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Multi-energy Systems: The Smart Grid beyond Electricity

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Something about myself

- Born in the tip of the heel of the Italian boot
- MSc Power Systems, 2002, Politecnico di Torino, Italy
- Visiting researcher, 2004, Trondheim, Norway
- PhD in Energy Systems, 2006, Politecnico di Torino, Italy
- Research Fellow, 2006-2007, Politecnico di Torino, Italy
- Post Doc, 2008-2011, Imperial College London, UK
- Lecturer, 2011 - current, University of Manchester, UK

  (Power system operation and economics, Smart grids and Sustainable electricity systems)
- 2 books, 5 book chapters, >70 papers on environomics of energy systems

Something about myself /ctd

- Main expertise and interests:
  - Integrated energy systems (electricity, heat, cooling, gas, water, transport, ...) and multi-generation (electricity, heat, cooling, ...)
  - Techno-economic and environmental impact of new technologies on operation and planning and distribution networks
  - Energy systems environomics
  - Business modelling for emerging multi-energy systems (smart communities and smart cities)
  - Multi-energy planning under uncertainty (decision theory and risk analysis, real options valuation, portfolio theory)

Outline of the talk

- Context and challenges
  - It’s not only about electricity
- Moving beyond electricity-only
  - Distributed Multi-Generation (DMG)
  - Flexible demand from other energy vectors
  - Multi-energy networks
- Final remarks

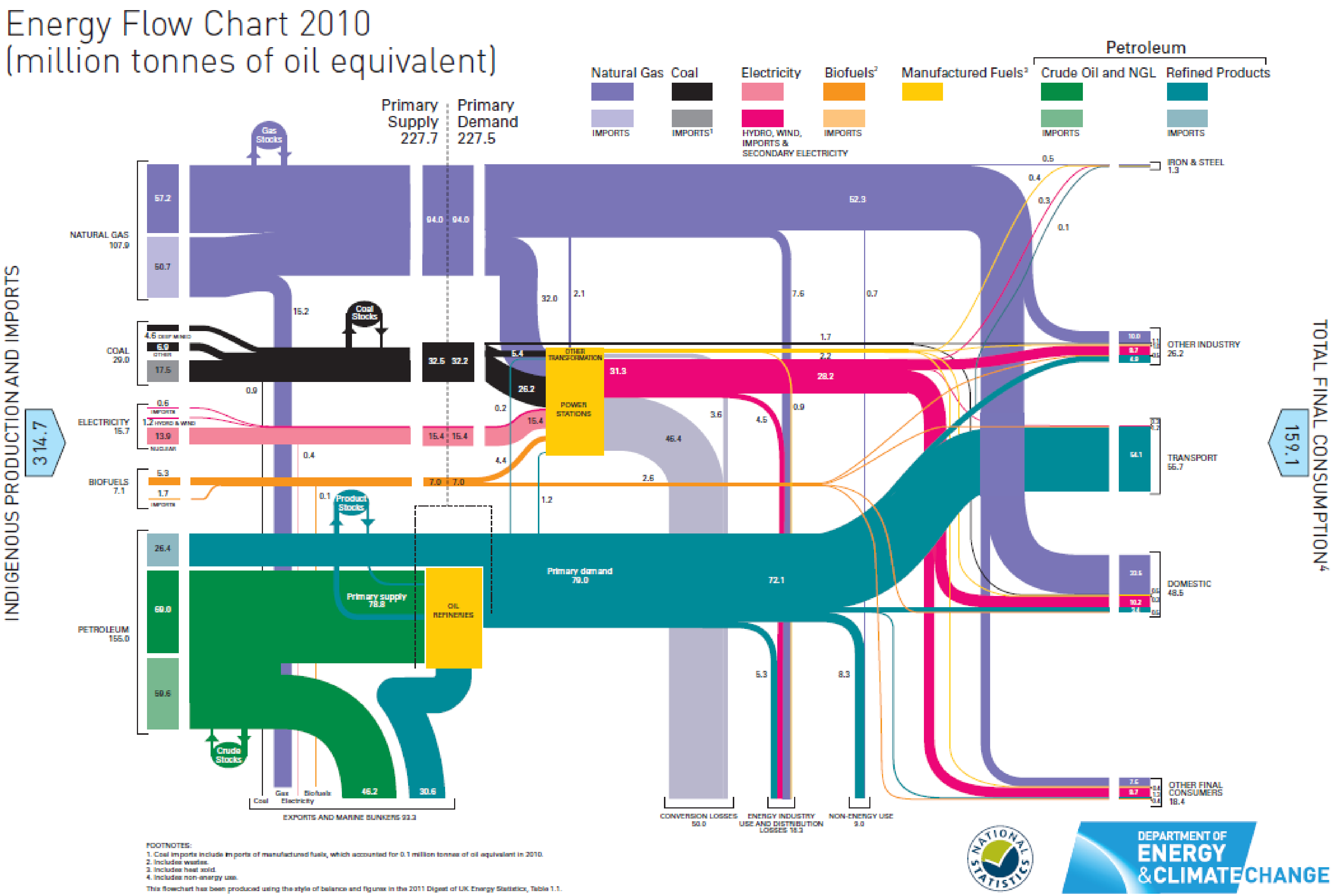
Context and challenges

- Challenging environmental targets
- Volatile and uncertain energy prices
- Need for network and generation investment in the medium to long term
- Smart approaches to optimize asset utilisation, but with unclear business cases in many situations
- Envisaged increasing penetration of intermittent and unpredictable (wind) and inflexible (nuclear, Carbon Capture and Storage - CCS) generation –> need for *flexibility*

Context and challenges

- *But.. it's not only about electricity*
- Heat and cooling as major contributions to energy consumption and GHG emissions
- Classical de-coupling of energy vectors is inefficient (operation and planning) -> need for *efficiency increase*
- Moving from "*power*" to "*energy*" Smart Grid paradigm -> unlocking hidden sources of **flexibility:**
  - *multi-generation and enabling factors/technologies* - e.g., heat networks
  - *multi-energy demand and storage*
  - *integrated* operation and planning of energy networks under uncertainty (centralization levels)

It’s not only about electricity

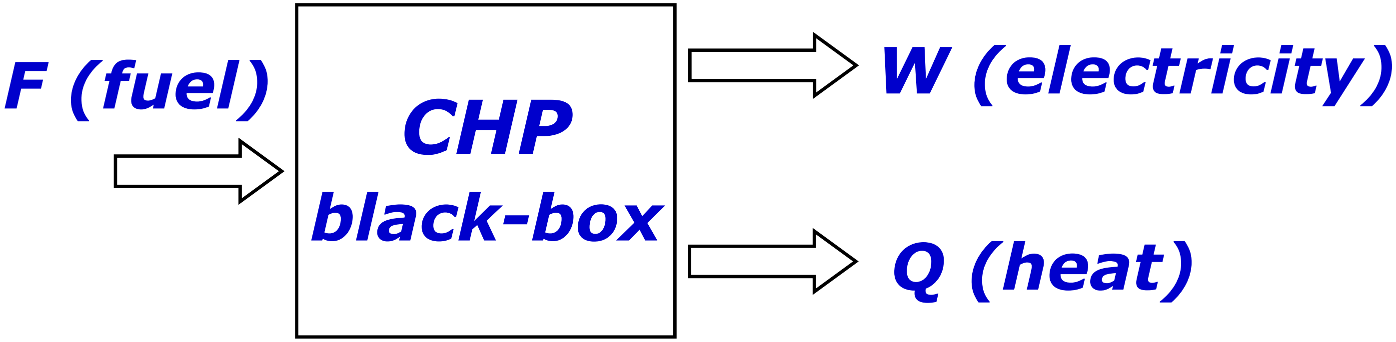


Increasing thermal generation efficiency: let's multi-generate

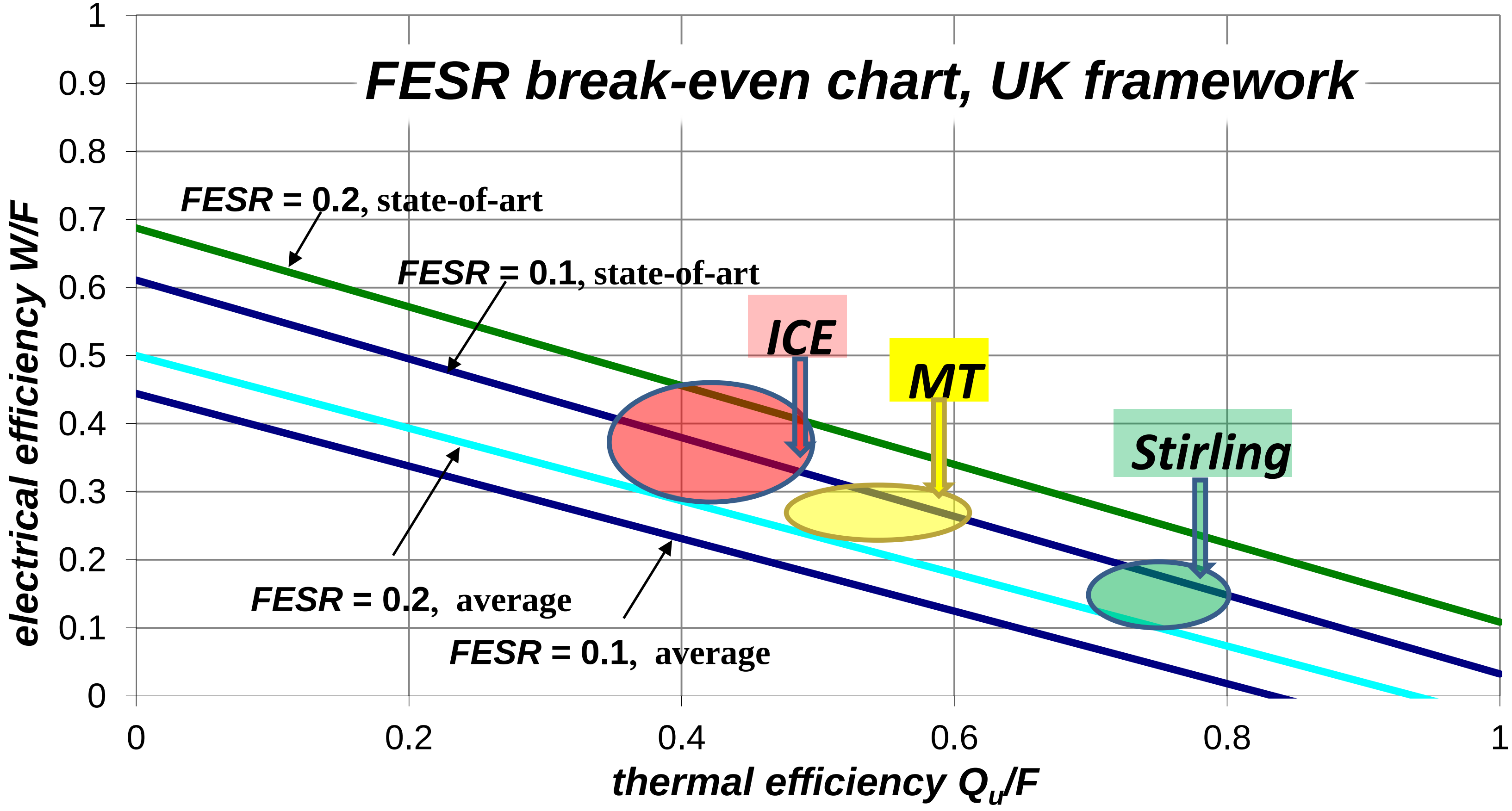
- ***Cogeneration*** (or ***CHP***, Combined Heat and Power)

  -> *simultaneous production* of electricity and heat from a fuel source

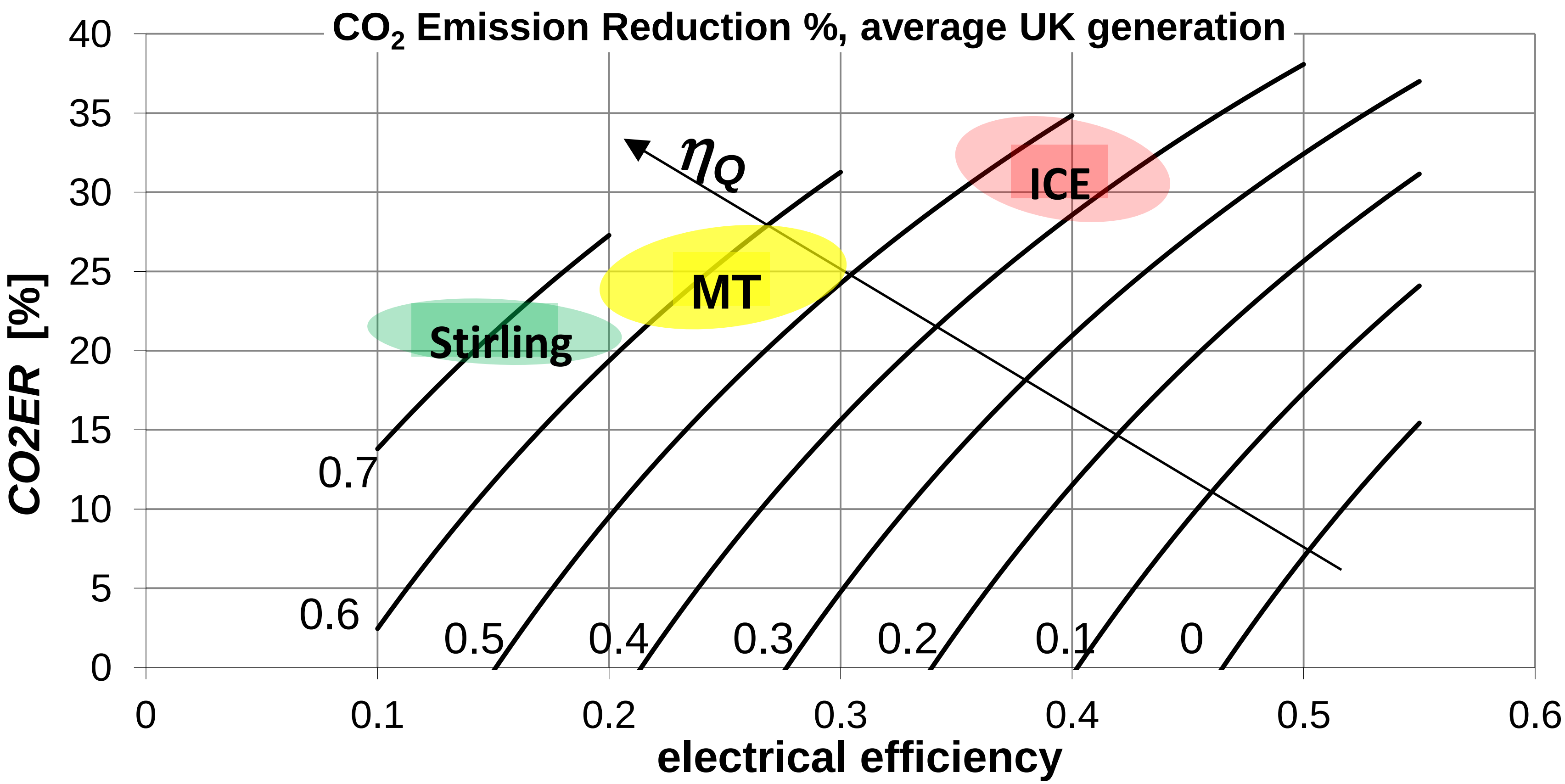
- Cogeneration effectiveness depending on the possibility of increasing ***environmental performance*** relative to *separate production* (SP)



Micro-CHP potential to save primary energy



Emission reduction potential from micro-CHP



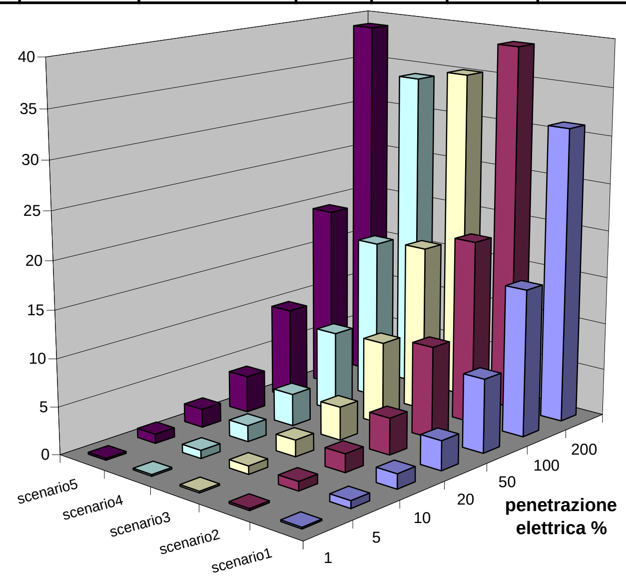
Not only CO2: local and global emission evaluations

- Application: Italian urban areas, regional territory; Energy load scenario: Q / W = 4

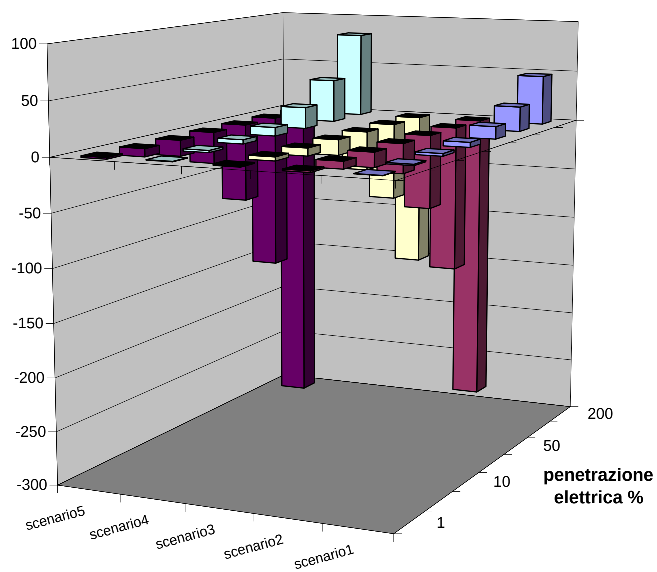
		Scenario 1 [% share]	2	3	4	5
	[kW_e]	25	0	15	0	0
MT	100	25	0	10	0	0
	75	25	0	15	100	0
	60	25	0	10	0	0
	30	25	0	25	0	0
ICE	180	0	50	25	0	0
	980	0	50	15	0	100

	Rated Efficiencies		Emission Factors [mg/kWh_e]				
	η_W	η_Q	NO_x	CO	THC	SO_x	PM
MT	0.29	0.48	170	0	1	0	0
	0.23	0.50	450	23	45	0	0
	0.26	0.52	70	47	8	0	0
	0.27	0.49	95	635	1	0	0
ICE	0.34	0.49	1500	1000	0	0	0
	0.37	0.46	1300	870	0	0	0

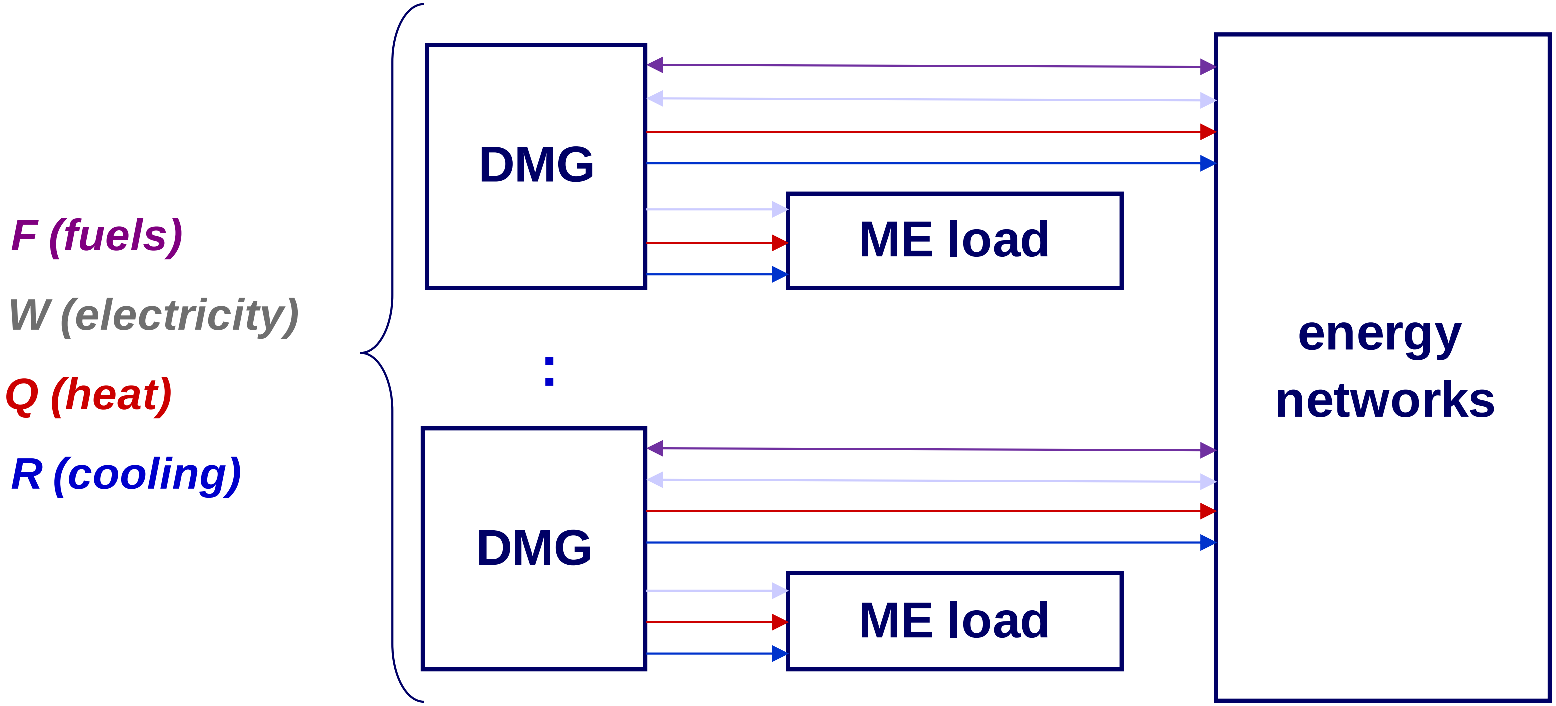
CO2ER%



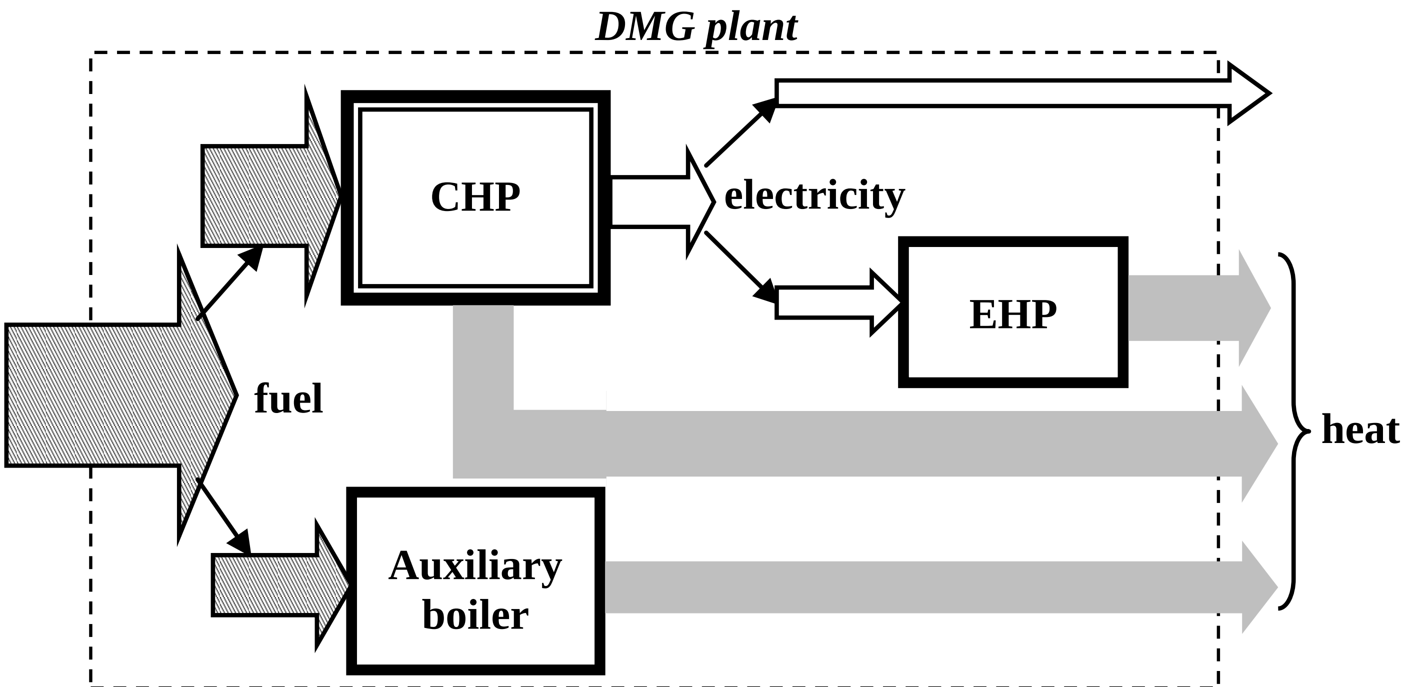
NOXER%



From cogeneration to flexible Distributed Multi-Generation (DMG)



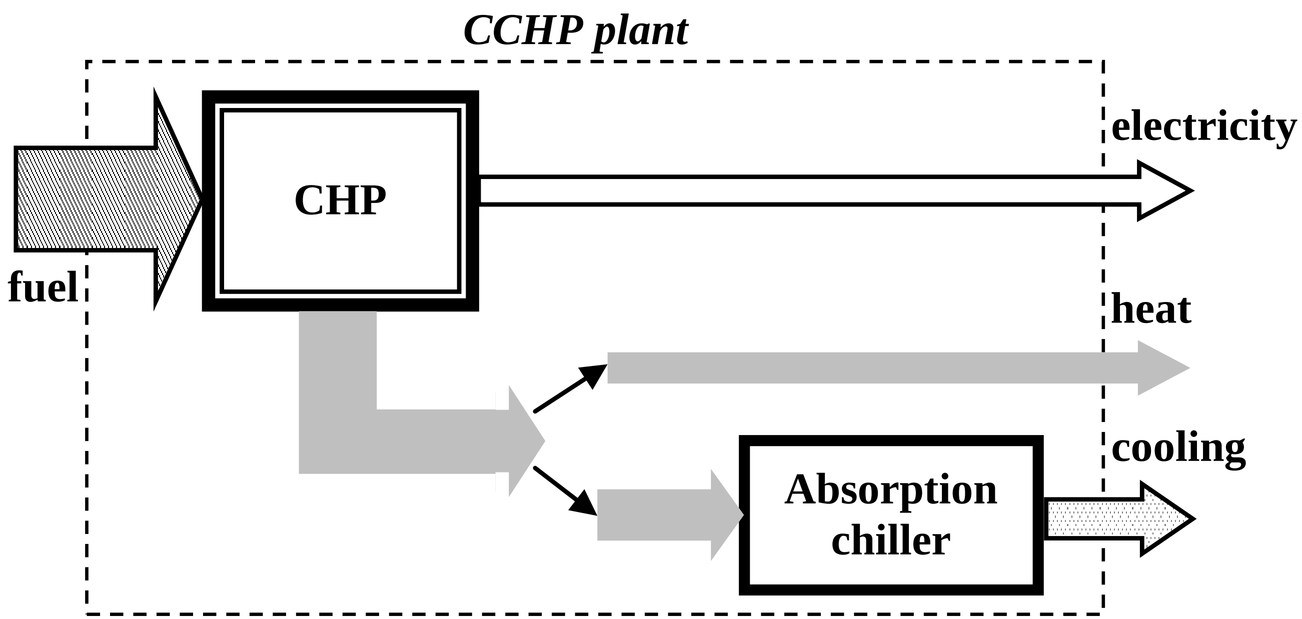
Flexible Distributed Multi-Generation (DMG)



Example of DMG plant for generation of electricity and heat, with CHP prime mover, auxiliary boiler and electric heat pump:

Virtual CHP Plant - VCHPP

Flexible Distributed Multi-Generation (DMG)

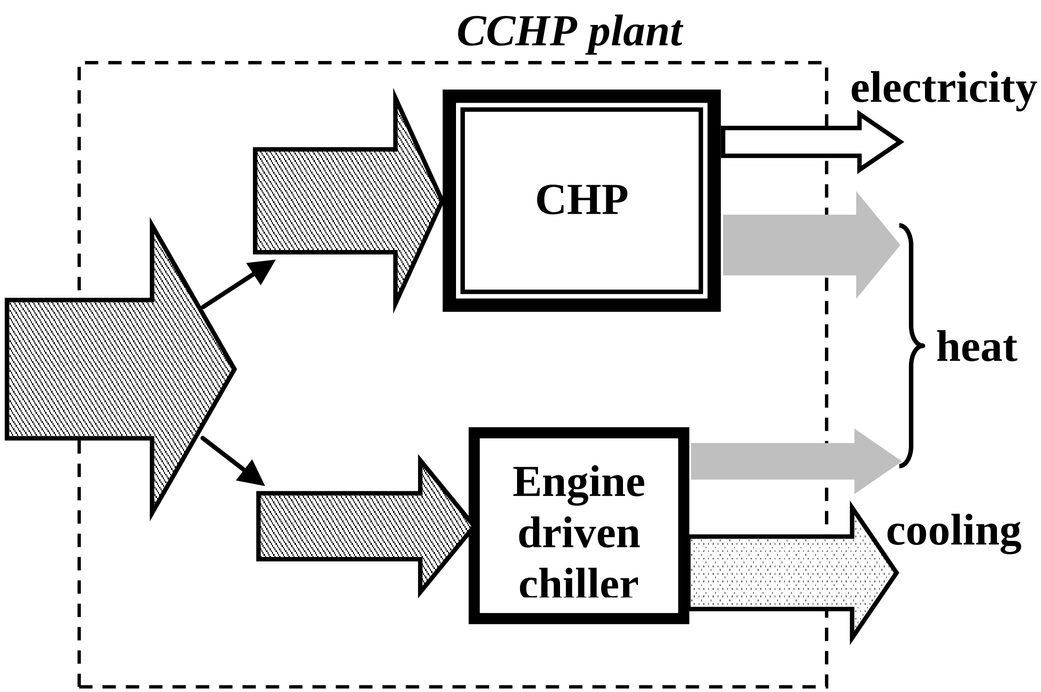


Example of *bottoming* generation in a

Combined Cooling Heat and Power (**CCHP**) plant

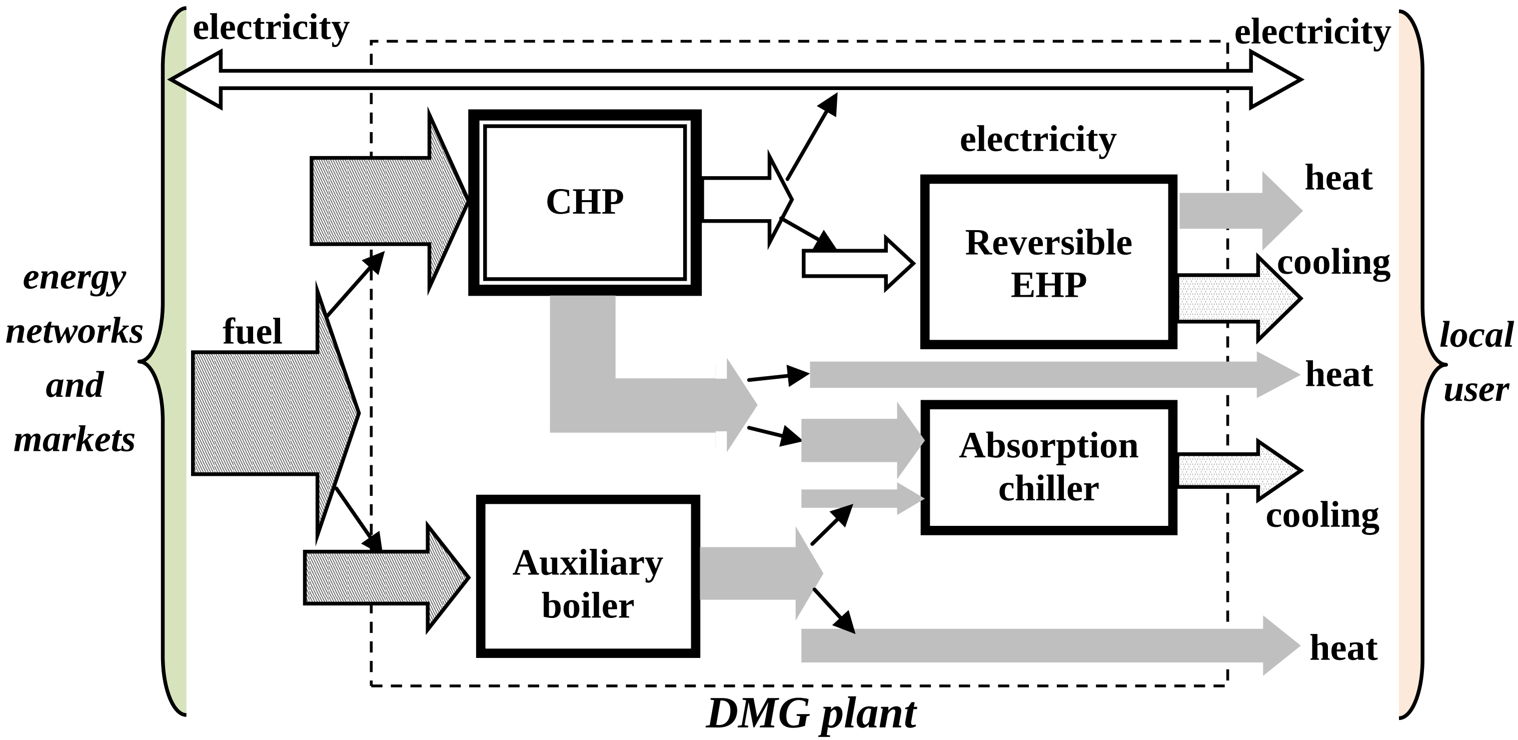
(CHP prime mover cascaded to an absorption chiller)

Flexible Distributed Multi-Generation (DMG)



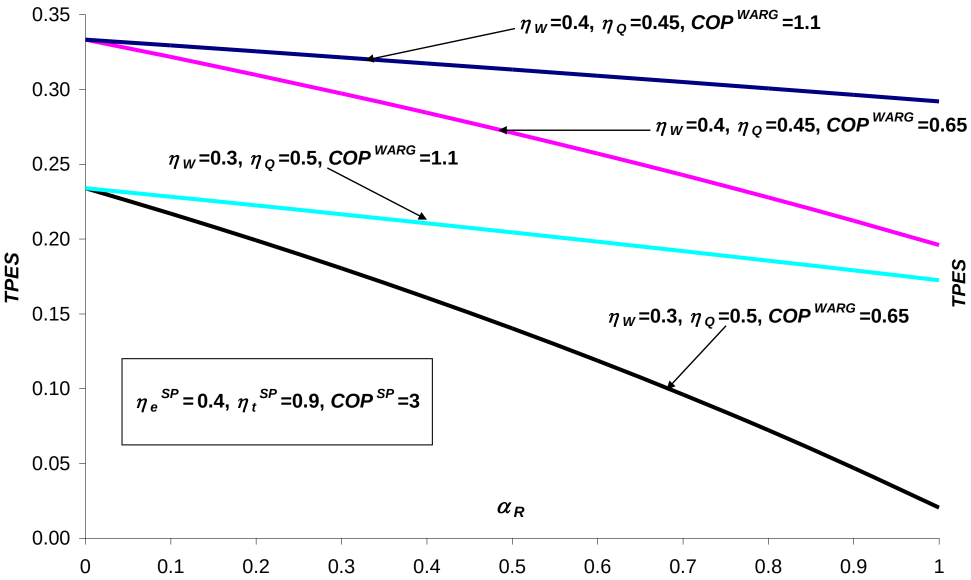
Example of *parallel* generation in a CCHP plant (CHP prime mover with in parallel an engine-driven chiller with heat recovery)

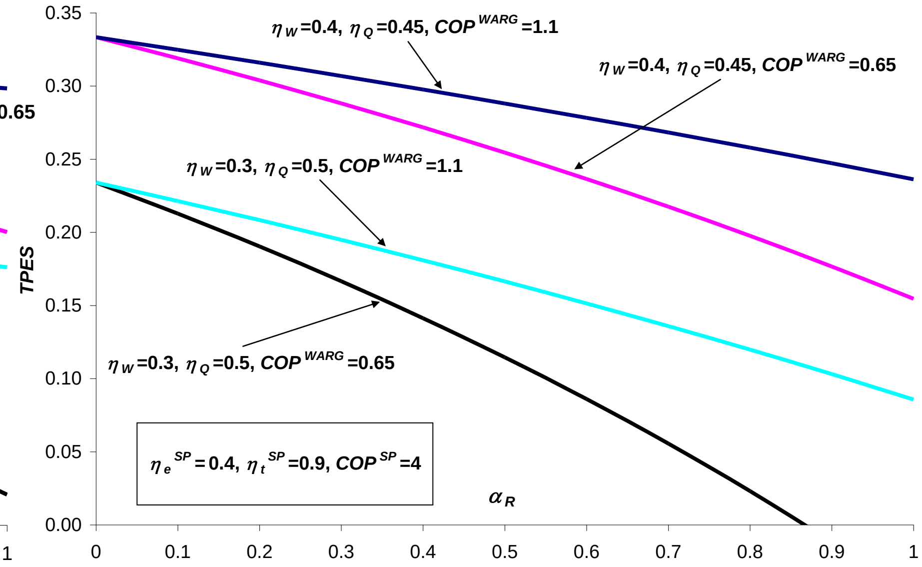
Flexible Distributed Multi-Generation (DMG)

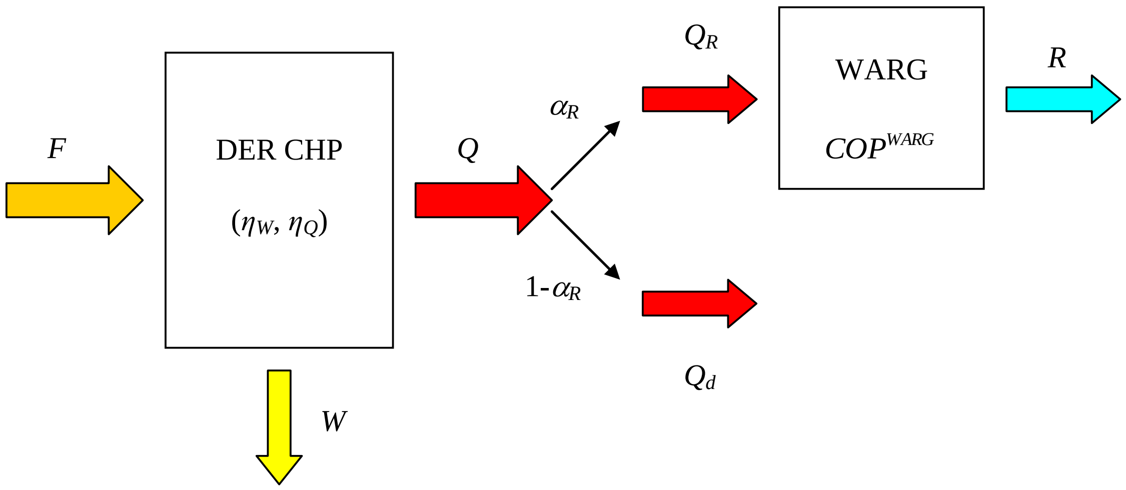


Example of multi-machine flexible CCHP plant

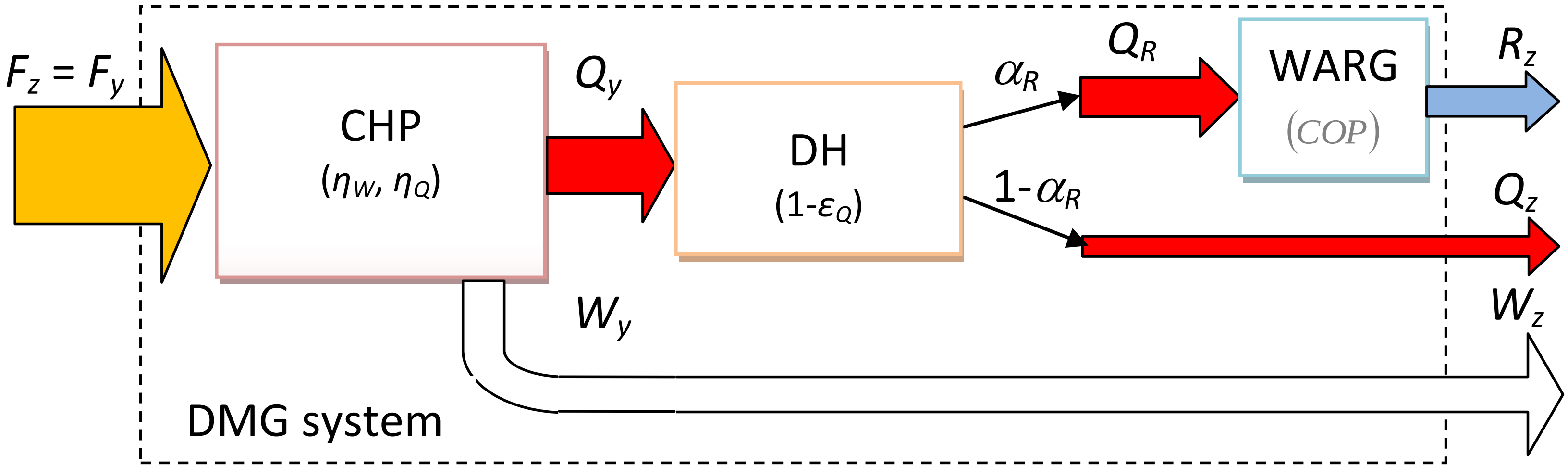
Energy saving potential from a CCHP plant







Emission reduction potential from a CCHP plant in a district energy system

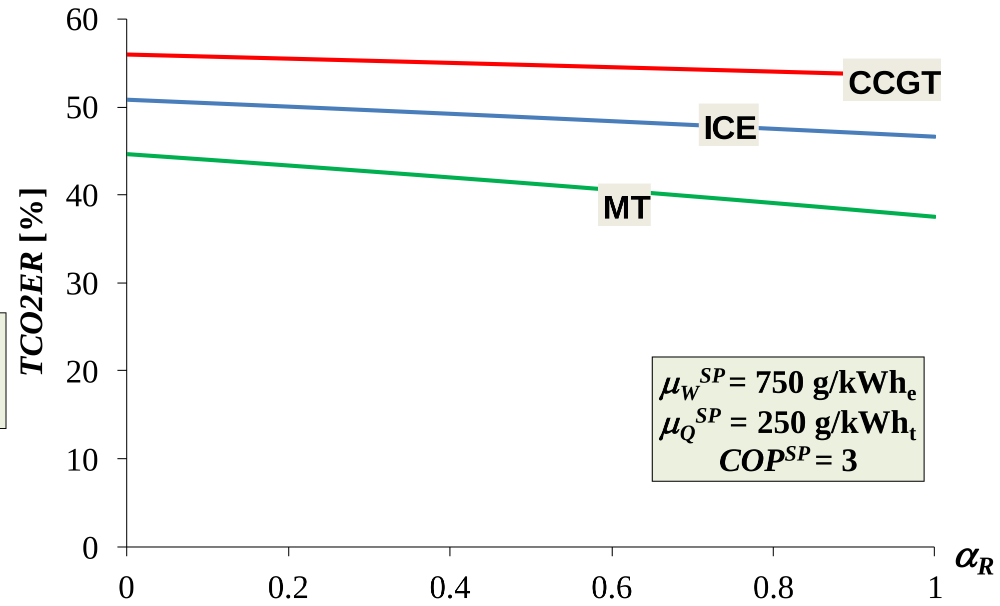


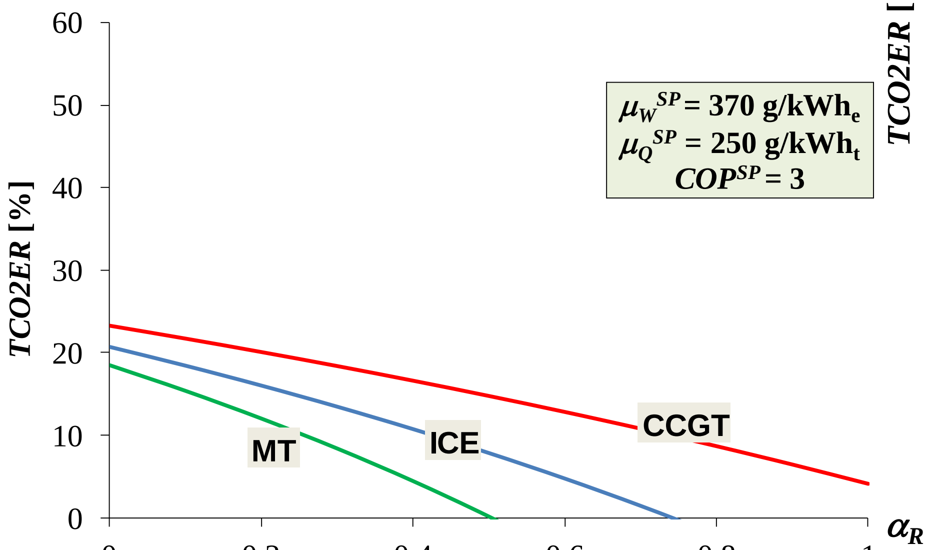
	CHP electrical capacity [MWe]	η_W [pu]	η_Q [p.u.]	*COP* [p.u.]	ε_Q [p.u.]
MT	0.1	0.3	0.55	0.7	0.01
ICE	5	0.4	0.45	0.7	0.05
CCGT	100	0.5	0.35	0.7	0.10

Source: P. Mancarella,D Distributed Multi-Generation Options to Increase Environmental Efficiency in Smart Cities, IEEE PES General Meeting 2012, San Diego, July 2012

Emission reduction potential from a CCHP plant in a district energy system

***TCO2ER* with coal-fired marginal plant**

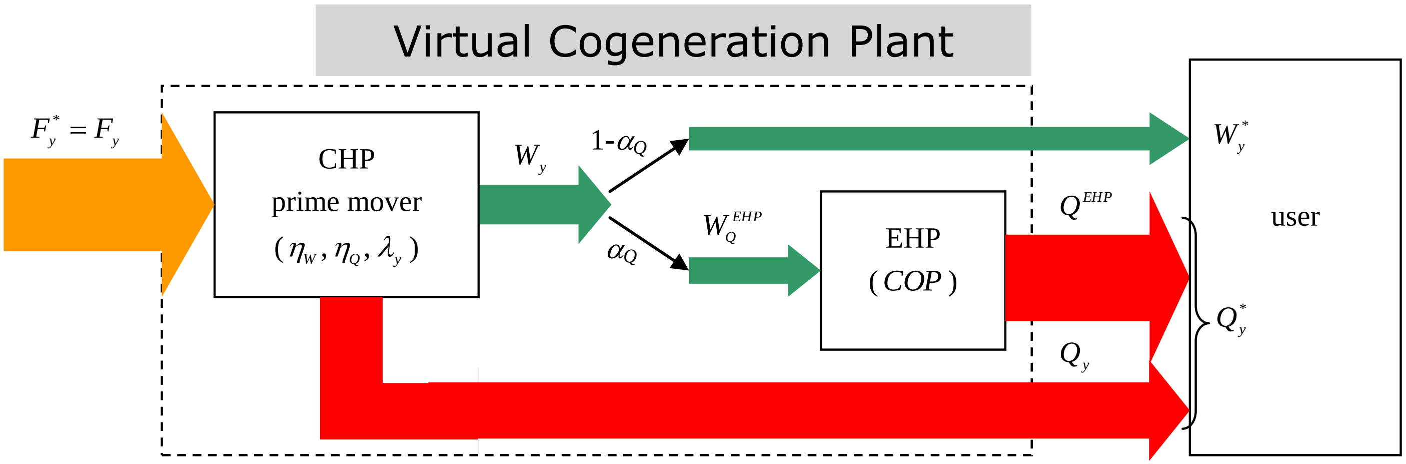


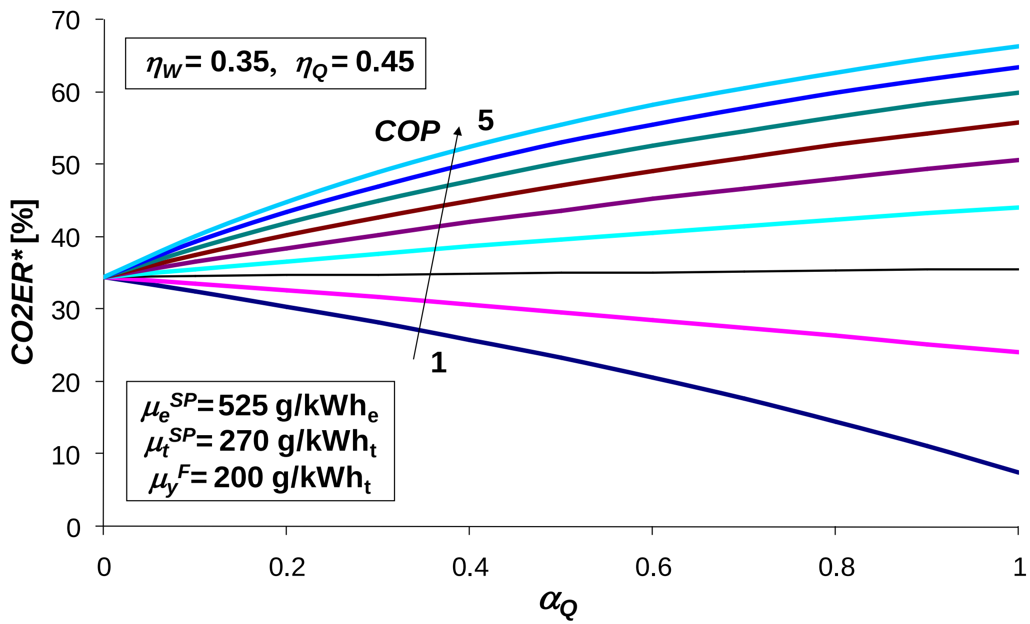


***TCO2ER* with CCGT marginal plant**

Source: P. Mancarella,D Distributed Multi-Generation Options to Increase Environmental Efficiency in Smart Cities, IEEE PES General Meeting 2012, San Diego, July 2012

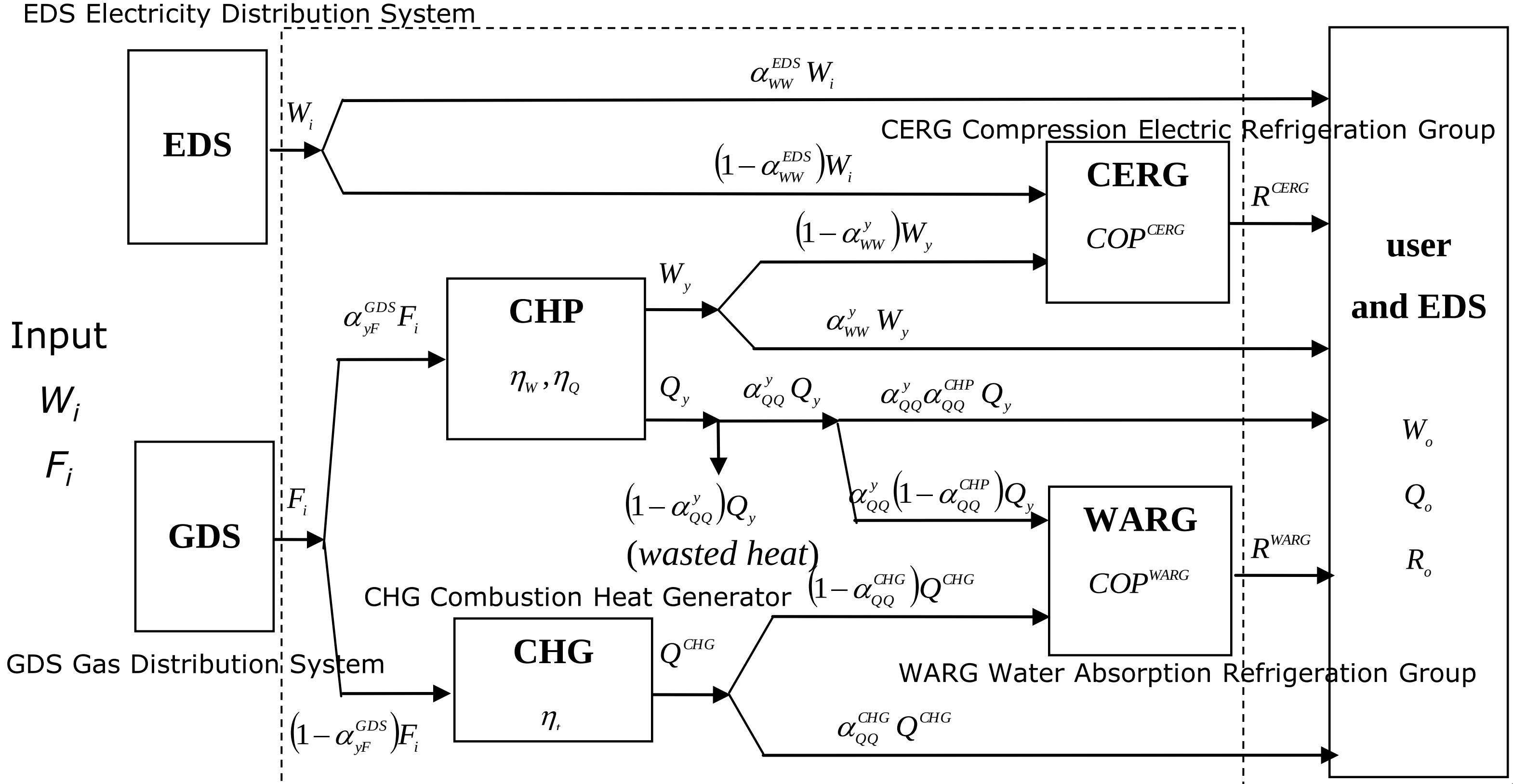
Emission reduction from flexible DMG for electricity and heat





Source: P. Mancarella, Cogeneration systems with electric heat pumps: Energy-shifting properties and equivalent plant modelling, Energy Conversion and Management 50 (2009) 1991–1999

Matrix modelling of a flexible DMG system for real-time demand response



Λ-transform

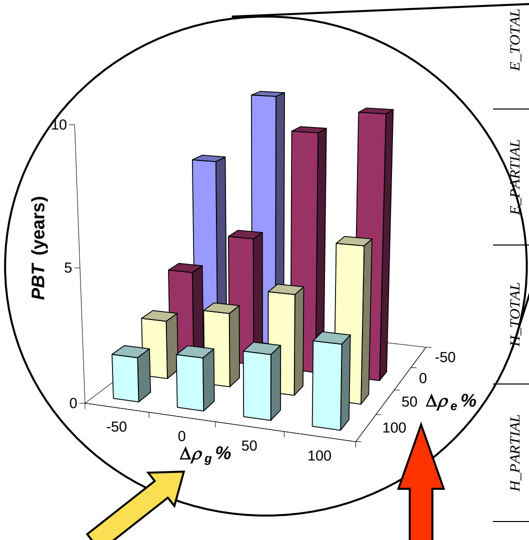
$$\begin{pmatrix} W_o \\ Q_o \\ R_o \end{pmatrix} = \begin{pmatrix} \eta_{WF} & \eta_{WW} \\ \eta_{QF} & \eta_{QW} \\ \eta_{RF} & \eta_{RW} \end{pmatrix} \cdot \begin{pmatrix} F_i \\ W_i \end{pmatrix} \Rightarrow \begin{pmatrix} W_o \\ Q_o \\ R_o \end{pmatrix} = \begin{pmatrix} \alpha_{WW}^{y}\,\alpha_{Fy}^{GDS}\,\eta_W & \alpha_{WW}^{EDS} \\ \alpha_{QQ}^{CHG}(1-\alpha_{Fy}^{GDS})\eta_t + \alpha_{QQ}^{y}\,\alpha_{Fy}^{GDS}\,\eta_Q & 0 \\ \eta_{RF} & COP_c^{CERG}(1-\alpha_{WW}^{EDS}) \end{pmatrix} \begin{pmatrix} F_i \\ W_i \end{pmatrix}$$

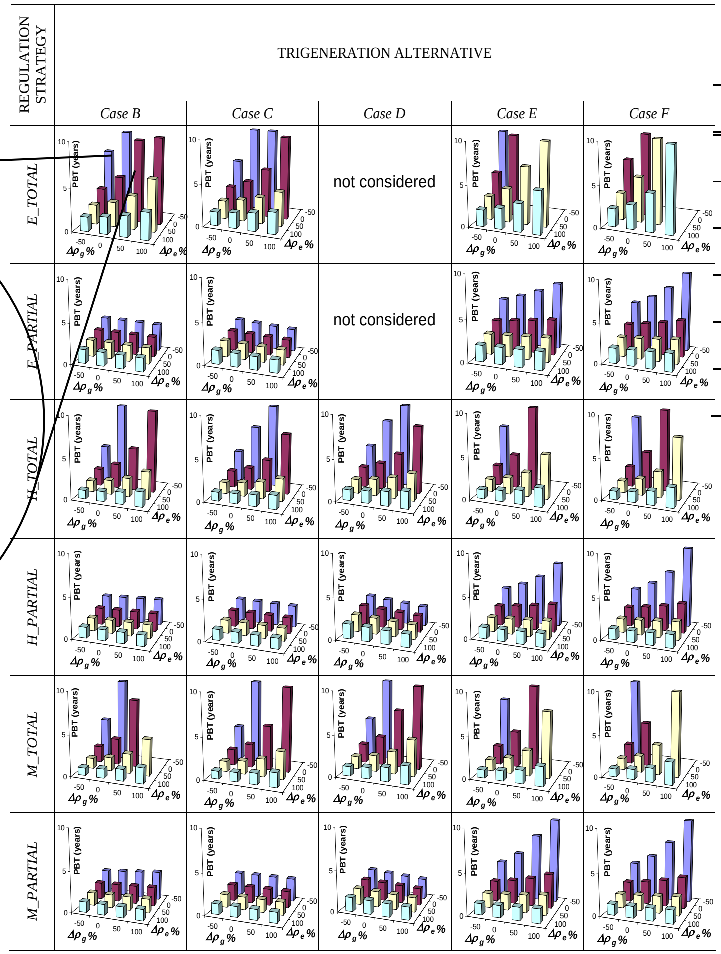
$$\eta_{RF} = COP_c^{CERG}(1-\alpha_{WW}^{y})\alpha_{Fy}^{GDS}\eta_W + COP_c^{WARG}\left[(1-\alpha_{QQ}^{CHG})(1-\alpha_{Fy}^{GDS})\eta_t + \alpha_{QQ}^{y}\alpha_{Fy}^{GDS}\eta_Q\right]$$

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

DMG planning and robust optimization: cope with multi-energy uncertainty

PBT limited to 10 years





$\Delta\rho_g$%=gas price per cent variation

$\Delta\rho_e$%=electricity price per cent variation

Equipment

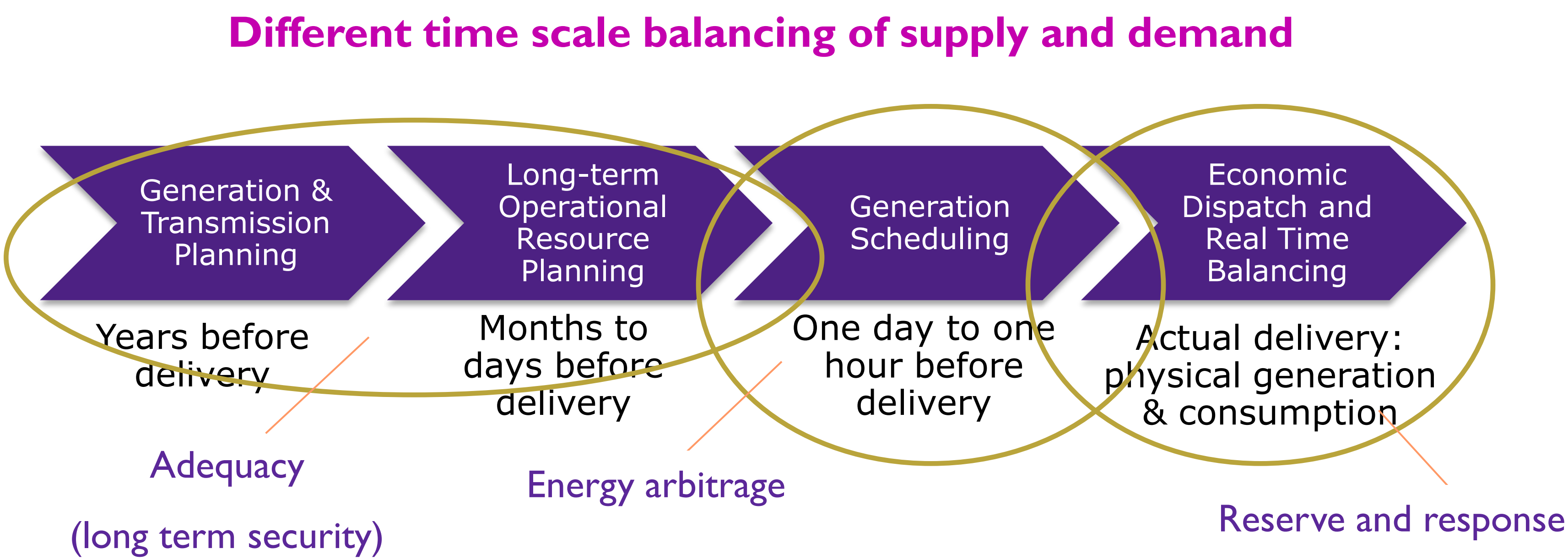
case	heat	cooling	electricity
A	CHG	CERG	EDS
B	CHP + CHG	CERG	CHP + EDS
C	CHP+ HRCERG + CHG	HRCERG	CHP + EDS
D	CHP+ EHP + CHG	EHP	CHP + EDS
E	CHP + CHG	GARG	CHP + EDS
F	CHP + CHG	WARG	CHP + EDS

Control strategies

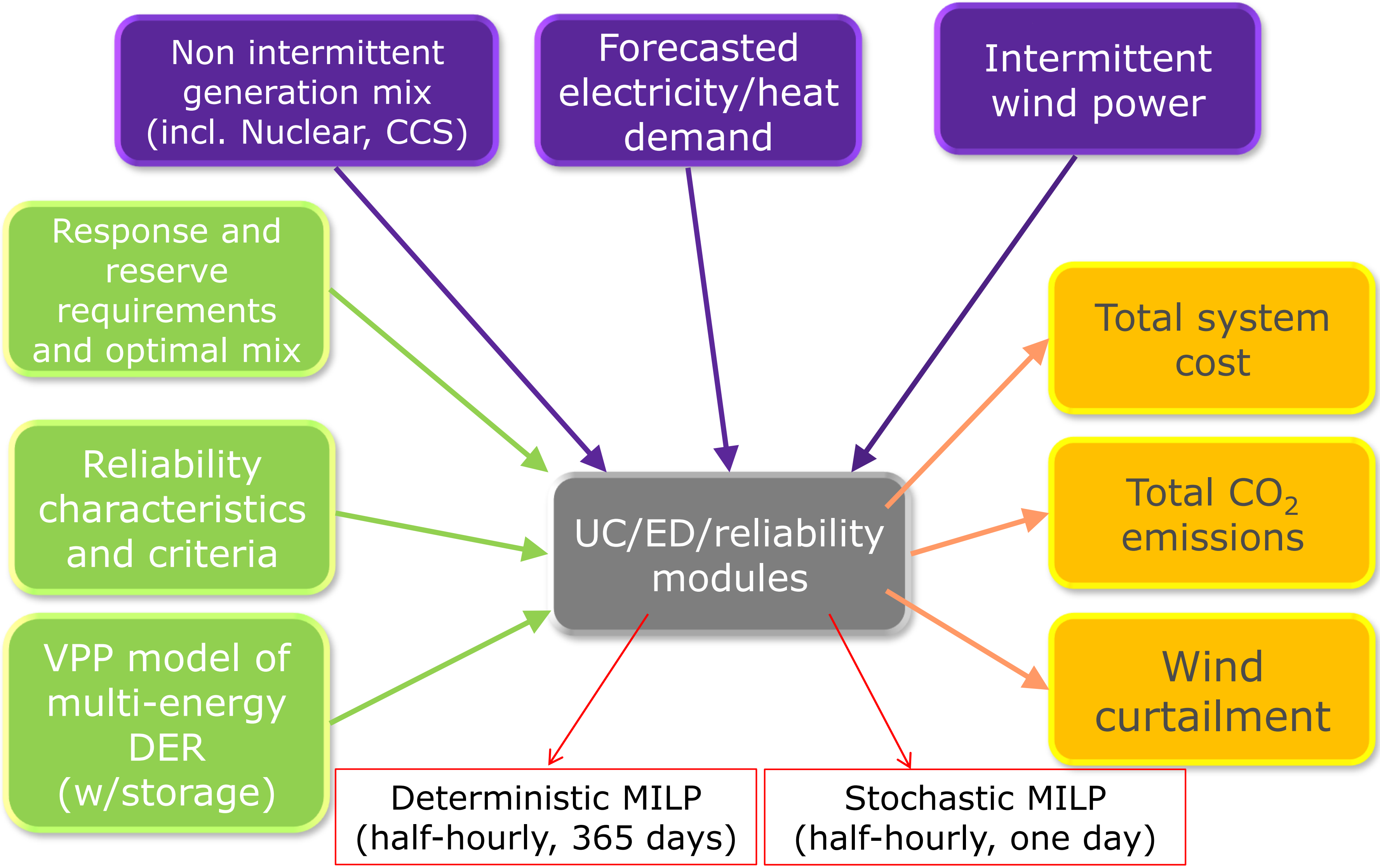
- *E_TOTAL*: electrical load-following
- *E_PARTIAL*: Smart electrical
- *H_TOTAL*: heating load-following
- *H_PARTIAL*: Smart thermal
- *M_TOTAL*: CHP always full power
- *M_PARTIAL*: Smart CHP full power

Source: G. Chicco and P. Mancarella, From cogeneration to trigeneration: profitable alternatives in a competitive market, IEEE Transactions on Energy Conversion, Vol. 21, No.1, March 2006, pp.265-272

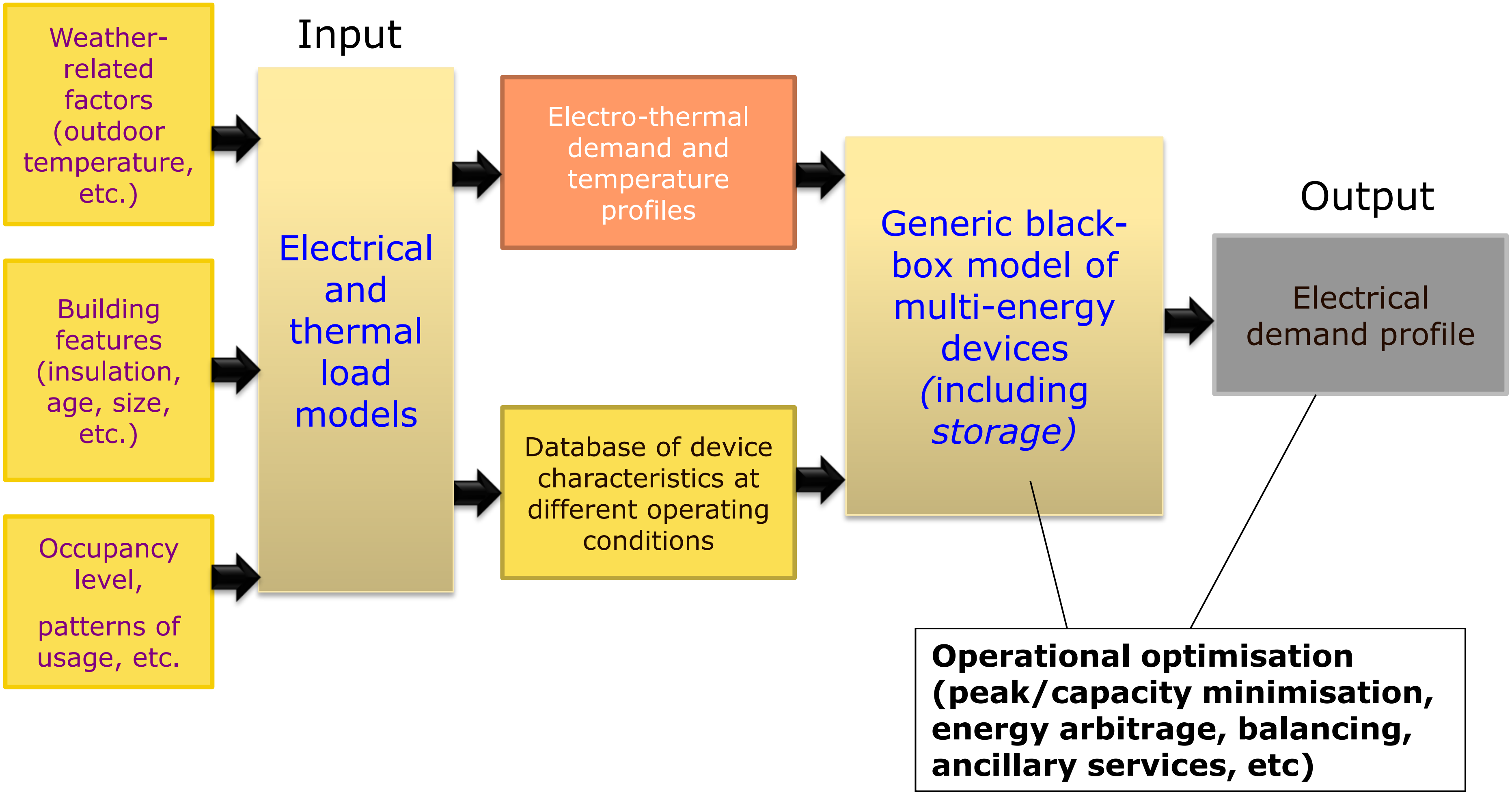
Can flexible demand from other energy vectors provide balancing services?



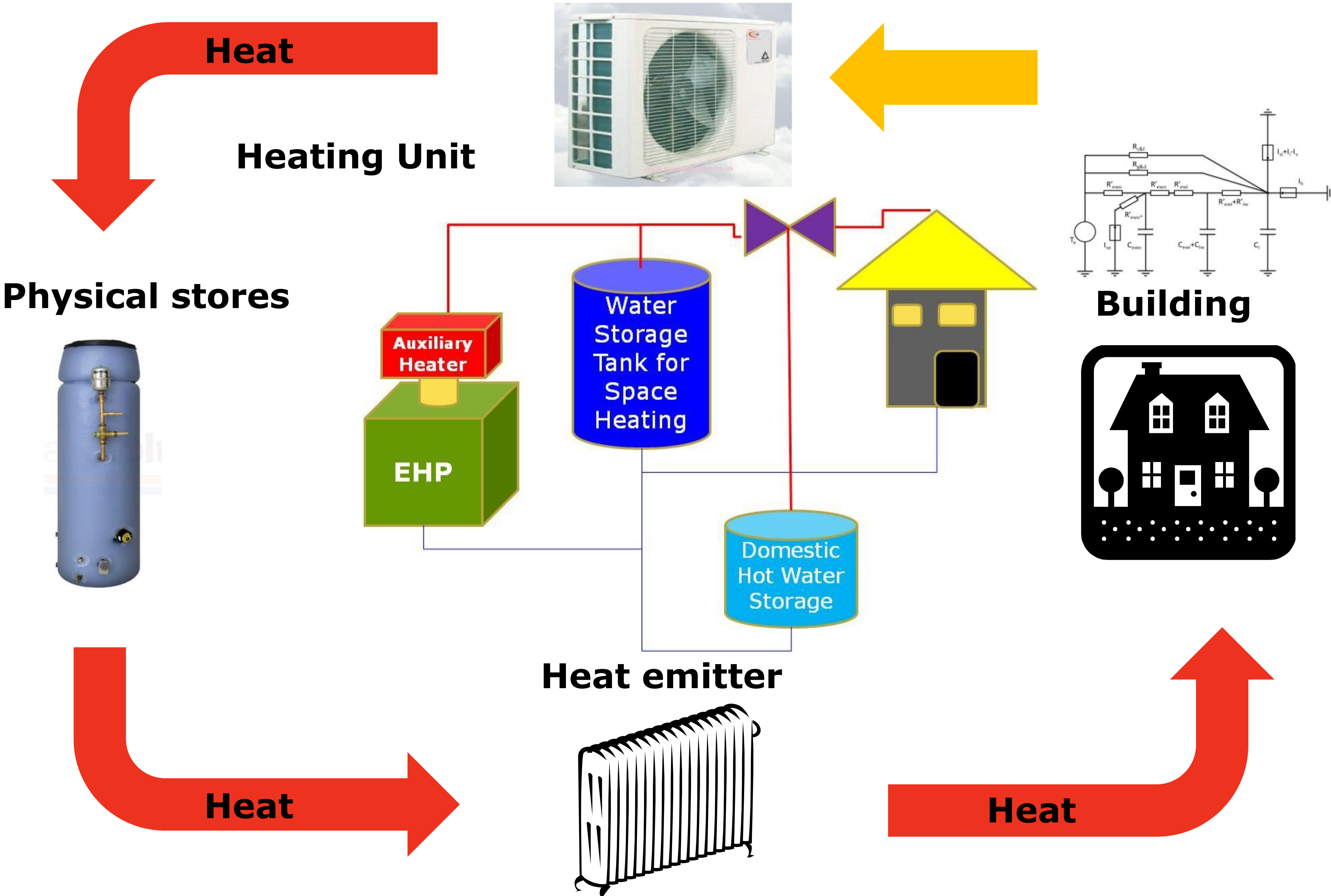
Multi-energy system level techno-economic and environmental analysis



Physical model of demand-side flexible multi-energy technologies

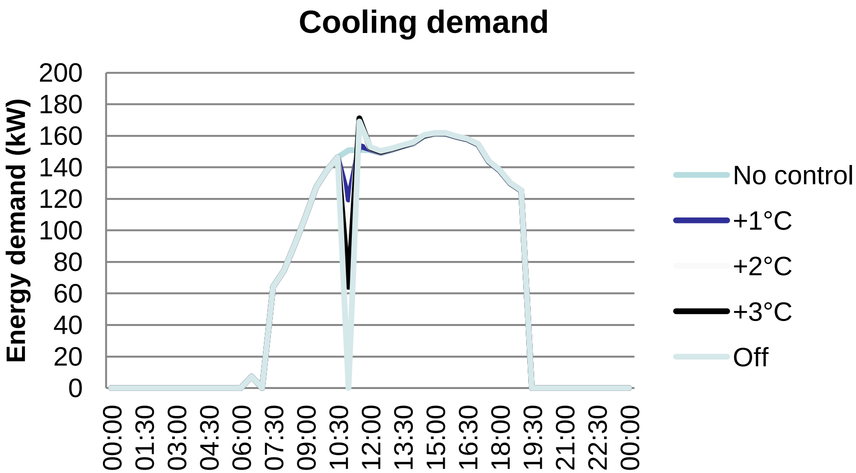


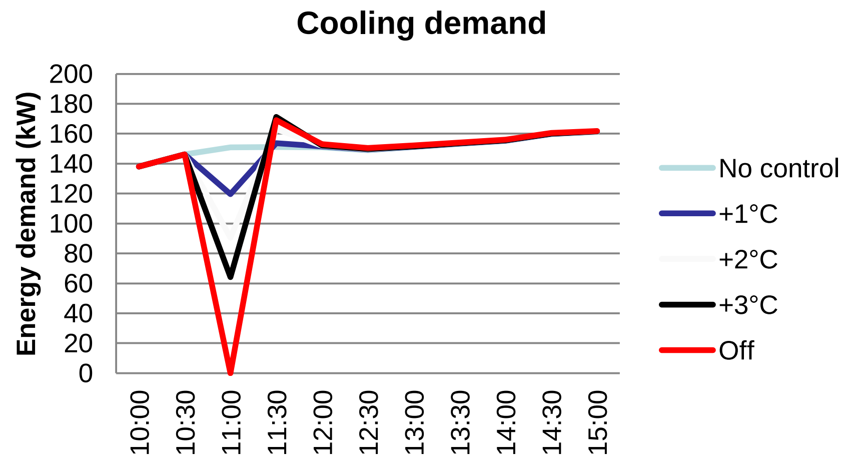
Flexibility from heat

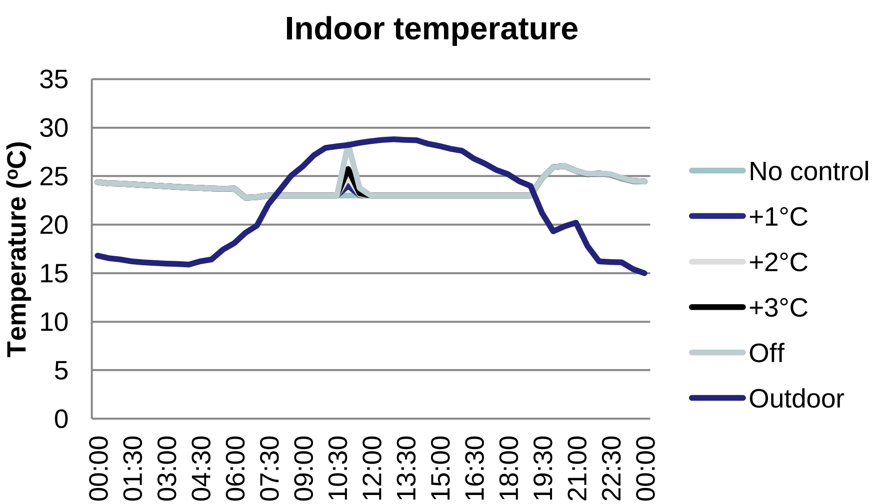


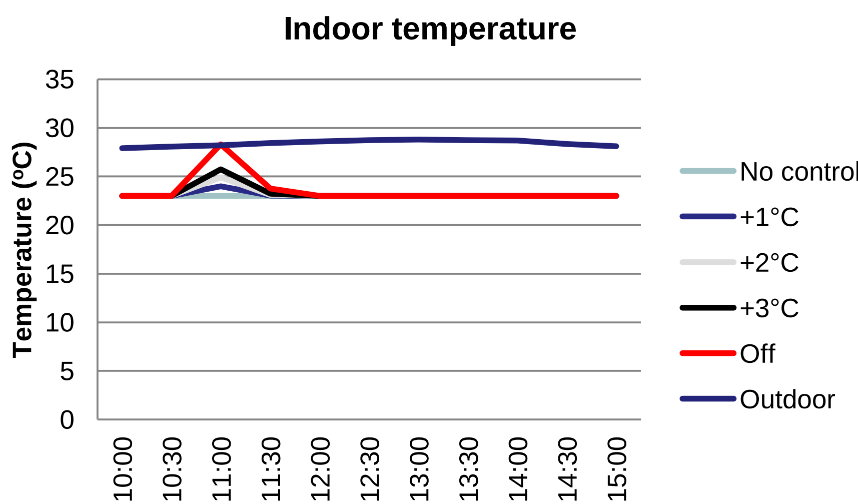
Flexible demand for the Smart Grid: Storing other energy vectors

Cooling control actions and comfort level in commercial buildings

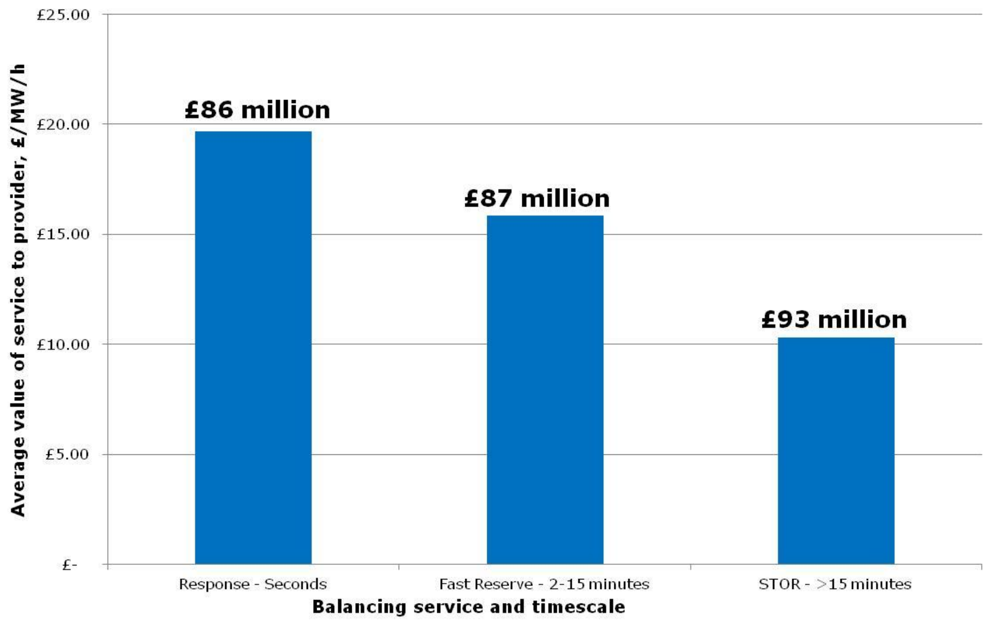




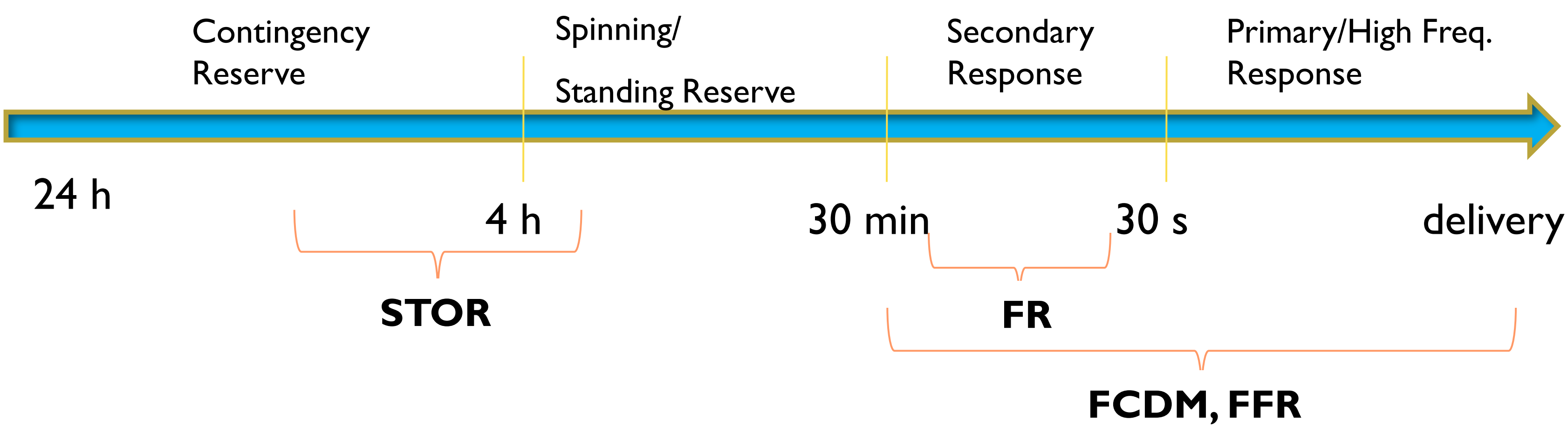




A business case for flexible demand from multi-energy systems?

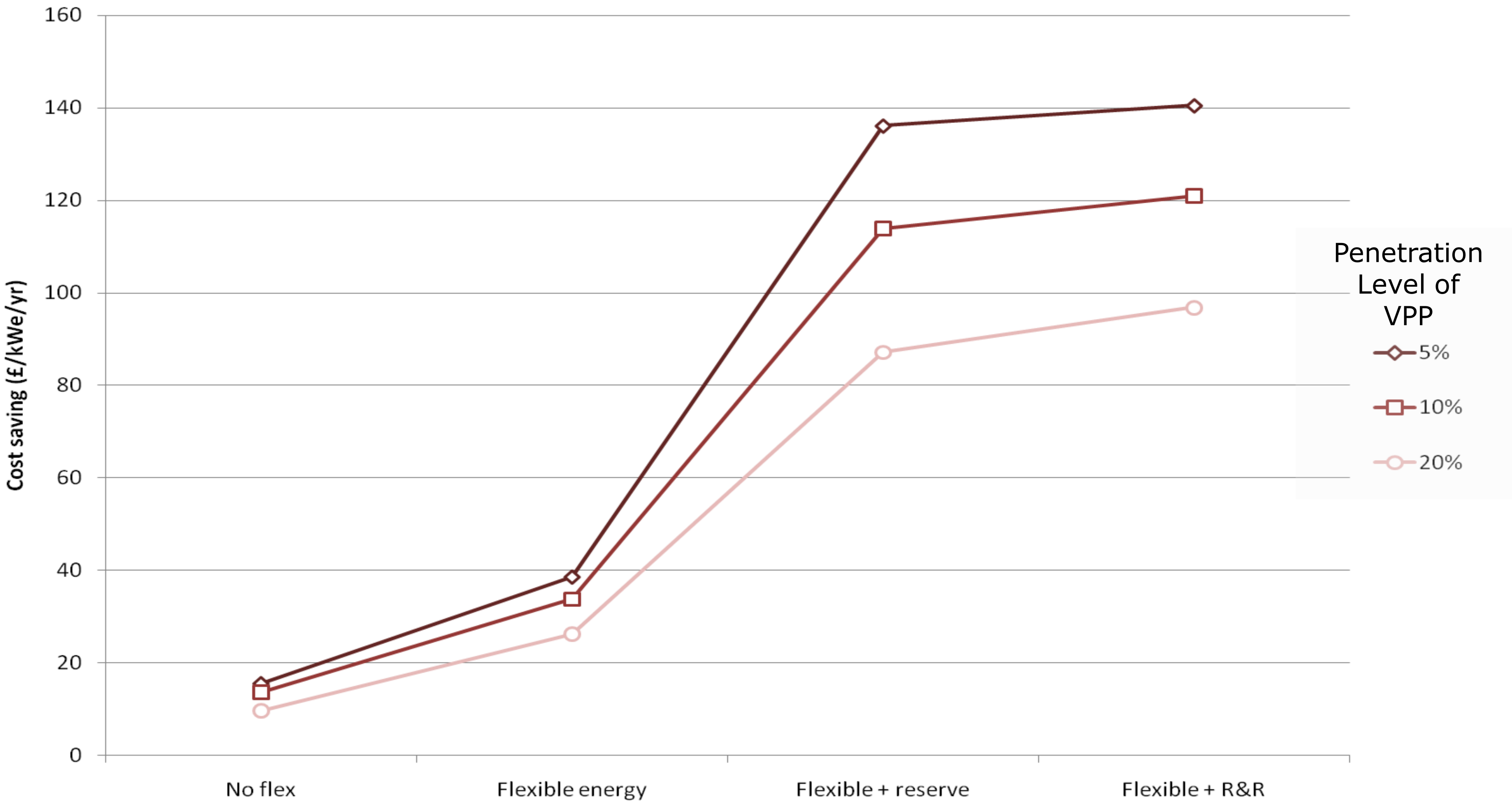


National Grid Reserve and Response Time Scales



CHP-based Microgrid as a Flexible Virtual CHP Plant to balance wind

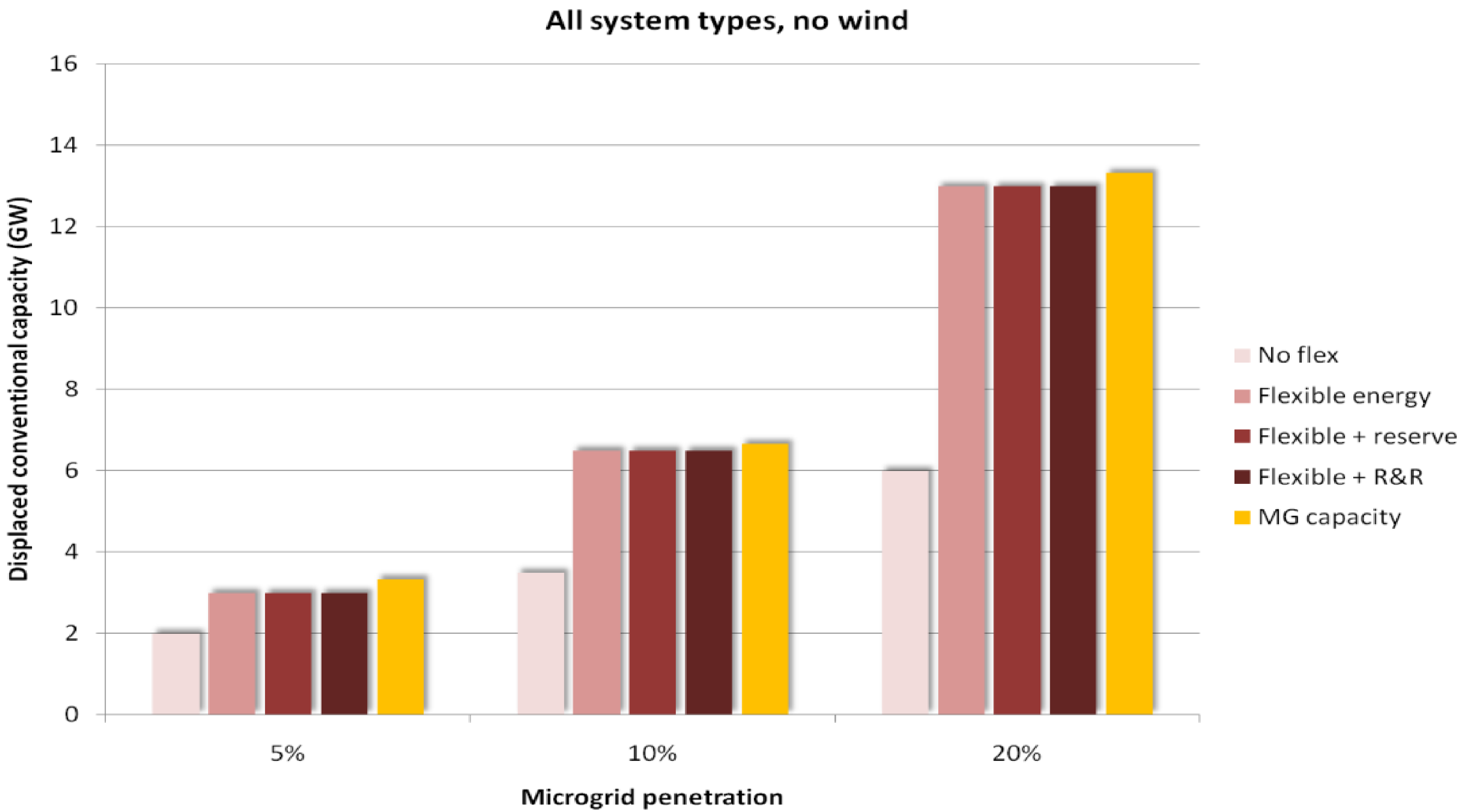
Future low-flexible system (CCS-nuclear-wind)



Source: P. Mancarella et al, Report on economic, technical and environmental benefits of Microgrids in typical EU electricity systems, WPH, EC FP6 More Microgrids project

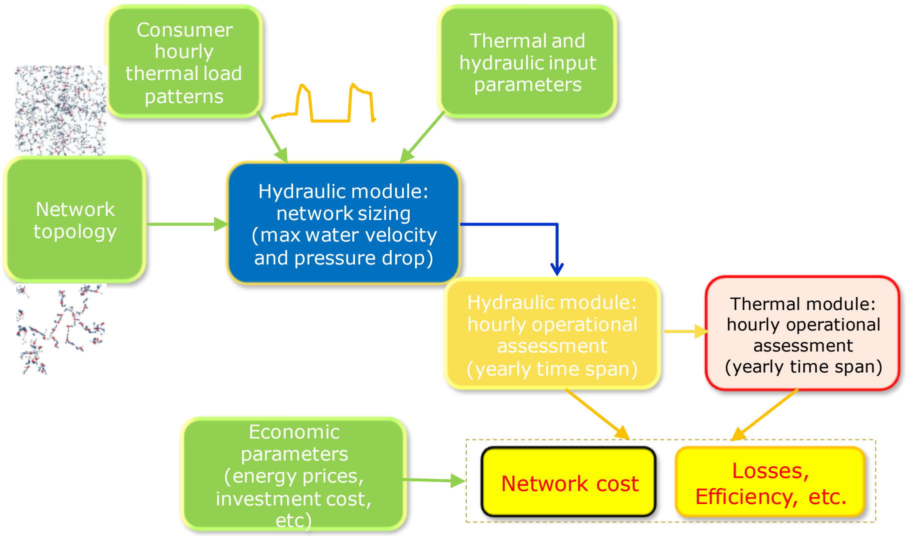
Microgrid Flexible VCHPP and system planning

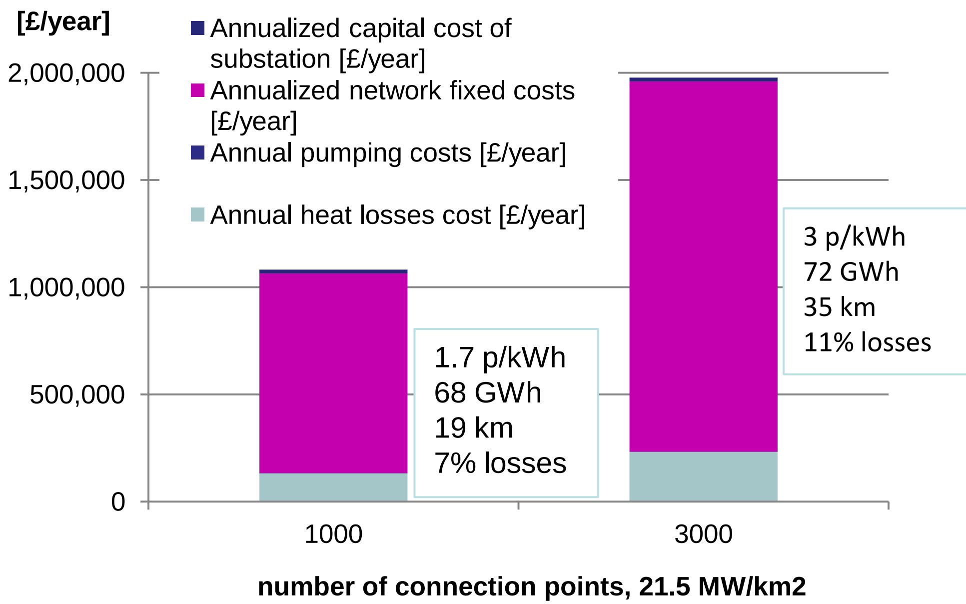
Conventional generation capacity economically displaced

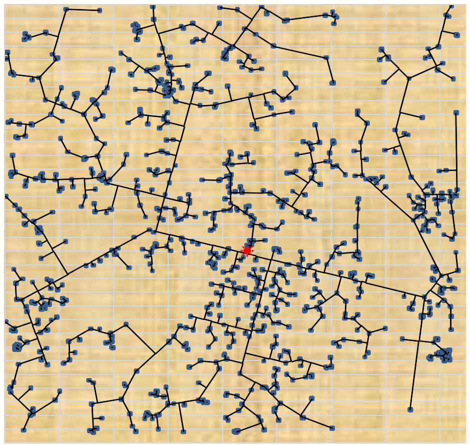


Source: P. Mancarella et al, Report on economic, technical and environmental benefits of Microgrids in typical EU electricity systems, WPH, EC FP6 More Microgrids project

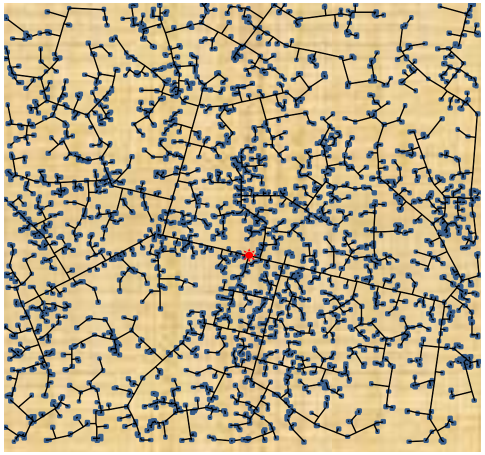
Multi-energy networks:
heat networks as integrated energy systems enablers



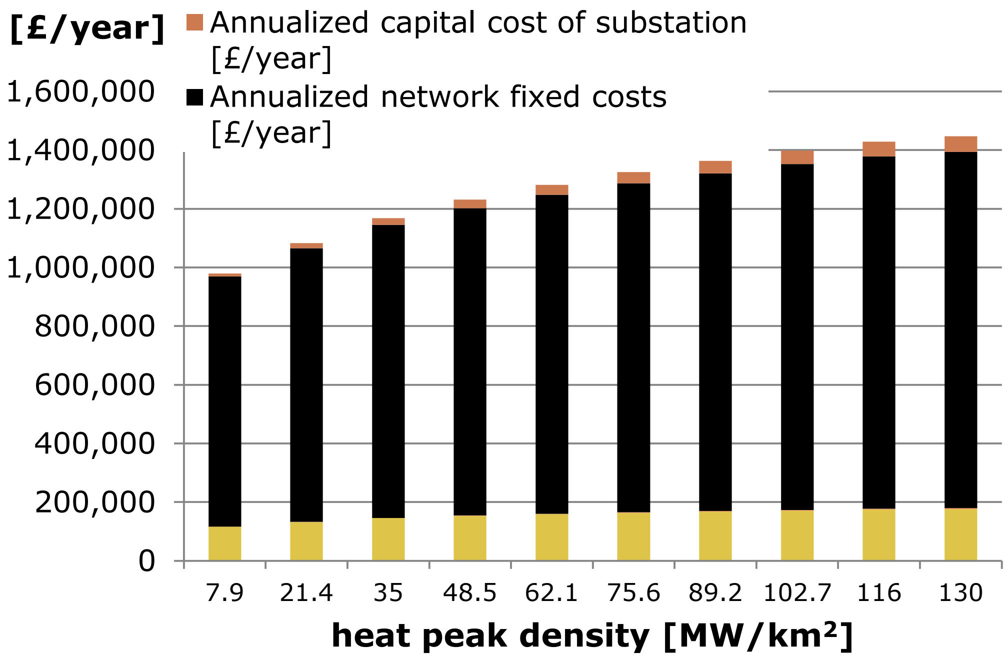




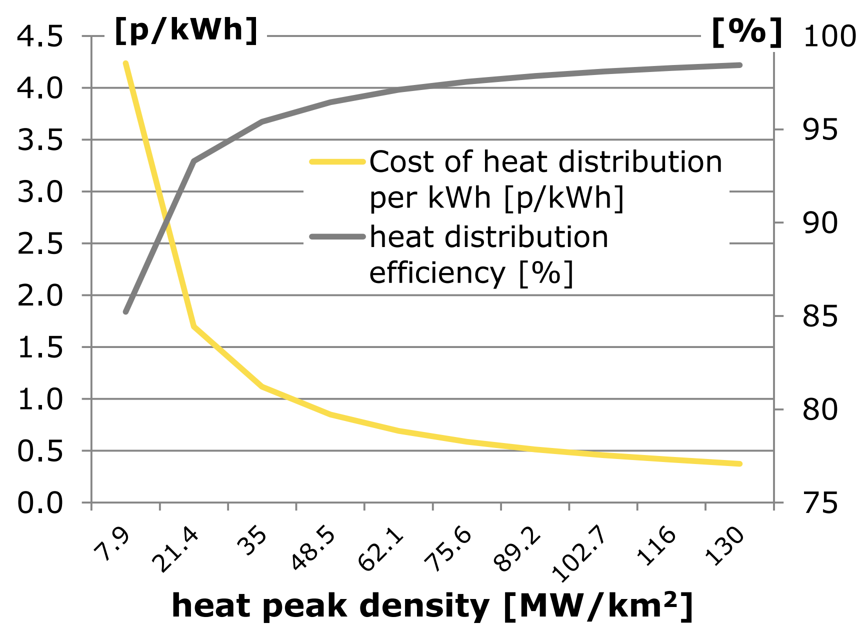
- For same peak heat density and similar overall energy consumption network costs can be very different
- This depends on both heat density/network length
- Strategic electricity and heat network tools are needed



Case study example: heat network cost breakdown and performance

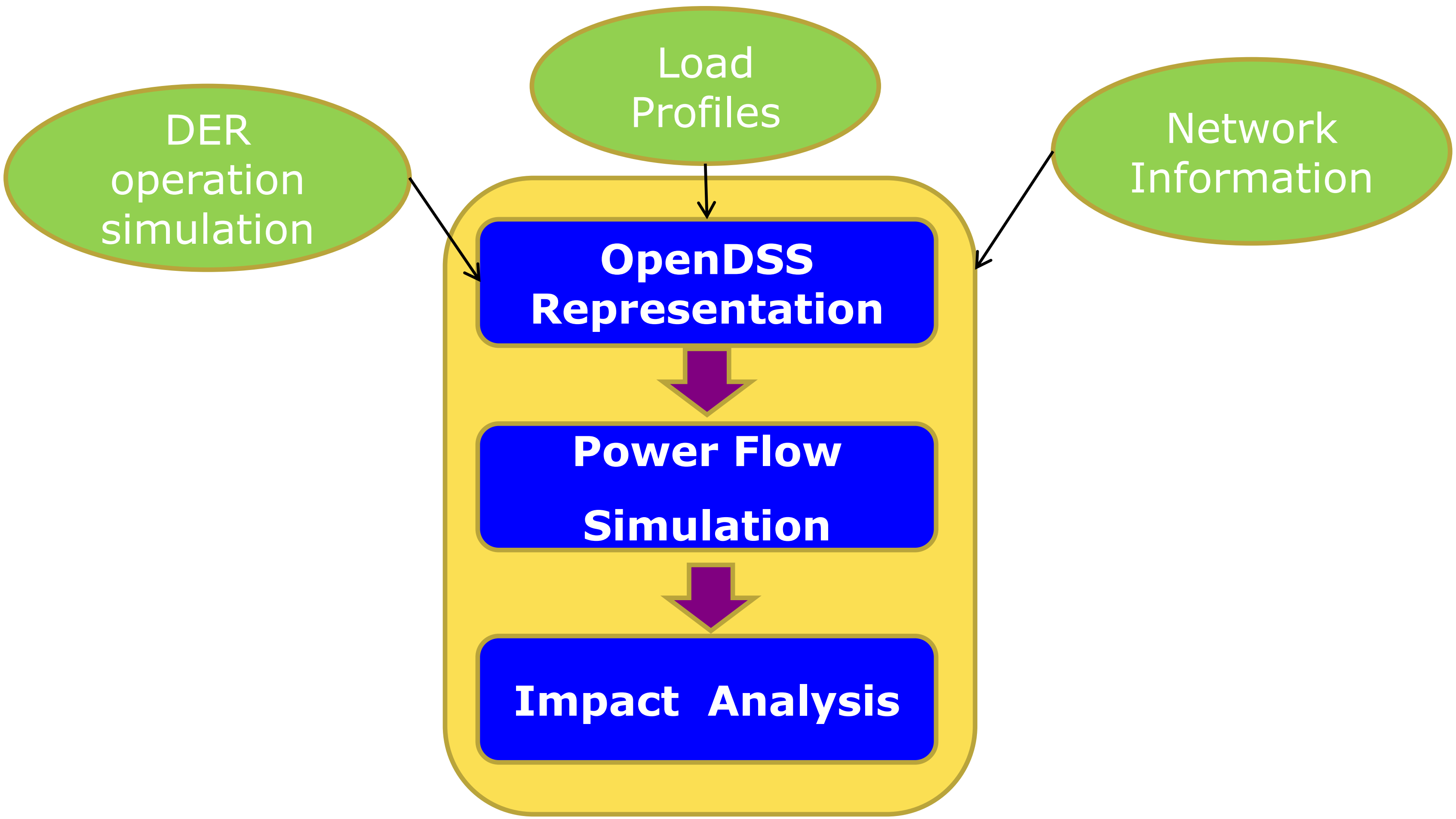


- Overall network cost tends to saturate with load density
- Network investment cost (based on 30 years, 7% discount rate) most substantial (due to excavation cost), followed by heat losses cost



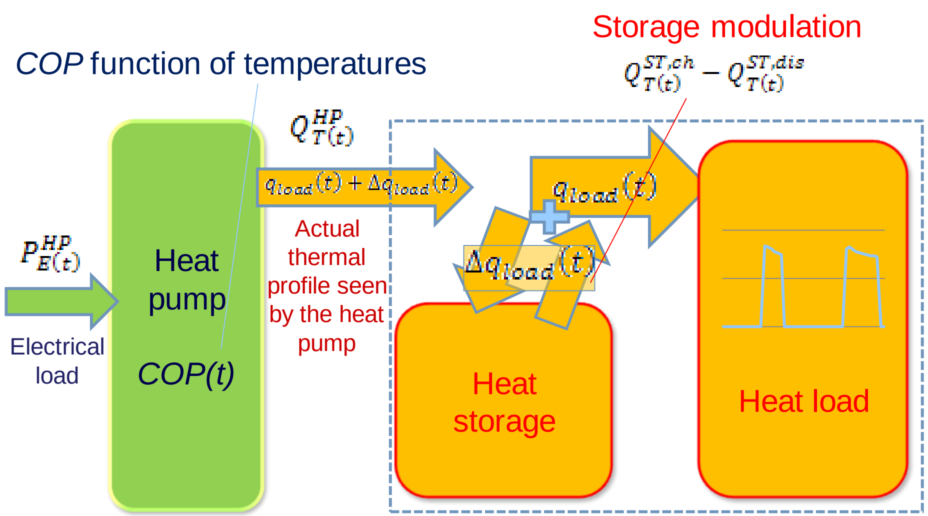
- Specific distribution cost per kWh decreases significantly with heat density and then tends to saturate
- Heat distribution efficiency has a similar but opposite behaviour (increases and saturates with heat density)

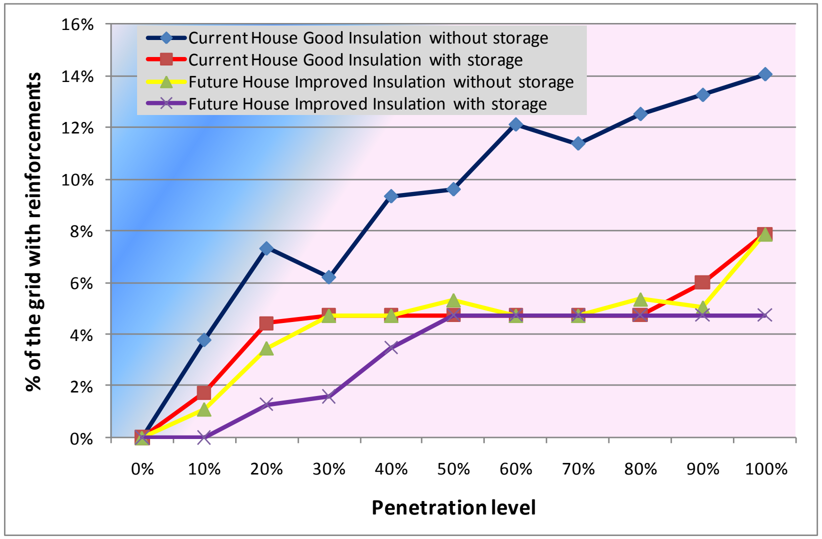
A tool for multi-energy systems electrical distribution network impact modelling



Example: can load-side thermal storage provide network support?

- Impact analysis for different penetration levels of Electric Heat Pumps (EHPs) with/without storage, in current and future houses





Network reinforcements

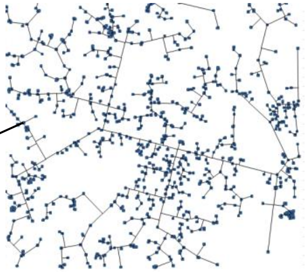
- The insulation improvement (**storage in buildings**) and/or the physical storage (**storage in hot water**) decrease the EHP impacts on distribution networks

- Reinforcements saturate at 5% for penetration levels above 50% because the feeder conductors need to be changed anyway

- **CBA**: is thermal insulation, storage and relevant ICT cheaper than copper? In which cases?

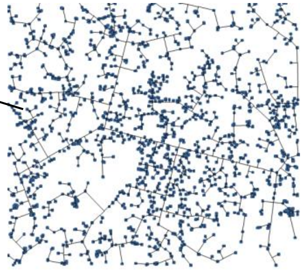
Optimal electro-thermal distribution *network design*: competition between energy vectors

- Greenfield design of electricity and heat distribution infrastructure in new built areas
- Assessment of the network cost of an electrical-only option (with EHP) vs electricity-and-heat networks option
- Analysis for different load densities and network lengths



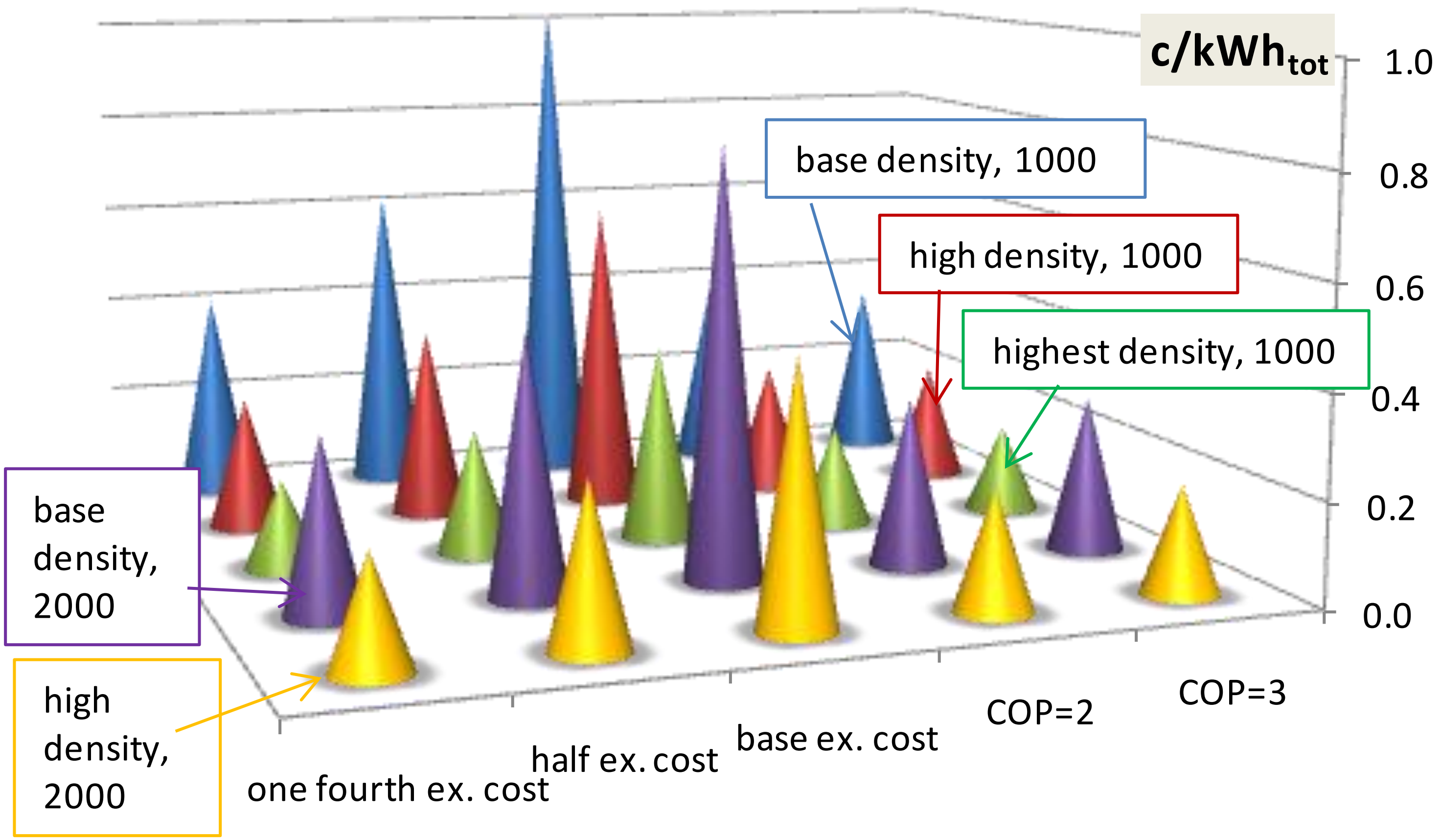
Electro-thermal characteristics used in the greenfield design case study

		Case A	*Case B*
Number of customers		1000	2000
Electrical peak density [MVA/km^2]	Base	8.6	17.2
	High	17	34
	Highest	34	---
Thermal peak [MW_{th}/km^2]	Base	39	78
	High	77.9	155.5
	Highest	154.4	---
Network length [km]		19	28



Source: P. Mancarella et al, Fractal models for electro-thermal network studies, PSCC 2011, Stockolm, Sweden, August 2011

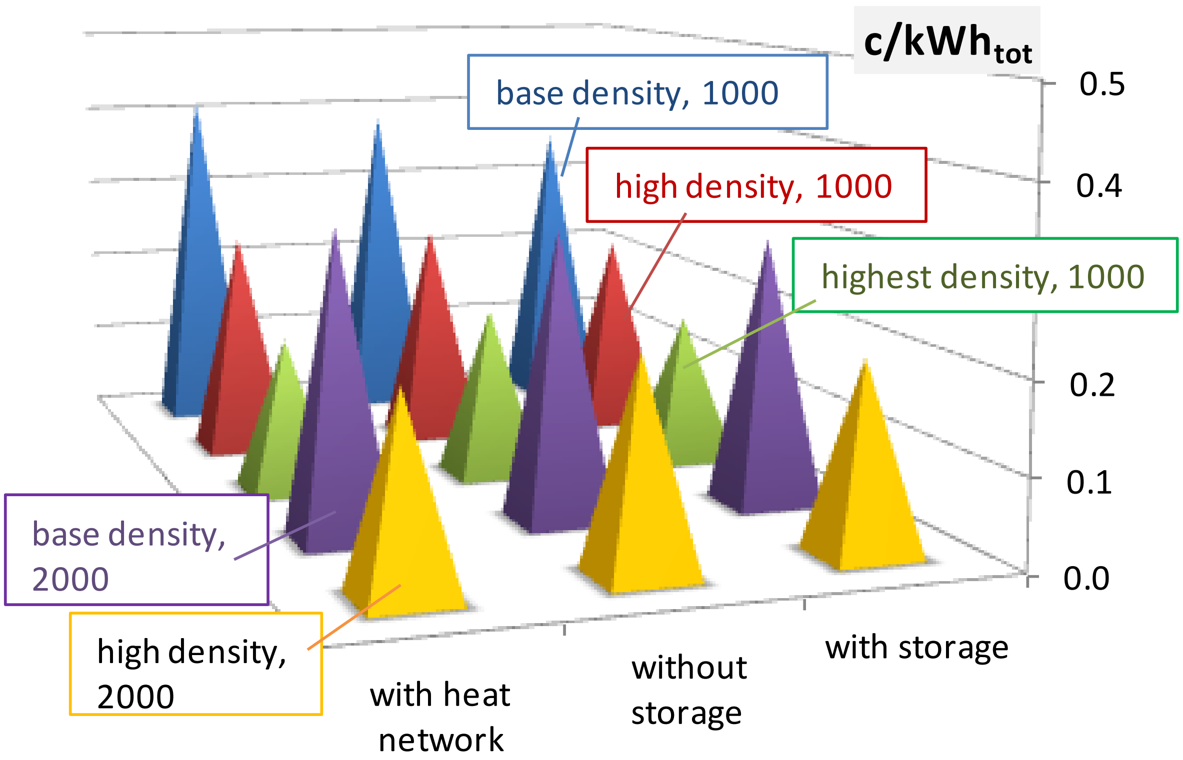
Optimal electro-thermal network design: Cost of the different options, £/kWh$_{e+th}$



Analysis for different excavation costs and EHP performance

Source: P. Mancarella et al, Fractal models for electro-thermal network studies, PSCC 2011, Stockolm, Sweden, August 2011

Potential for thermal storage in network design



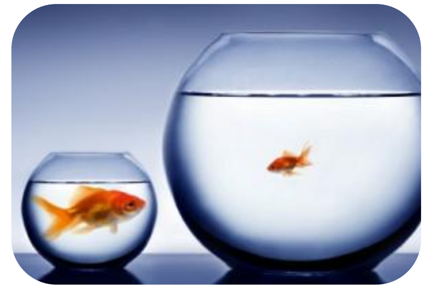
Storage system capable to reduce about 30% of the peak can bring down the cost by 10% to 15% (losses-driven optimal network design)

Flexibility in planning under uncertainty: Real Options Valuation (ROV)

- Decisions taken in light of subsequent information leading to

Deferral

Expansion

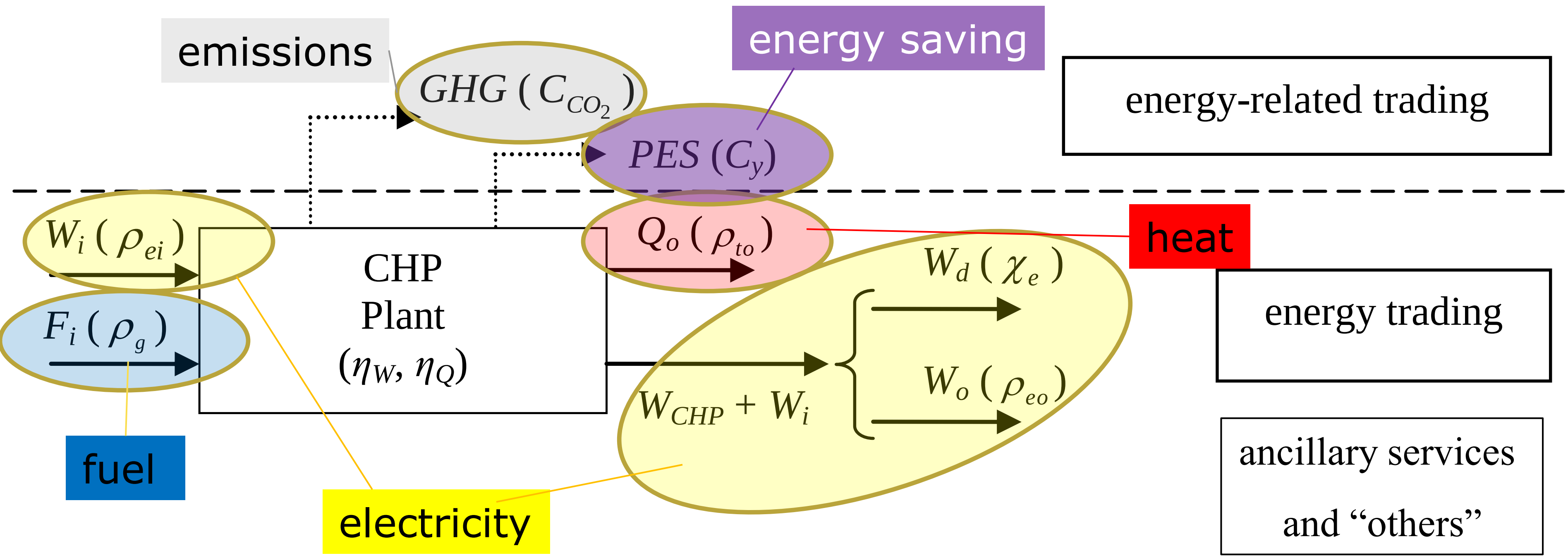


Contraction

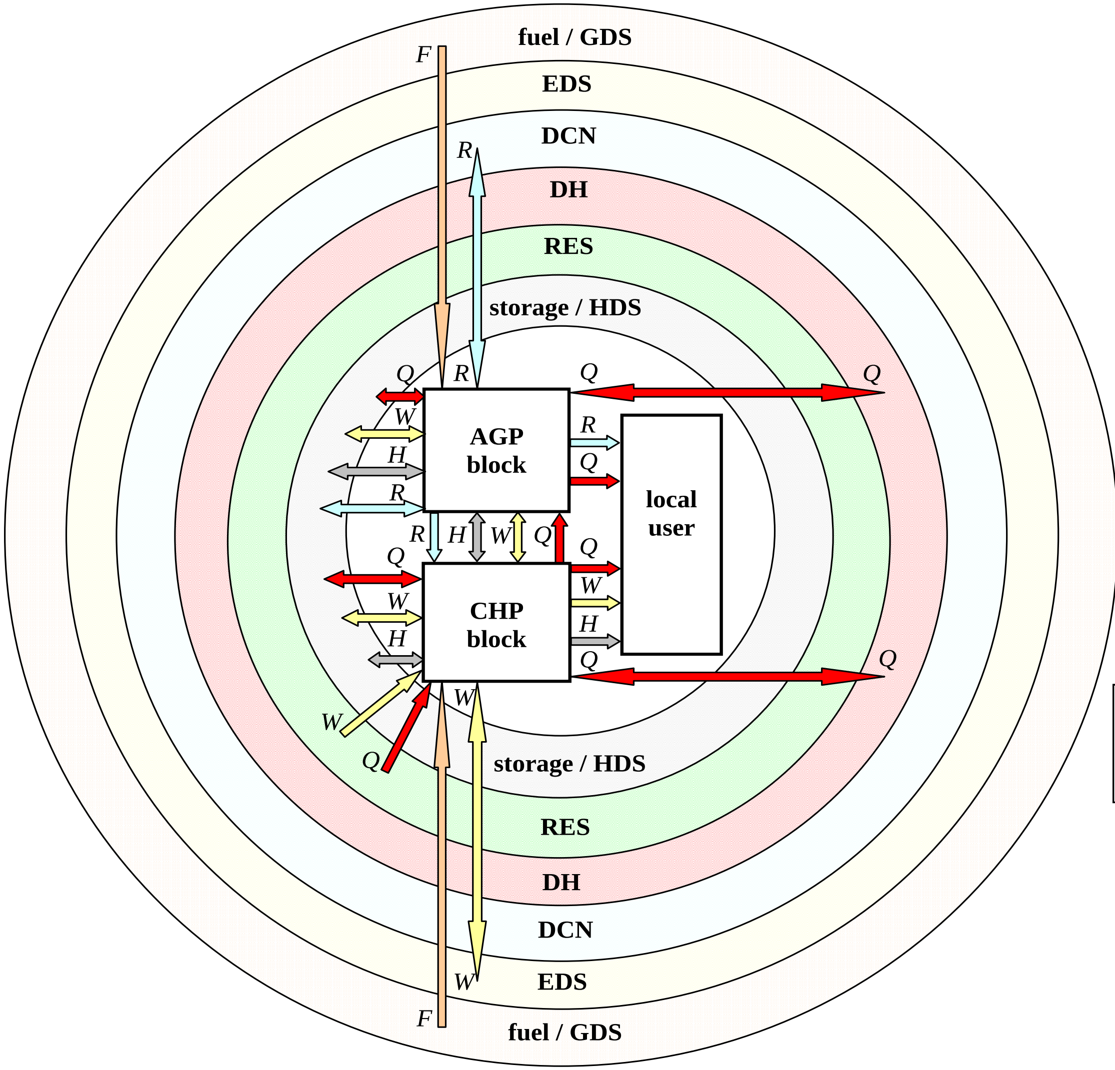
Abandonment

- Optimal timing of investment – what is the value of waiting and stage-expanding?
- Optimal technology mix for multi-energy networks
- Flexibility of technology investment under large scale uncertainty
- Applications:
  - Generation investment
  - Multi-energy network expansion
  - Optimal multi-service contracts for innovative business models

Multi-commodity and multi–service resources portfolio optimization under small-scale uncertainty



A Multi-Energy 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

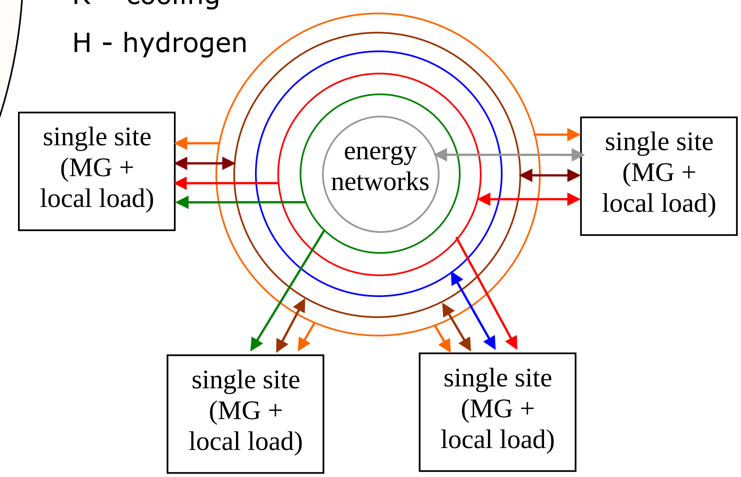
MG – Multi-Generation

W – electricity

Q – heat

R – cooling

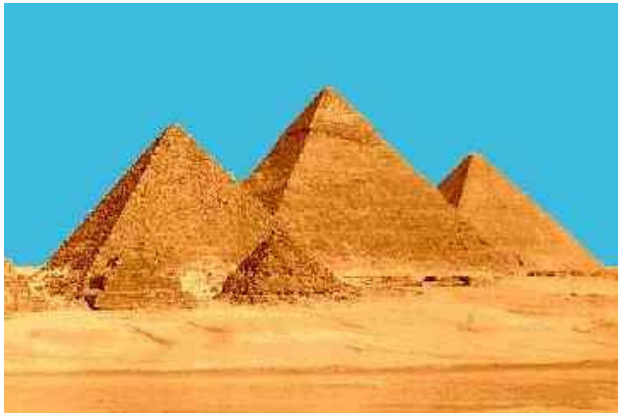
H - hydrogen



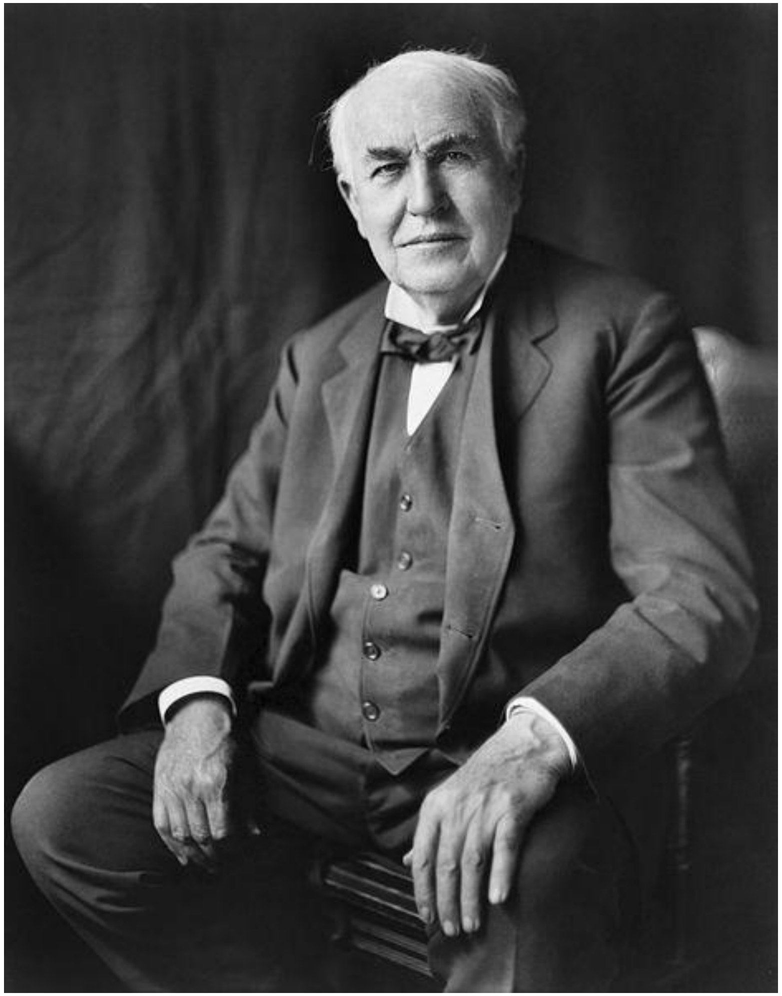
Source: P. Mancarella, G. Chicco, *Distributed Multi-Generation Systems: Energy Models and Analyses*, Nova, 2009

What’s so challenging?

July 20, 1969, at 20:17:39



Back to the origin of power systems…



There is no innovation without a business case

Thank you

Any Questions?

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Multi-energy Systems: The Smart Grid beyond Electricity

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