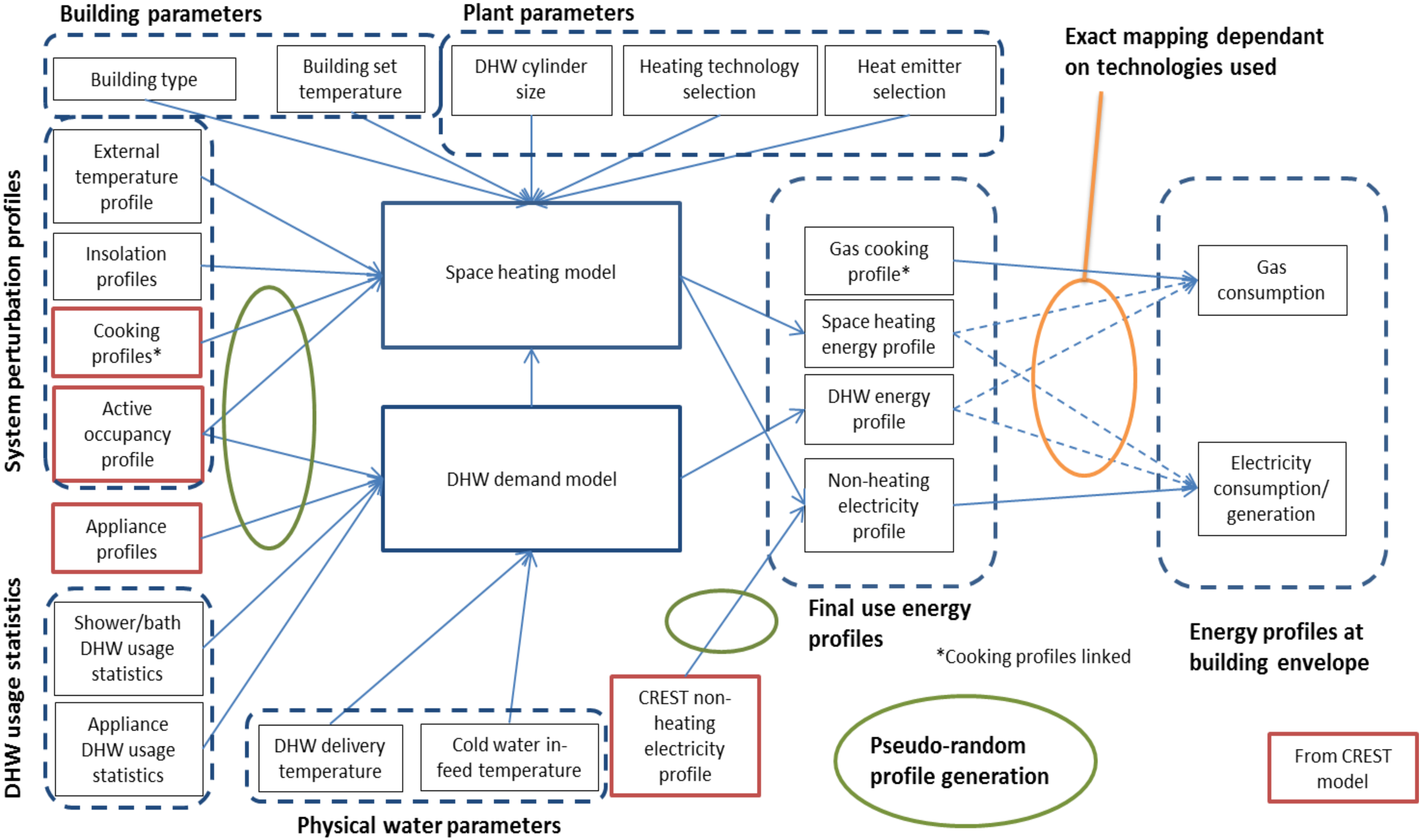


Heat emitters



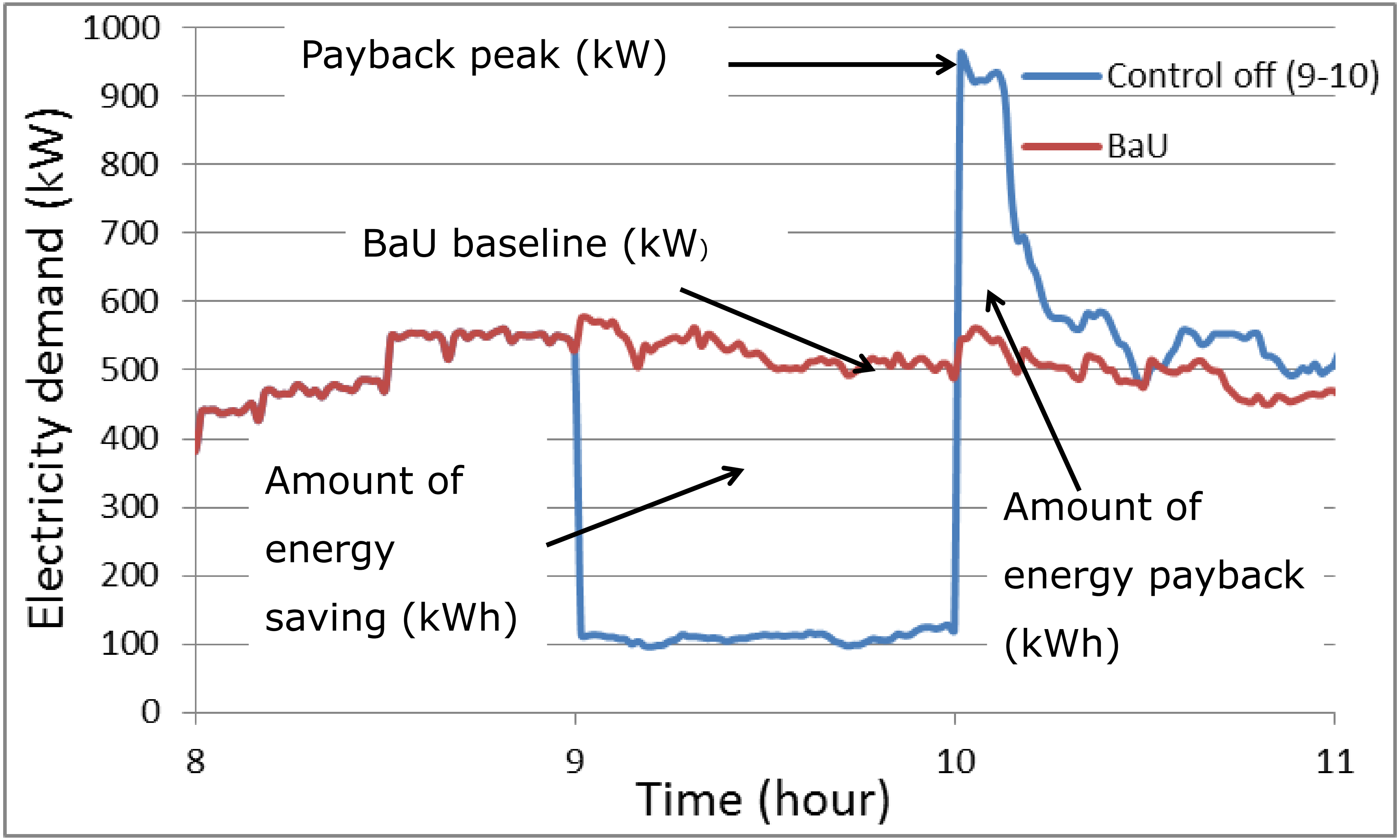
N. Good, L. Zhang, A. Navarro Espinosa, and P. Mancarella, High resolution modelling of multi-energy demand profiles, Applied Energy, 2015

Physical modelling of multi-energy demand in buildings for flexibility studies

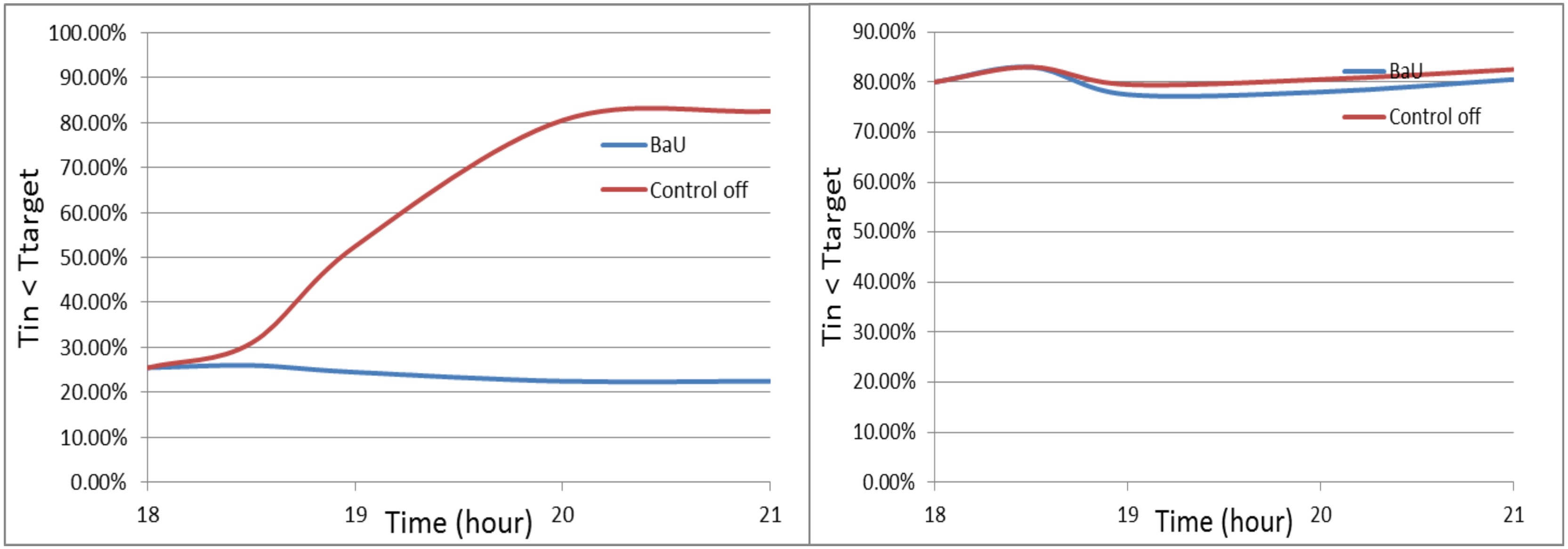


N. Good, L. Zhang, A. Navarro Espinosa, and P. Mancarella, High resolution modelling of multi-energy demand profiles, Applied Energy, Volume 137, 1 January 2015, Pages 193–210, 2014

Technical model of virtual storage: Example of up-flexibility



Virtual storage in buildings: "negative losses" and comfort level arbitrage



- Heating units compulsory off from 18 to 21
- Dwelling type: 200 modern (medium insulation) semi-detached houses
- Heating Units: ASHP with electric boiler
- Heat emitter: Radiator (left) and Underfloor (right)
- Season: Winter weekday
- Location: North West of England

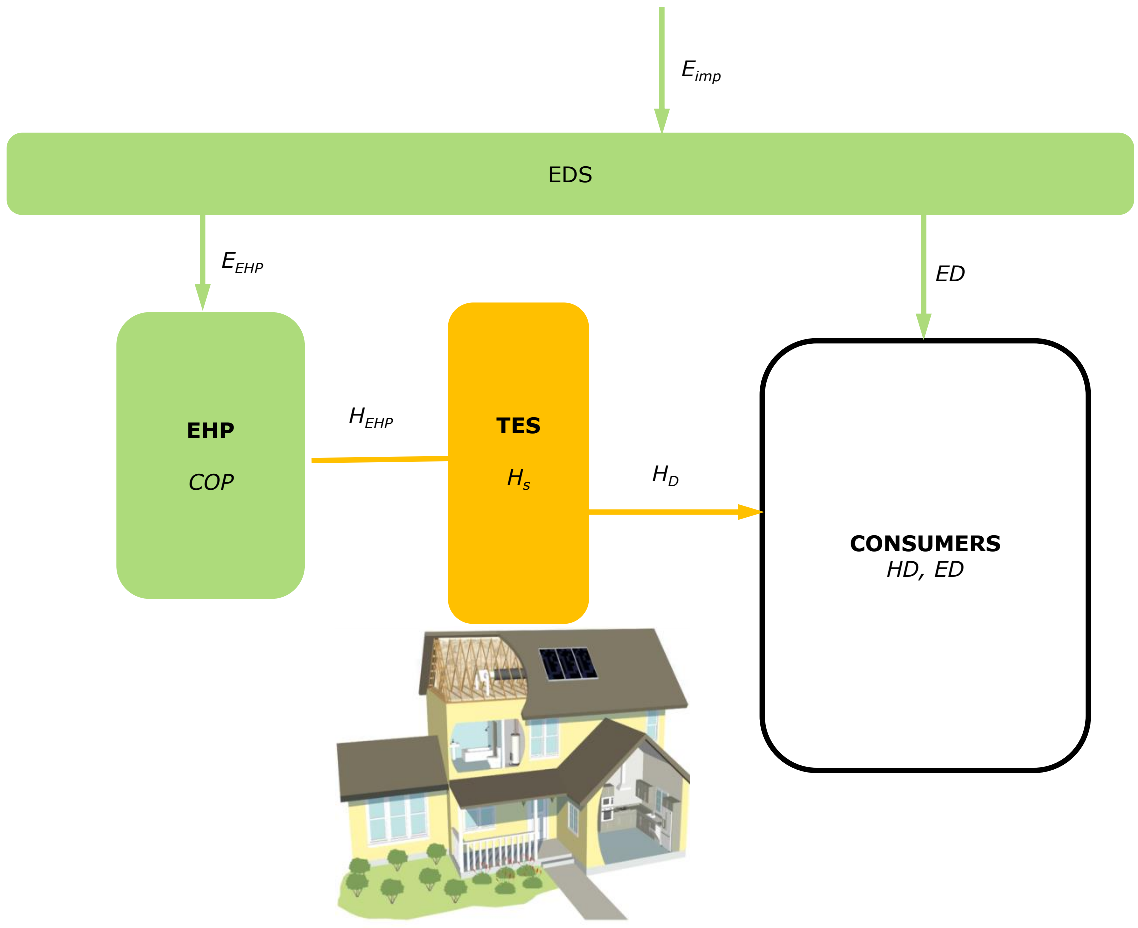
N. Good, E. Karangelos, A. Navarro-Espinosa, and P. Mancarella, Optimization under uncertainty of thermal storage based flexible demand response with quantification of thermal users' discomfort, IEEE Transactions on Smart Grid, 2015

Example of up-flexibility from building virtual storage and comfort tradeoff: ASHP with immersion heater and underfloor heating

Probability of indoor temperature below target temperature, when control starts at 18 PM

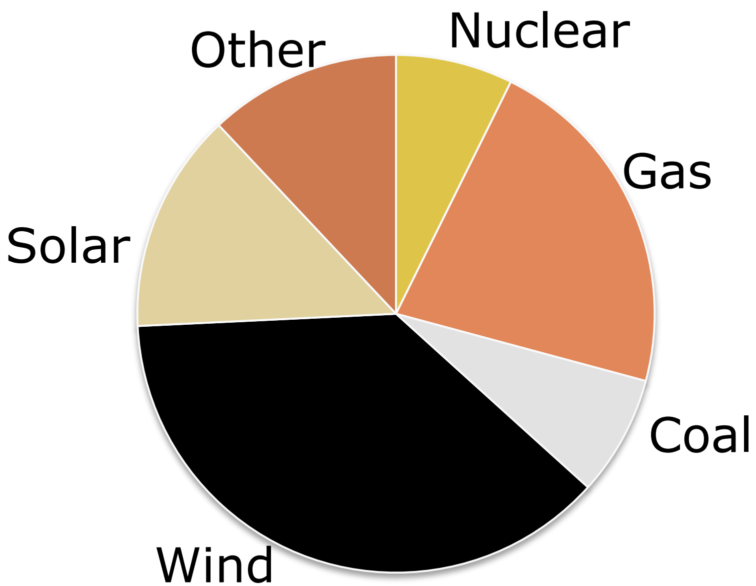
	Control duration	30 min	Bau	1h	Bau	2h	Bau	3h	Bau
Time	18	18:30		19		20		21	
win wd	below	78.00%	77.00%	79.50%	77.50%	80.50%	78.00%	82.50%	80.50%
	1 degree below	51.00%	47.50%	51.50%	43.50%	68.00%	39.00%	79.00%	34.00%
	2 degree below	22.50%	19.00%	23.00%	16.00%	34.00%	10.50%	42.50%	9.50%

Can we provide down-flexibility too?



Future Great Britain generation portfolio

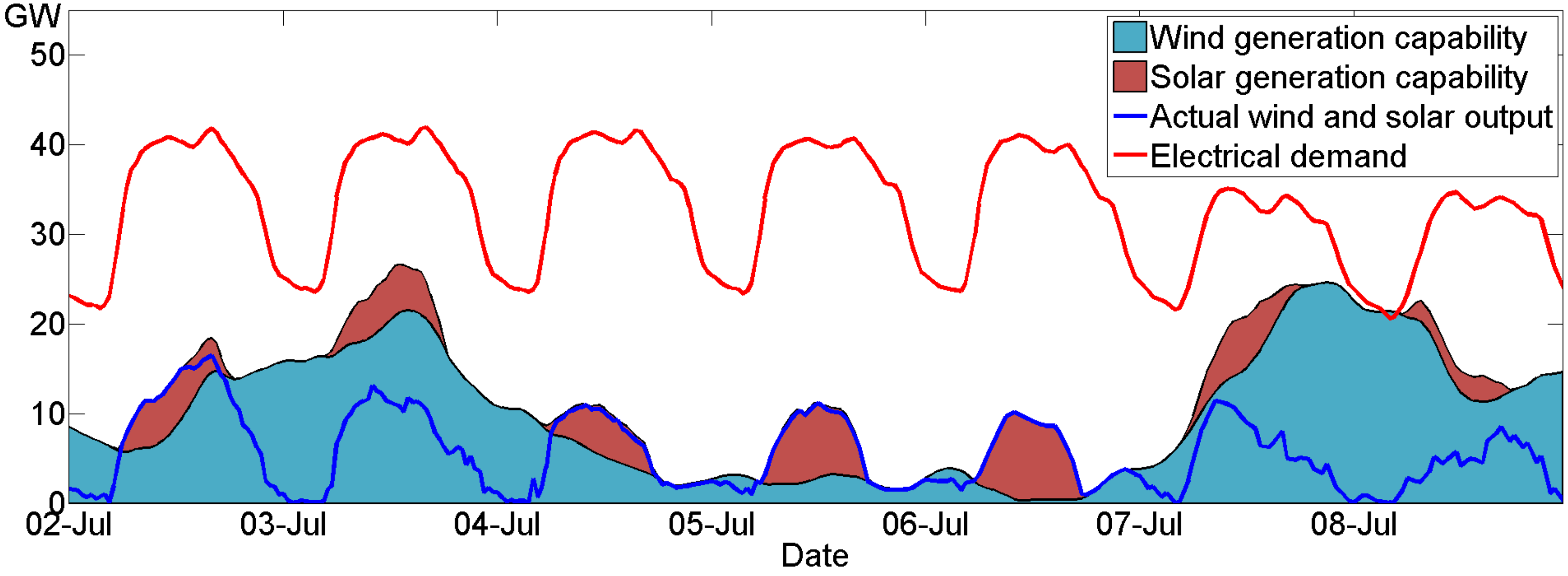
- National Grid's `Gone Green' scenario predicts in 2035:
  - 55 GW installed capacity of wind generation
  - 20 GW installed capacity of solar generation



Total installed capacity: 177GW

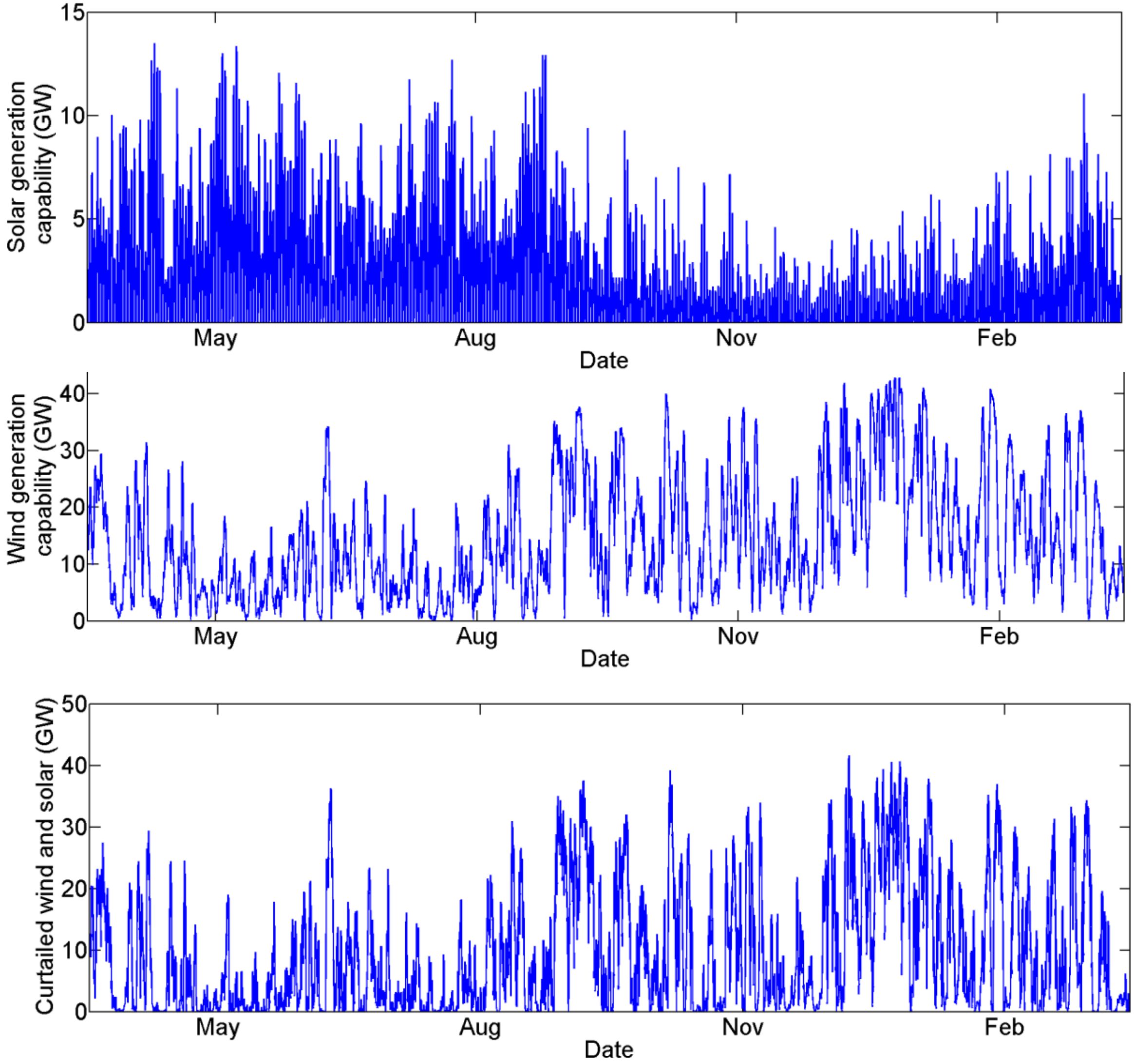
S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Example of curtailment levels



S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Annual levels of unutilised renewables



Annually

- 79.4 TWh of renewable generation unutilised (without power-to-gas)
- 57% of renewable generation capability is otherwise curtailed

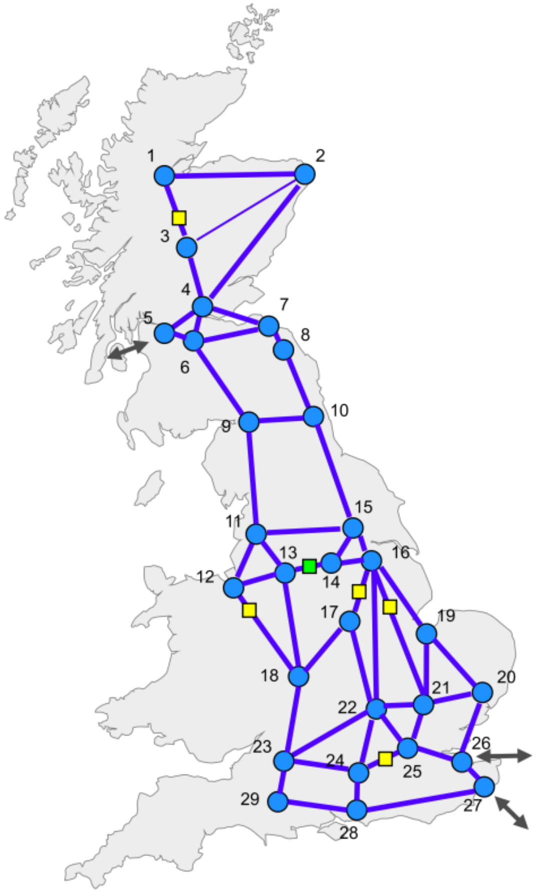
S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Down-flexibility and arbitrage with large scale penetration of renewables: power-to-gas (P2G) storage

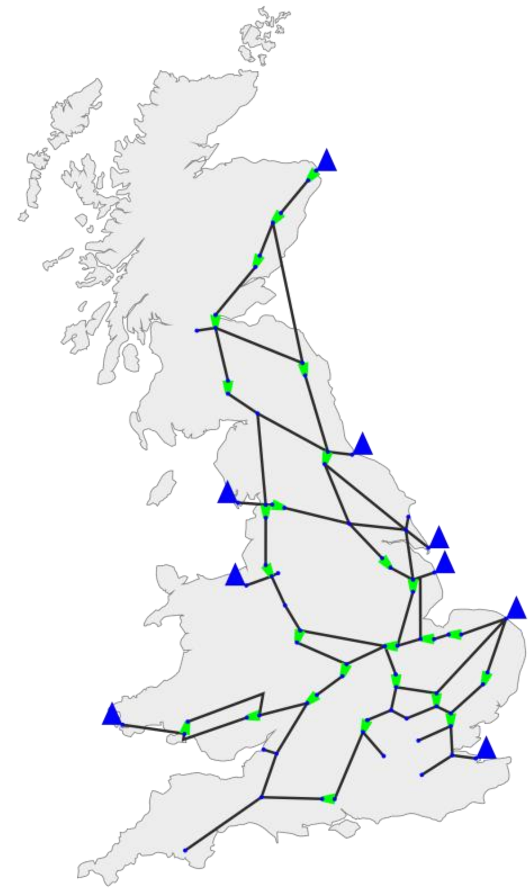
- Excess of renewables, also due to grid stability reasons and constraints
- Power-to-heat as an effective means of deploying flexibility from heat in an integrated manner with a time scale in the order of one to few days
- How do we deal with seasonal flexibility?
- Can we do something with gas?
  - Power-to-gas (P2G)
  - "Electrification" of gas via electrolysis and H2 formation
  - Hic et nunc power to gas arbitrage
  - Electricity and gas network arbitrage
  - Seasonal storage of electricity in the gas network

GB gas and electrical network modelling

- Gas and electrical networks coupled at gas turbines and combined heat-and-power facilities
- Power-to-gas adds an additional point of coupling between gas and electrical networks



Electrical transmission network



Gas transmission network

S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Levels of hydrogen content of gas in gas network

- Wide ranging technical and legislative restrictions limits to H_2 content of the gas in natural gas networks
- Unknown factors (e.g., age and applicability of home boilers, gas engines, etc.) suggest legislative limits to remain restrictive

	Limit to hydrogen content of gas in network (% vol.)
Current NTS limit	0.1%
Proposed relaxation to limit for GB distribution networks	3%
German trials	10%
Dutch trials	12%
Level at which blended hydrogen begins to affect gas boilers	~17%
French trials	20%

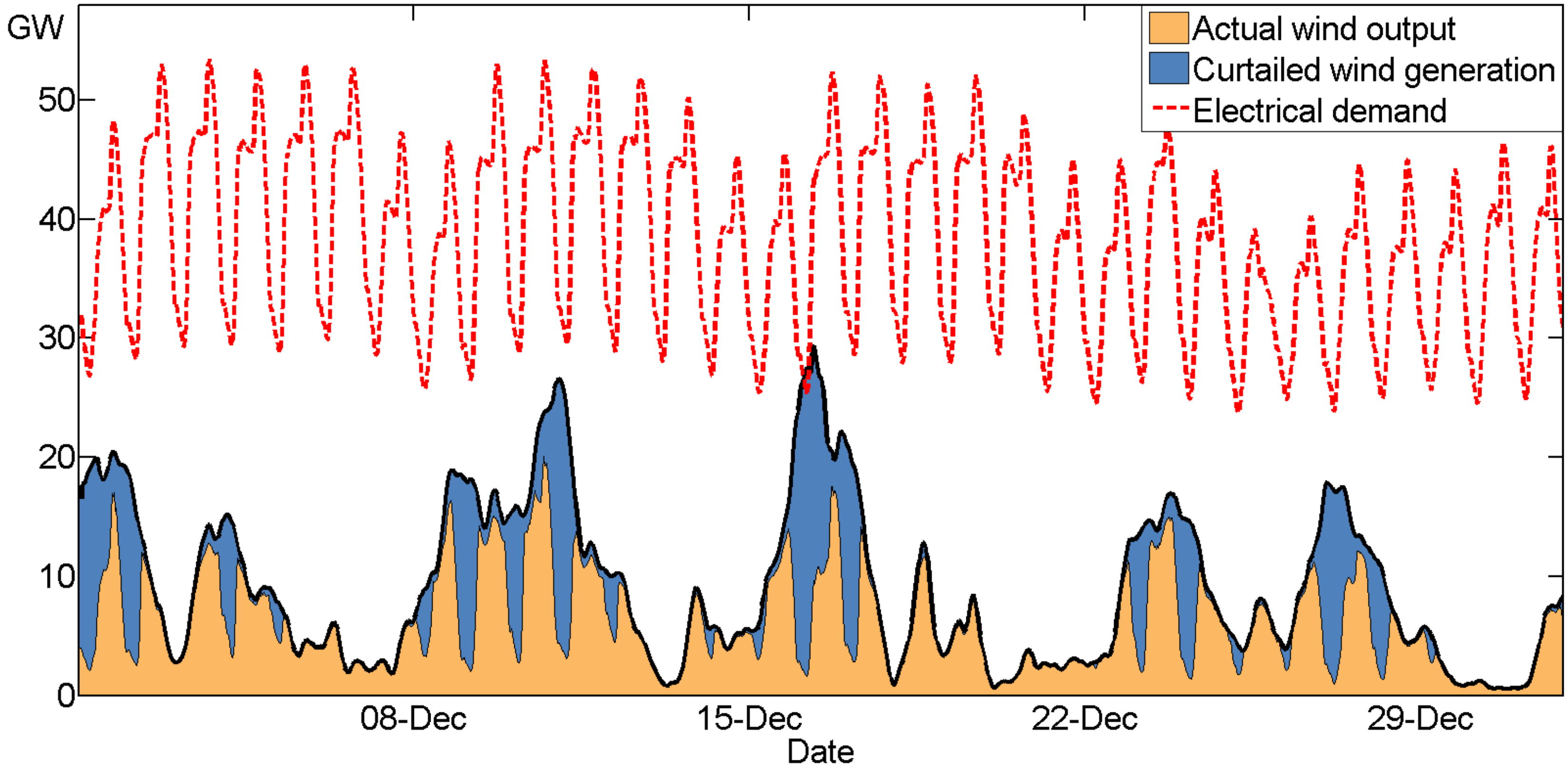
Power-to-gas required to meet hydrogen production potential

Limit to hydrogen content of gas in network (% vol.)	Average winter gas demand	Average summer gas demand
3%	1.7GW$_e$	0.9GW$_e$
10%	5.6GW$_e$	3.2GW$_e$
17%	9.5GW$_e$	5.4GW$_e$

(assuming 74% efficiency of hydrogen production and consequent network injection)

S. Clegg and P. Mancarella, Storing renewables in the gas network: modelling of power-to-gas (P2G) seasonal storage flexibility in low carbon power systems, *submitted to IET Generation, Transmission and Distribution, March 2015, under second review*.

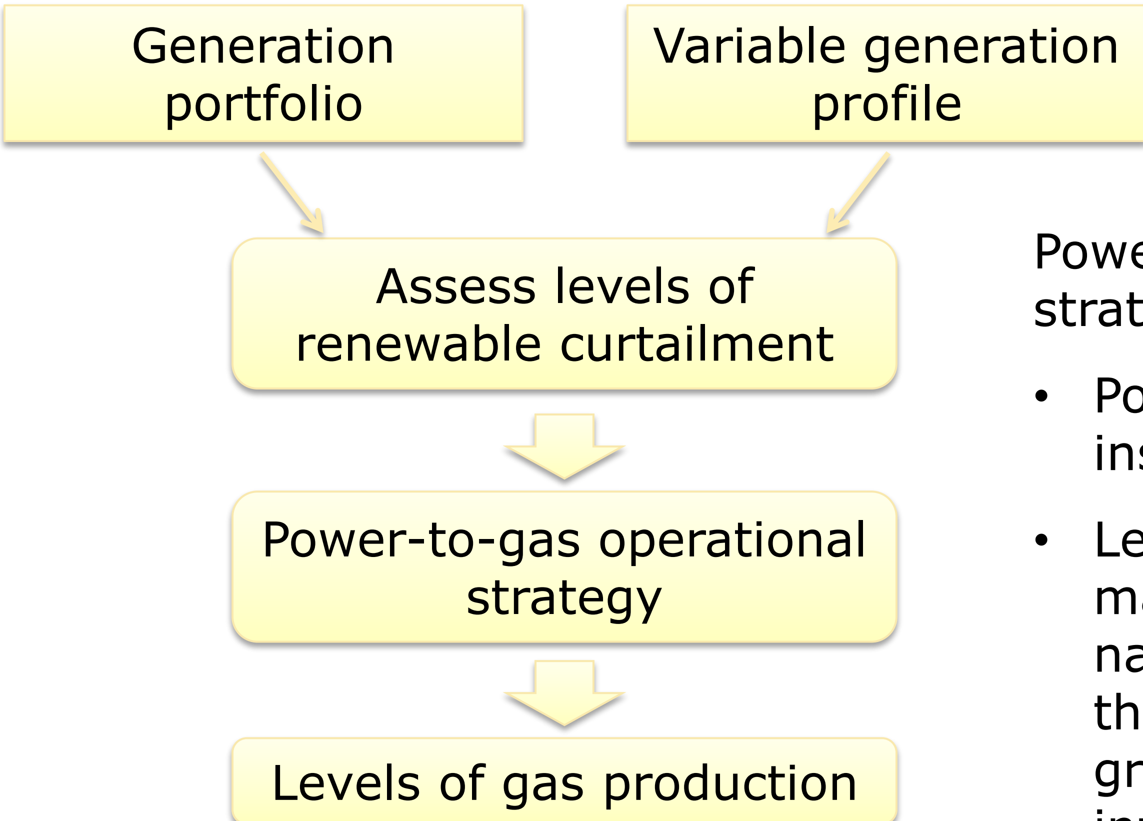
Wind curtailment



- Total curtailed wind 2.3TWh for December

S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Power-to-gas modelling



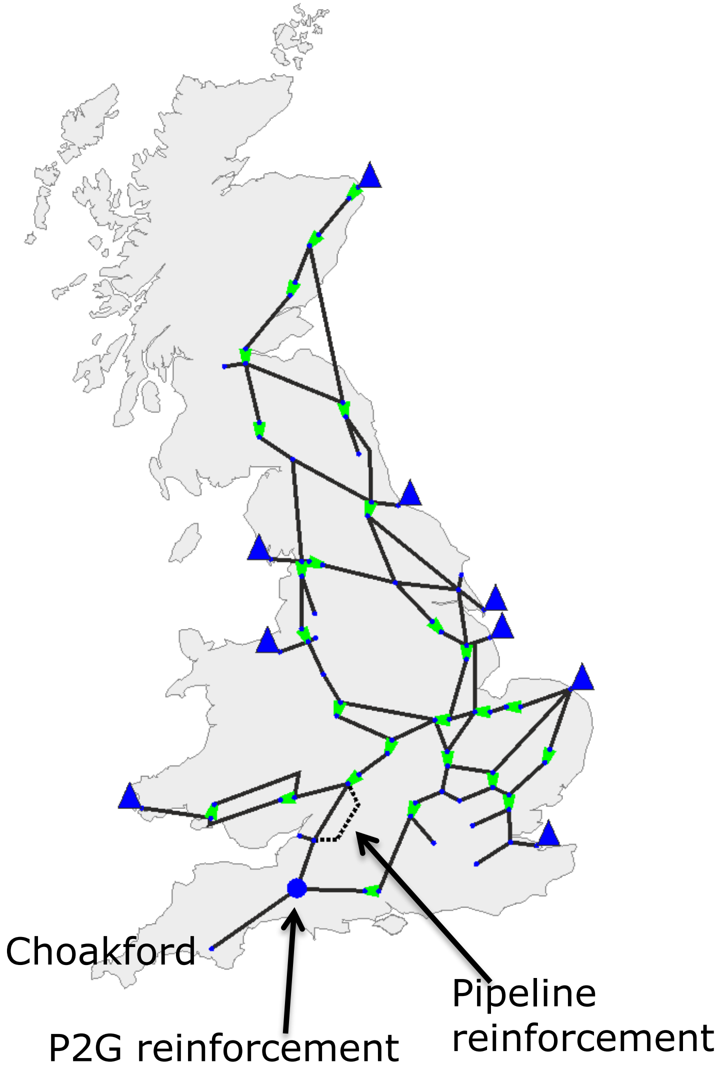
Power-to-gas operational strategies consider:

- Power-to-gas facility installation capacities
- Levels of hydrogen which may be blended with natural gas (higher throughput allowing greater hydrogen injection)
- Possibility to store H2 or transform it into methane

S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Application – Relief of gas network constraints (network arbitrage)

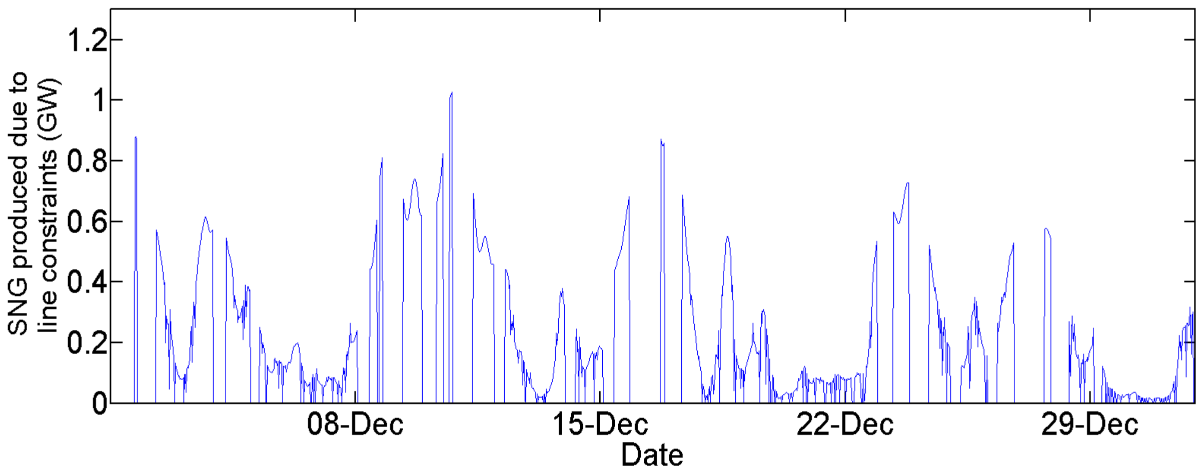
- To what extent could power-to-gas be used as a substitute for gas network reinforcement?
- If investment is made in gas storage for power-to-gas, could this increase the viability of gas storage above increased linepack via pipeline expansion?

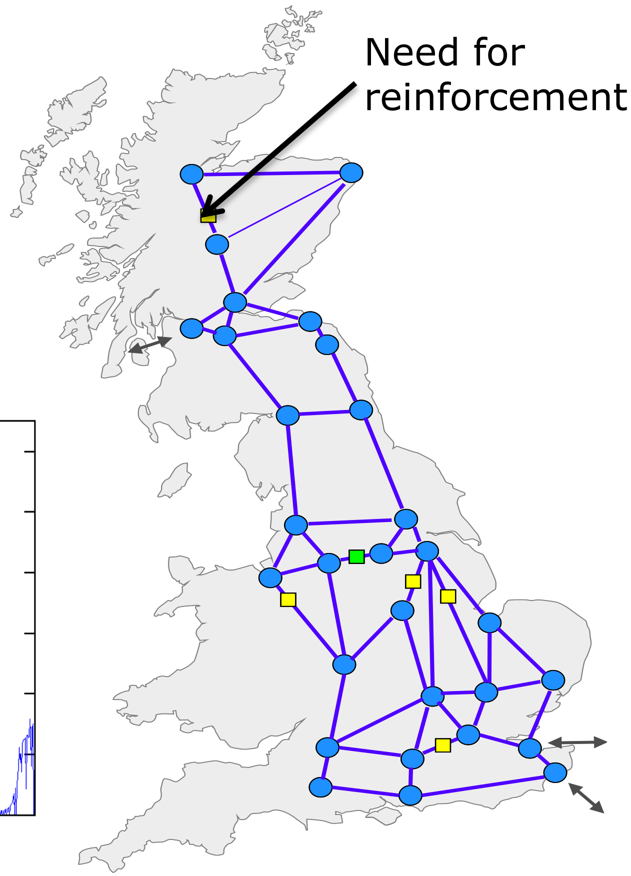


S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

Application – Relief of electrical network constraints (network arbitrage)

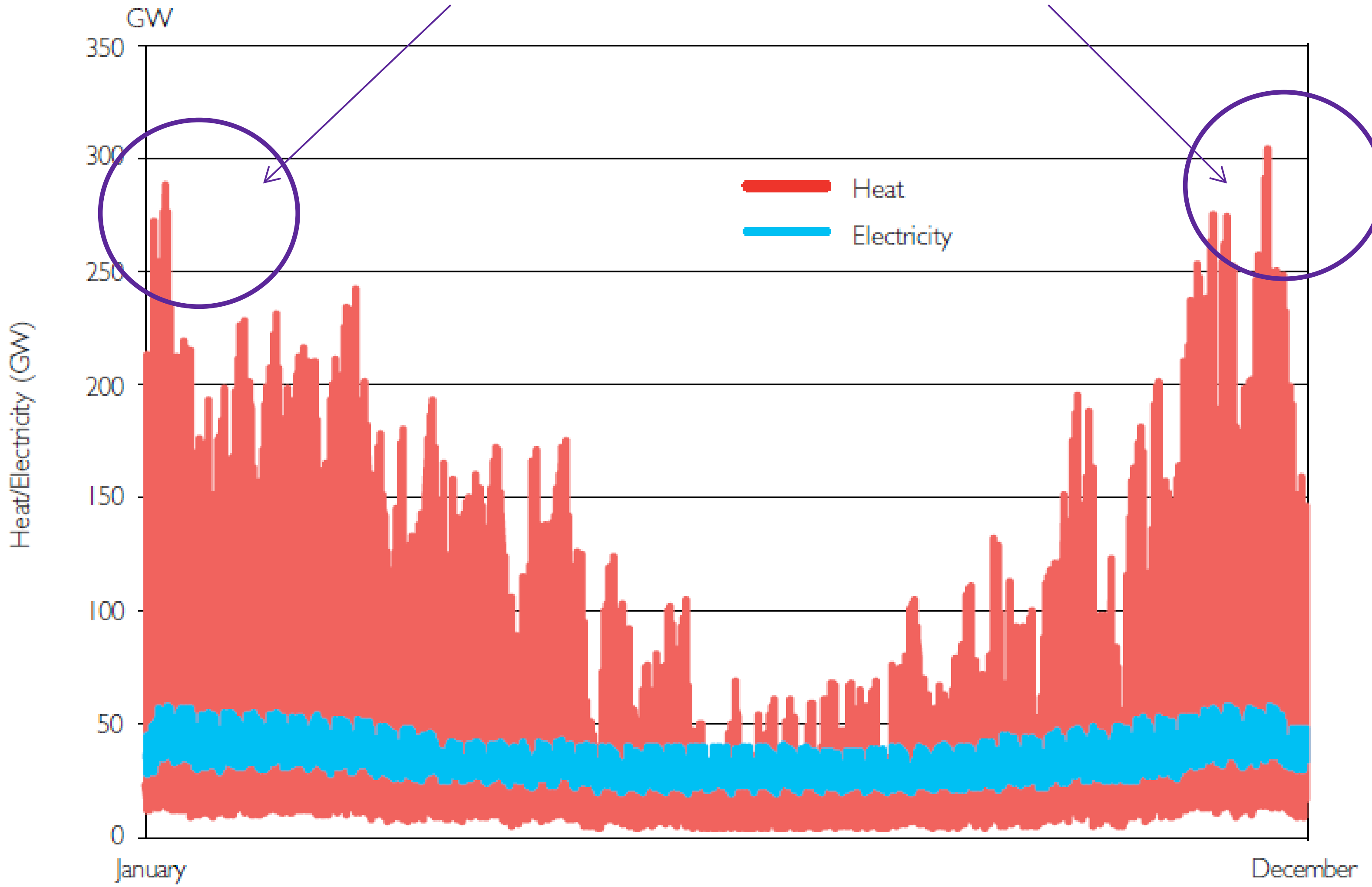
- To what extent could power-to-gas be used to by-pass electrical network constraints?





S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*.

A glance into the future: Electrification



Source: Courtesy of Imperial College. For illustrative purposes only and based on actual half-hourly electricity demand from National Grid and an estimate of half hourly heat demand.

Integrated electricity-heat-gas network modelling

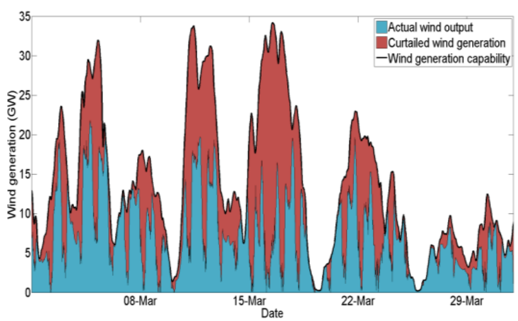
OPF

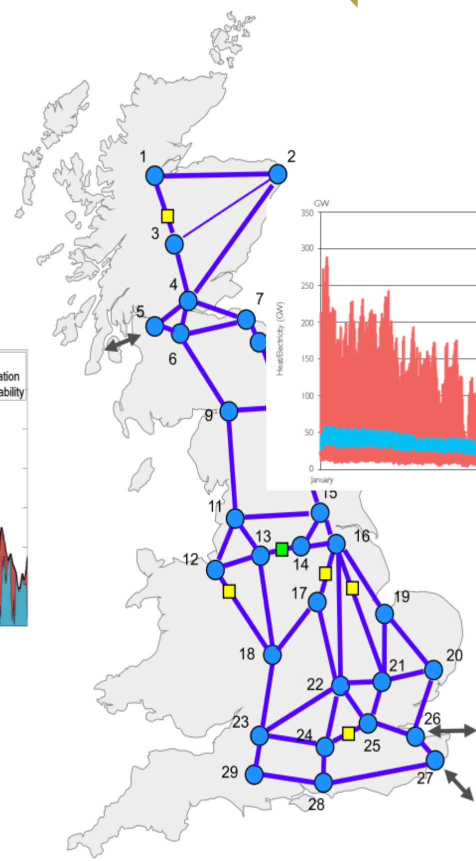
Curtailed renewable generation

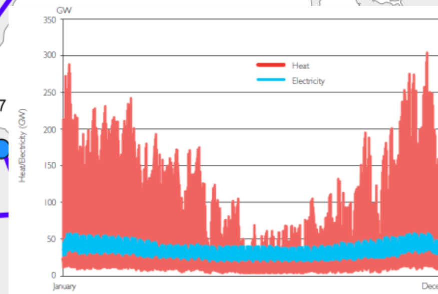
Form hydrogen or synthetic natural gas

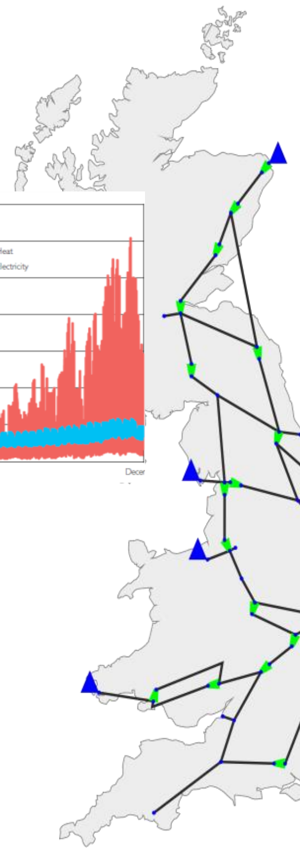
Use natural gas network as means to store and transport gas

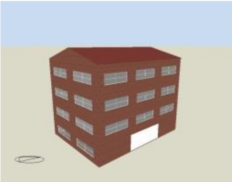
Use as low grade fuel for heating or electrical generation







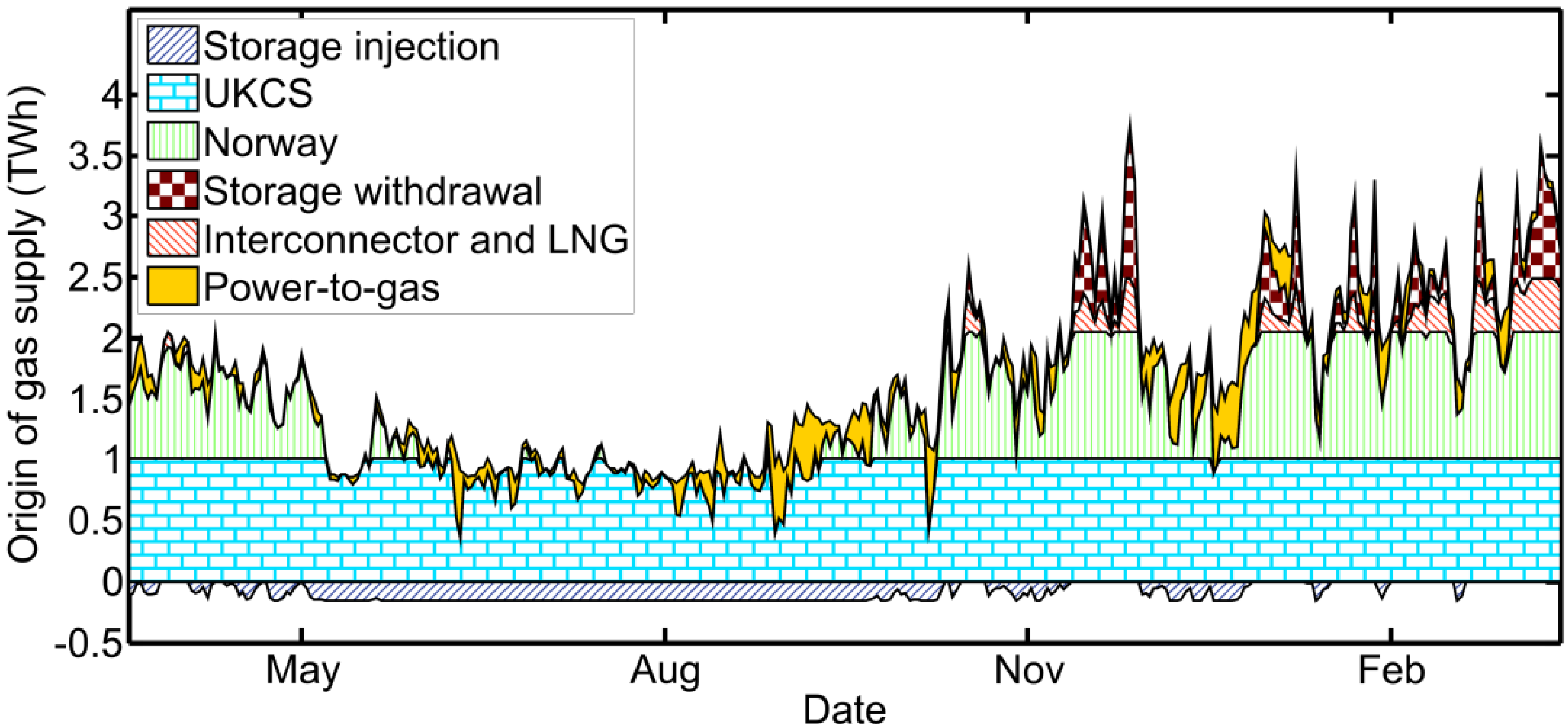




Electrical network model – 29 buses

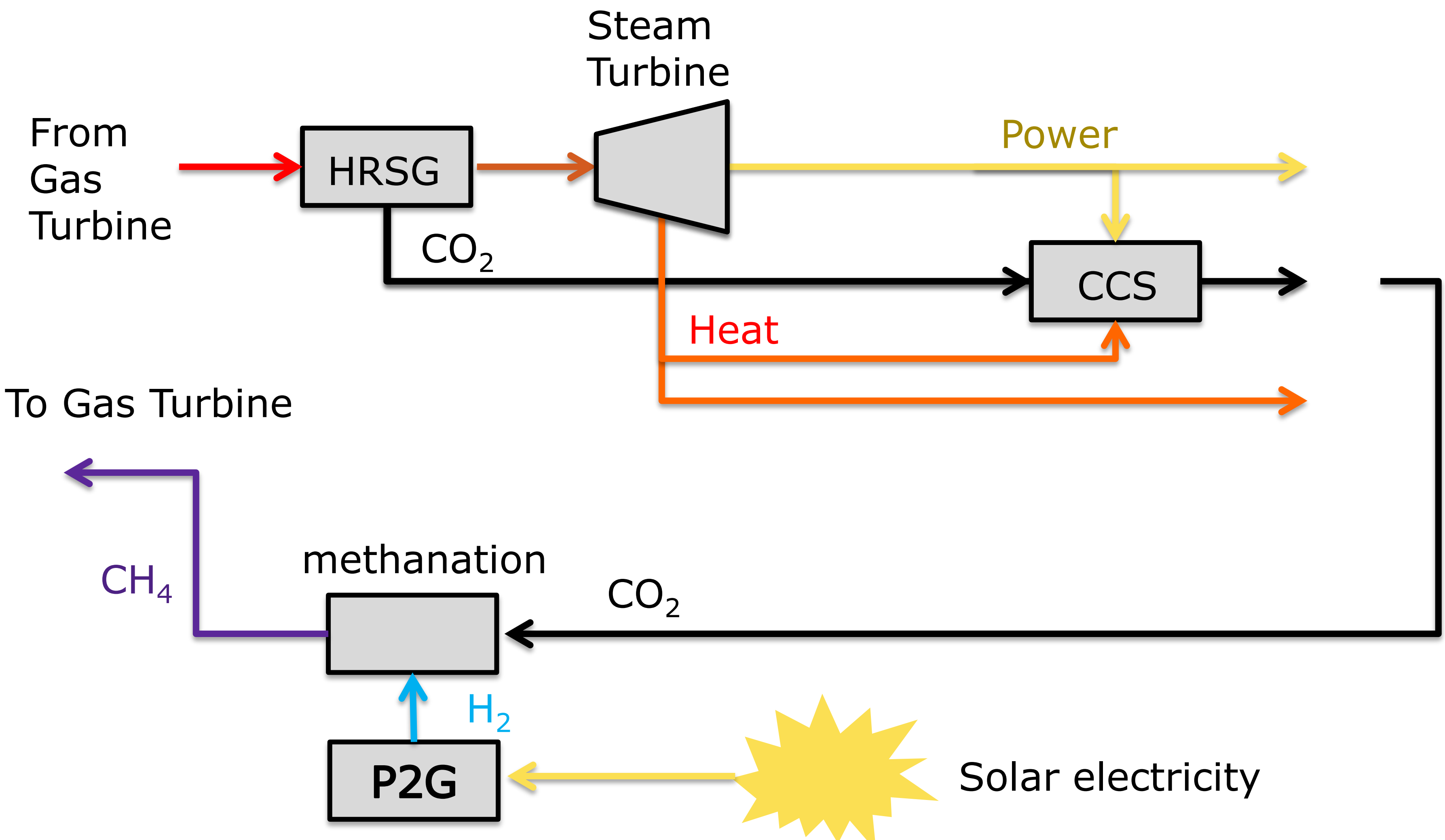
Gas network model – 71 buses

Application: Power-to-gas seasonal storage



S. Clegg and P. Mancarella, Storing renewables in the gas network: modelling of power-to-gas (P2G) seasonal storage flexibility in low carbon power systems, *submitted to IET Generation, Transmission and Distribution, March 2015, under second review*.

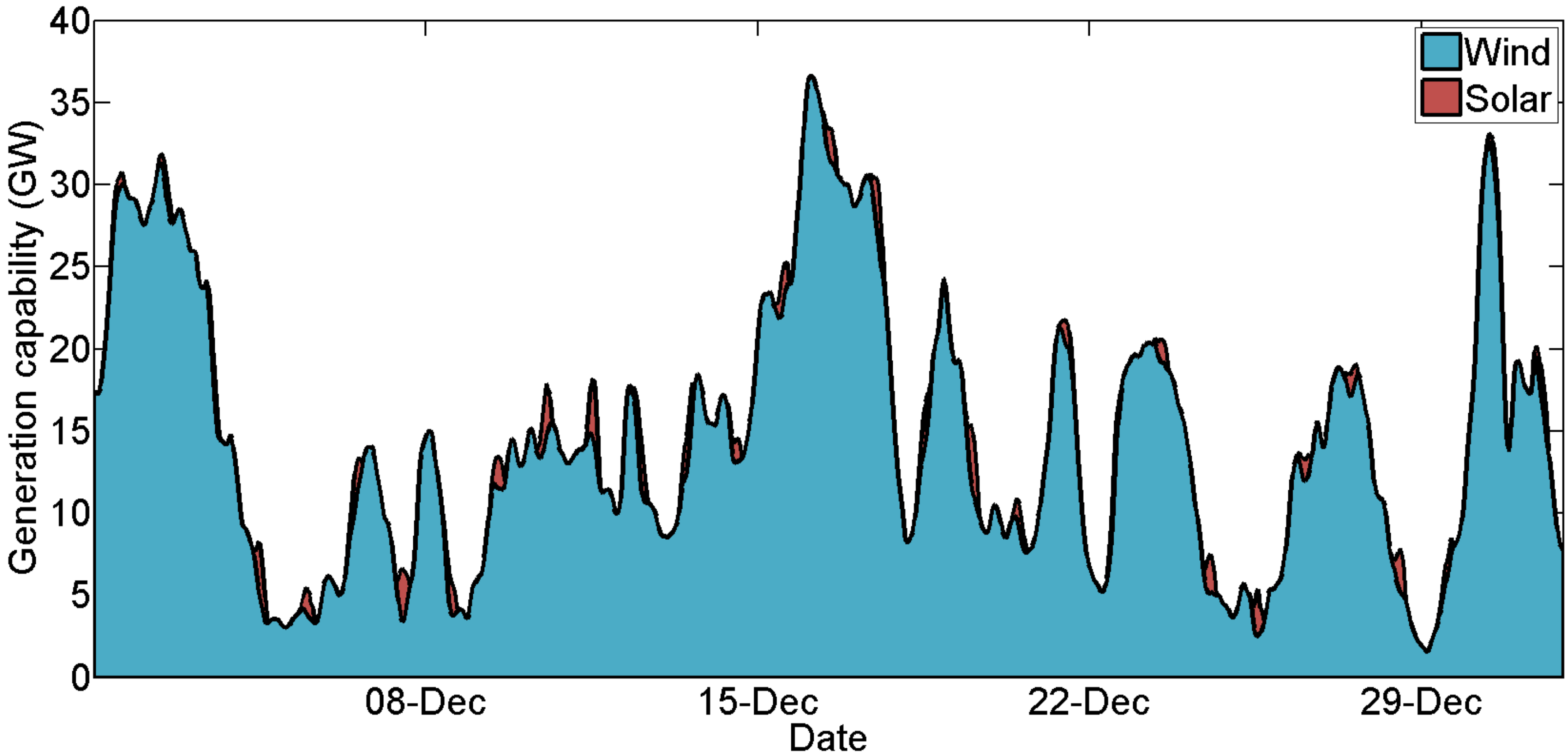
More multi-energy interactions and flexibility in the future?



Renewables and the gas network: Transfer of variability

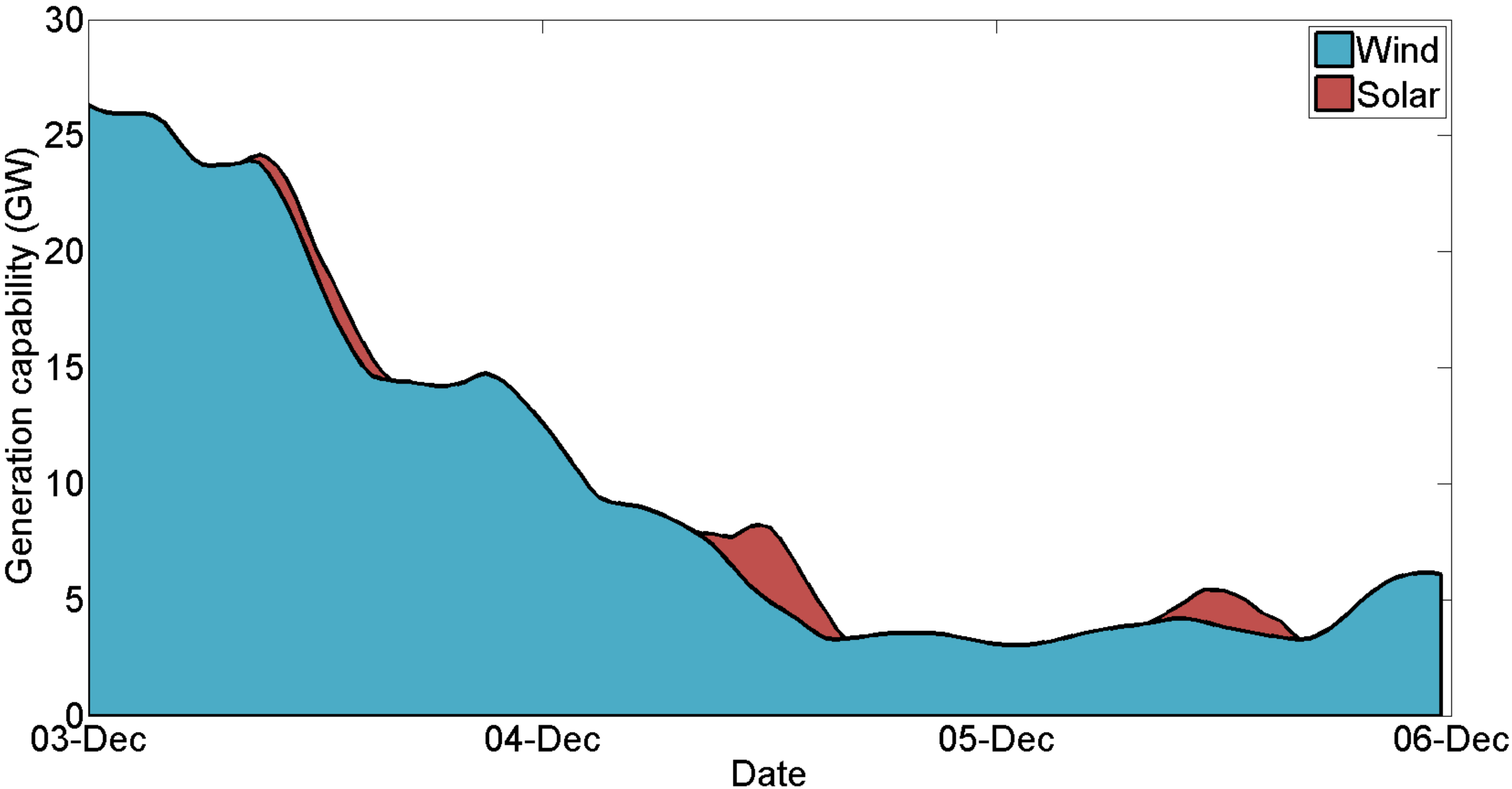
- Gas networks require gas to be transported for many hours from sources to power stations
- Delay between implementation and effect of reconfiguration of the gas network's operation (e.g., additional supplies, storage withdrawal, compressor station usage, etc.)
- System "linepack" is required to allow for unpredicted changes in demand
- The effect of intermittent generation on CCGTs is becoming dominant source of UK gas network demand uncertainty
- **Can the gas network constrain the electrical network operation?**

Example of future RES production in the UK

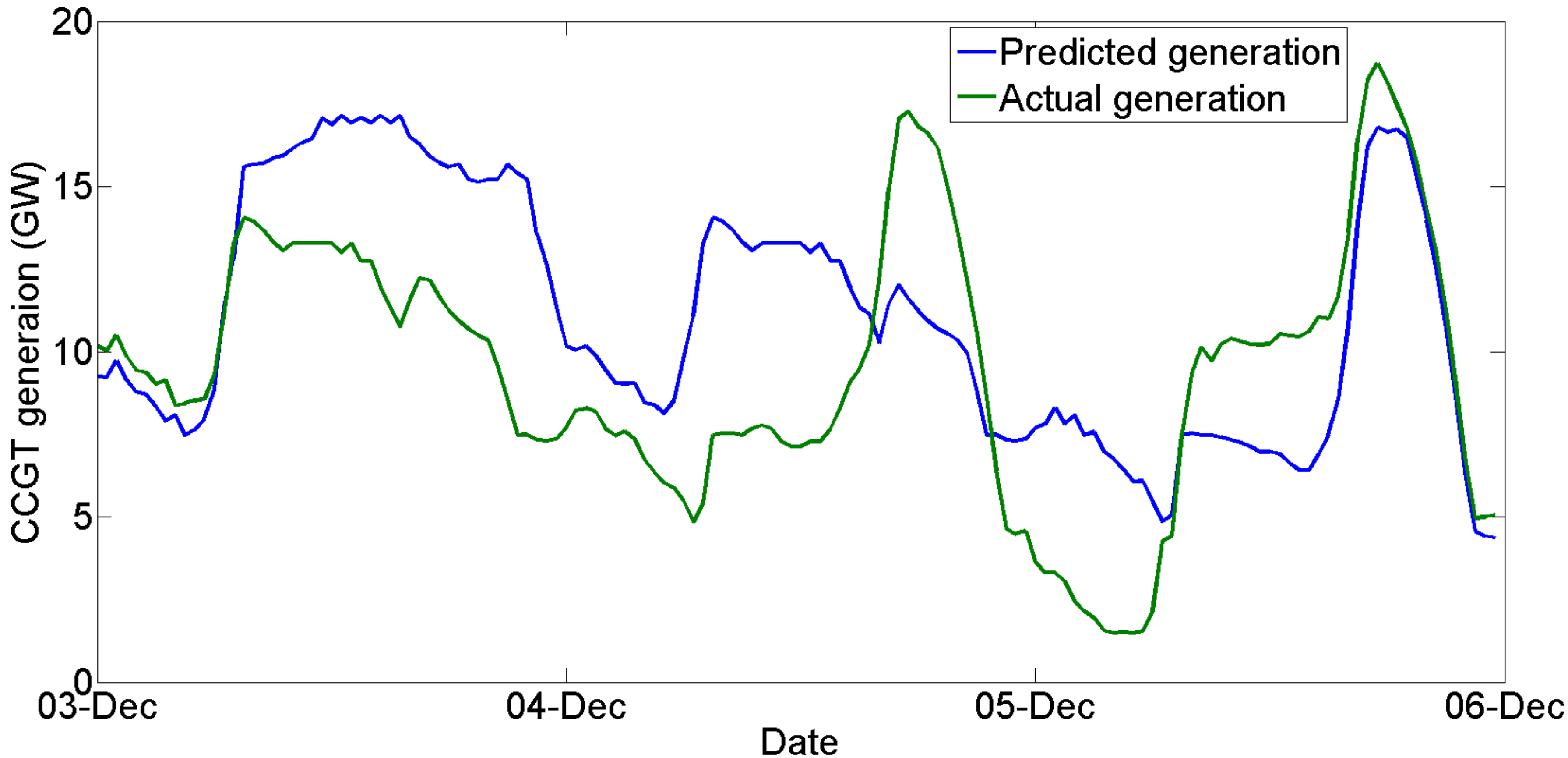


National Grid's 2030 Gone Green Scenario: Wind 47.5 GW, PV 15.6 GW

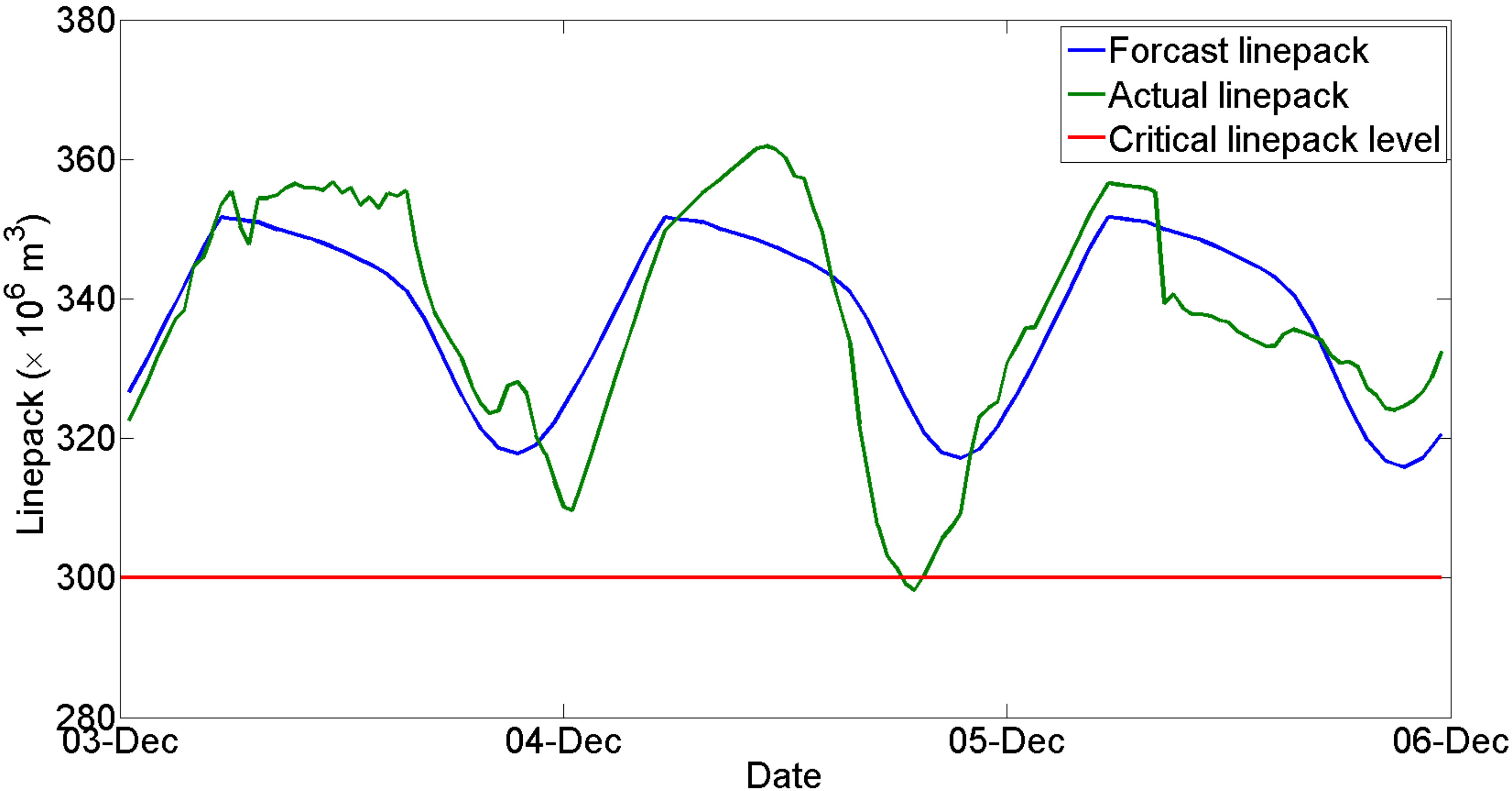
A closer look…



Case Study:
Impact of renewables on gas network – Effect on CCGT generation



Effect on linepack on gas network



You'll hopefully see more soon in:

S. Clegg and P. Mancarella, Integrated electrical and gas transmission network flexibility assessment in low carbon multi-energy systems, *IEEE Transactions on Sustainable Energy, April 2015, under second review*.

Back to the future...

Concluding remarks

- Rethinking the entire energy system
  - “Optimal” electrical systems framed within an overall optimal (energy) system framework
- Operational flexibility in the power system can be effectively provided by other energy vectors and services
- We’ll see new sets of constraints arising in classical Unit Commitment models in a multi-energy context
- Economic and commercial issues besides technical issues
- Complex, challenging, but fascinating

Selected references

Multi-energy systems and distributed multi-generation framework

- P.Mancarella, Multi-energy systems: an overview of models and evaluation concepts, Energy, Vol. 65, 2014, 1-17, *Invited paper*
- P.Mancarella and G.Chicco, Distributed multi-generation systems. Energy models and analyses, Nova Science Publishers, Hauppauge, NY, 2009
- G.Chicco and P.Mancarella, Distributed multi-generation: A comprehensive view, Renewable and Sustainable Energy Reviews, Volume 13, No. 3, April 2009, Pages 535-551
- P.Mancarella, Urban energy supply technologies: multigeneration and district energy systems, Book Chapter in the book “Urban energy systems: An integrated approach”, J.Keirstead and N.Shah (eds.), Taylor and Francis, in press, 2012

Selected references

Operational flexibility in multi-energy systems

- P. Mancarella and G.Chicco, Real-time demand response from energy shifting in Distributed Multi-Generation, IEEE Transactions on Smart Grid, vol. 4, no. 4, Dec. 2013, pp. 1928-1938
- T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, Vol. 71, 2014, pages 516-533
- N. Good, E. Karangelos, A. Navarro-Espinosa, and P. Mancarella, Optimization under uncertainty of thermal storage based flexible demand response with quantification of thermal users' discomfort, IEEE Transactions on Smart Grid, 2015
- Y. Kitapbayev, J. Moriarty and P. Mancarella, Stochastic control and real options valuation of thermal storage-enabled demand response from flexible district energy systems, Applied Energy, 2014
- S. Altaher, P. Mancarella, and J. Mutale, Automated Demand Response from Home Energy Management System under Dynamic Pricing and Power and Comfort Constraints, *IEEE Transactions on Smart Grid, January 2015*.
- G.Chicco and P.Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, Energy, Volume 34, No. 3, March 2009, Pages 261-273.

Selected references

<u>Integrated electricity and gas operation</u>

- S. Clegg and P. Mancarella, Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on the electrical and gas transmission networks, *IEEE Transactions on Sustainable Energy, accepted for publication, April 2015*
- S. Clegg and P. Mancarella, Integrated electrical and gas transmission network flexibility assessment in low carbon multi-energy systems, invited submission to the IEEE Transactions on Sustainable Energy, April 2015, under second review
- S. Clegg and P. Mancarella, Storing renewables in the gas network: modelling of power-to-gas (P2G) seasonal storage flexibility in low carbon power systems, submitted to IET Generation, Transmission and Distribution, March 2015, under second review

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Thank you

Any Questions?

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FLEXIBILITY IN
INTEGRATED ENERGY SYSTEMS
AND VIRTUAL STORAGE

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