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COOPERATE

BUSINESS CASES FOR DISTRIBUTED MULTI-ENERGY SYSTEMS

Pierluigi Mancarella, PhD

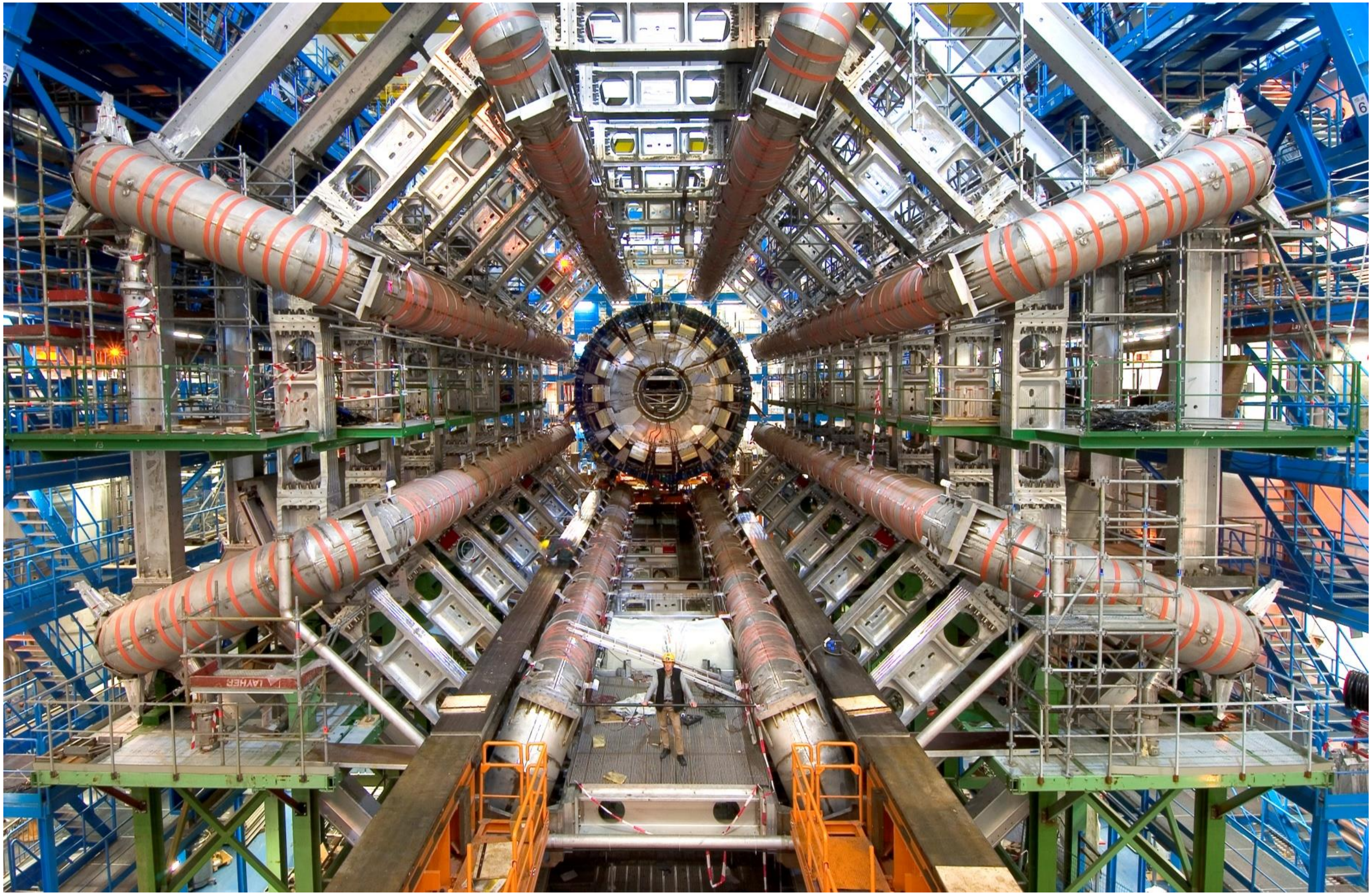
Reader in Future Energy Networks

The University of Manchester, Manchester, UK

p.mancarella@manchester.ac.uk

Energy Systems Integration Facility, NREL, Golden, USA – 04/08/2015

Why are we talking about business cases?



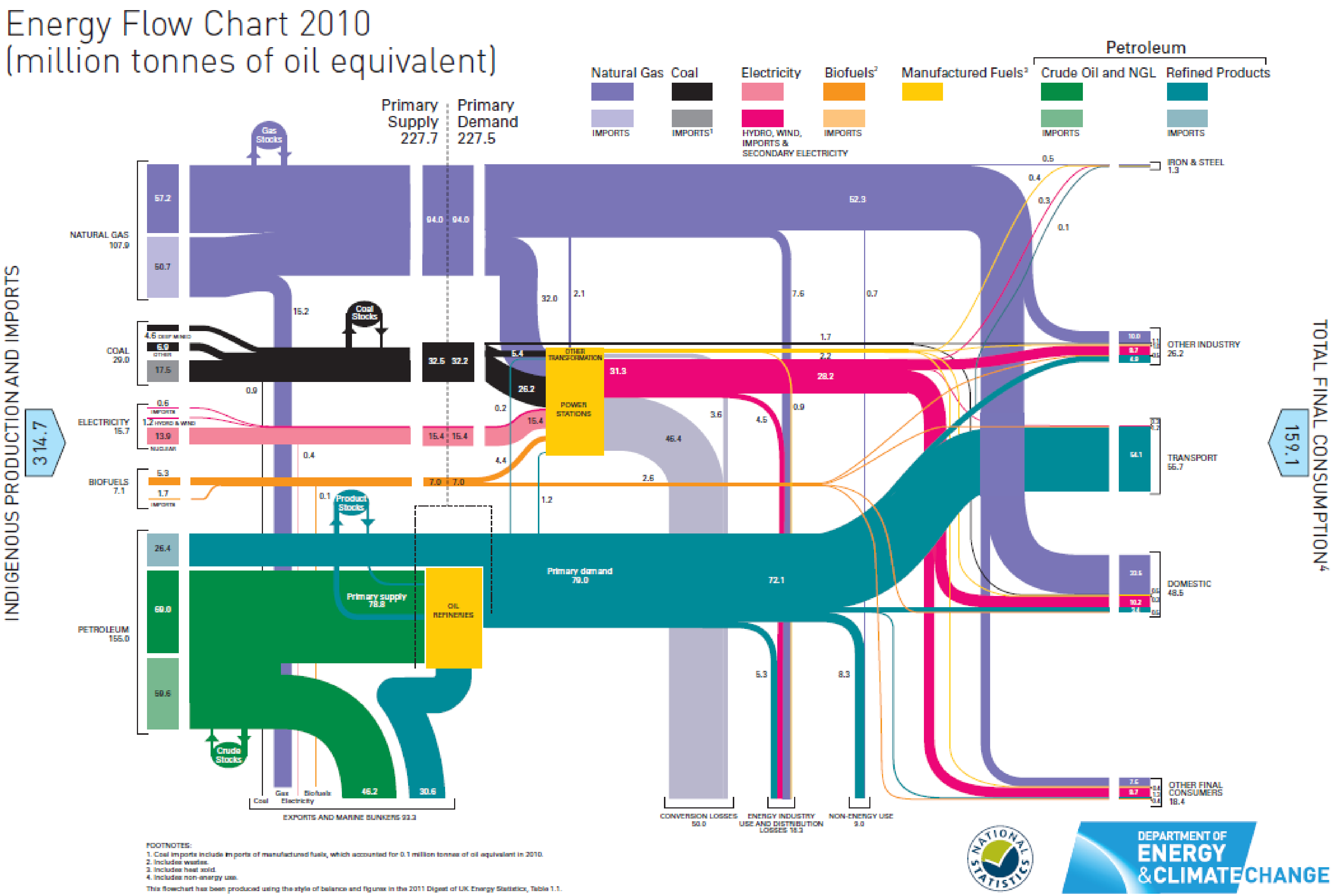
Contents

- Context and challenges
- Basic concepts of distributed multi-energy systems
- Business case framework
  - Physical and economic flows and flexibility
  - External and internal markets
  - Mapping and cost benefit analysis
- Case study
  - Operational optimization
  - Flexible investment
- Concluding remarks

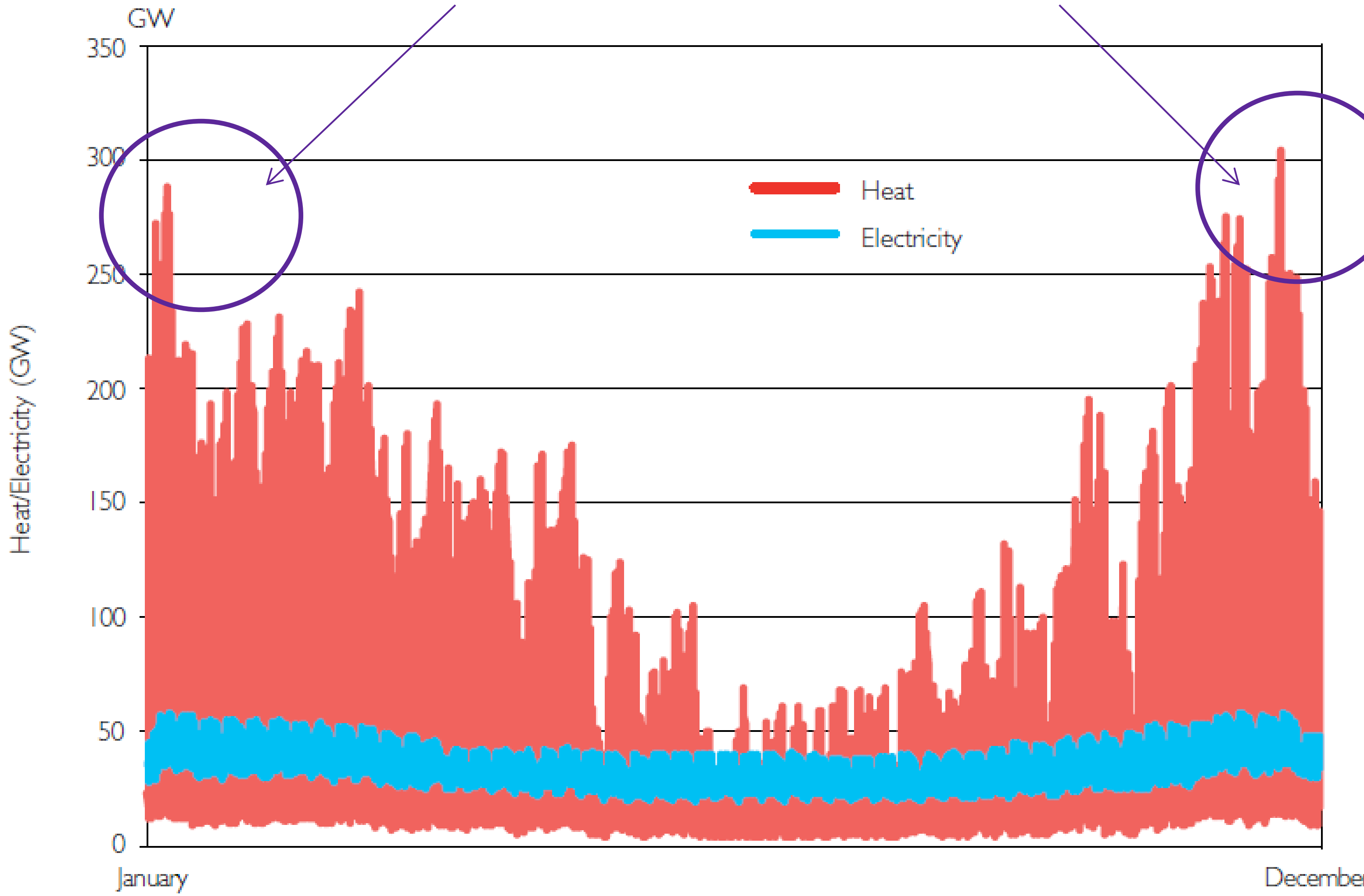
Context and challenges

- Challenging environmental targets
- Economic and financial uncertainty
- Increasing need for flexibility and provision of security in lower inertia systems
- Major contribution to energy consumption and GHG emissions coming from non-electrical usage
- Classical de-coupling of energy vectors and services is environmentally and economically inefficient
- By 2050, over 70% of the world population will live in cities
    - Opportunity for Energy Systems Integration (ESI) in (smart) buildings, districts, cities

It’s not only about electricity



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.

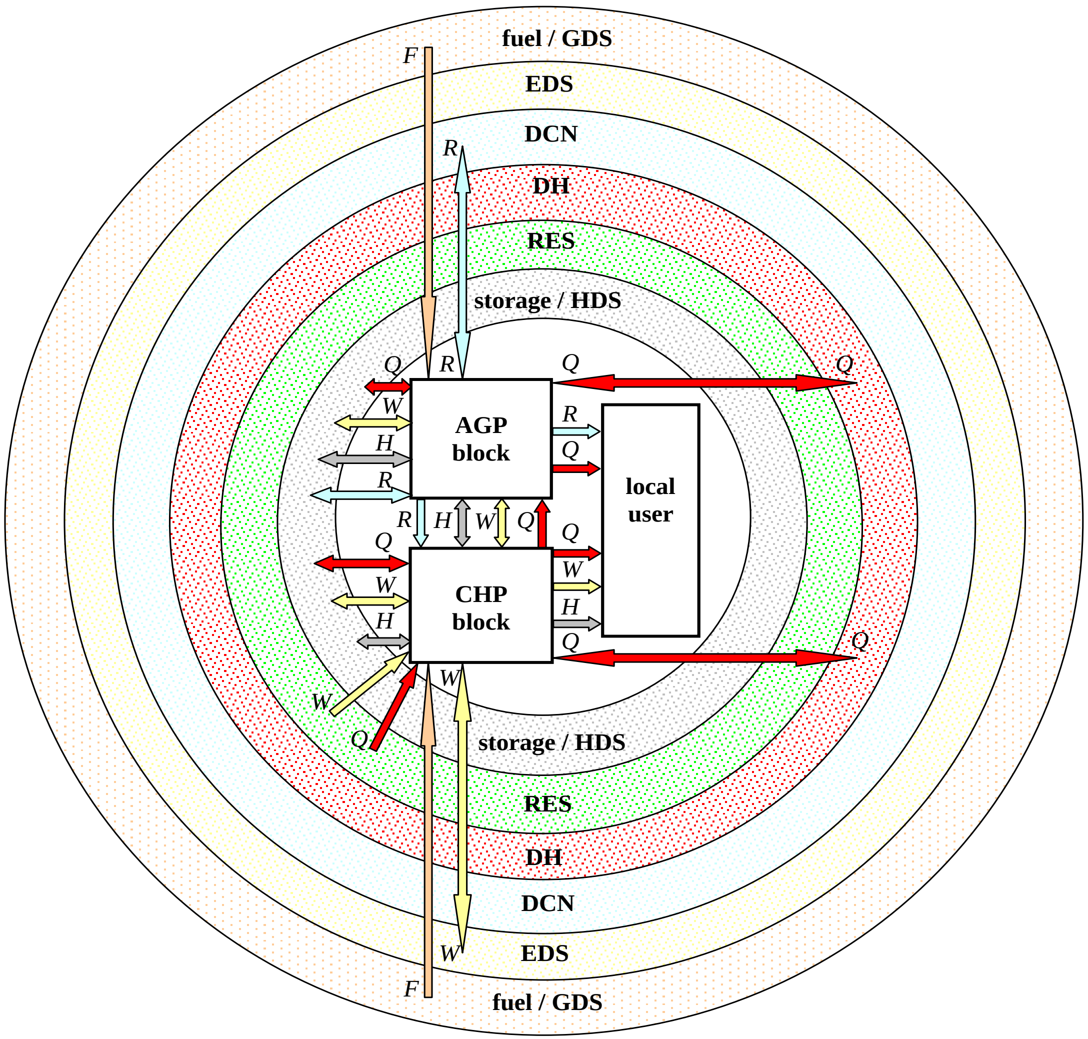
Rethinking the energy system: The Smart Multi-energy Grid Vision

- *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

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

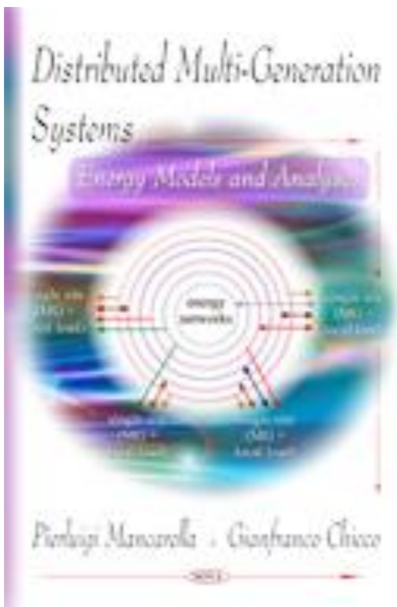
GDS – Gas Distribution System

HDS – Hydrogen Distribution Network

MG – Multi-Generation

W – electricity, Q – heat, R – cooling

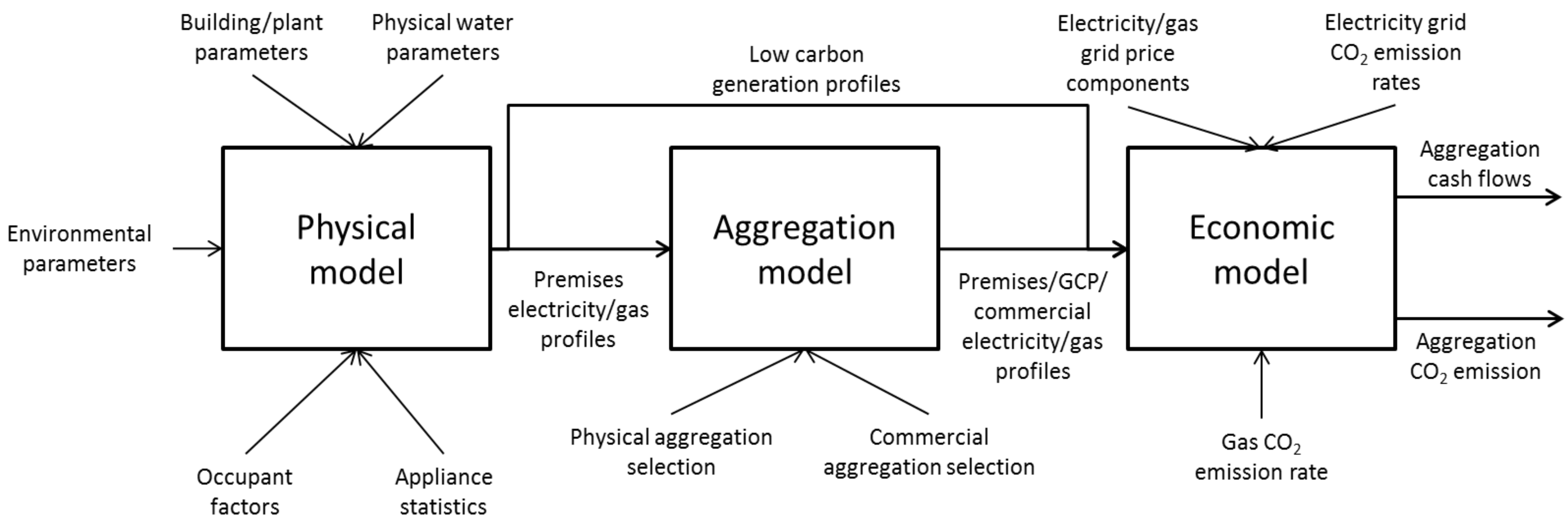
H – hydrogen, F - Fuel



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

Techno-economic modelling of distributed multi-energy systems

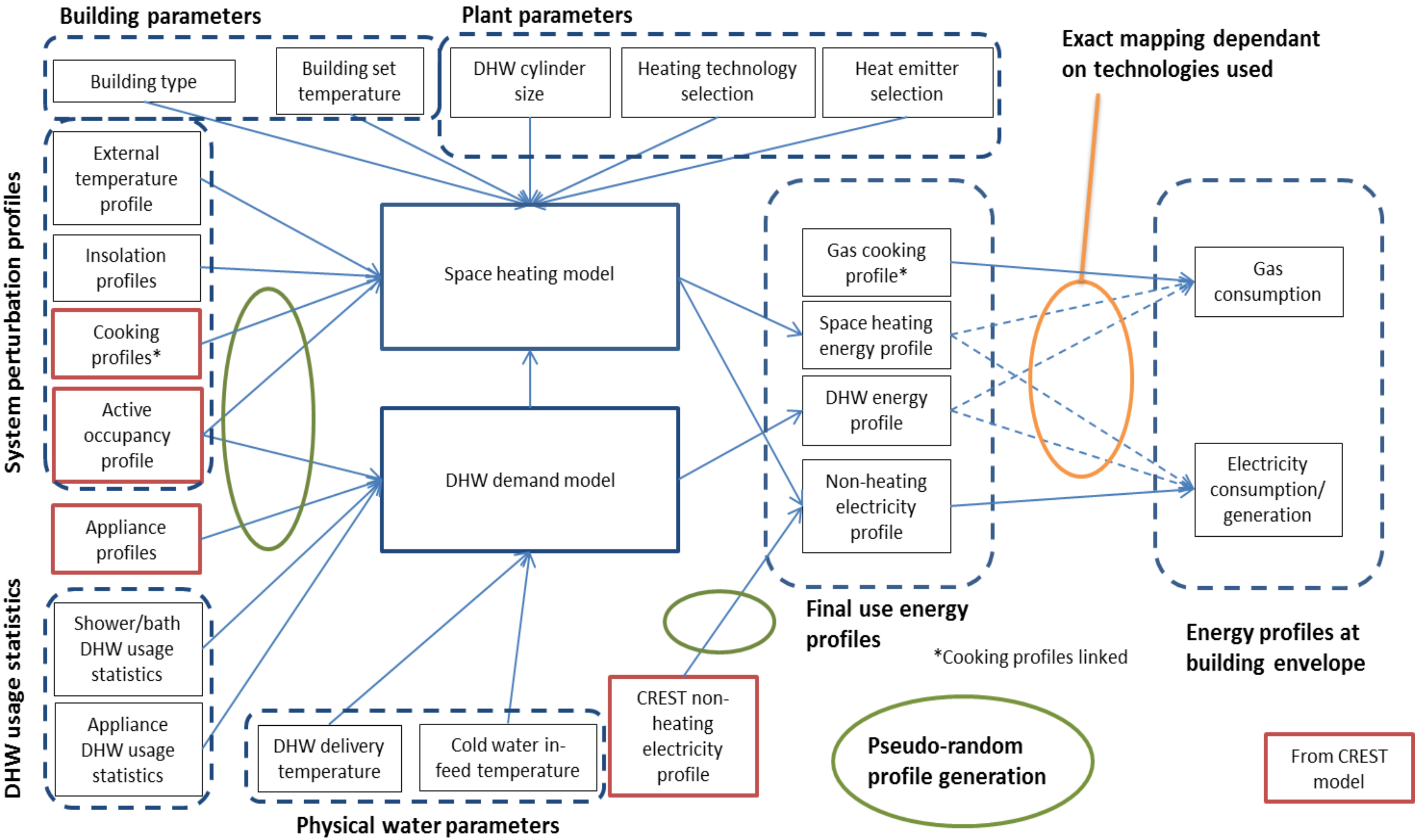


N. Good, E.A. Martinez-Cesena, and P. Mancarella, Techno-economic assessment and business case modelling of low carbon technologies in distributed multi-energy systems, *Applied Energy, Special Issue on Integrated Energy Systems, May 2015, under review.*

Setting up a business case framework for distributed multi-energy systems

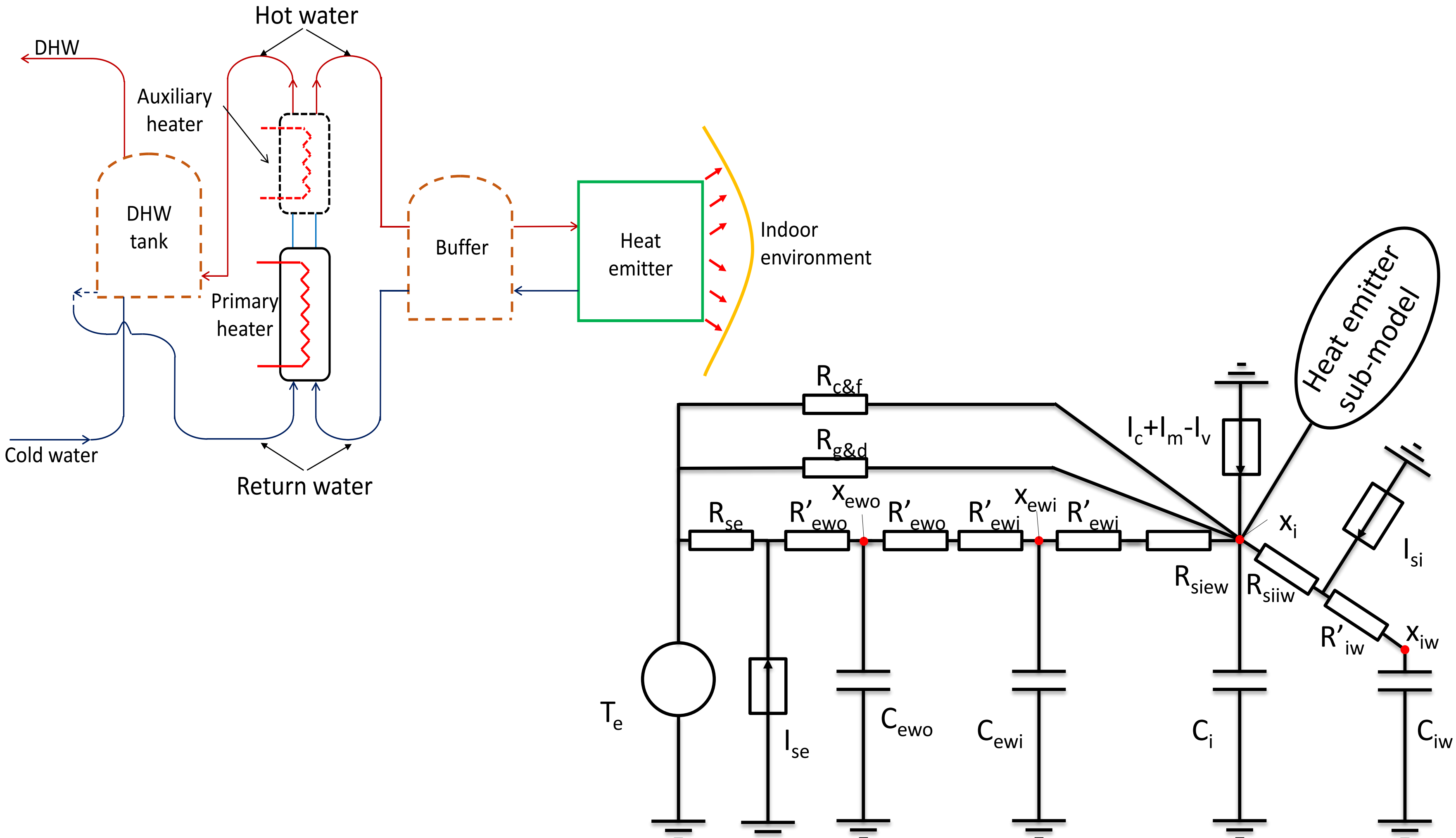
- Physical modelling
  - Demand
  - Network multi-vector energy flows
- Flexibility analysis
  - Physical
  - Economic
- Where is value extracted from (cash flows analysis)
  - Markets
  - Commercial arrangements and actors
- How is the value allocated across the actors ("mapping")
  - Internally (unlocking flexibility)
  - Externally (value chain)
- How are enabling facilities invested into?
  - Cost Benefit Analysis
  - Dealing with planning uncertainty

Physical modelling of demand



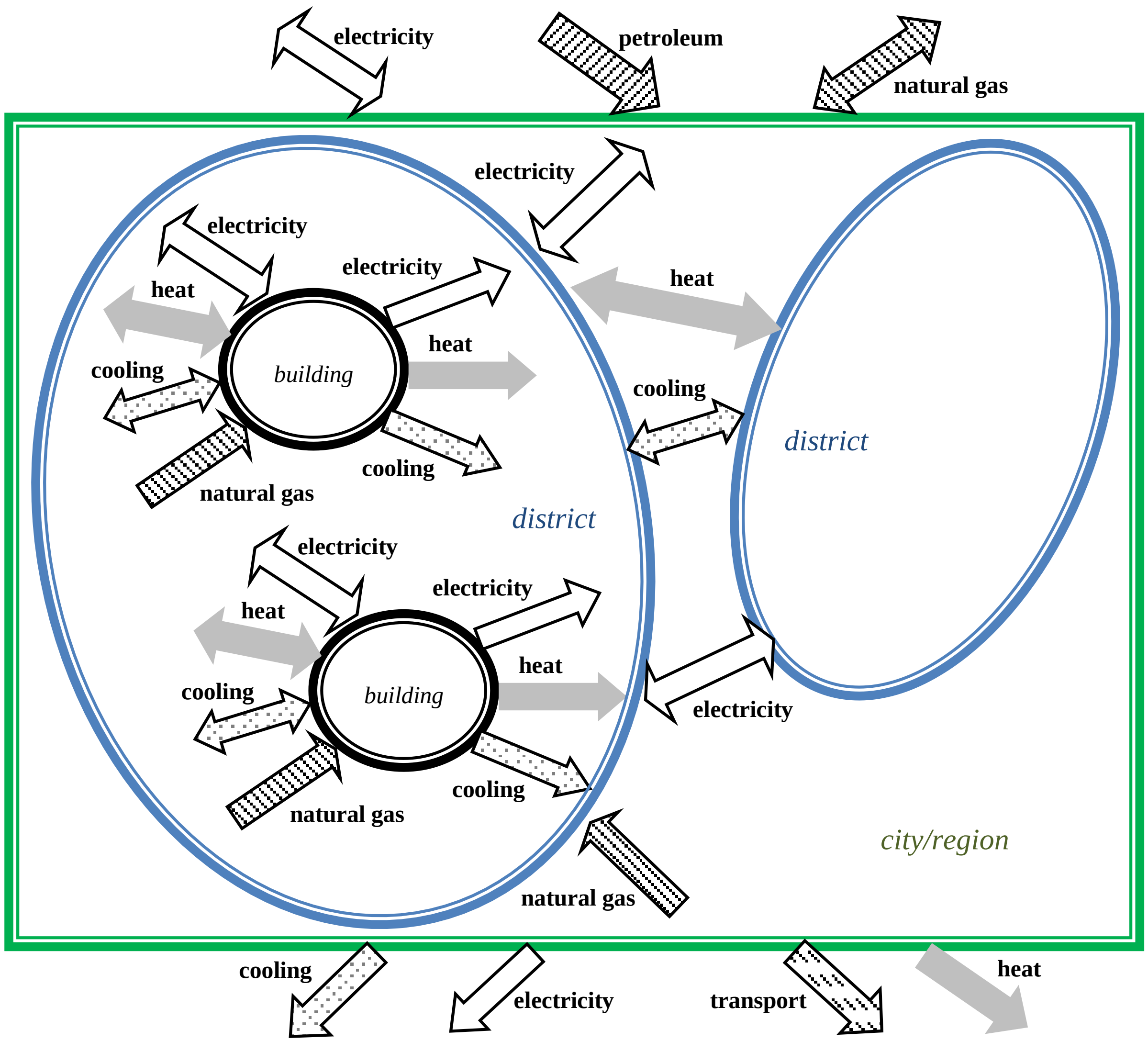
N. Good, L. Zhang, A. Navarro Espinosa, and P. Mancarella, High resolution modelling of multi-energy demand profiles, Applied Energy, Volume 137, 1 January 2015, Pages 193–210, 2014

Reduced order building models



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

Aggregation: from buildings to districts



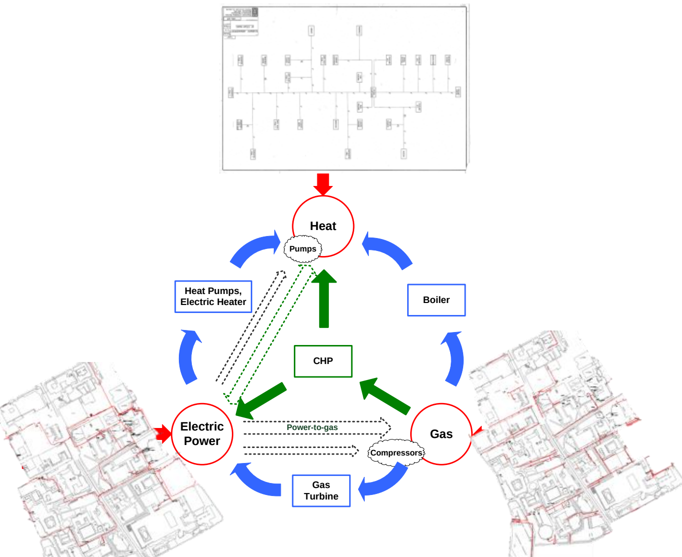
P.Mancarella, Multi-energy systems: an overview of models and evaluation concepts, Energy, Vol. 65, 2014, 1-17, 2014, *Invited paper*

Multi-vector distributed energy network modelling

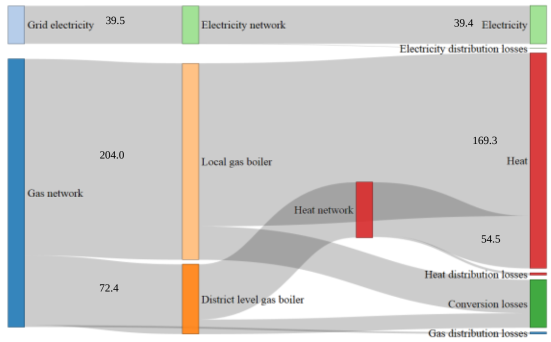
- Incidence matrices of each network ("local" topology)
- Network coupling through conversion components ("global" topology)
- Newton-Raphson solutions of coupled multi-vector equations:
  - Active and reactive power (voltages and angles)
  - Heat mass flow rates and temperatures
  - Gas volume flow rates
- Tool implemented in Matlab with Excel interface
- "Real" and "virtual" sensors

X. Liu and P. Mancarella, Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems, Submitted to Applied Energy, May 2015, under second review

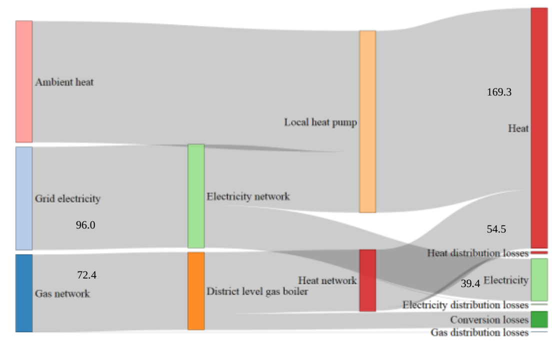
Physical Flows at the UoM



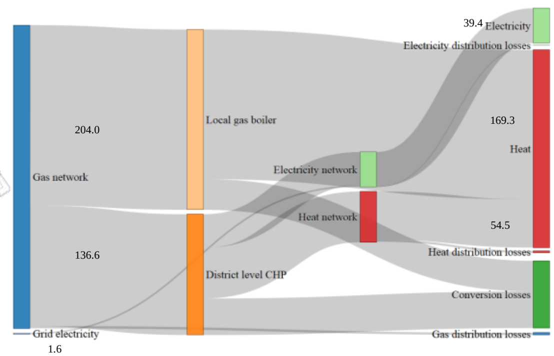
Flows of energy between electricity, heat and gas networks through conversion components



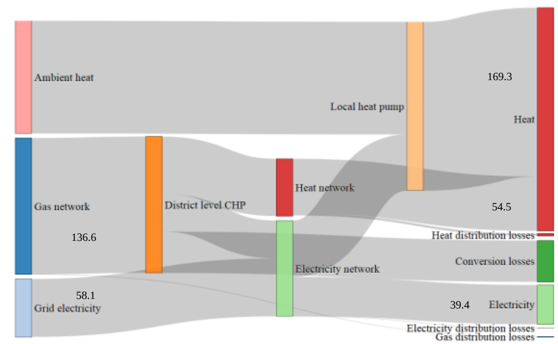
(a) Scenario 1: District level gas boilers + local gas boilers



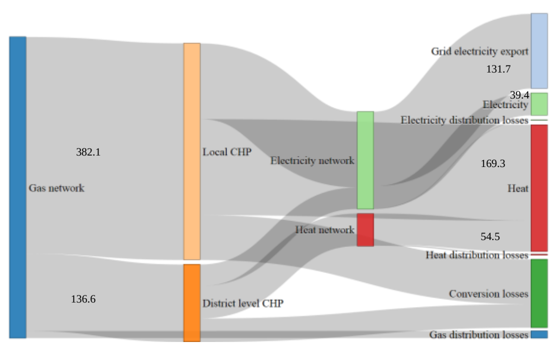
(b) Scenario 2: District level gas boilers + local heat pumps



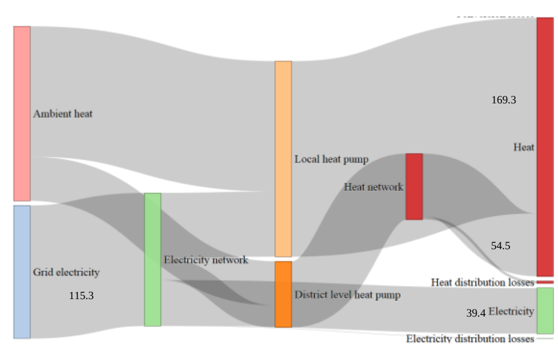
(c) Scenario 3: District level CHP + local gas boilers



(d) Scenario 4: District level CHP + local heat pumps



(e) Scenario 5: District level CHP + local CHP

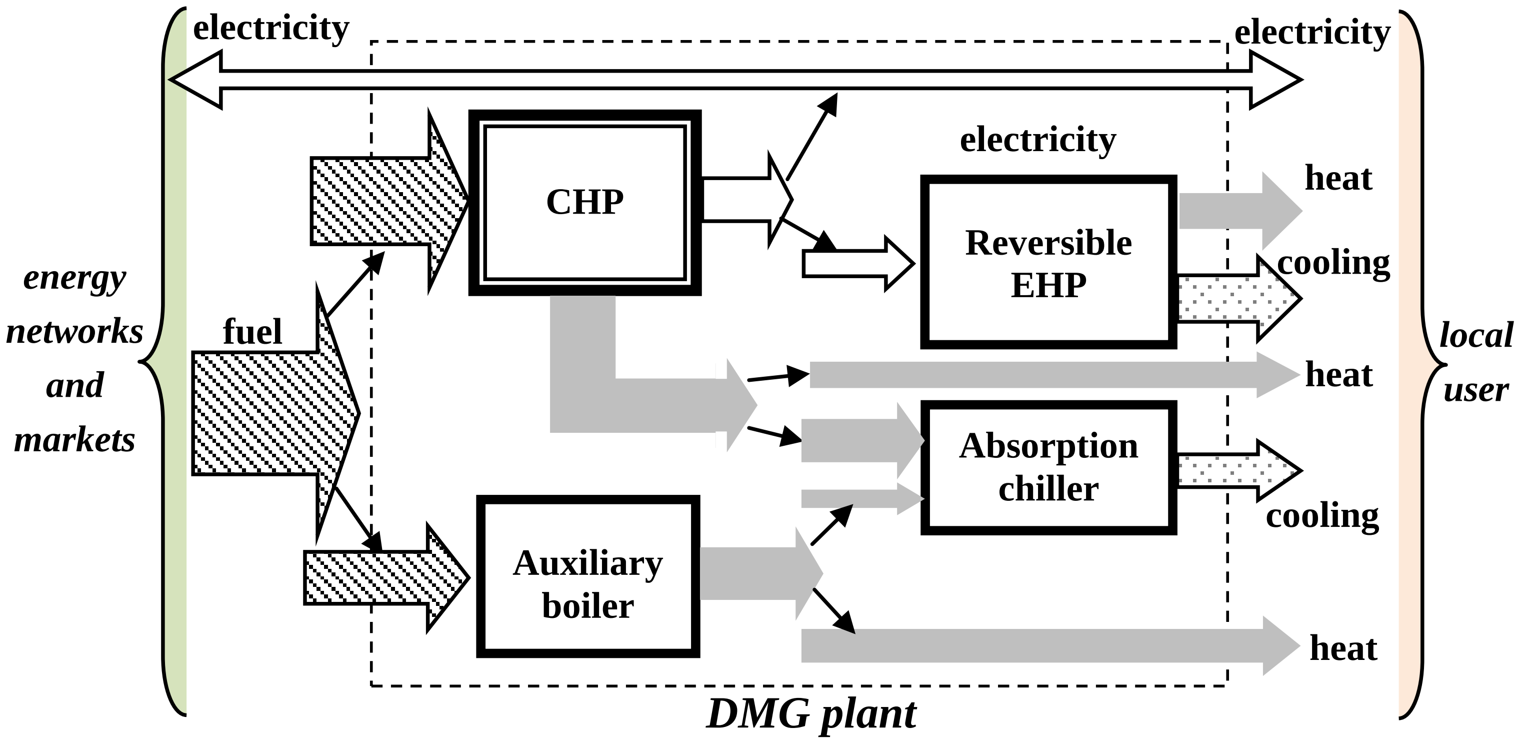


(f) Scenario 6: District level heat pumps + local heat pumps

Figure 1: Flows of energy between electrical, heat and gas networks in total 24 hours for each Scenario

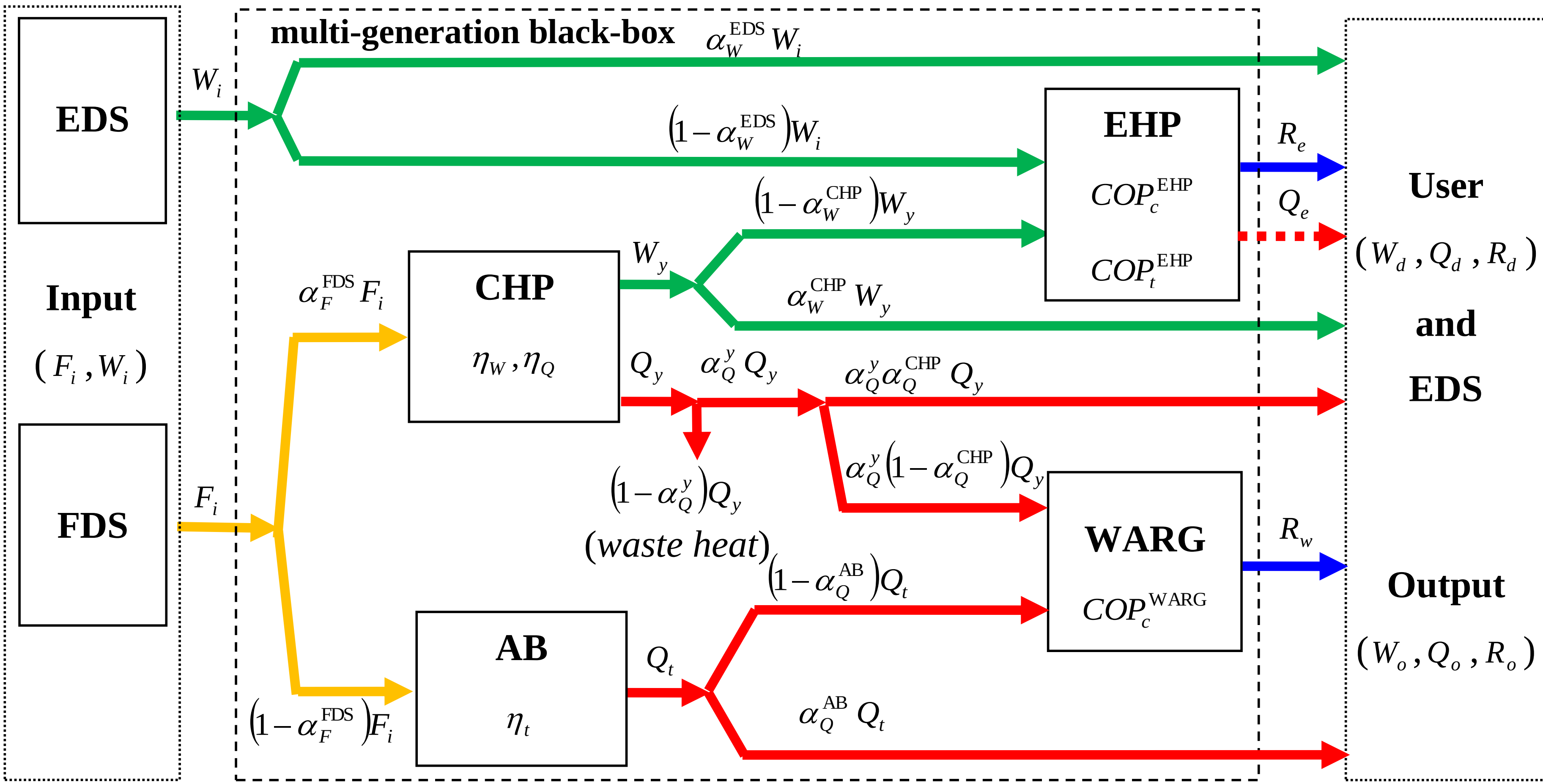
X. Liu and P. Mancarella, Modelling, assessment and Sankey diagrams of integrated electricity-heat-gas networks in multi-vector district energy systems, Submitted to Applied Energy, May 2015, under second review

Real time operational flexibility from Distributed Multi-Generation (DMG)



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

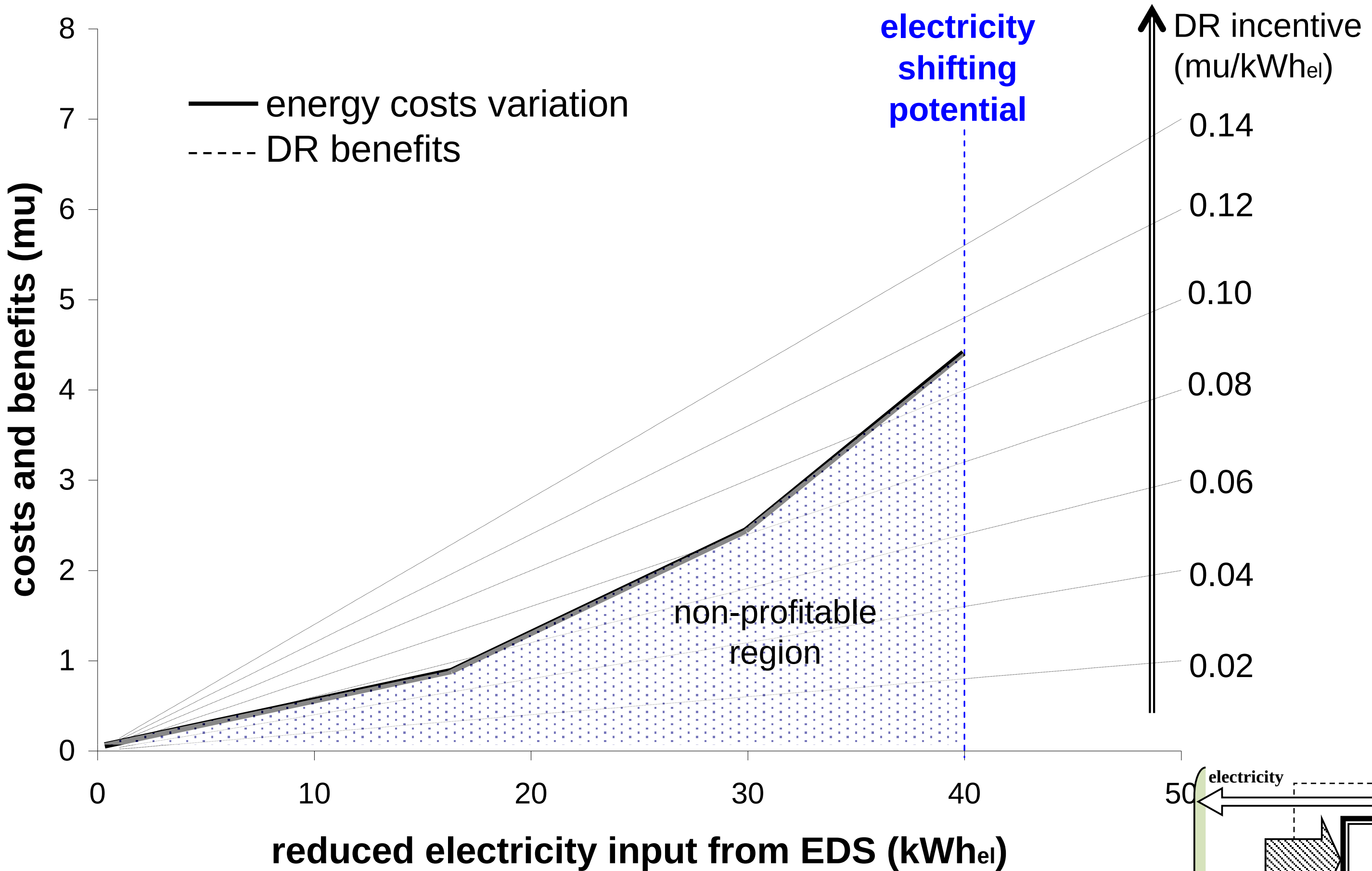
Flexibility in distributed multi-generation: Baseline optimization and *physical* flexibility

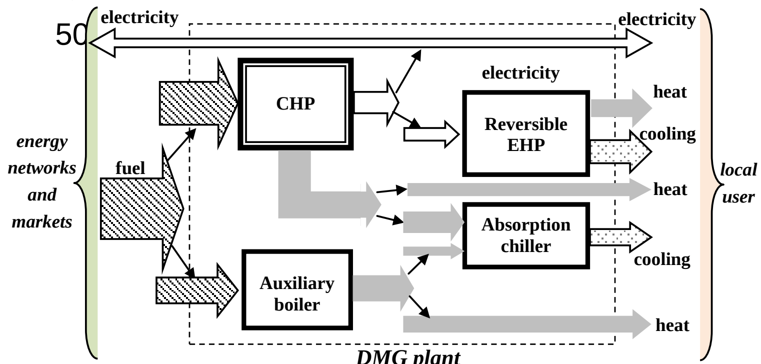


G.Chicco and P.Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, Energy, Volume 34, No. 3, March 2009, Pages 261-273

P. Mancarella and G.Chicco, Real-time demand response from energy shifting in Distributed Multi-Generation, IEEE Transactions on Smart Grid, December 2013

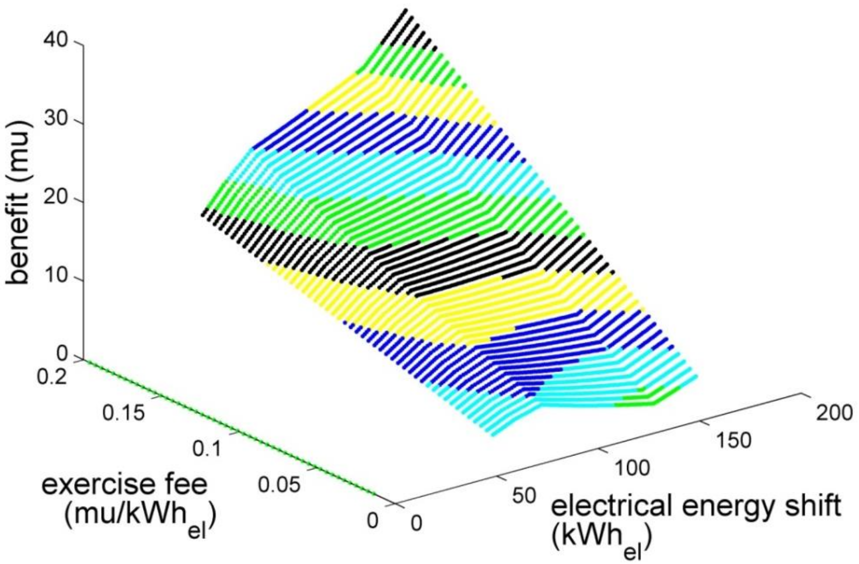
Economic flexibility and real-time DR



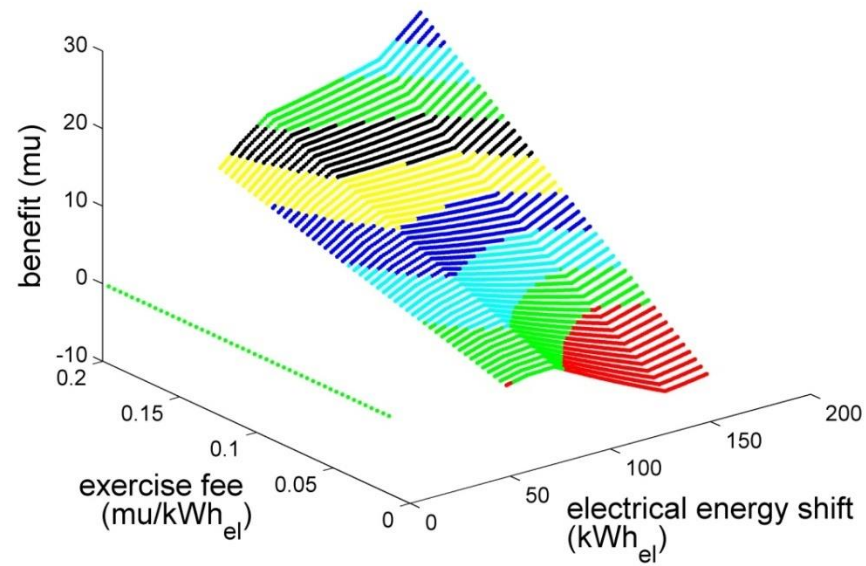


Source: P. Mancarella and G.Chicco, Real time Demand Response from Distributed Multi-Generation, *IEEE Trans. on Smart Grid, 2013*

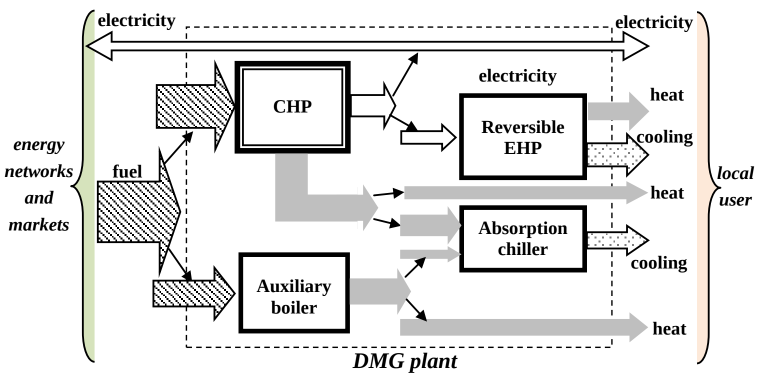
Provision of ancillary services: profitability maps



availability fee 0.05 mu/kW/halfhour



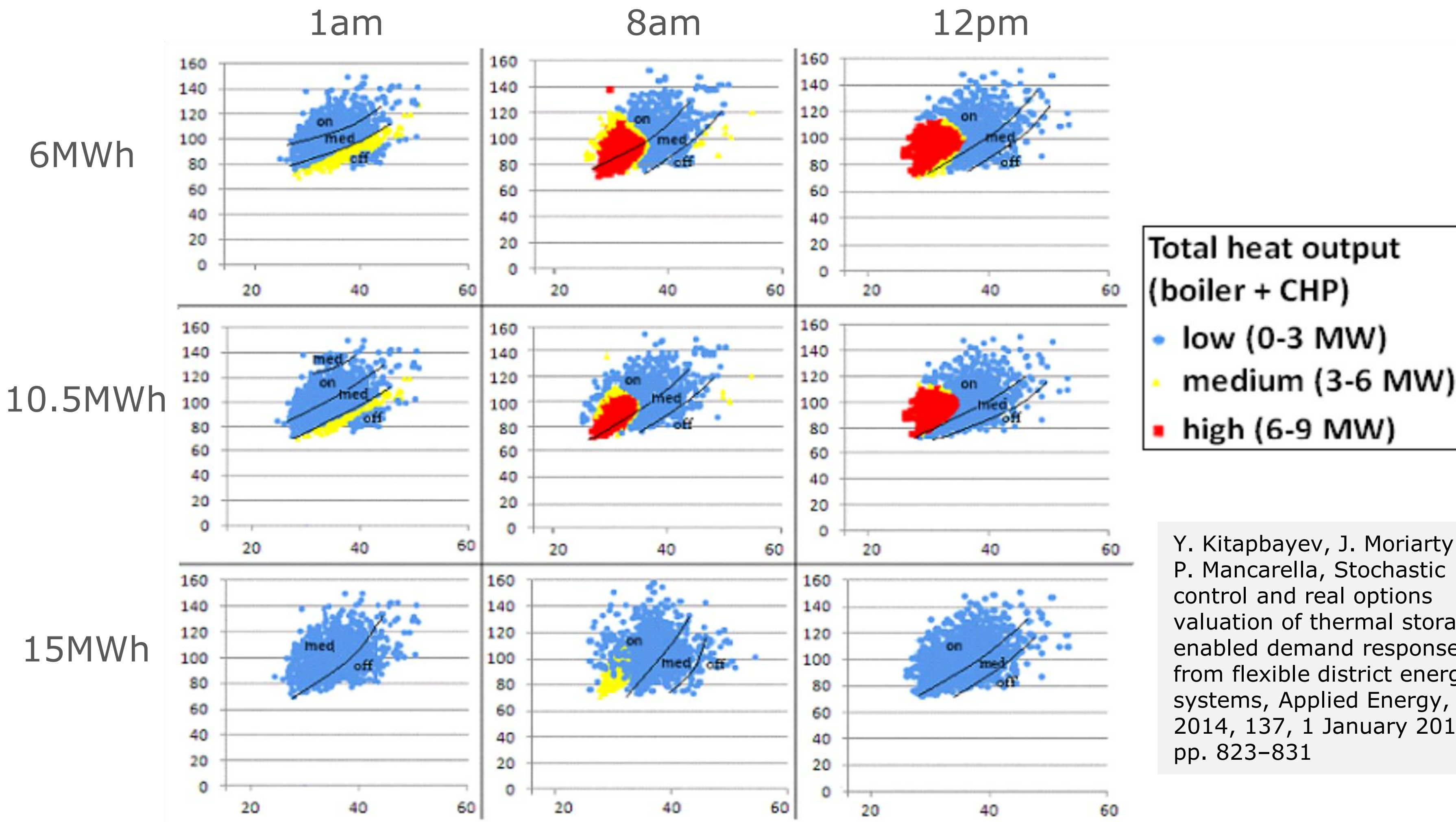
availability fee 0.02 mu/kW/halfhour



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

Dealing with operational uncertainty: Multi-energy DR as Real options

Strategy map for three times of day and for three levels of stored heat



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, 137, 1 January 2015, pp. 823–831

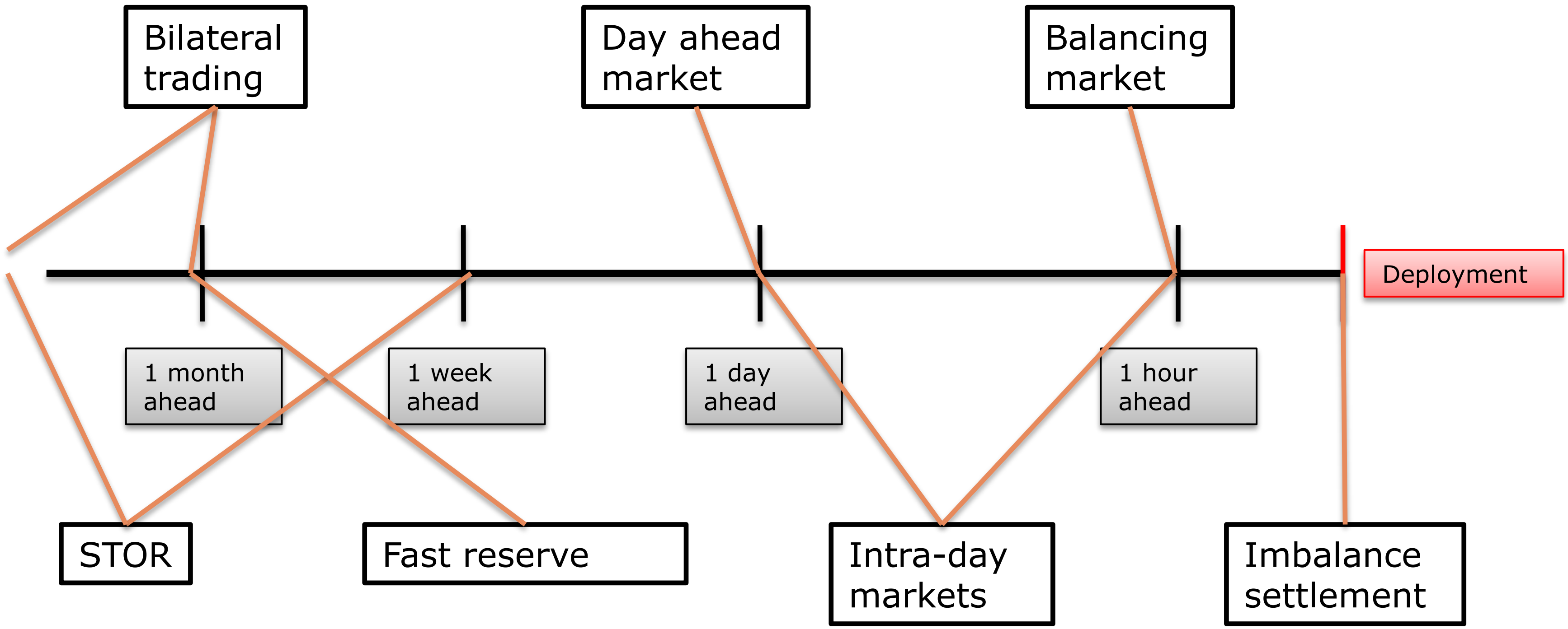
J. Schachter and P. Mancarella, Demand Response Contracts as Real Options: A Probabilistic Evaluation Framework under Short-Term and Long-Term Uncertainties, *IEEE Transactions on Smart Grid, 2015*.

Where is value extracted from? External market framework

- Electricity
  - Forward and day-ahead markets
  - Balancing markets, “real-time” markets
  - Ancillary services markets
  - “Network” markets
  - “Flexibility” markets
  - “Reliability” markets
- Gas
- Comfort (temperature, ventilation, ... -> heat/cooling)
- Energy externalities (emissions/efficiency)

External market framework: example

External market frameworks dictate the process by which values and costs are created



Commercial structures and Actors

External actors

Transmission system operator

ICT providers

Gas supplier

district

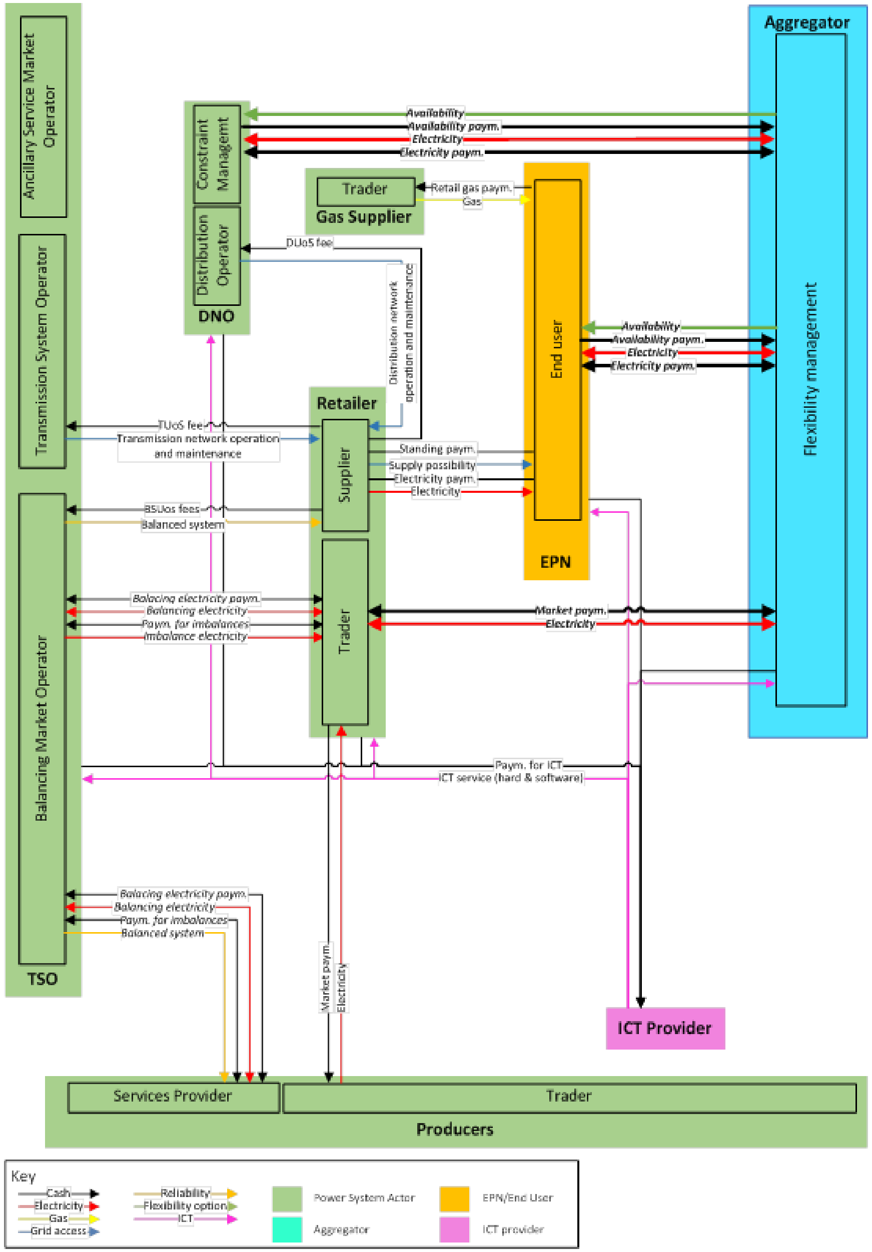
Distribution network/system operator

Retailer

Aggregators

Producers

Example: external flow mapping



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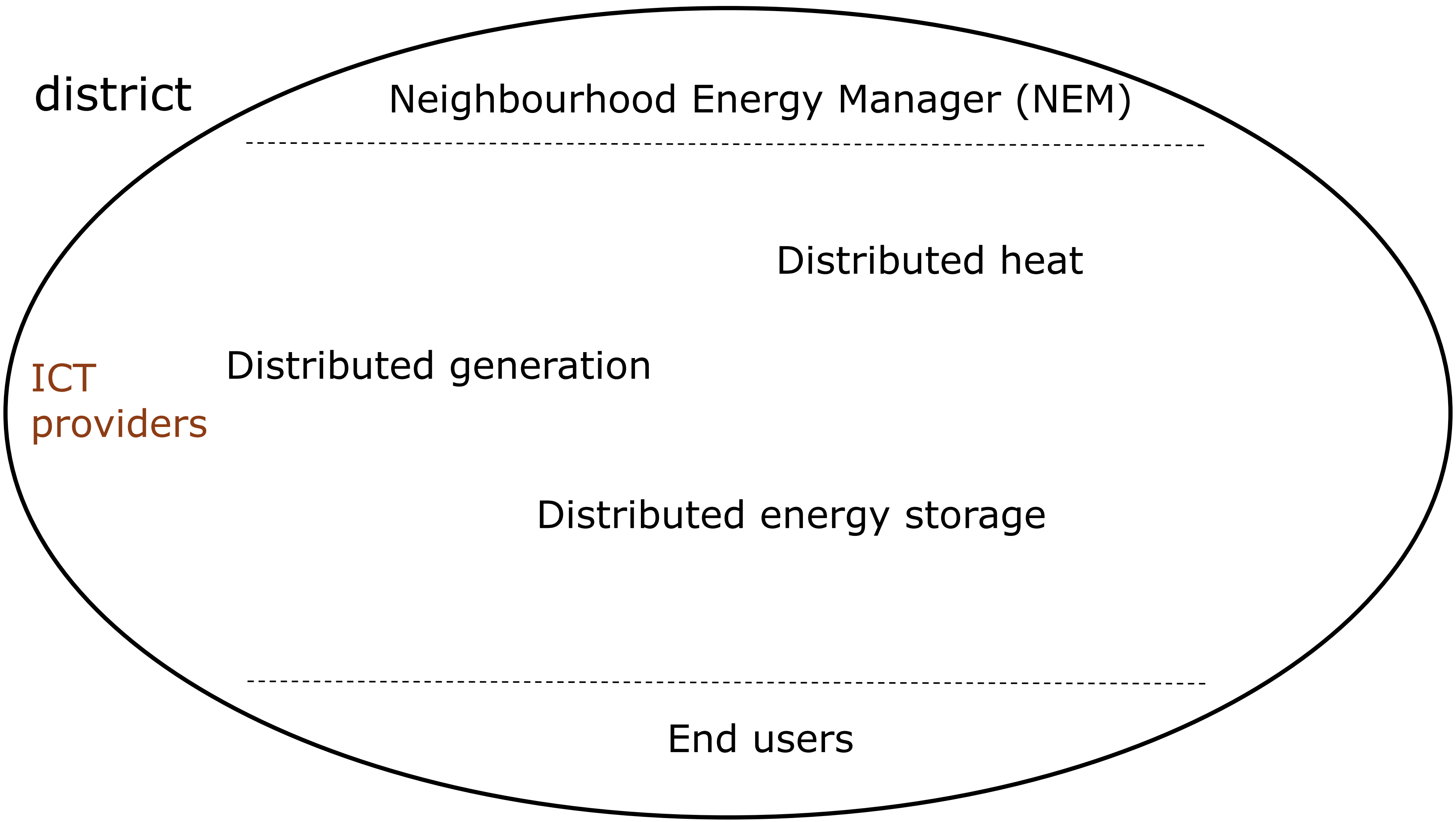
Example: interaction matrix

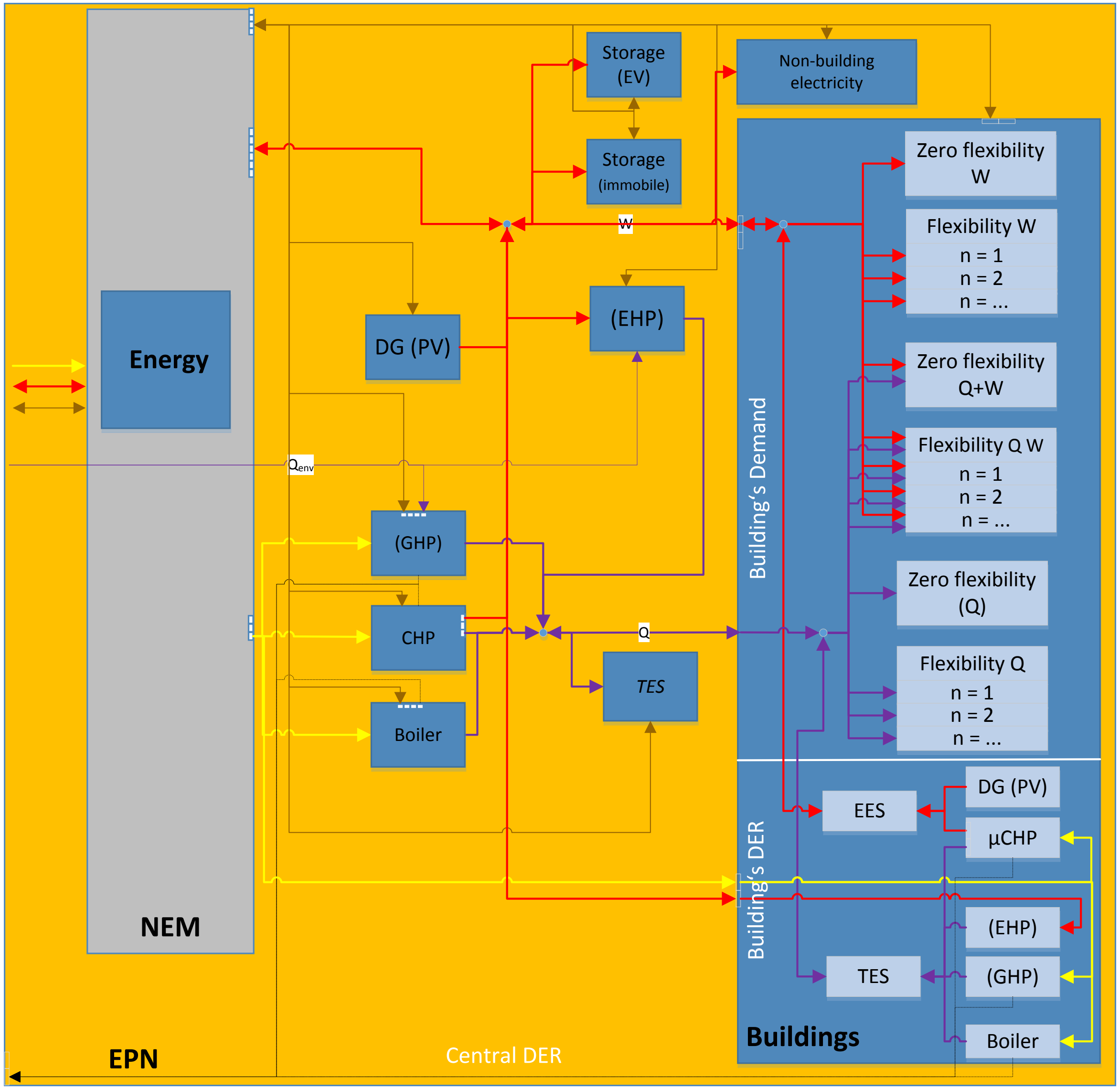
Sum of cash		Actor 2	Payment						
		Retailer - Aggregator					TSO	EPN	
Actor 1	Good/Service	BSUoS fee	DUoS fee	Payment for electricity	TUoS fee	Payment for gas	Payment for electricity	Payment for electricity	Payment for gas
DSO	Distribution network operation and maintenance		■						
Producer	Electricity (BM market)						■		
	Electricity (wholesale market)			■					
	Electricity (imbalance market)						■		
Retailer-Aggregator	Electricity (BM market)						■		
	Electricity (retail market)							■	
	Electricity (imbalance market)						■		
	Gas								■
TSO	Balanced system	■							
	Transmission network operation and maintenance				■				
Gas supplier	Gas					■			

Actors

Internal actors



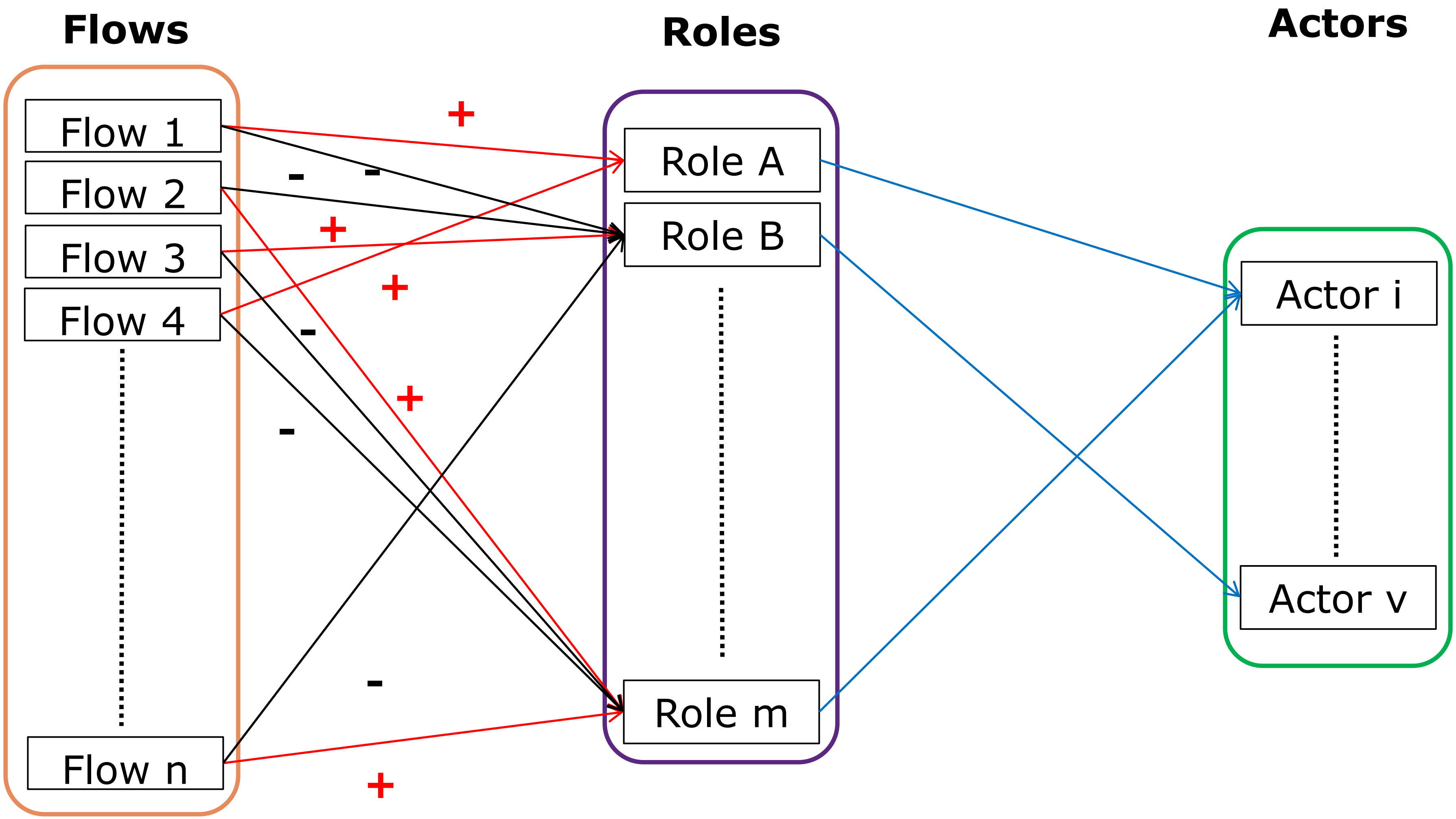
Internal EPN physical mapping



Internal market framework

- Internal market frameworks determines how value and costs are allocated within the distributed systems (e.g., a district, a microgrid, an aggregator's portfolio)
  - Tariffs, contracts, etc
  - Ownership options for enabling equipment
  - Crucial for boosting participation and investment decisions

How do we "align" services, share benefits and reduce fixed and transaction costs? *Flow-Role-Actor mapping*



Market and contractual arrangements:

Service activation and benefit re-allocation in external actors

- Benefits may need to be re-allocated amongst actors for some business cases, in order to compensate some actors for lost revenue

- (Fixed) costs can also be shared between actors

	Actor 1	Actor 2	Actor 3	Actor 4	Actor 5	Actor 6	Actor 7	Actor 8
Actor 1	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Actor 2	0.80	1.00	0.00	0.00	0.00	0.30	0.00	0.00
Actor 3	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Actor 4	0.00	0.00	0.00	1.00	0.00	0.10	0.00	0.00
Actor 5	0.00	0.00	0.00	0.00	1.00	0.20	0.00	0.00
Actor 6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Actor 7	0.00	0.00	0.00	0.00	0.00	0.40	1.00	0.00
Actor 8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Example: DNO, TSO and suppliers

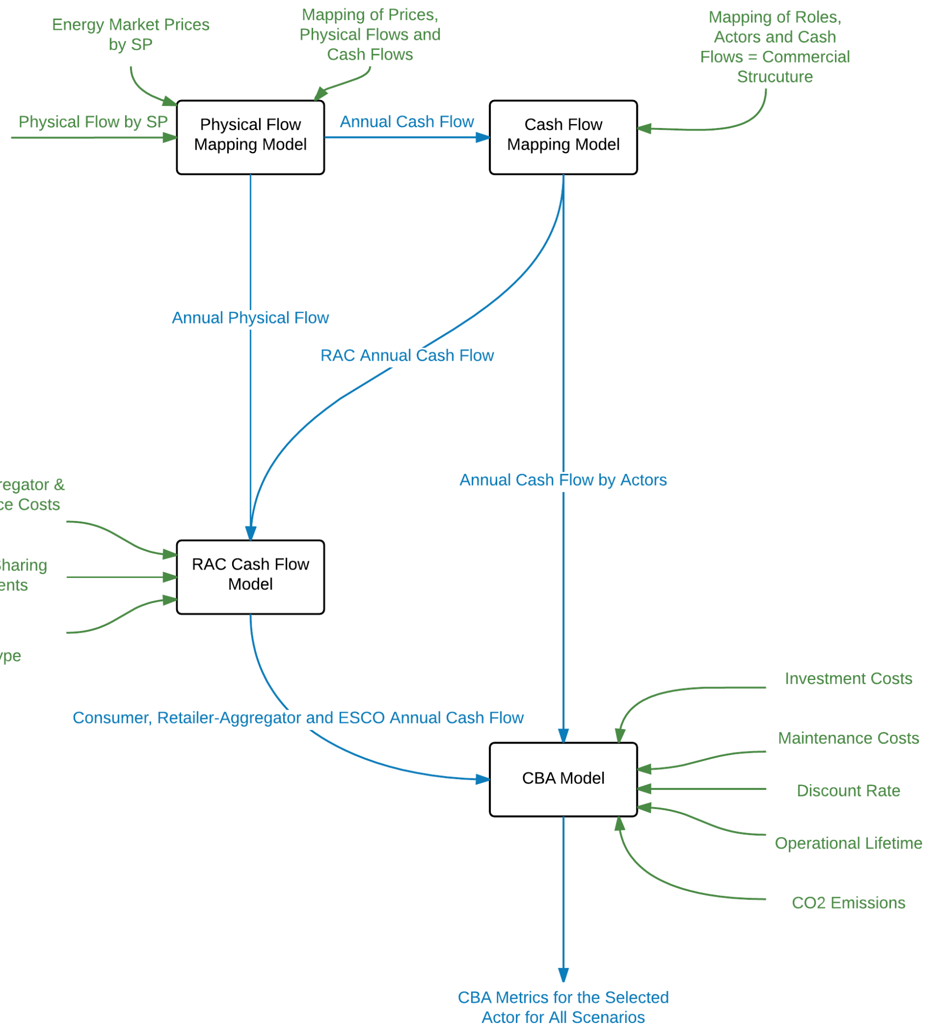
-> *Share* or *alignment* of the services?

Cost Benefit Analysis (CBA) model

Steps

1. Operational costs for each actor derived from the mapping method (ultimately from the employed model)
2. Investment costs specified per actor
3. Discount rates applied by actor, enabling the variance in cost of capital for different actors to be appreciated
4. Distribution of the benefits of flexibility can be shared amongst actors according to user prescription

Business Case Modelling Flow Chart



RAC=Retailer, Aggregator, Consumers

Figure courtesy of Mr Christopher Heltorp

Developing a multi-temporal framework for district energy system investment under uncertainty

- Short term (days) and medium term (months) time frames
  - Small scale uncertainties
    - Probabilistic analysis (e.g., Monte Carlo simulations)
- Long term time frame (many years, planning horizon)
  - Large scale uncertainty
    - Scenario-based
    - Multi-parametric scenario analysis ("stationariety")
    - Robust optimization/Decision theory ("worst case")

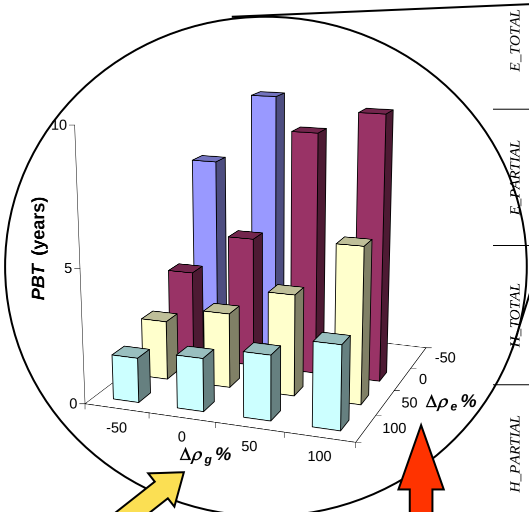
E.Carpaneto, G.Chicco, P.Mancarella, and A.Russo,
Cogeneration planning under uncertainty.
Part I: Multiple time frame approach,
Applied Energy, Vol. 88, Issue 4, April 2011, Pages 1059-1067

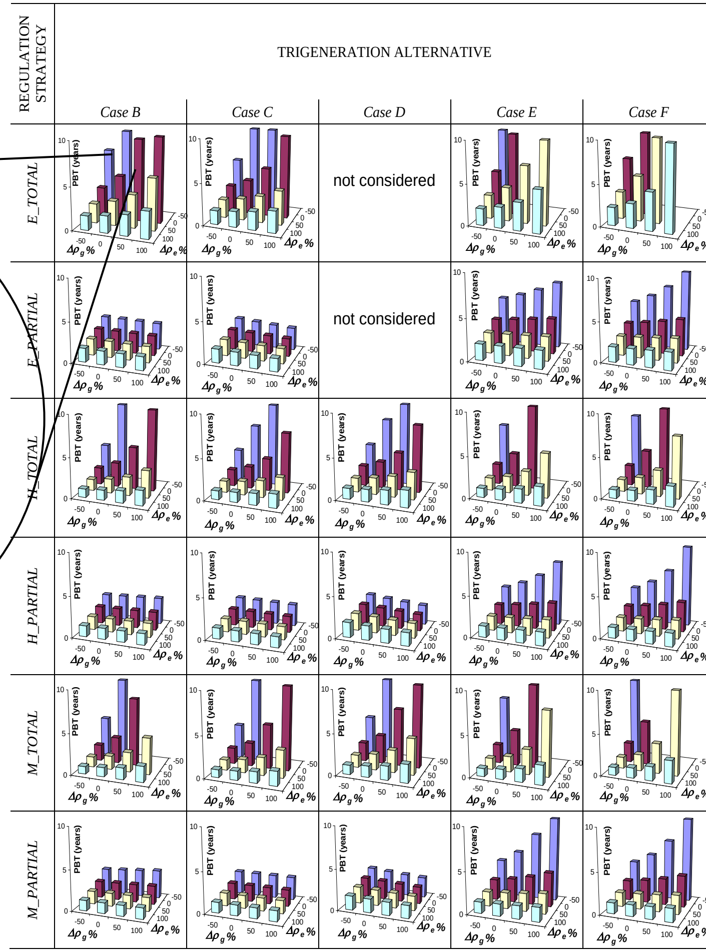
E.Carpaneto, G.Chicco, P.Mancarella, and A.Russo,
Cogeneration planning under uncertainty.
Part II: Decision theory-based assessment of planning alternatives,
Applied Energy, Vol. 88, Issue 4, April 2011, Pages 1075-1083

Coping with uncertainty in planning: multi-parametric sensitivity analysis (looking for scenario “stationariety”)

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

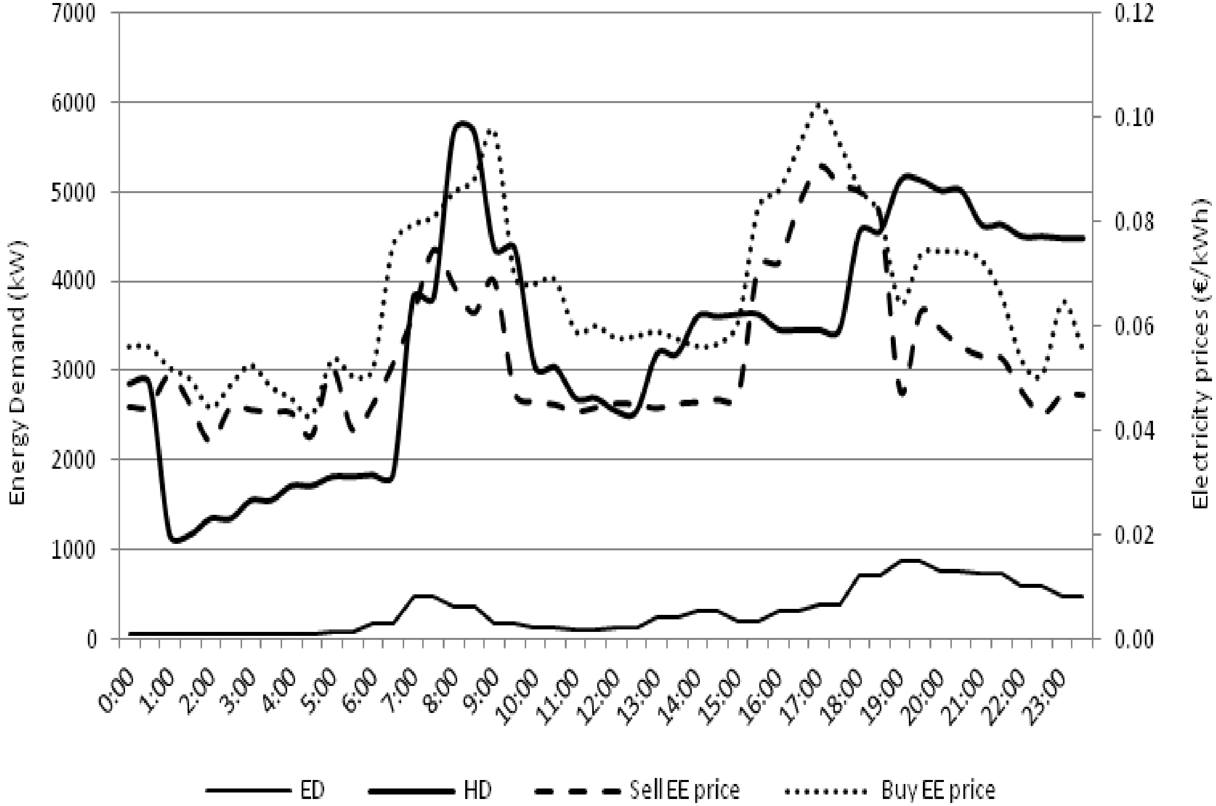
Business case in smart multi-energy systems: example of district energy system

- A district energy system supplying 1000 customers
- The system can comprise EHP, CHP and TES technologies
  - EHP have a COP of 3.0
  - CHP have a 35% and 45% electrical and thermal efficiency respectively
  - Boilers have an efficiency of 85%

Demand	Average power	Peak power	Yearly consumption
Electrical	293kW	872kW	2567MWh
Thermal	1798kW	5672kW	15753MWh

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

Operational flexibility: example

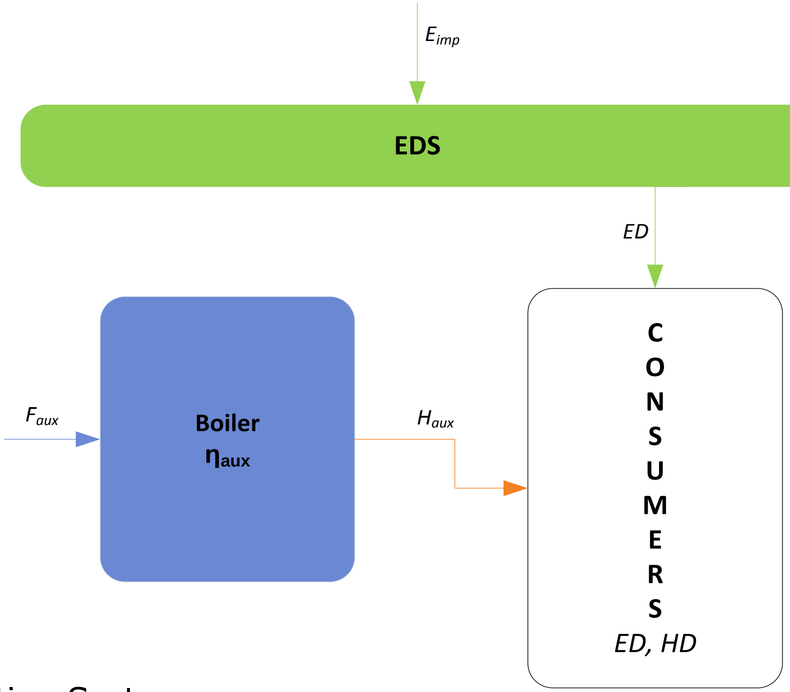


- Short term variability of electricity and gas prices
- Heat and electricity demand modelled with hourly profiles for typical days (four profiles)

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

Today - Inflexible

- Separate energy vector production
- How efficient is this? How flexible is this?



EDS = Electricity Distribution System

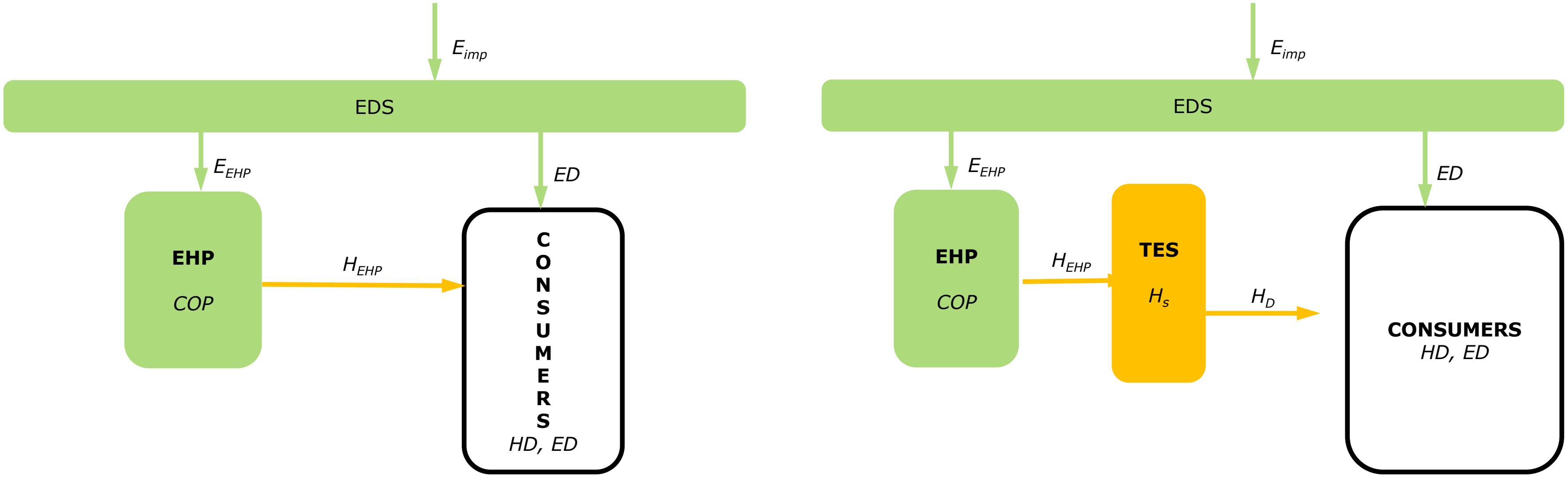
ED = Electricity Demand

HD = Heat Demand

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

Tomorrow – How flexible?

- All-electric future
- More efficient? How renewable?
- How flexible?



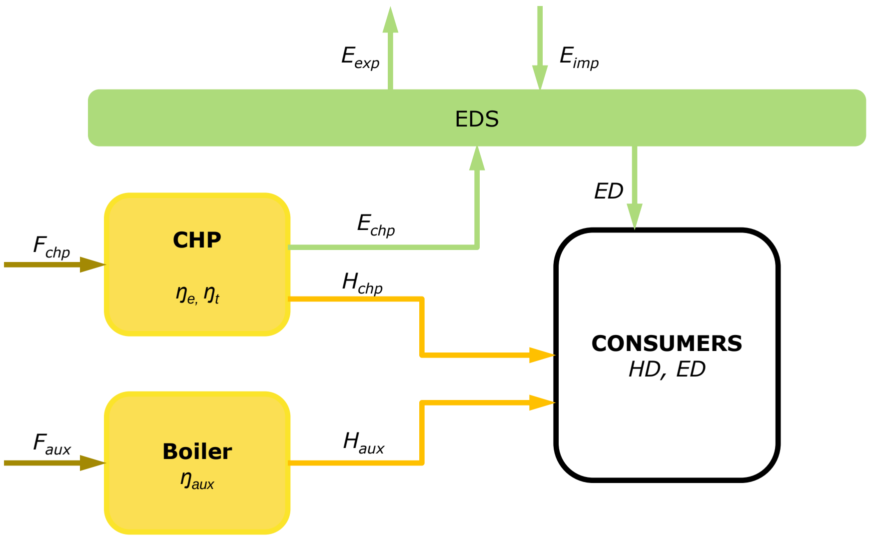
EHP = Electric Heat Pump

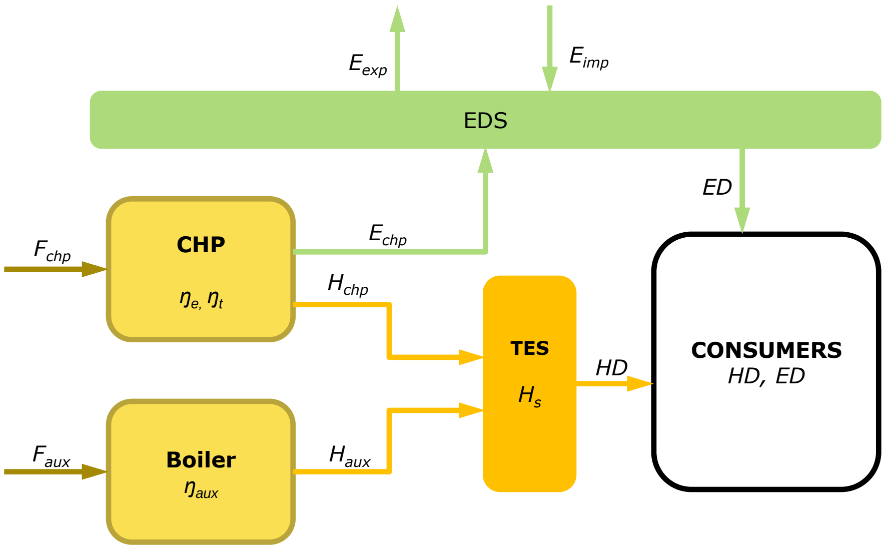
COP = Coefficient of Performance

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

Today – How flexible?

- Cogeneration, in case coupled with TES
- Flexible response
  - Depends on the size of the storage





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

“Static” optimal solution

	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6	TYPE 7
CHP (kW)				4000	3000	2500	2000
Electrical efficiency				0.35	0.35	0.35	0.35
Thermal efficiency				0.45	0.45	0.45	0.45
Boiler (kW)	6000	6000	6000	6000	6000	6000	6000
Boiler efficiency	0.85	0.85	0.85	0.85	0.85	0.85	0.85
TES (m^3)			200		200		200
EHP (kW_{th})		5000	3000			2000	2000
COP		3.0	3.0			3.0	3.0

TYPE 1 = Boiler

TYPE 2 = EHP

TYPE 3 = EHP+TES

TYPE 4 = CHP

TYPE 5 = CHP+TES

TYPE 6 = CHP+EHP

TYPE 7 = CHP+EHP+TES

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

Economic analysis: results and value of operational flexibility

- Optimal operation in a day-ahead market

DMG type		Operational cost (€/year)	Δcost wrt Type 1 (%)
Type 1	*Boiler (reference)*	625,440	---
Type 2	EHP	479,599	-23%
Type 3	EHP+TES	445,660	-29%
Type 4	CHP	462,691	-26%
Type 5	CHP+TES	422,436	-32%
Type 6	CHP+EHP	342,684	-45%
Type 7	***CHP+EHP+TES***	312,198	***-50%***

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

“Static” economic analysis: base case investment

	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6	TYPE 7
CHP (kW)				4000	3000	2500	2000
Electrical efficiency				0.35	0.35	0.35	0.35
Thermal efficiency				0.45	0.45	0.45	0.45
Boiler (kW)	6000	6000	6000	6000	6000	6000	6000
Boiler efficiency	0.85	0.85	0.85	0.85	0.85	0.85	0.85
TES (m^3)			200		200		200
EHP (kW_{th})		5000	3000			2000	2000
COP		3.0	3.0			3.0	3.0

CHP (€/kWh_e)	600
EHP (€/kWh_t)	240
TES (€/m^3)	840
O&M (€/MWh)	8
Discount rate (%)	3-10
Investment period (years)	15

TYPE 1 = Boiler

TYPE 2 = EHP

TYPE 3 = EHP+TES

TYPE 4 = CHP

TYPE 5 = CHP+TES

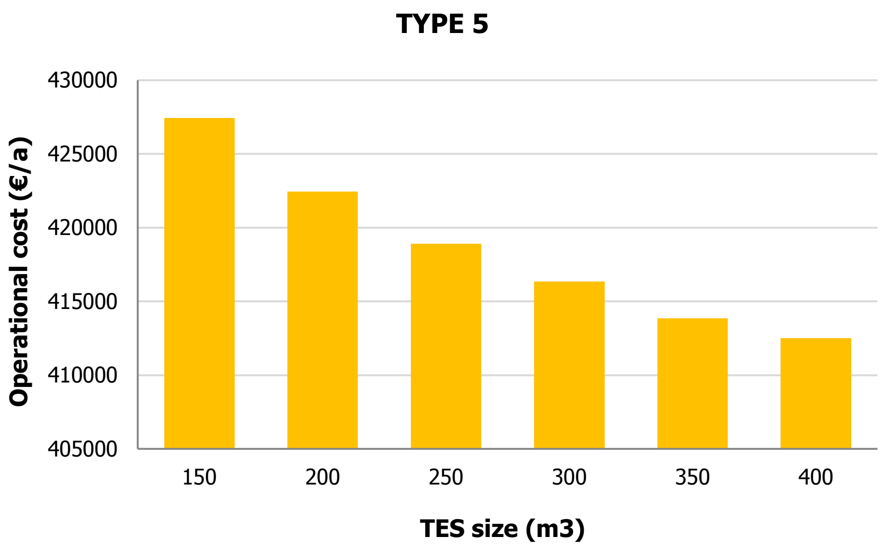
TYPE 6 = CHP+EHP

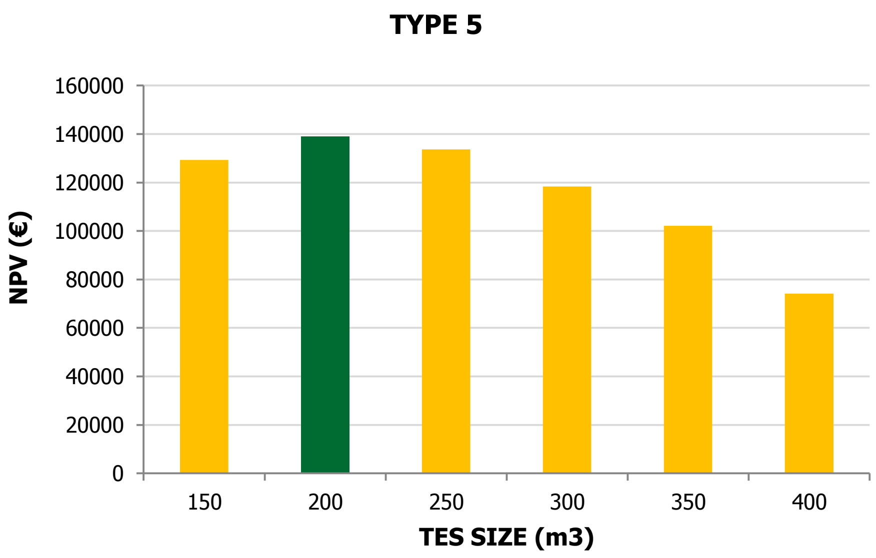
TYPE 7 = CHP+EHP+TES

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

Investment analysis: sensitivity to DMG sizes

- Larger storage – lower operational cost
- Optimal size as a trade-off between operational cost and investment

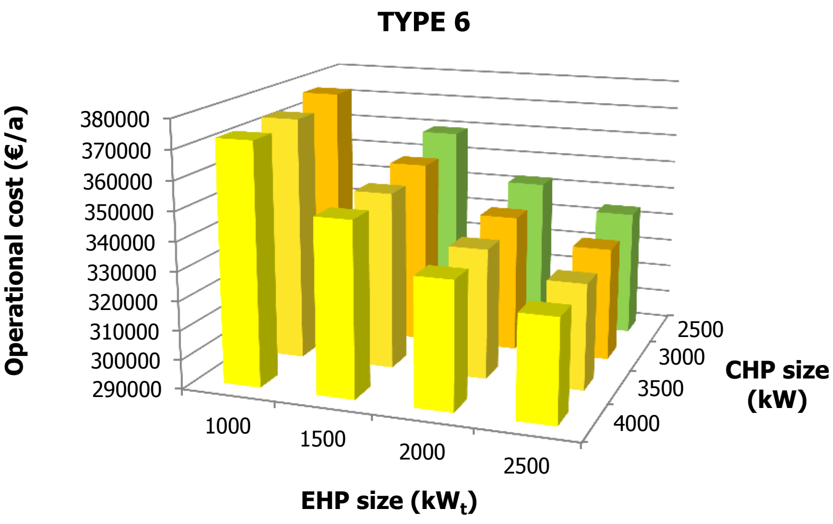


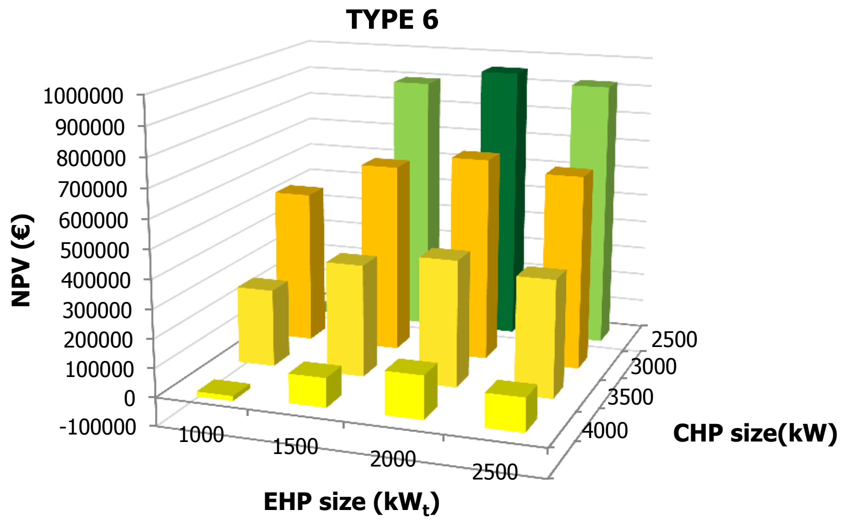


T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

Investment analysis: sensitivity to DMG sizes

- Thermal power ratio CHP:EHP ≈ 1:1
- Significant NPV differences for different CHP and EHP sizes
- Flexible, lower operation cost than type 5, higher NPV

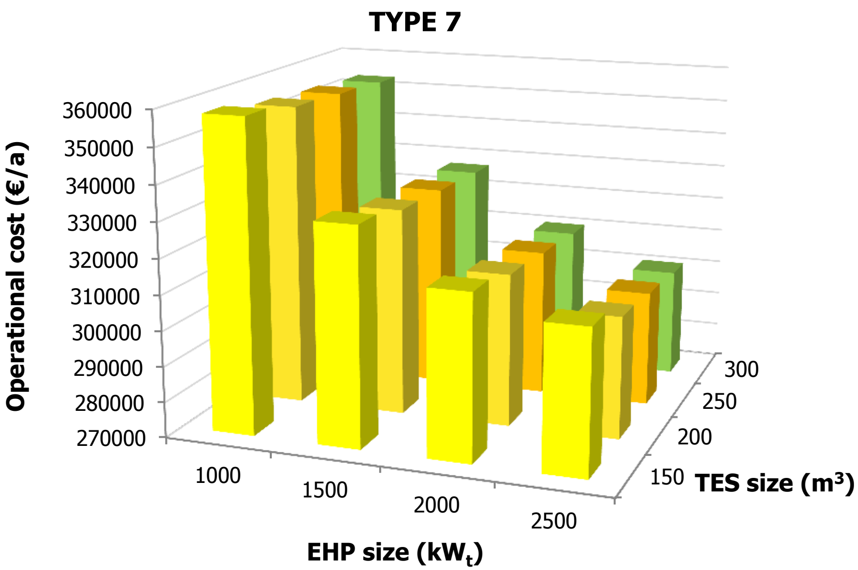


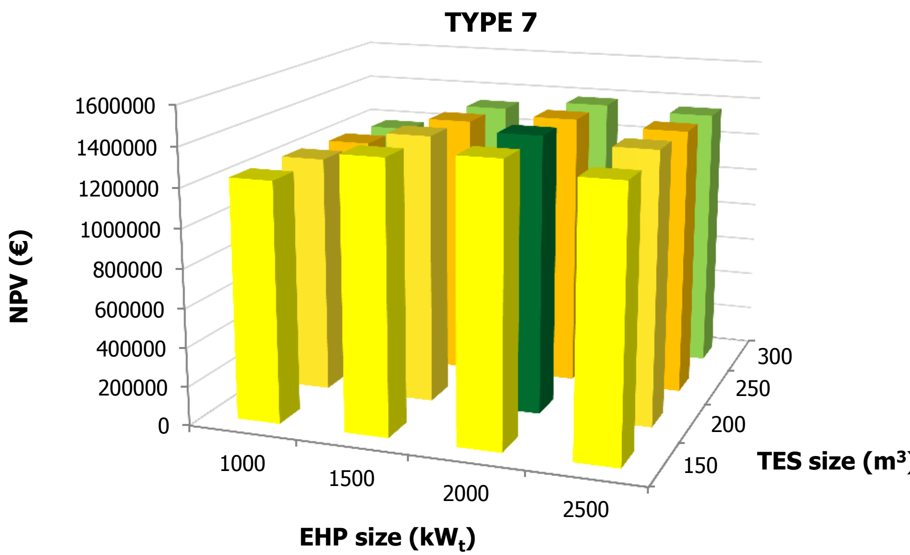


T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

Investment analysis: sensitivity to DMG sizes

- Unit coupling
- Best characteristics of each unit

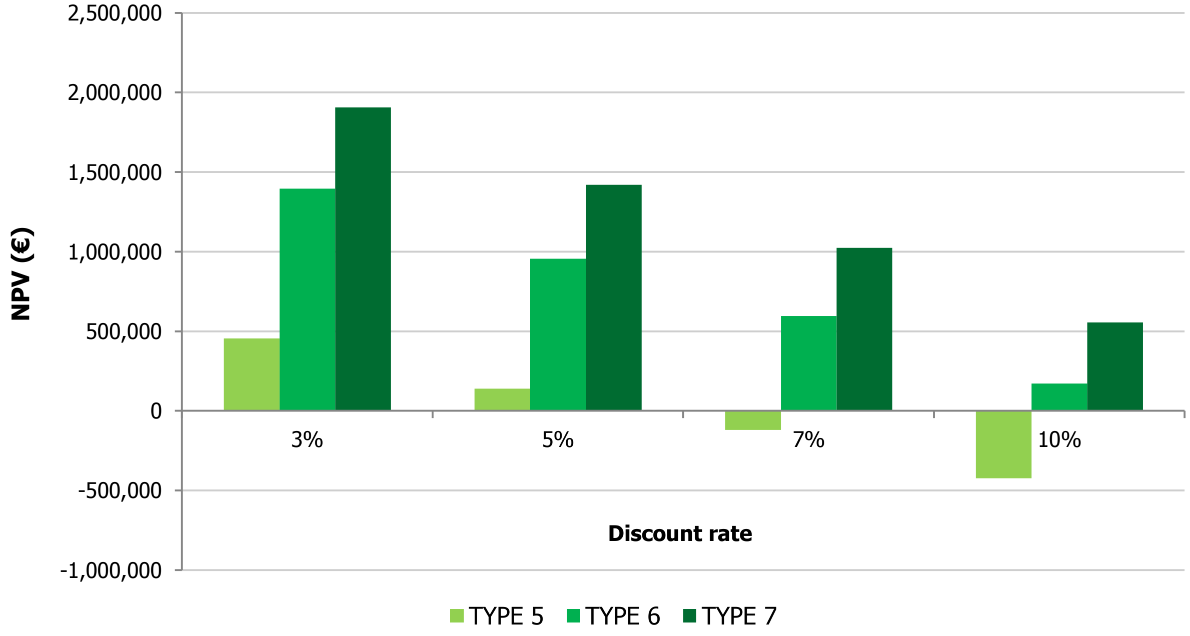




T. Capuder and P. Mancarella, Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options, Energy, 2014

“Static” investment analysis: sensitivity to discount rates

- Higher NPV (wrt reference case) for type 6 and type 7 units
- Faster return of investment
- Less sensitive to higher discount rates



TYPE 1 = Boiler

TYPE 2 = EHP

TYPE 3 = EHP+TES

TYPE 4 = CHP

TYPE 5 = CHP+TES

TYPE 6 = CHP+EHP

TYPE 7 = CHP+EHP+TES

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

Flexibility-in-planning a multi-energy system

- Studies based on a deterministic price model
  - What if things change throughout the lifetime?
- Underlying uncertainties
- Robustness or flexibility?

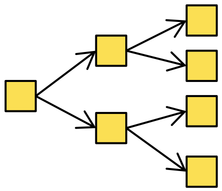
Flexibility to cope with uncertainty in planning: stochastic optimization and Real Options

1. Sensitivity analysis

Scenario modelling → Energy system design optimisation

List of potential designs (upgrades) for the district energy system

2. Stochastic design optimisation



E.A. Martinez-Cesena, T. Capuder and P. Mancarella, Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty, *IEEE Transactions on Smart Grid*, 2015

Flexible multi-energy system expansion

- How much the lifetime feasibility of a multi-energy system change with the underlying uncertain inputs (prices)?
- How "flexible-in-planning" is a multi-energy system?
- How can we analyse optimal (evolving) investment decisions based on a range of scenarios?
- Research objectives:
  – Examine existing philosophies for the assessment of investment decisions considering uncertainty
  – Explore traditional and "flexible" (options-based) philosophies

E.A. Martinez-Cesena, T. Capuder and P. Mancarella, Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty, *IEEE Transactions on Smart Grid*, 2015

Case study example

- Long term uncertainties in electricity and gas prices are modelled using scenarios for 50%, 100%, 150% and 200% of their current value (16 combinations)
- EHP, CHP and TES capacity can be upgraded by multiples of 500kWt, 500kWe and 50m^3, respectively
- The maximum capacities considered for EHP, CHP and TES are 5500 kW, 5000kW and 750m^3 (795 combinations)

Note: This example is a simplified version of the model and examples found in "E.A. Martinez-Cesena, T. Capuder and P. Mancarella, Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty, *IEEE Transactions on Smart Grid*, 2015"

Results: *Investments in deterministic scenarios (1)*

Optimal investment matrix

Gas	Electricity price								
Price		50%		100%		150%		200%	
50%	EHP	2000	£3.5M	0	£3.1M	0	£0.3M	0	-£2M
	CHP	0		2500		3500		4000	
	TES	100		250		450		650	
100%	EHP	3500	£3.8M	2500	£5.8M	1000	£5.5M	0	£2.7M
	CHP	0		1000		3000		4000	
	TES	400		200		300		650	
150%	EHP	3500	£3.9M	4000	£6.4M	2500	£7.9M	2000	£7.6M
	CHP	0		0		1500		3000	
	TES	450		550		250		350	
200%	EHP	3500	£3.9M	4000	£6.5M	3500	£8.8M	3000	£9.8M
	CHP	0		0		1000		1500	
	TES	500		600		300		300	

Results: *Investments in deterministic scenarios (2)*

- Storage can provide EHP and/or CHP flexibility to operate based on profits maximisation schedules rather than demand driven schedules
- **EHP coupled with storage becomes an attractive option when gas prices are high**

Results: *Investments in deterministic scenarios (3)*

Optimal investment matrix

Gas	Electricity price								
Price		50%		100%		150%		200%	
50%	EHP	2000	£3.5M	0	£3.1M	0	£0.3M	0	-£2M
	CHP	0		2500		3500		4000	
	TES	100		250		450		650	
100%	EHP	3500	£3.8M	2500	£5.8M	1000	£5.5M	0	£2.7M
	CHP	0		1000		3000		4000	
	TES	400		200		300		650	
150%	EHP	3500	£3.9M	4000	£6.4M	2500	£7.9M	2000	£7.6M
	CHP	0		0		1500		3000	
	TES	450		550		250		350	
200%	**EHP**	**3500**	**£3.9M**	4000	£6.5M	3500	£8.8M	3000	£9.8M
	CHP	**0**		0		1000		1500	
	TES	**500**		600		300		300	

Results: *Investments in deterministic scenarios (4)*

- Storage can provide EHP and/or CHP flexibility to operate based on profits maximisation schedules rather than demand driven schedules
- EHP coupled with storage becomes an attractive option when gas prices are high
- **CHP coupled with storage are an attractive alternative when electricity prices are high**

Results: *Investments in deterministic scenarios (5)*

Optimal investment matrix

Gas	Electricity price								
Price		**50%**		**100%**		**150%**		**200%**	
50%	EHP	2000	£3.5M	0	£3.1M	0	£0.3M	**0**	**-£2M**
	CHP	0		2500		3500		**4000**	
	TES	100		250		450		**650**	
100%	EHP	3500	£3.8M	2500	£5.8M	1000	£5.5M	0	£2.7M
	CHP	0		1000		3000		4000	
	TES	400		200		300		650	
150%	EHP	3500	£3.9M	4000	£6.4M	2500	£7.9M	2000	£7.6M
	CHP	0		0		1500		3000	
	TES	450		550		250		350	
200%	EHP	3500	£3.9M	4000	£6.5M	3500	£8.8M	3000	£9.8M
	CHP	0		0		1000		1500	
	TES	500		600		300		300	

Results: *Investments in deterministic scenarios (6)*

- Storage can provide EHP and/or CHP flexibility to operate based on profits maximisation schedules rather than demand driven schedules
- EHP coupled with storage becomes an attractive option when gas prices are high
- CHP coupled with storage are an attractive alternative when electricity prices are high
- **A system with both EHP and CHP coupled with storage becomes attractive when electricity and gas prices are high**

Results: *Investments in deterministic scenarios (7)*

Optimal investment matrix

Gas	Electricity price								
Price		50%		100%		150%		200%	
50%	EHP	2000	£3.5M	0	£3.1M	0	£0.3M	0	-£2M
	CHP	0		2500		3500		4000	
	TES	100		250		450		650	
100%	EHP	3500	£3.8M	2500	£5.8M	1000	£5.5M	0	£2.7M
	CHP	0		1000		3000		4000	
	TES	400		200		300		650	
150%	EHP	3500	£3.9M	4000	£6.4M	**2500**	**£7.9M**	**2000**	**£7.6M**
	CHP	0		0		**1500**		**3000**	
	TES	450		550		**250**		**350**	
200%	EHP	3500	£3.9M	4000	£6.5M	**3500**	**£8.8M**	**3000**	**£9.8M**
	CHP	0		0		**1000**		**1500**	
	TES	500		600		**300**		**300**	

Results: *Investments in deterministic scenarios (8)*

Gas price	Electricity price				
		50%	**100%**	**150%**	**200%**
50%	Do nothing	£3.93M	£4.94M	£5.95M	£6.96M
	Optimum	£3.51M	£3.10M	£0.35M	-£2.64M
	Difference	**10%**	**37%**	**94%**	**138%**
100%	Do nothing	£6.82M	£7.83M	£8.84M	£9.85M
	Optimum	£3.88M	£5.88M	£5.58M	£2.76M
	Difference	**43%**	**25%**	**37%**	**72%**
150%	Do nothing	£9.70M	£10.71M	£11.72M	£12.73M
	Optimum	£3.91M	£6.46M	£7.94M	£7.64M
	Difference	**60%**	**40%**	**32%**	**40%**
200%	Do nothing	£12.59M	£13.60M	£14.61M	£15.62M
	Optimum	£3.93M	£6.50M	£8.87M	£9.85M
	Difference	**69%**	**52%**	**39%**	**37%**

Uncertainty study: *Generalities*

- In practice, the environment of the district energy system is likely to change throughout time
- Accordingly, investment decisions have to be optimised not only based on a single scenario, but on a range of possible path-dependent scenarios
- How do I evolve/expand through uncertainties?
- Investment optimisation under uncertainty
  - traditional discounted cash flow techniques
  - options based approaches

Uncertainty study: *Traditional philosophy*

Traditional investment philosophy is modelled in two manners:

1. *Standard*: A single investment at the beginning of the project is considered (now or never decision)
2. *Staged*: Additional investments can be made in subsequent periods

Characteristics:

- Easy to perform
- Provides good investments if the future does not diverge far from the forecasts
- However, it can result in poor investments if the future diverges far from the forecasts

Uncertainty study: *Options based philosophy (1)*

Investments are made based on their value and flexibility to be adjusted in potential future scenarios

Characteristics:

- Produces highly flexible investments that tend to be financially sound on most potential future scenarios
- Can produce suboptimal investment decision when uncertainty is overestimated
- Flexible investments are preferred over robust ones

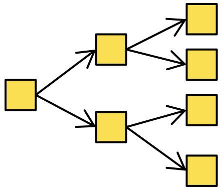
Uncertainty study: *Options based philosophy (2)*

1. Sensitivity analysis

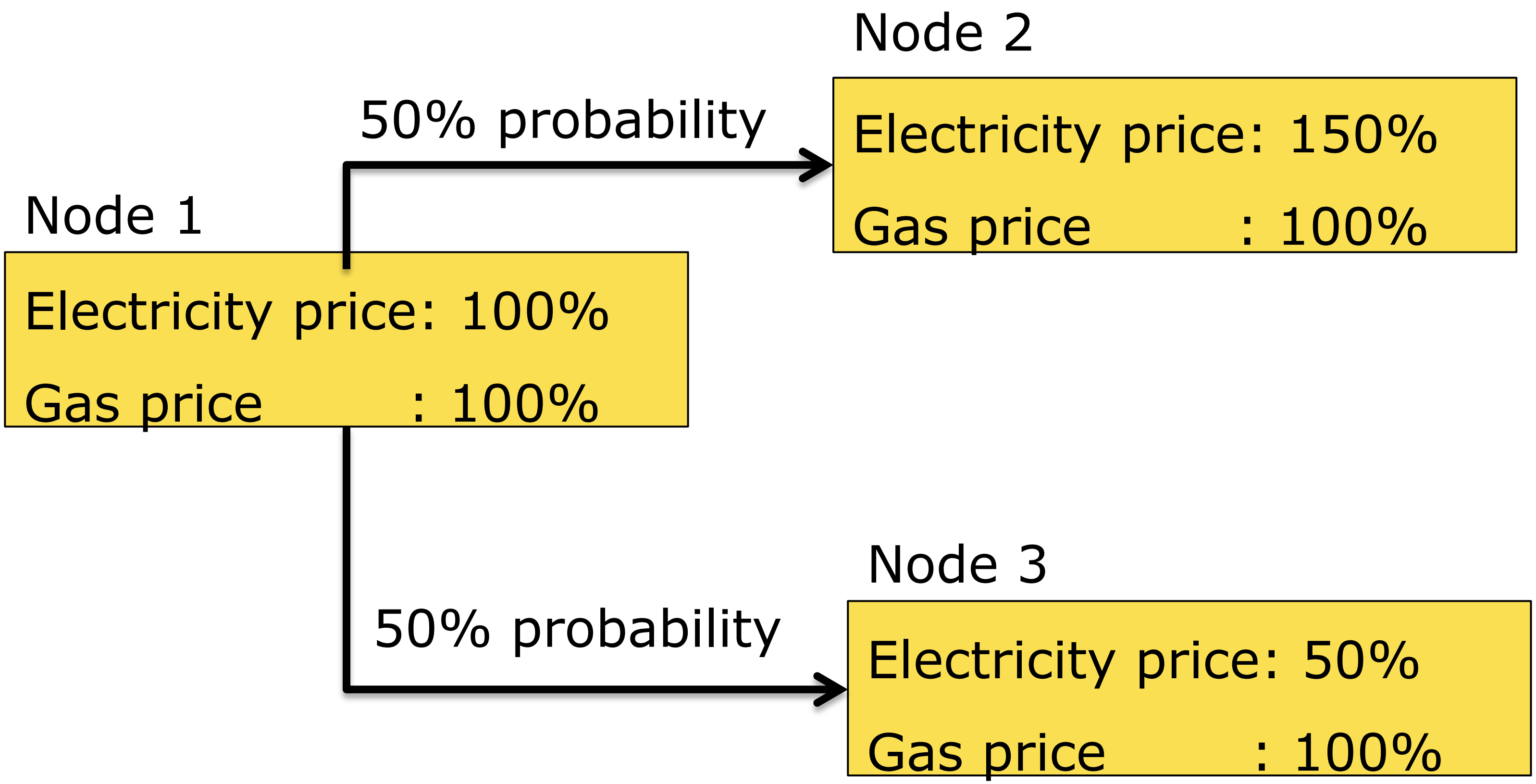
Scenario modelling → District system design optimisation

List of potential designs (upgrades) for the district energy system

2. Stochastic design optimisation



Example : *Scenario tree*



Example: *Some design alternatives*

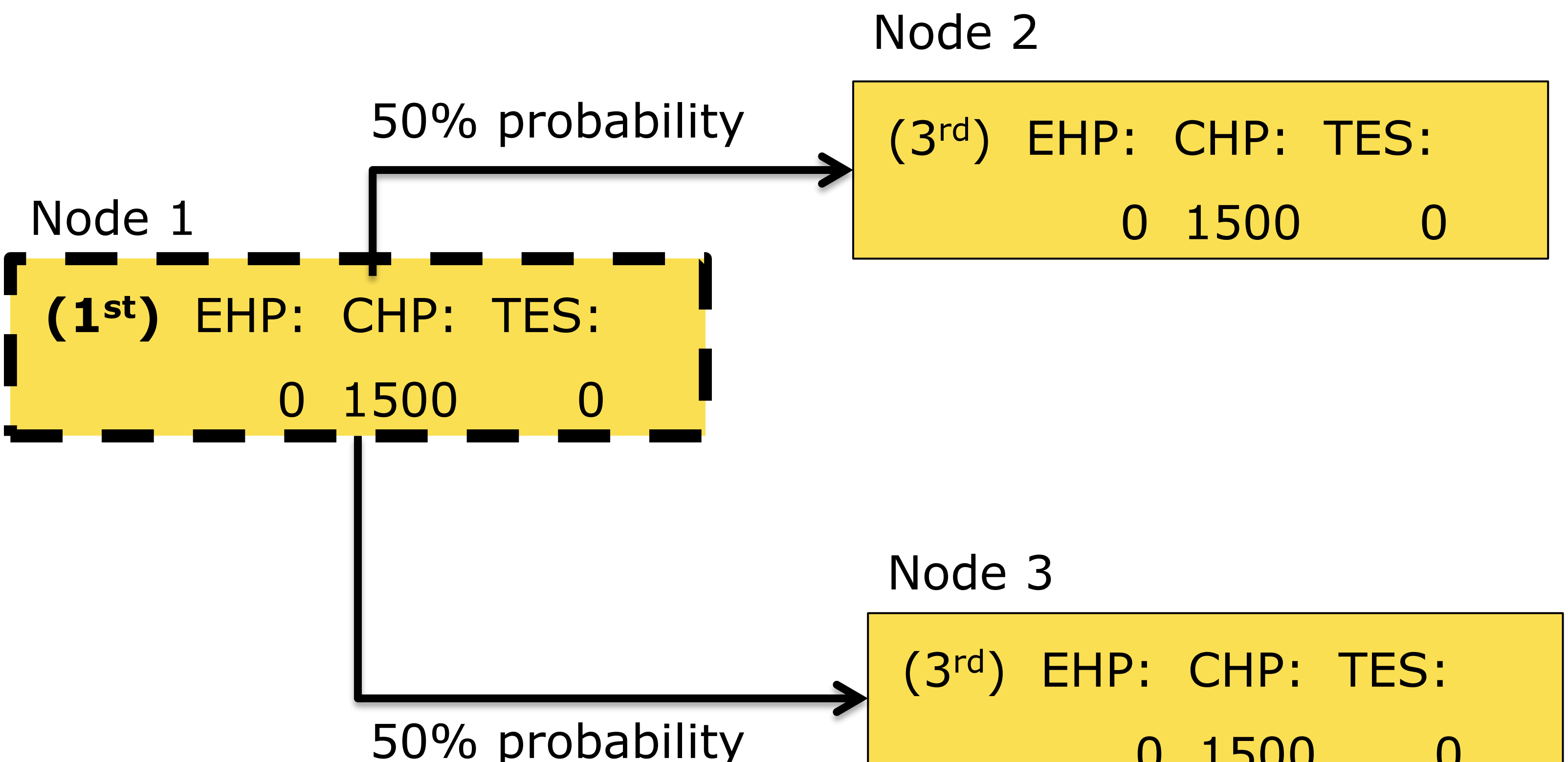
#	Design			Cost		
	EHP (kW)	CHP (kW)	TES (m^3)	Node 1	Node 2	Node 3
1	0	0	0	£10.1M (2nd)	£5.7M (5th)	£4.4M (2nd)
2	1000	0	0	£12.3M (3rd)	£5.5M (4th)	£10.2M (4th)
3	3500	0	400	£17.2M (5th)	£10.8M (6th)	**£2.5M (1st)**
4	0	1500	0	**£9.3M (1st)**	£4.3M (3rd)	£4.8M (3rd)
5	0	2500	150	£15.7M (4th)	£11.1M (7th)	£11.1M (5th)
6	1000	3000	0	£18.6M (7th)	£4.0M (2nd)	£11.3M (6th)
7	1000	3000	300	£18.5M (6th)	**£3.5M (1st)**	£11.5M (7th)

Example: *Traditional investment scheme (1)*

- This scheme seeks the best “now or never” investment
- In this example, it is the 1st rank solution for node one considering that node two or node three will materialize in the future
- The investment decision is optimal for node one
  – However, it is sub-optimal for other nodes

Example: *Traditional investment scheme (2)*

Expected discounted cost: *£9.3M*



Example: *Traditional investment scheme (staged) (1)*

- This scheme seeks the best “now or never” investment decisions in each node constrained to investments previously made
- Investment in node one remains the same (1^{st} rank)
- An investment is made in node two to reduce overall energy system costs
- A convenient investment cannot be made in node three due to the constraints imposed by previous decisions in node one

Example: *Traditional investment scheme (staged)* (2)

Expected discounted cost: *£8.9M*

Node 1

(1st) EHP: CHP: TES:

0 1500 0

50% probability

Node 2

(1st) EHP: CHP: TES:

1000 3000 300

50% probability

Node 3

(3rd) EHP: CHP: TES:

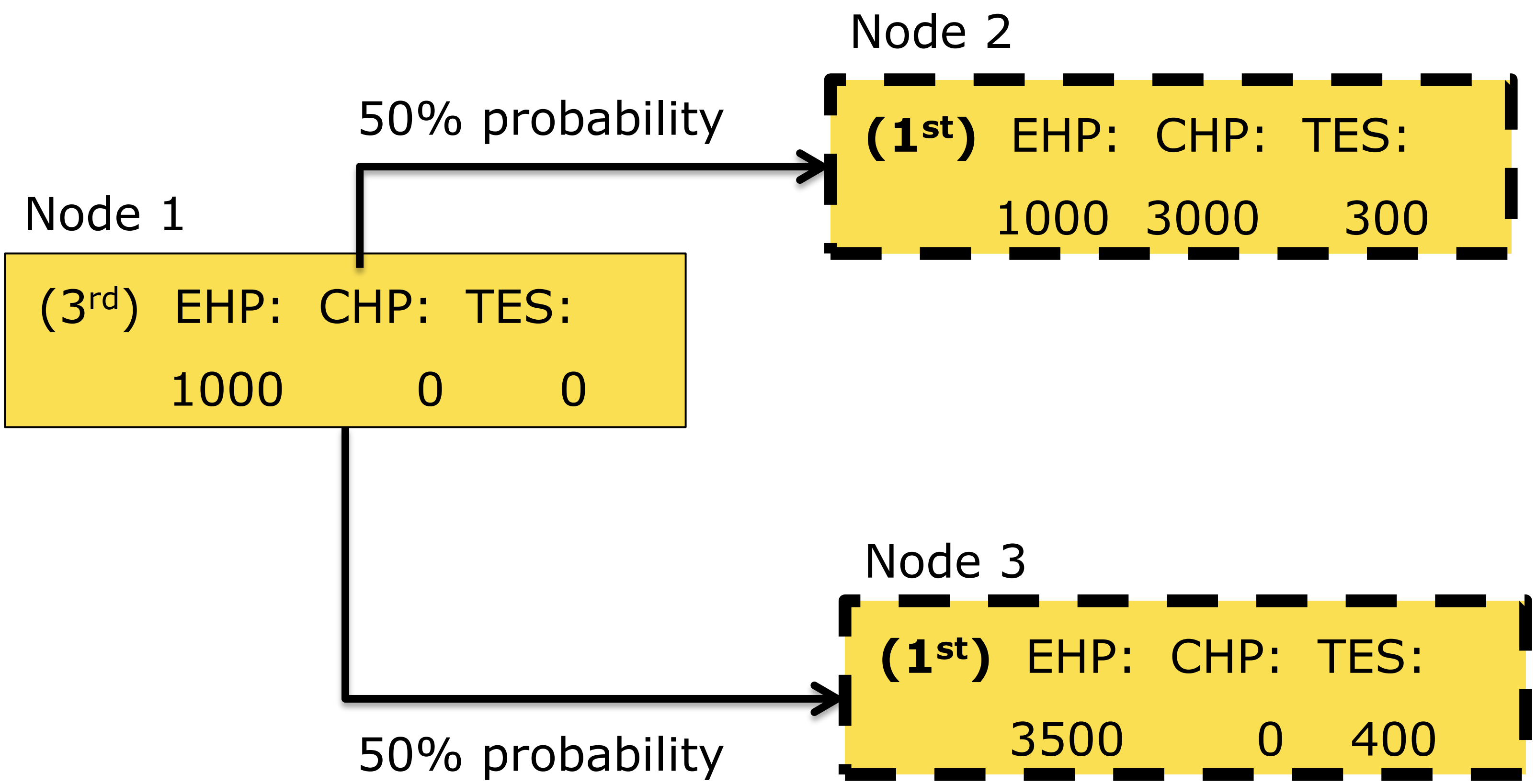
0 1500 0

Example: *Options based scheme (1)*

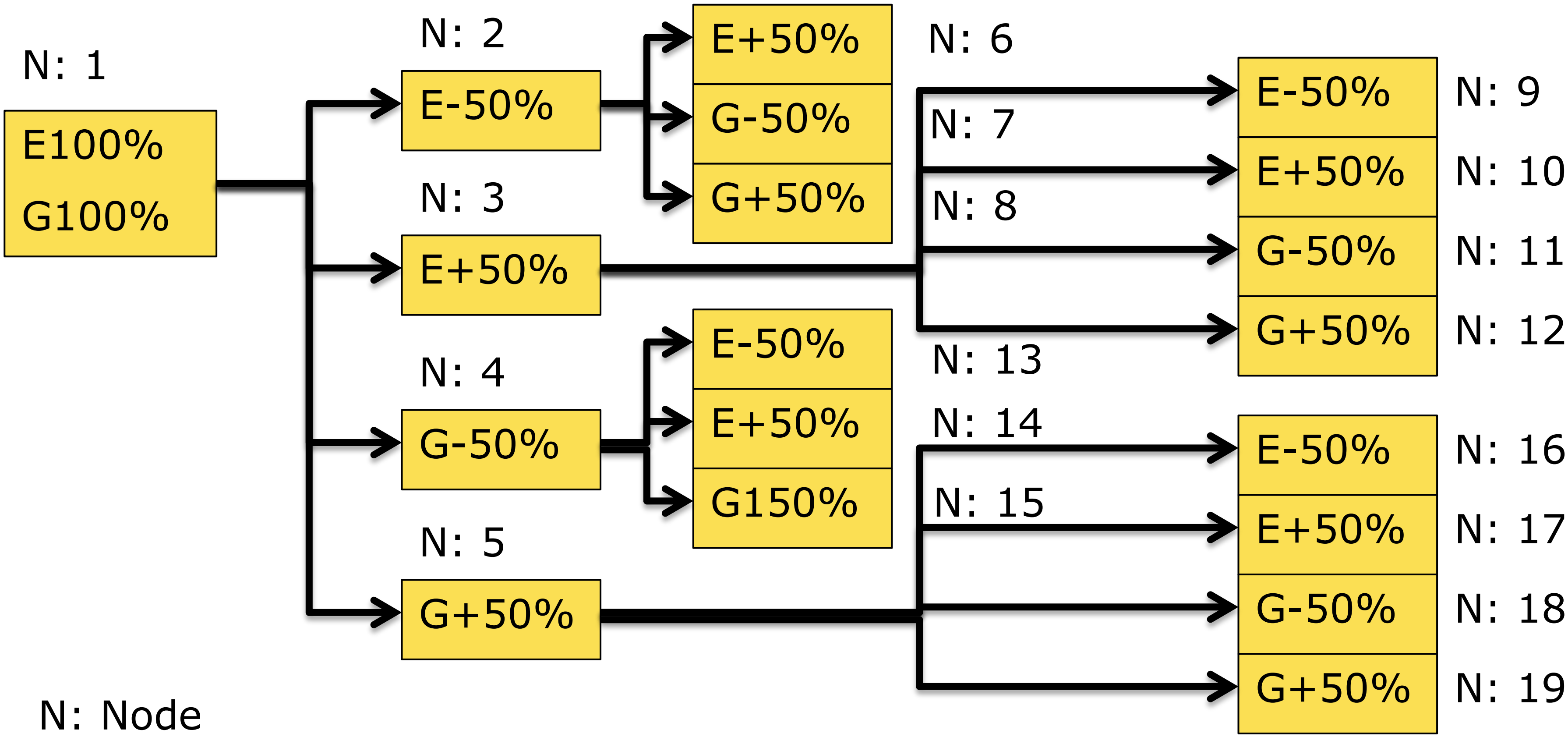
- This scheme seeks flexible investment decisions that can be adjusted in response to the evolution of uncertainty
- Instead of selecting the best solution for node one, the ***3rd*** best solution is chosen
- The solution can be upgraded to the ***1st*** rank investment in both node two and node tree

Example: *Options based scheme (2)*

Expected discounted cost: *£7.5M*



Case study: *Scenario tree*



N: Node

E: Electricity price

G: Gas price

Results: *System design and upgrades (1)*

	Node	Traditional			Options based		
		EHP	CHP	TES	EHP	CHP	TES
Stage 1	1	2500	1500	0	1500	1000	0
Stage 2	2	2500	1500	0	**2500**	1000	0
	3	2500	1500	0	1500	**1500**	**200**
	4	2500	1500	0	1500	**1500**	**150**
	5	**3500**	1500	**300**	**3000**	1000	**250**

Results: *System design and upgrades (2)*

Stage 3

N	**Traditional**			**Options based**		
	EHP	CHP	TES	EHP	CHP	TES
6	2500	1500	**250**	2500	1000	**250**
7	2500	1500	**100**	2500	1000	**100**
8	**3500**	1500	**450**	**3500**	1000	**450**
9	2500	1500	**250**	**2500**	1500	**250**
10	2500	1500	0	1500	**4000**	**600**
11	2500	**3000**	0	1500	**3500**	**450**
12	2500	1500	**300**	**2500**	1500	**300**
13	2500	1500	**100**	**2000**	1500	**150**
14	2500	**3000**	0	1500	**3500**	**450**
15	2500	1500	**250**	**2500**	1500	**250**
16	3500	1500	**450**	**3500**	1000	**450**
17	3500	1500	300	3000	**1500**	**300**
18	3500	1500	300	3000	1000	250
19	3500	1500	300	**3500**	1000	**300**

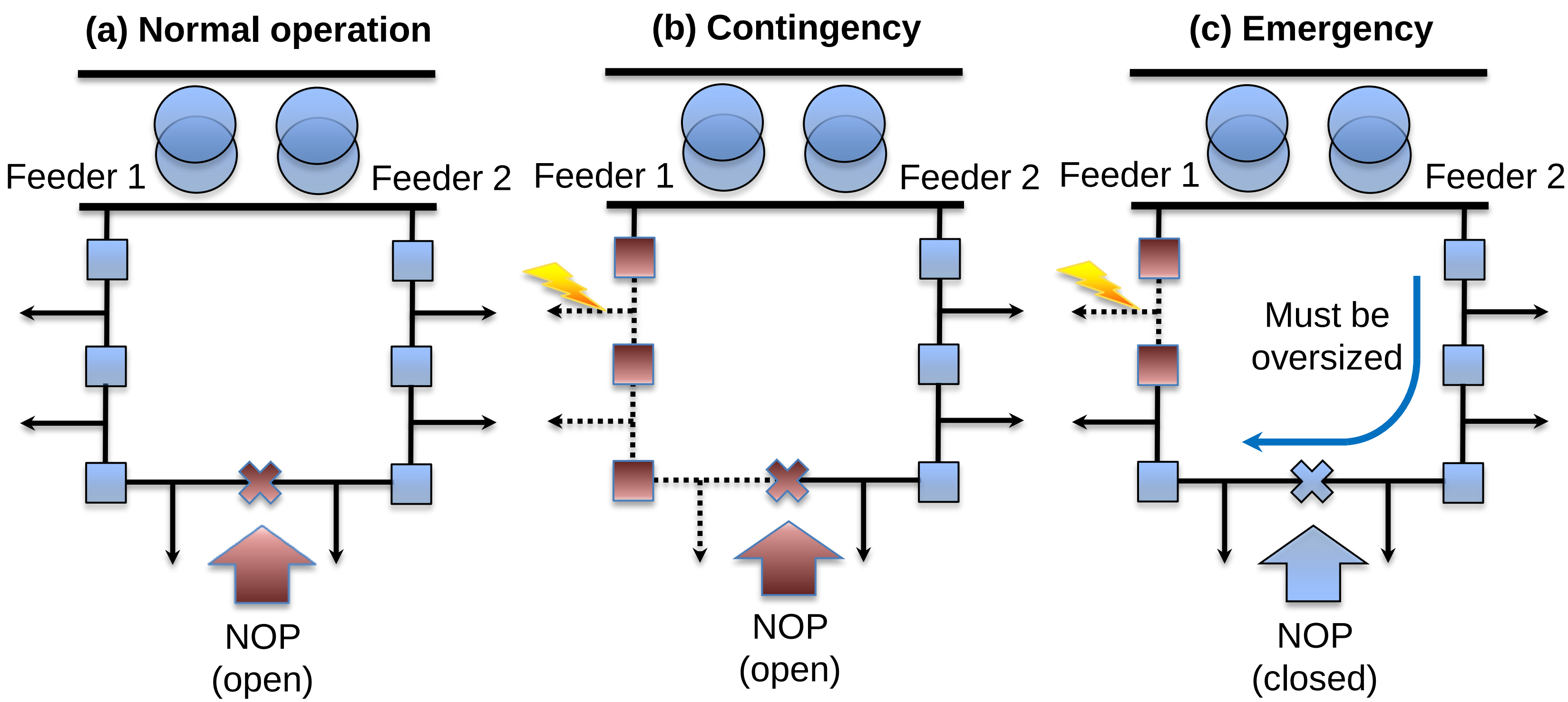
Results: *Expected cost*

Investment scheme	Expected discounted cost
Do nothing	£10.5 M
Traditional	£9.1 M
Traditional (staged)	£7.7 M
Options based	£6.5 M

For details: "E.A. Martinez-Cesena, T. Capuder and P. Mancarella, Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty, *IEEE Transactions on Smart Grid*, 2015"

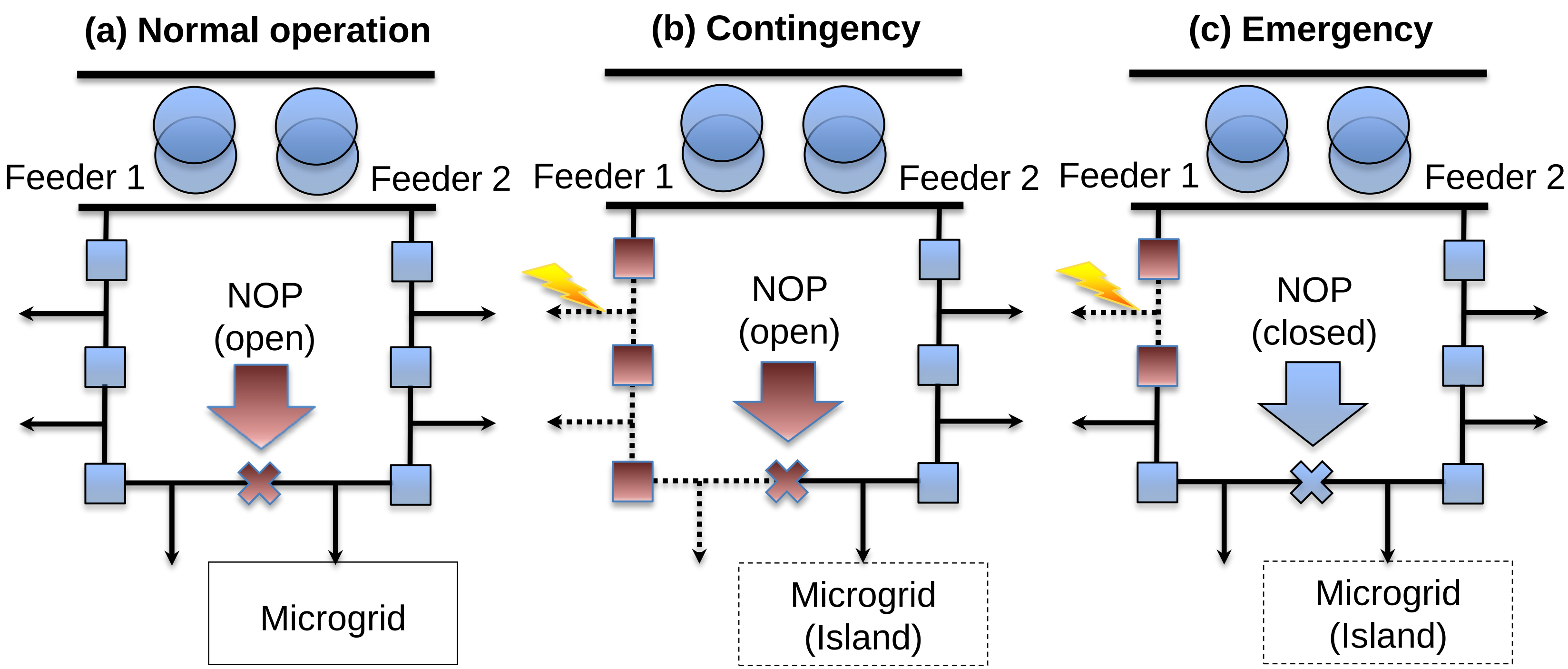
Boosting the business case – Distribution service (1/3)

- Distribution networks at the 11kV level are oversized to meet ~N-1 security considerations



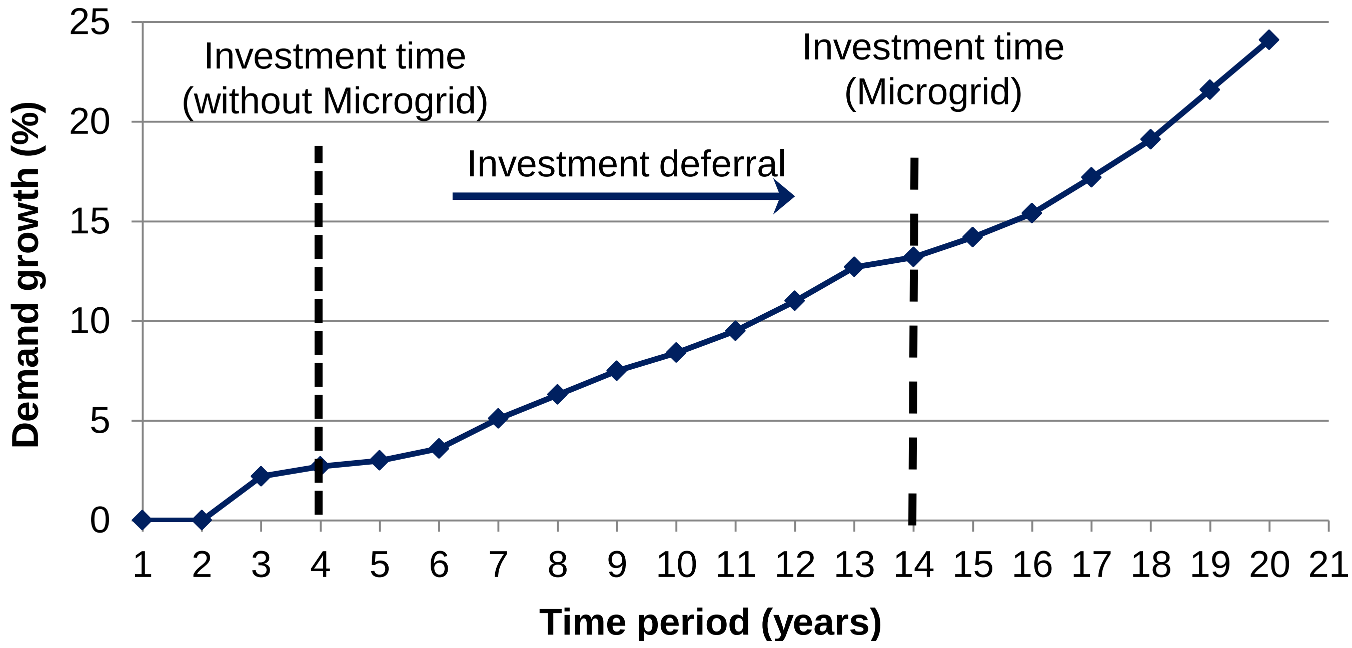
Distribution service (2/3)

- A Microgrid can operate as an island while the fault is being cleared, avoiding the need to oversize the feeders



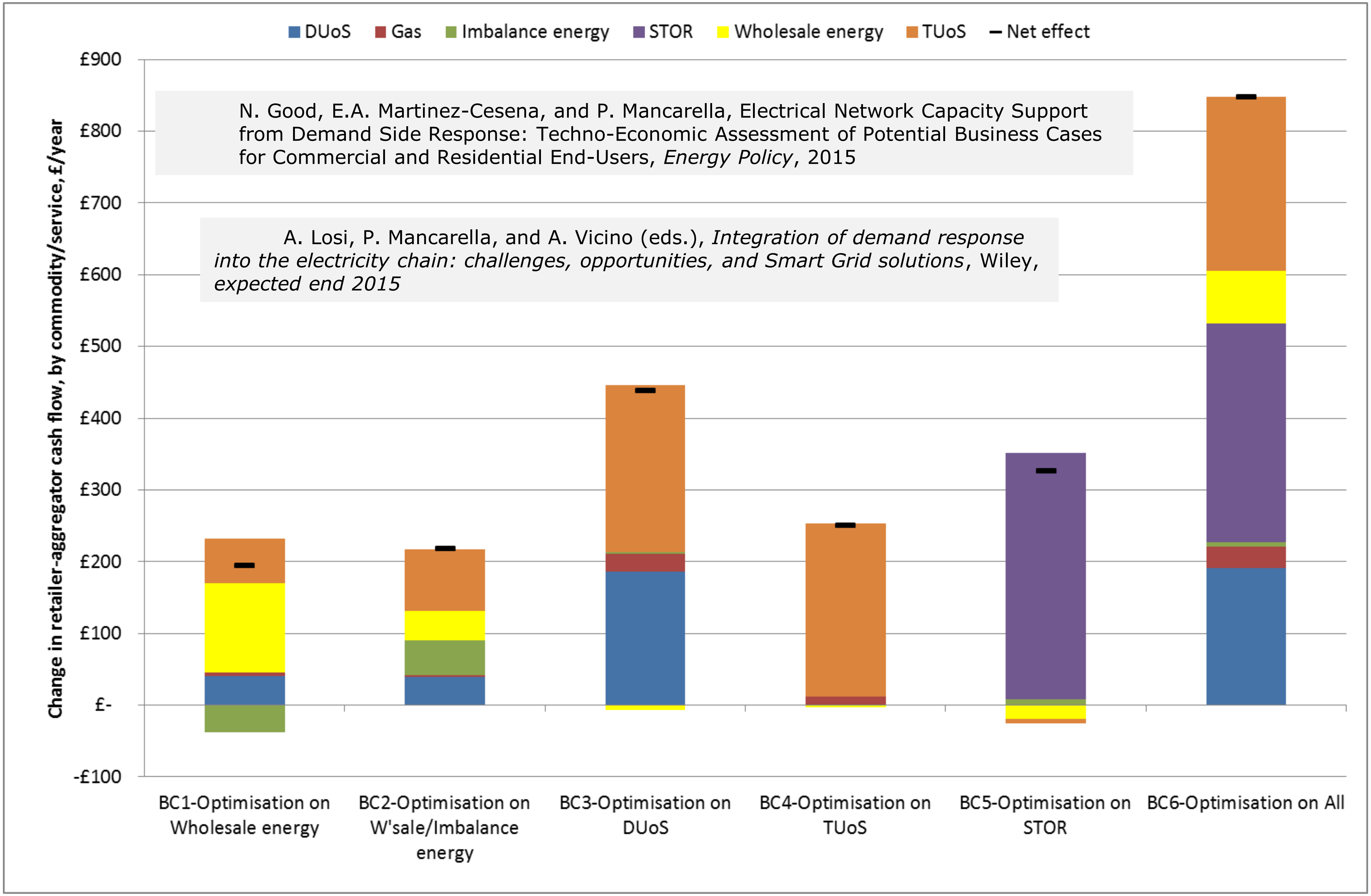
Distribution service (3/3)

- The service can be sold as post-contingency Demand Response (DR) to a DNO
- The DNO would save investment costs in the form or network reinforcement deferral or avoidance



N. Good, E.A. Martinez-Cesena, and P. Mancarella, Electrical Network Capacity Support from Demand Side Response: Techno-Economic Assessment of Potential Business Cases for Commercial and Residential End-Users, *Energy Policy*, 2015

Business case results: aggregator's benefits

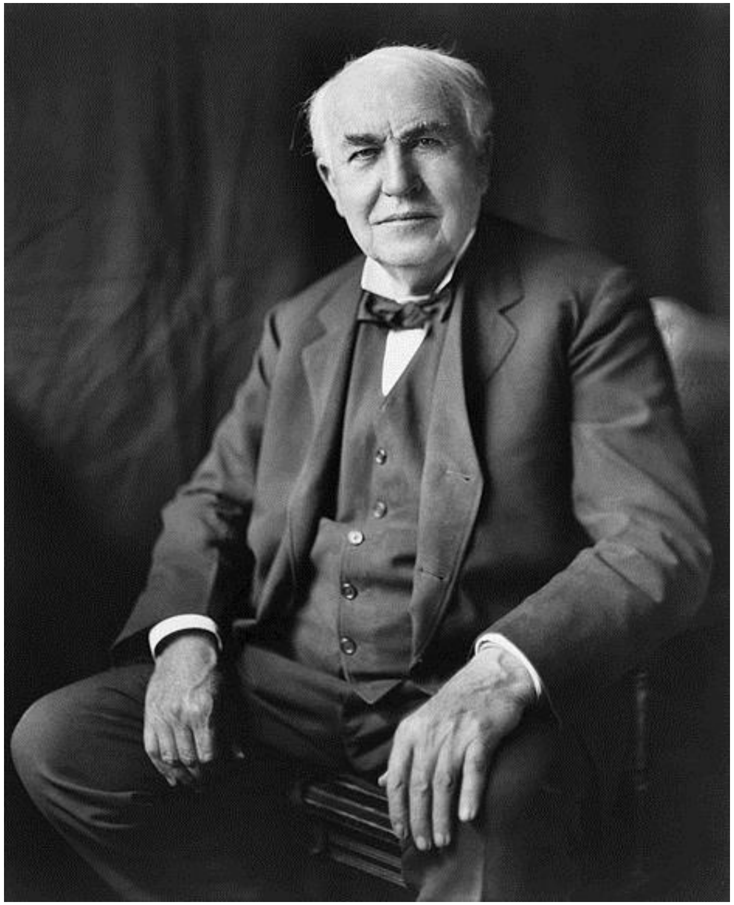


Concluding remarks

- Rethinking the energy system
- Key point: operational flexibility from energy vector switching
- Key point: flexible planning to truly reveal benefits from flexible multi-energy systems
- Networked effects of multiple commodities
- Modelling under uncertainty: operation and planning
- Full mapping critically needed to have a full understanding of the available business case opportunities and not to miss any
- Microgrid operation can add value to district energy system operation
- Results are case specific
- Barriers: regulation?
- Next: a tool for CBA of multi-energy systems is under development
  - Exercise in next iiESI course?

Back to the future...

Back to the future...



1878: “We will make electricity so cheap that only the rich will burn candles”

1882: Edison switched on his Pearl Street electrical power distribution system, which provided 110 volts DC to 59 customers in lower Manhattan

Edison’s power plant was a CHP one

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Planning under uncertainty and business cases of multi-energy systems

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Thank you

Any Questions?

p.mancarella@manchester.ac.uk

BUSINESS CASES FOR DISTRIBUTED MULTI-ENERGY SYSTEMS

Pierluigi Mancarella, PhD

Reader in Future Energy Networks

The University of Manchester, Manchester, UK

p.mancarella@manchester.ac.uk

Energy Systems Integration Facility, NREL, Golden, USA – 04/08/2015