Distinguished Lecture
Systèmes Multi-Energies

Flexibilités et services fournis aux réseaux

Cet événement proposé par la section française de l'IEEE PES (Power and Energy Society) s'inscrit dans le cadre du programme « **Distinguished Lecturers** ». A ce titre, le **Professeur Pierluigi Mancarella** interviendra pour présenter les principaux concepts sur la fourniture de flexibilité et de services aux réseaux électriques par les systèmes multi-énergies (MES) au sein desquels l'électricité interagit avec d'autres vecteurs et secteurs énergétiques comme la chaleur, le froid, le secteur du transport, du gaz, de l'hydrogène... La présentation s'appuiera sur des cas d'usage et des applications, issus de projets européens et australiens récents, en couvrant les aspects techniques, commerciaux et régulatoires. Elle inclut des travaux en cours, avec des producteurs, transporteurs et distributeurs d'électricité et de gaz, qui visent à déterminer comment les MES peuvent soutenir la transition énergétique en contribuant au développement de réseaux électriques et gaziers, économiques et résilients, avec de forts taux de pénétration de production renouvelable. La présentation abordera aussi les perspectives énergétiques long terme en envisageant des systèmes couplant électricité et hydrogène avec des taux de pénétration de production renouvelable (très) au-delà de 100%.

13 Octobre 2020
de 12h30 à 14h00
Microsoft Teams

12h30	***Accueil et introduction*** *Yannick Jacquemart (IEEE PES France)*
12h35	***Flexibility and grid services from multi-energy systems*** *Pierluigi Mancarella, Chair Professor of Electrical Power Systems, University of Melbourne*
	Questions

Inscription et Renseignements

Inscription en ligne gratuite : http://bit.ly/1gNuQWb

Après l'évènement, les présentations seront disponibles sur
http://ewh.ieee.org/r8/france/pes/

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teams@myvideo.ge.com ID de la conférence VTC : 1153914030
Autres instructions relatives à la numérotation VTC
Aide | Informations légales

Organisation et Parrainage

- Chapitre français de l'IEEE PES
- Avec l'appui des clubs techniques de la SEE

IEEE Power and Energy Society
Distinguished Lecturer Programme

Flexibility and grid services from multi-energy systems

Pierluigi Mancarella

The University of Melbourne, Australia, and The University of Manchester, UK

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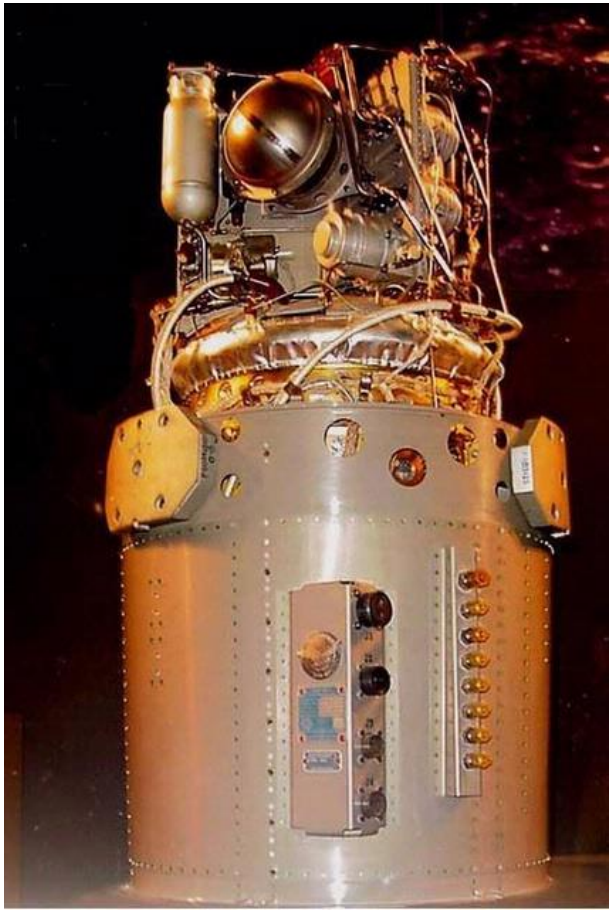
Online Distinguished Lecture for the French Chapter

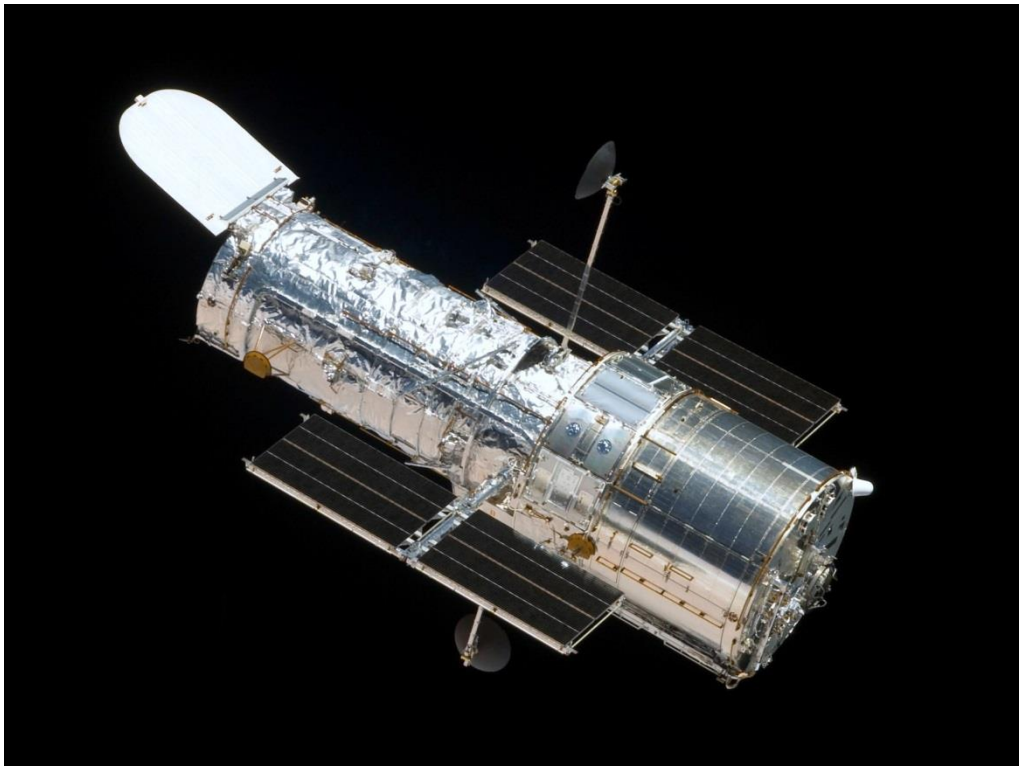
13th October 2020

Outline

- Background
- From power system flexibility to Multi-Energy System (MES) flexibility
- MES flexibility modelling and features
- MES and energy networks
- MES planning and resilience
- Concluding remarks

Back to the future!





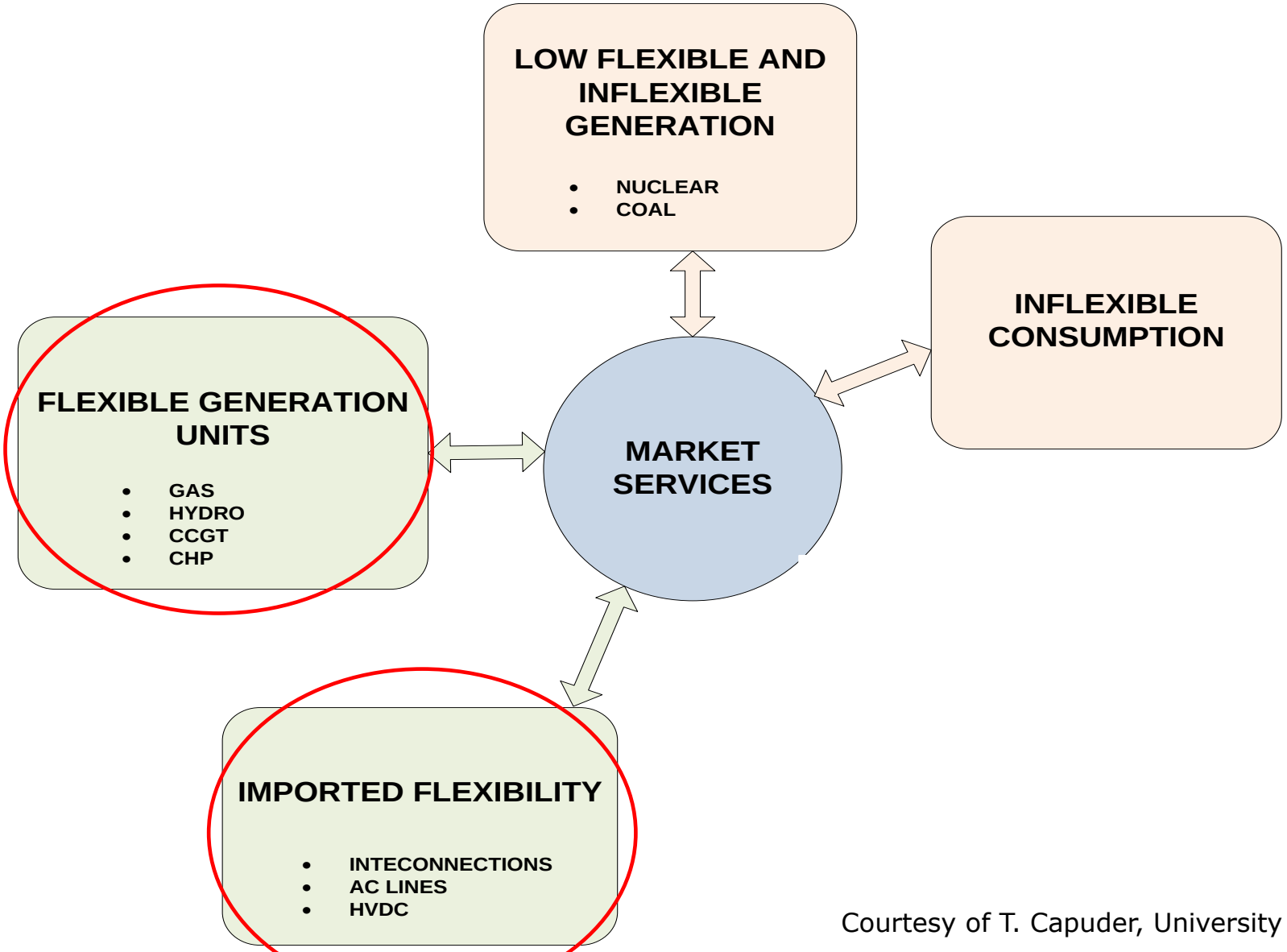
Power system flexibility

- Some definitions for *power system flexibility:*
  - "Technical ability to regulate the power exchange with the grid" (Ulbig, 2015)
  - "Ability to provide secure and economical supply-demand balance across spatial and temporal scales, by leveraging and seamlessly coordinating various controllable assets" (Dall'Anese, 2015)

Ulbig, et al., "Analyzing operational flexibility of electric power systems," *Int. J. Electr. Pow. En. Syst*. vol. 72, pp. 155–164, 2015

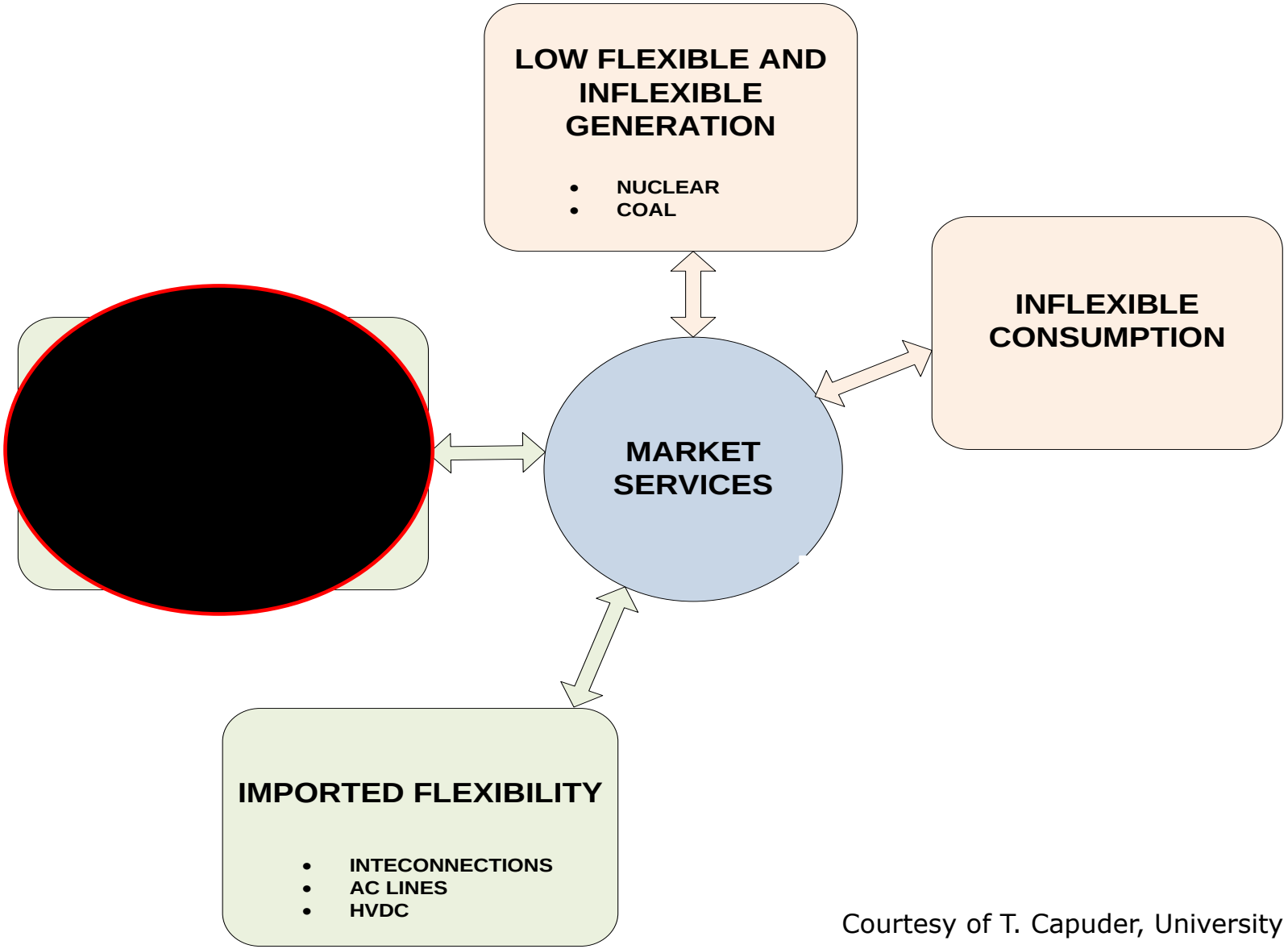
E. Dall'Anese, *et al.*, "Unlocking Flexibility: Integrated Optimization and Control of Multienergy Systems," *IEEE Power and Energy Magazine*, vol. 15, no. 1, pp. 43–52, 2017

Who provides flexibility, security and reliability today?



Courtesy of T. Capuder, University of Zagreb

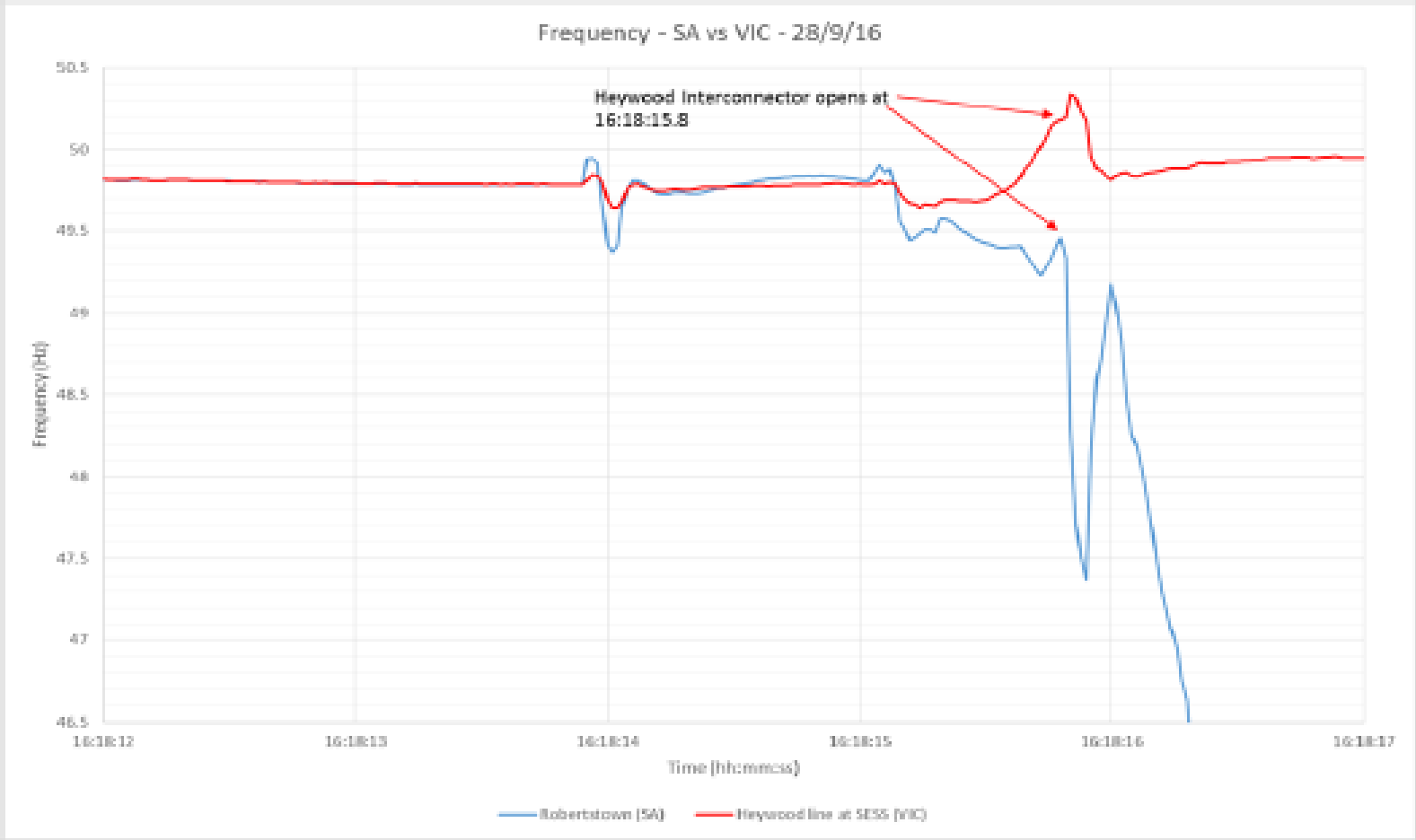
Who provides flexibility, security and reliability today?



Courtesy of T. Capuder, University of Zagreb

Is it a far future?

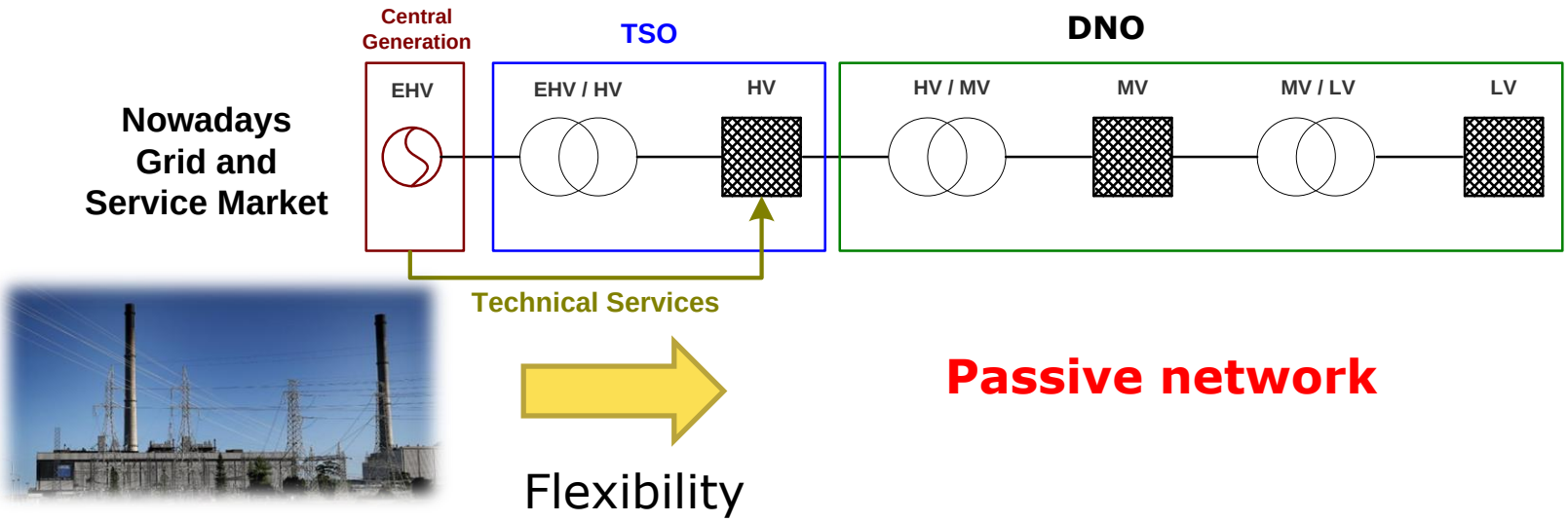
Figure 5 SA frequency compared to Victoria during event



Source: AEMO

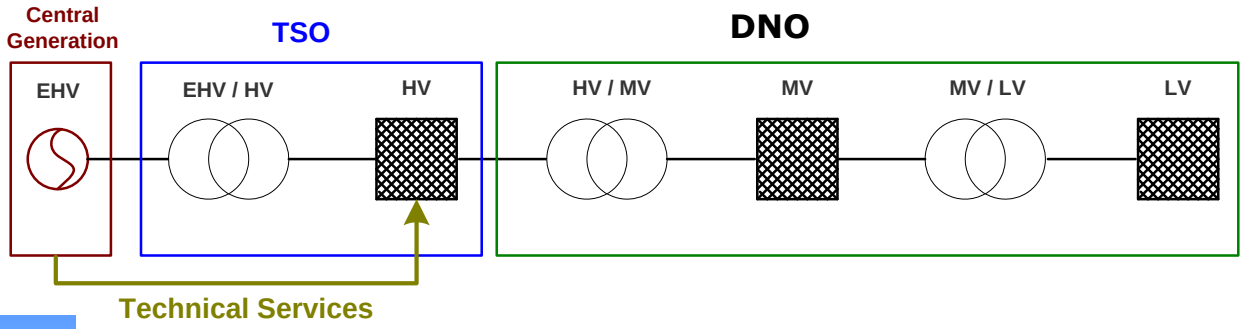
Who can help to solve flexibility and security problems?

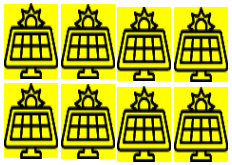
Traditional flow of flexibility



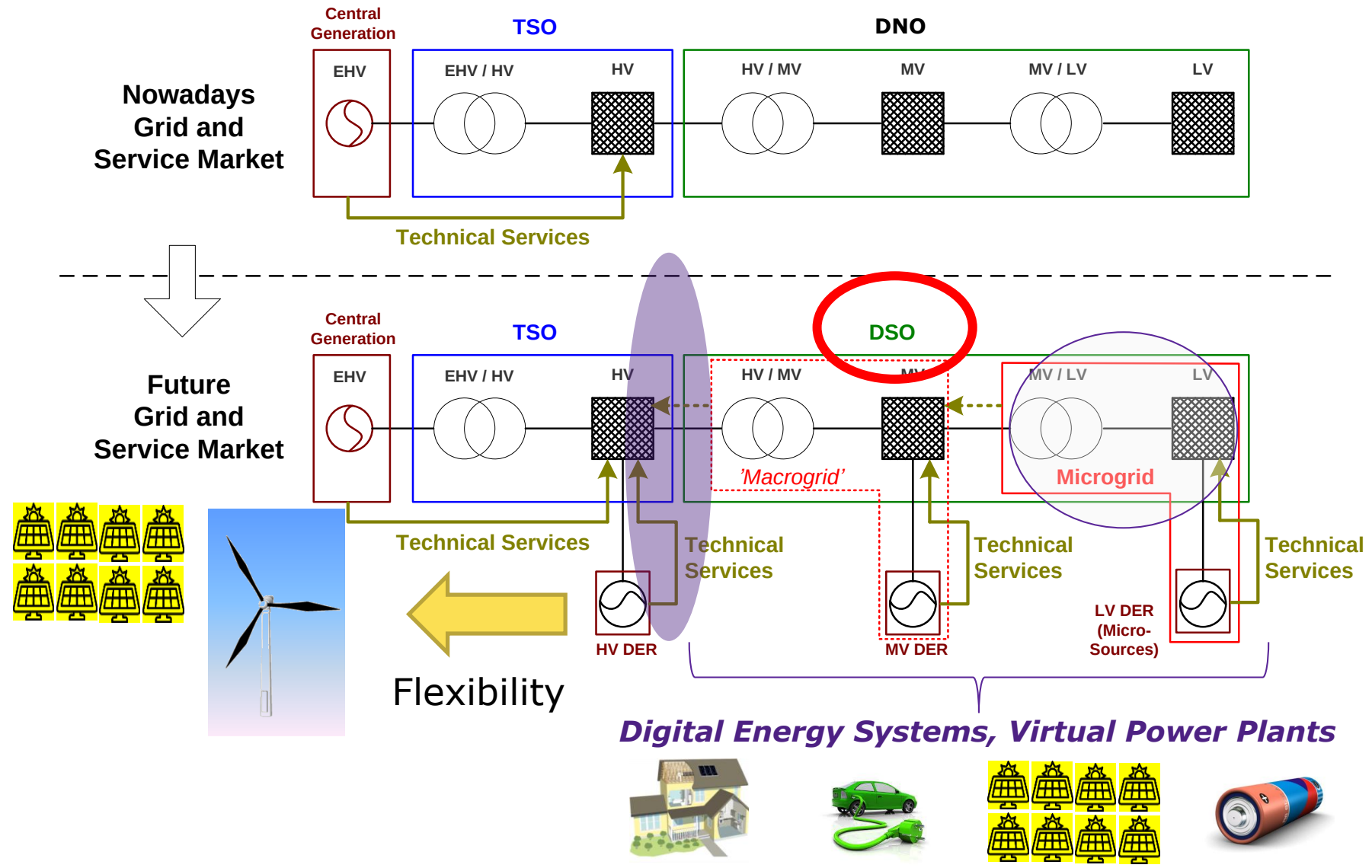
A changing system

Nowadays Grid and Service Market

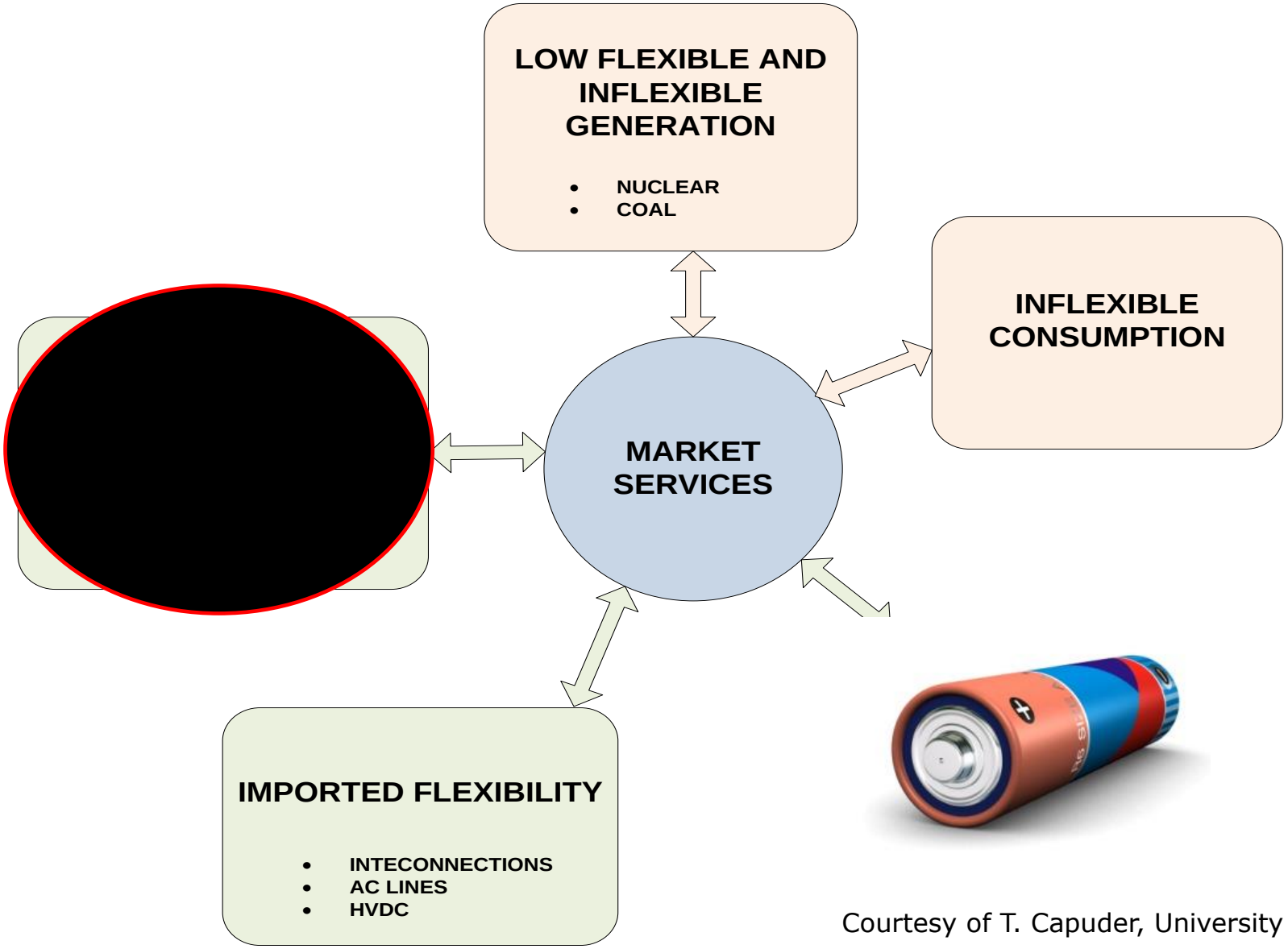




Who will provide flexibility tomorrow?



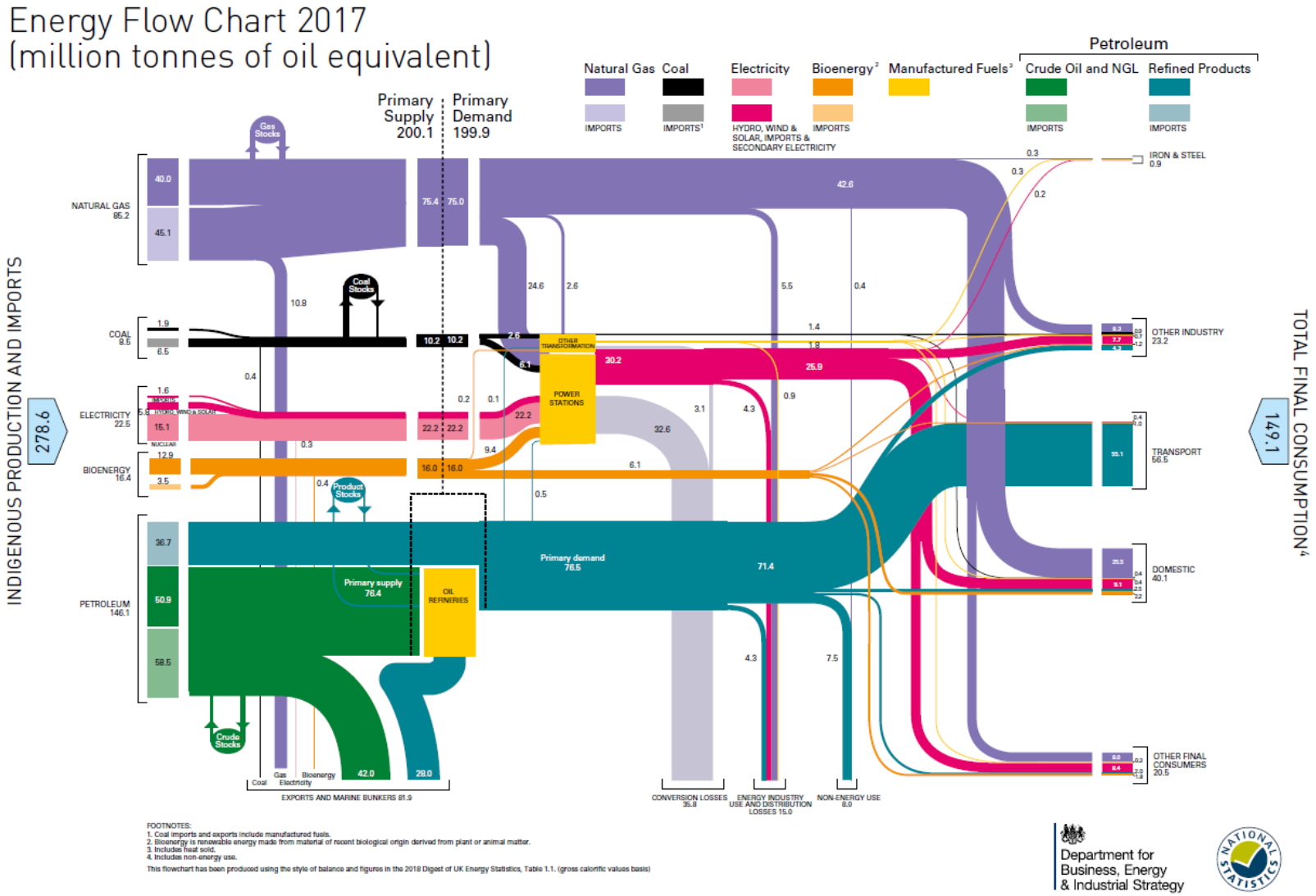
Flexibility in low-carbon power systems



Courtesy of T. Capuder, University of Zagreb

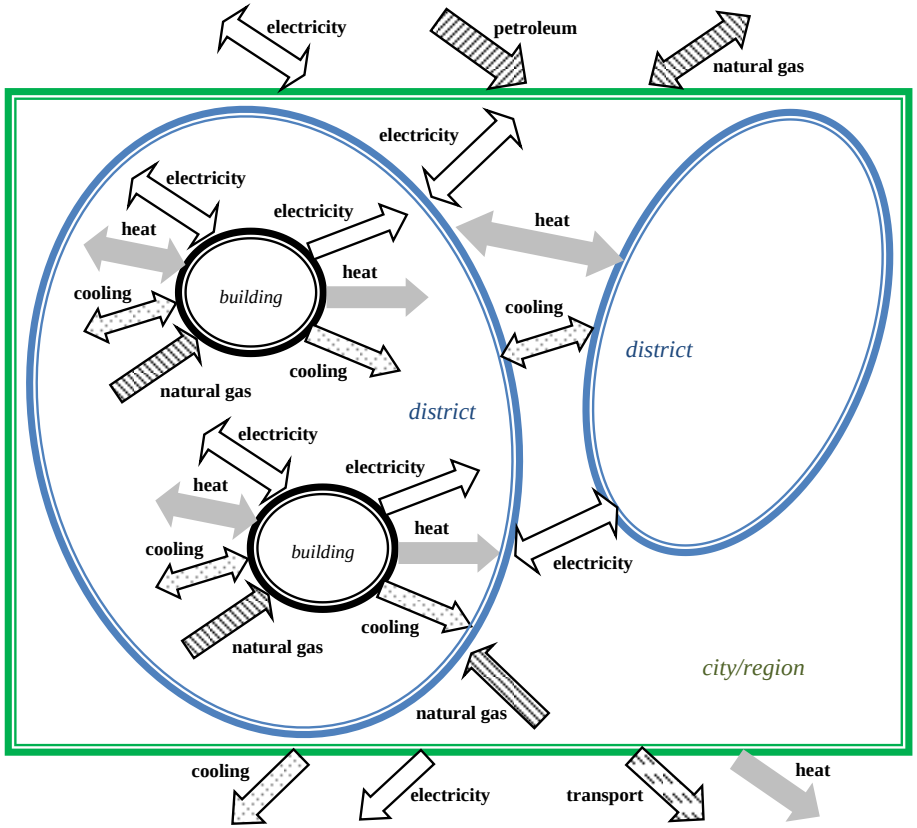
Still worried about delivering a low-carbon energy system?

The bigger picture: Sector coupling and multi-energy systems



What are Multi-Energy Systems?

"Systems in which electricity, heat, cooling, fuels, transport, and so on optimally interact with each other at various levels - for instance, within a district, city or region"



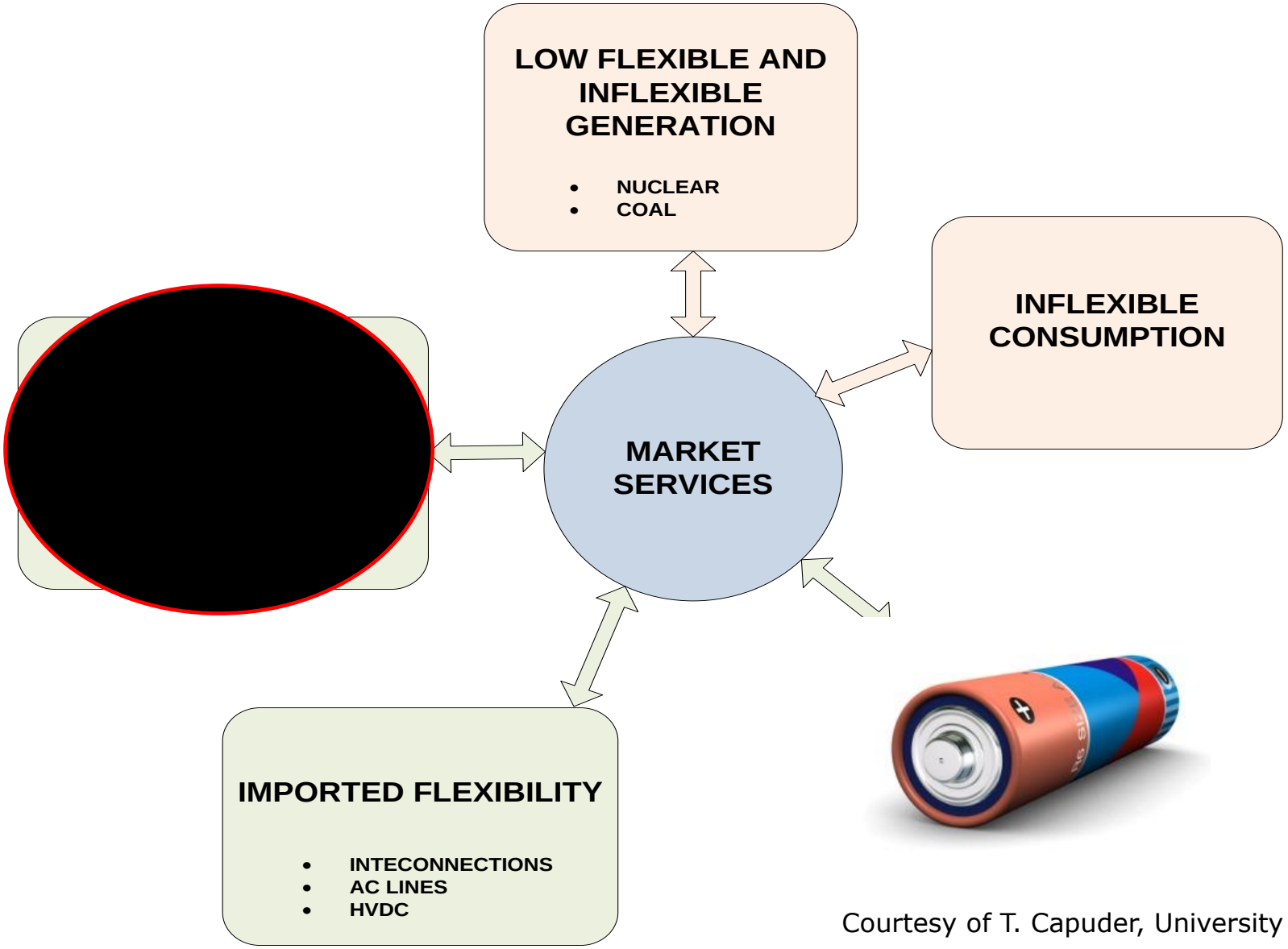
P.Mancarella, "*Multi-energy systems: an overview of models and evaluation concepts*", Energy, Vol. 65, 2014, 1-17, *Invited paper*

What is flexibility in MES terms?

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

G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

So, instead of this…



Courtesy of T. Capuder, University of Zagreb

… could we do this?

LOW FLEXIBLE AND INFLEXIBLE GENERATION

- NUCLEAR
- COAL

INFLEXIBLE CONSUMPTION

[redacted]

MARKET SERVICES

IMPORTED FLEXIBILITY

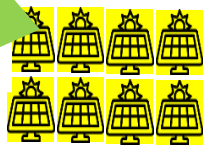
- INTECONNECTIONS
- AC LINES
- HVDC

Heating

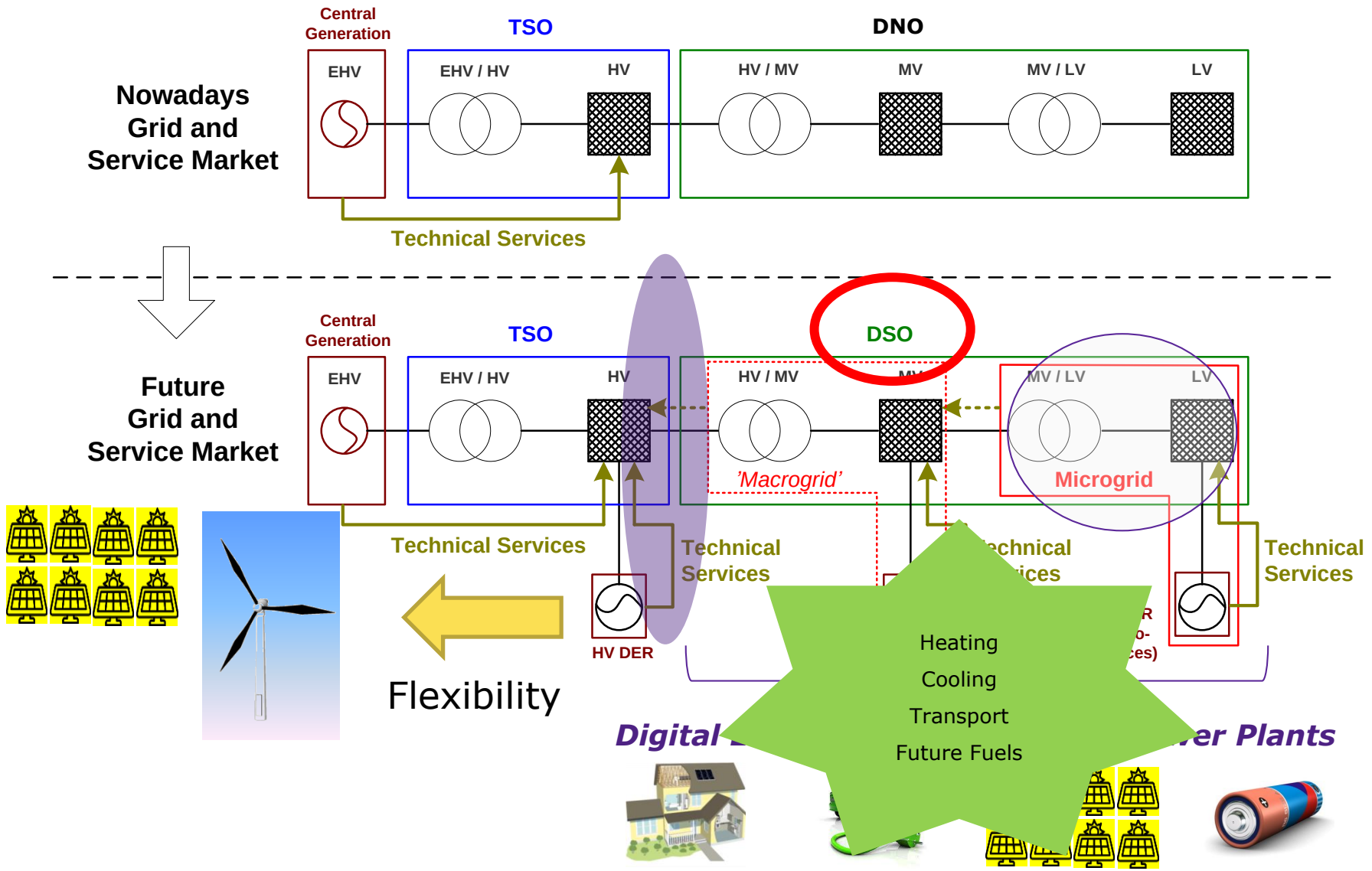
Cooling

Transport

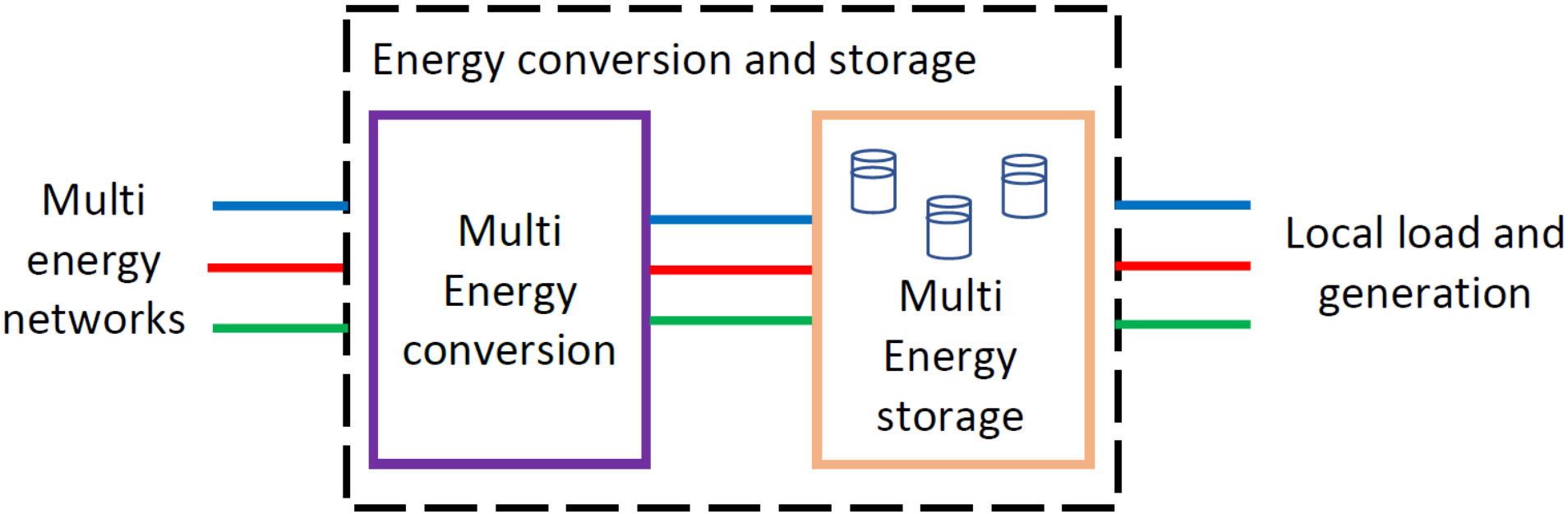
Future Fuels



Who will provide flexibility tomorrow?



Flexibility from DMES: "multi-energy node" model



$$\mathbf{S}\,\dot{\mathbf{e}} = \mathbf{H}\,\mathbf{v}_\mathrm{i} - \mathbf{v}_\mathrm{o}$$
$$= \mathbf{H}\,\mathbf{v}_\mathrm{i} - \boldsymbol{\xi} - \mathbf{w}$$

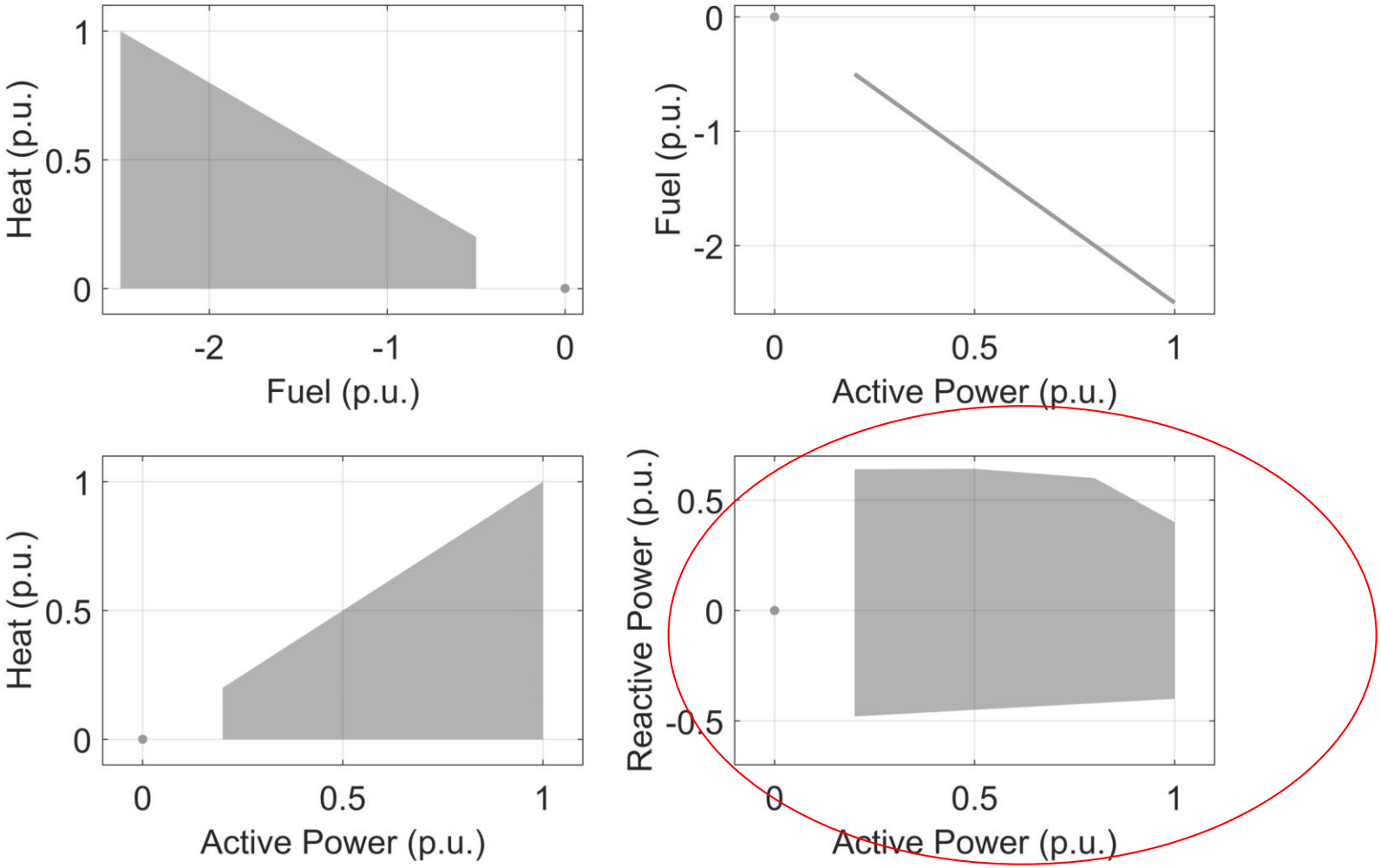
$$\boldsymbol{\xi} = \mathbf{v}_\mathrm{d} - \mathbf{v}_\mathrm{RES}$$
$$\mathbf{w} = \mathbf{v}_\mathrm{d}^{(c)} - \mathbf{v}_\mathrm{RES}^{(c)} - \mathbf{v}_\mathrm{o}^{(c)}$$

"The set of all feasible deviations in the flows of an energy vector from a given operating point, subject to multi-energy node constraints"

G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Where is MES flexibility coming from?
Multi-energy flexibility operational region (FOR)

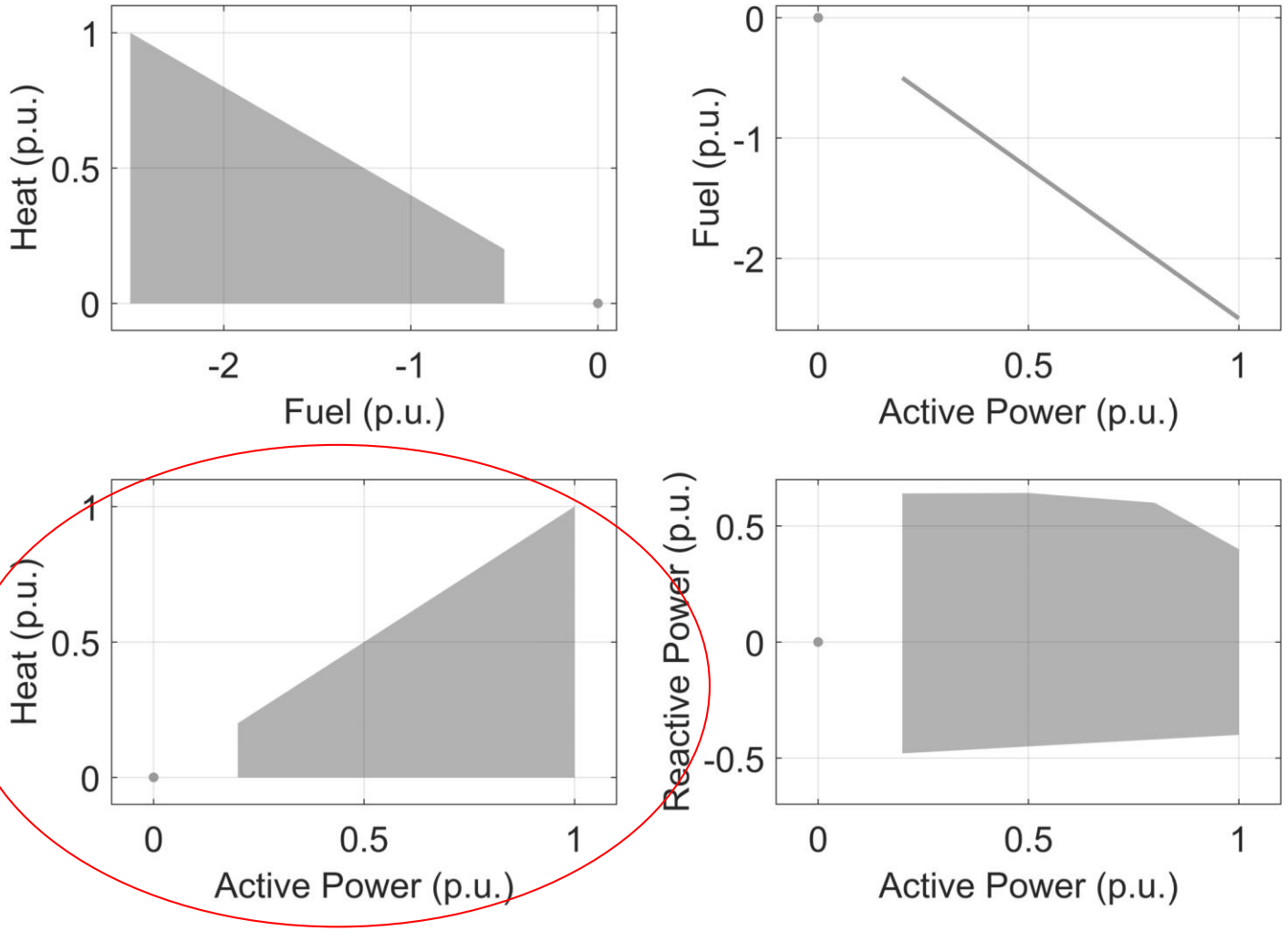
CHP example



G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

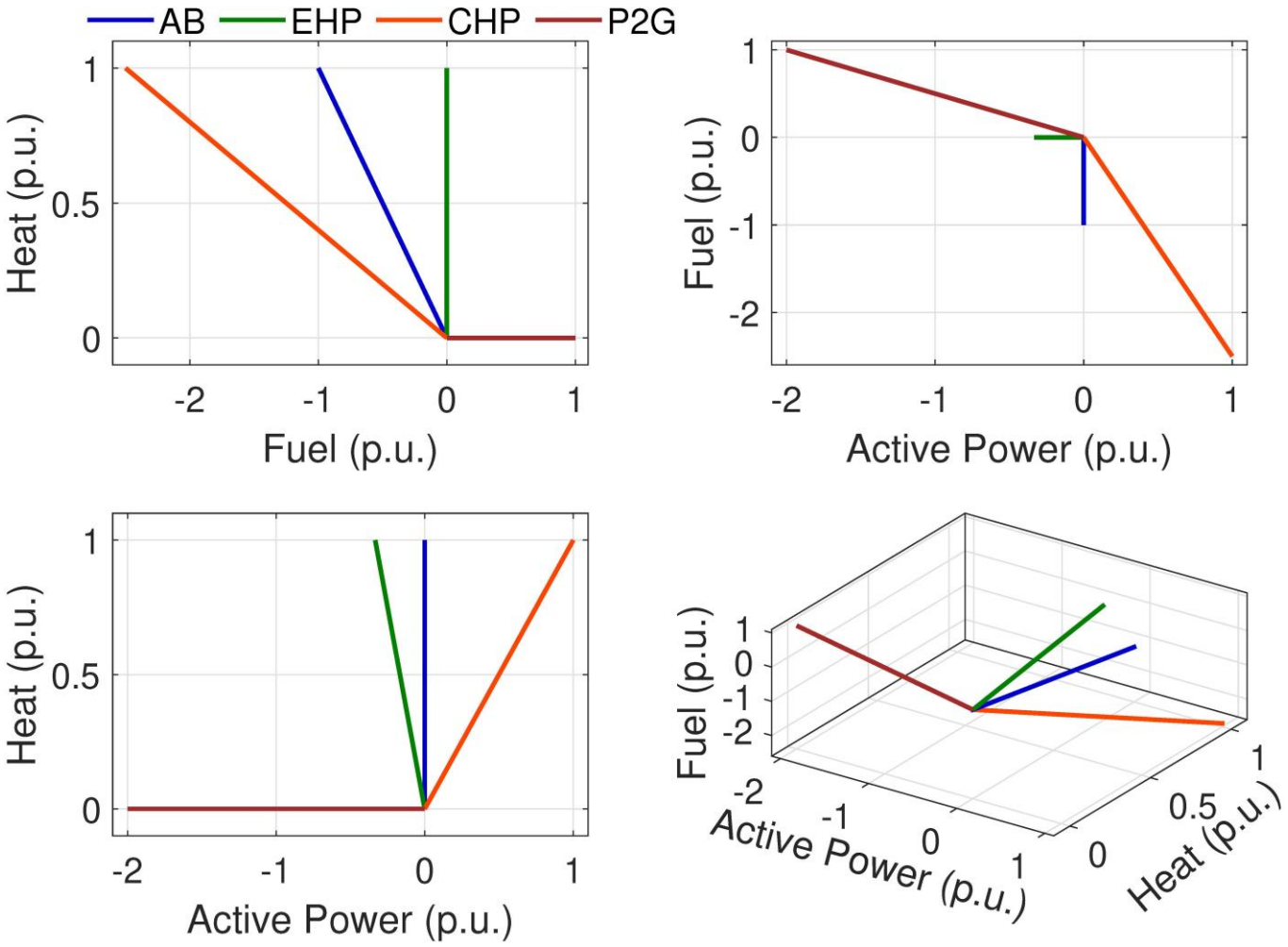
Multi-energy flexibility operational region (FOR)

CHP example



G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Aggregation of multi-energy device in MES: Linearised operating characteristics



Combined Heat and Power (CHP)
$P = 1$ p.u., $H = 1$ p.u.,
$\eta_e = 40\%$, $\eta_t = 40\%$, Min Stable Output =0
No waste heat allowed

Auxiliary Boiler (AB)
H =1 p.u., $\eta_{AB} = 100\%$

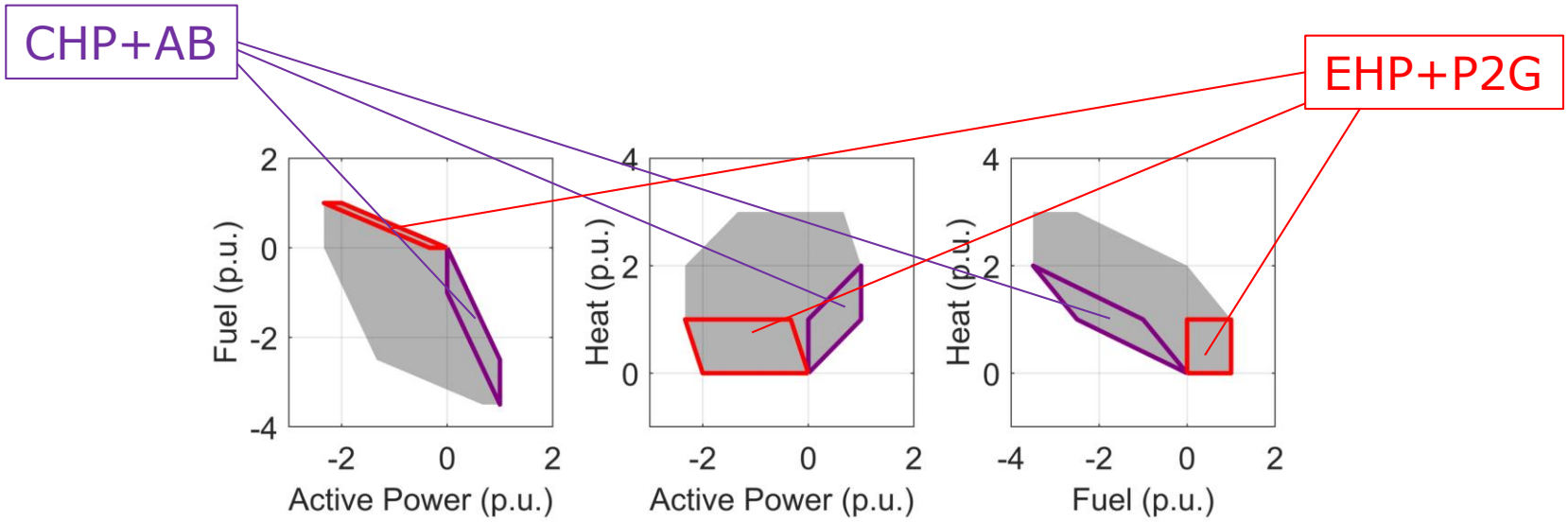
Electric Heat Pump (EHP)
$H = 1$ p.u., *COP*=3

Power-to-Gas (P2G)
(Electrolyser+Methaniser):
$F = 1$, $\eta_F = 50\%$

Thermal Storage (TS)
$H = 1$ p.u.

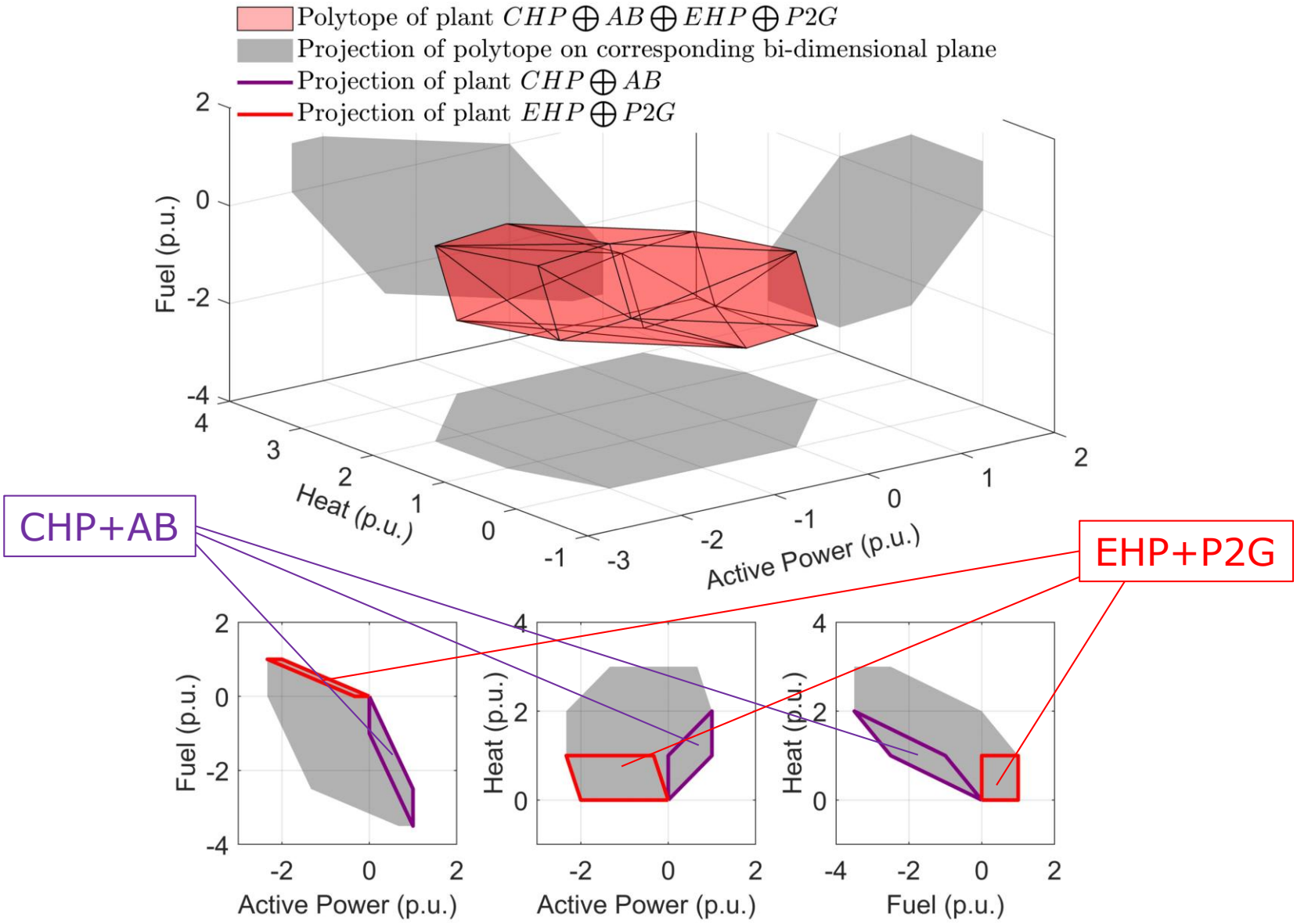
G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Aggregation of multi-energy device in MES



G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Aggregation of multi-energy device in MES



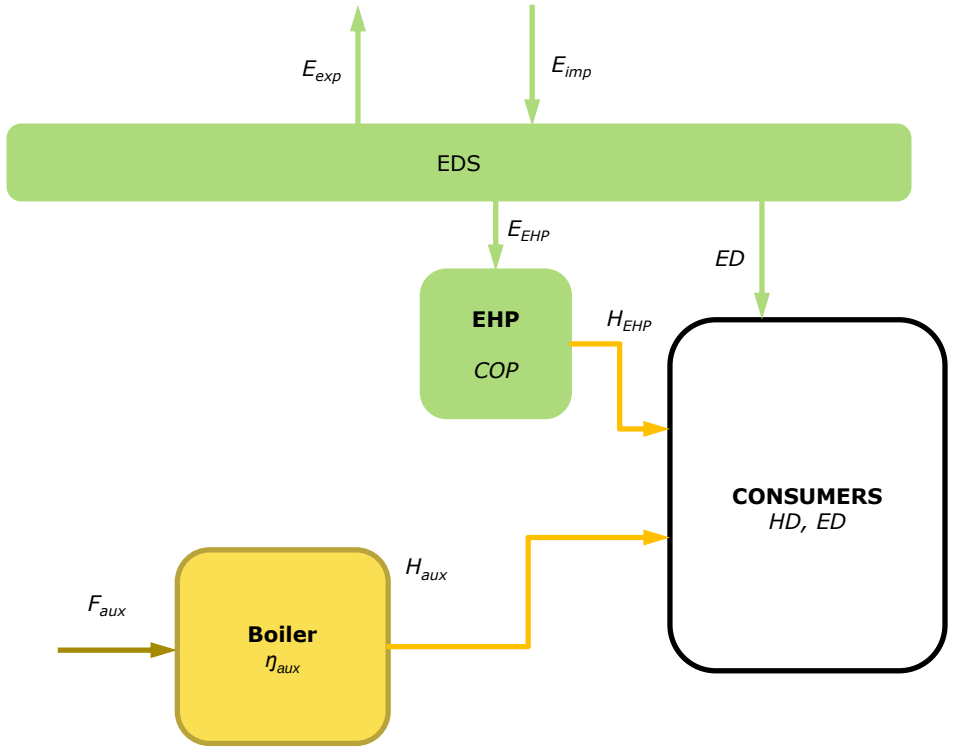
G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Flexibility features and applications

- Input energy vector shifting/arbitrage
  - *Electricity shifting potential*
- Output energy vector shifting/arbitrage
  - Power-to-X
- Temporal arbitrage via multi-energy storage
  - Virtual energy storage
- Multi-energy service curtailment
  - Comfort-to-power arbitrage
  - Relaxation of “soft” constraints
- Local renewable energy and multi-energy production curtailment

G. Chicco *et al.*, “Flexibility from distributed multienergy systems”, *Proceedings of the IEEE*, 2020

Multi-energy flexibility from input energy vector arbitrage



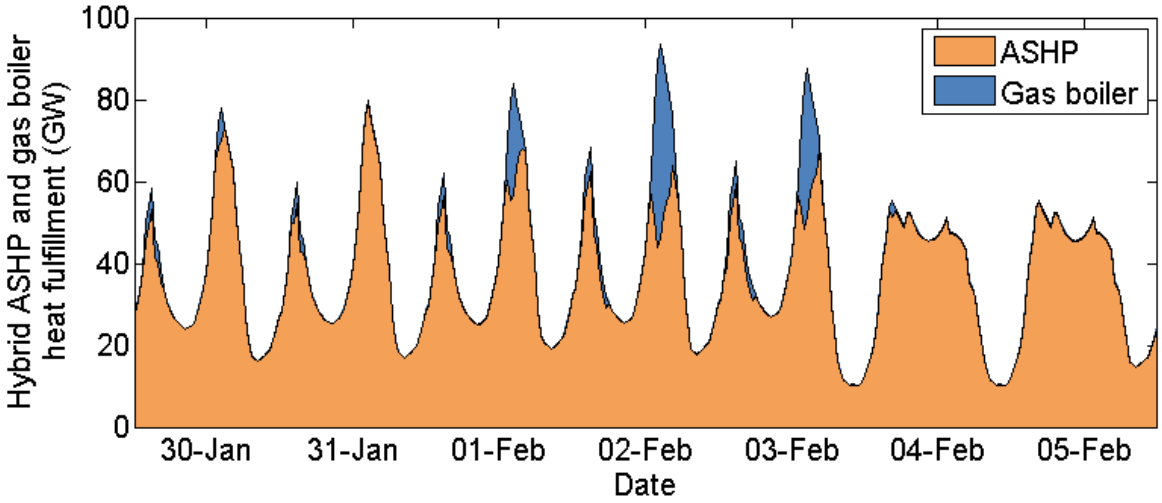
External energy vector arbitrage

T. Capuder and P. Mancarella, "Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options," *Energy*, vol. 71, pp. 516–533, 2014

Example operation of hybrid heating technologies: Integrated air-source heat pump and gas boiler

- Integrated air-source heat pump (ASHP) and gas boiler responds to power system needs – using gas boiler higher electricity price times

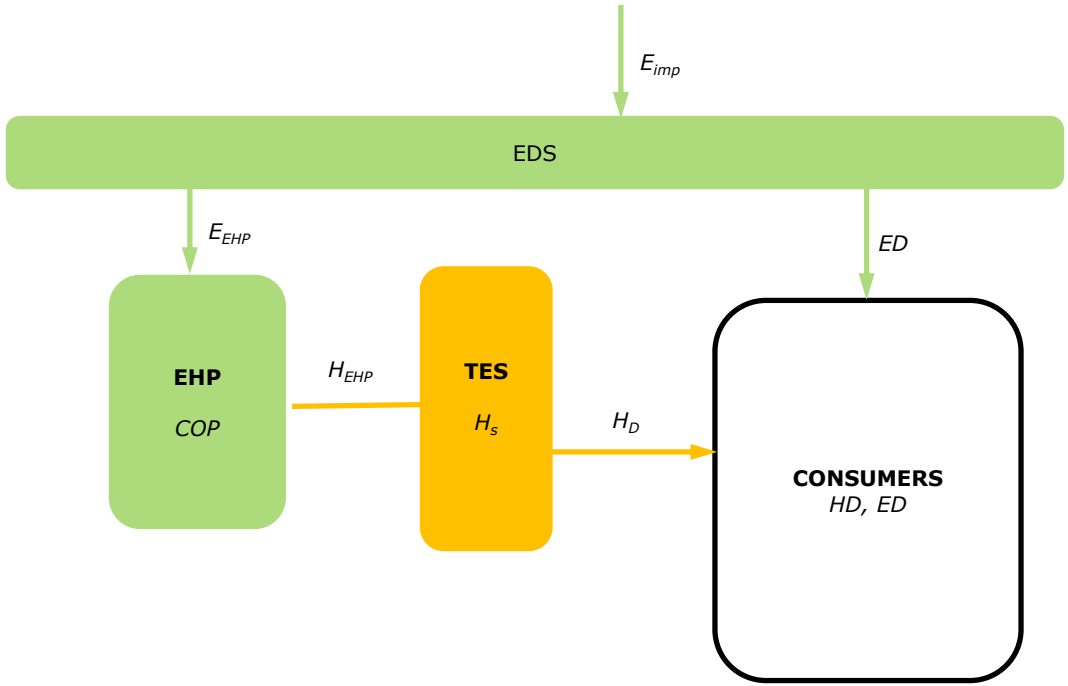
Scenario	Peak conventional generation	Minimum conventional generation
'ASHP'	88GW	29GW
'ASHP and boiler'	67GW	29GW



S. Clegg and P. Mancarella, "Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part II: Transmission Network Analysis and Low Carbon Technology and Resilience Case Studies", *Energy*, 2019

S. Clegg and P. Mancarella, "Integrated Electricity-Heat-Gas Modelling and Assessment, with Applications to the Great Britain System. Part I: High-Resolution Spatial and Temporal Heat Demand Modelling", *Energy*, 2019

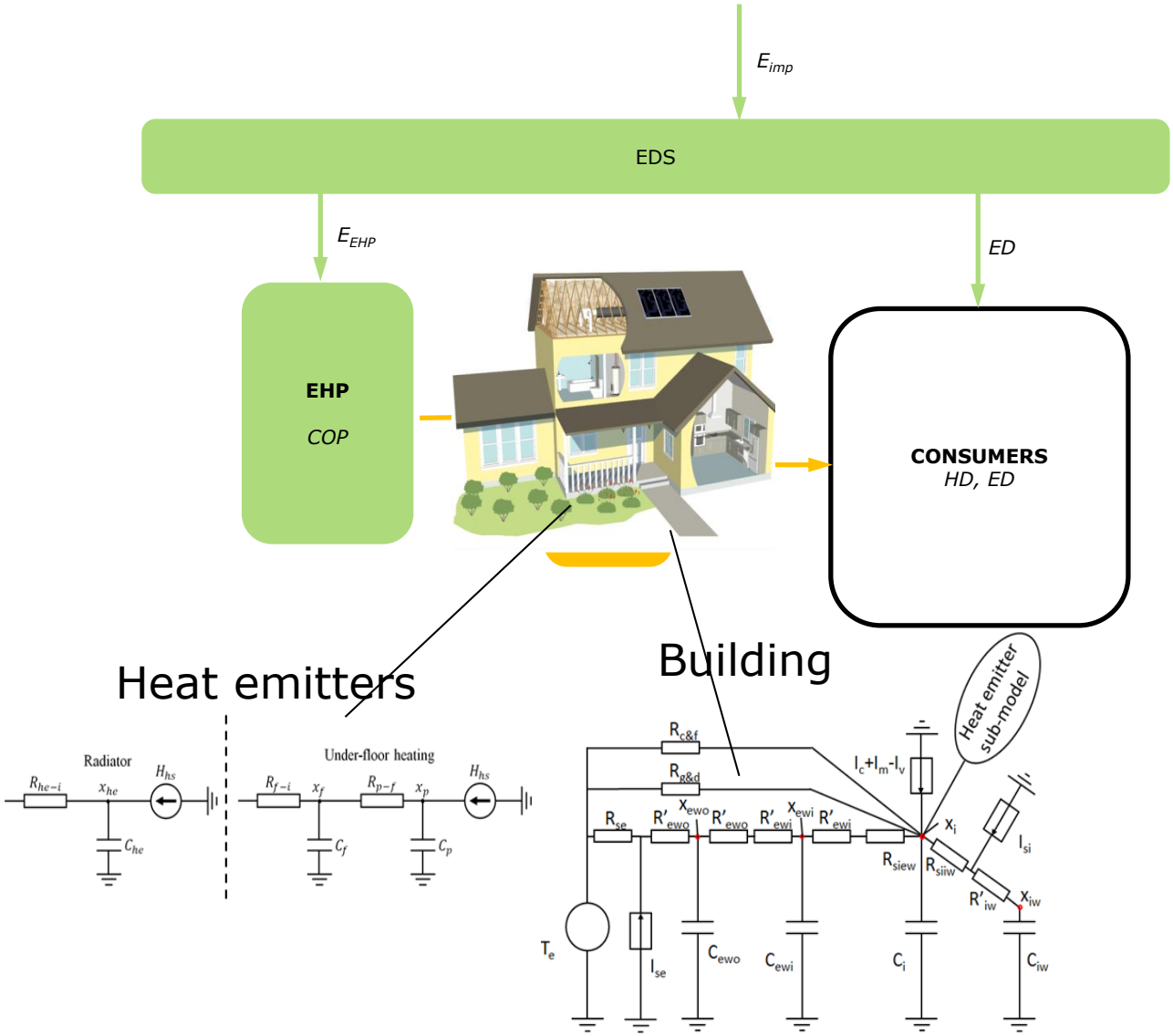
Output energy vector arbitrage: Power-to-heat



Heat load and thermal storage can be seen as an electricity sink and source of flexibility, e.g., for excess renewable electricity

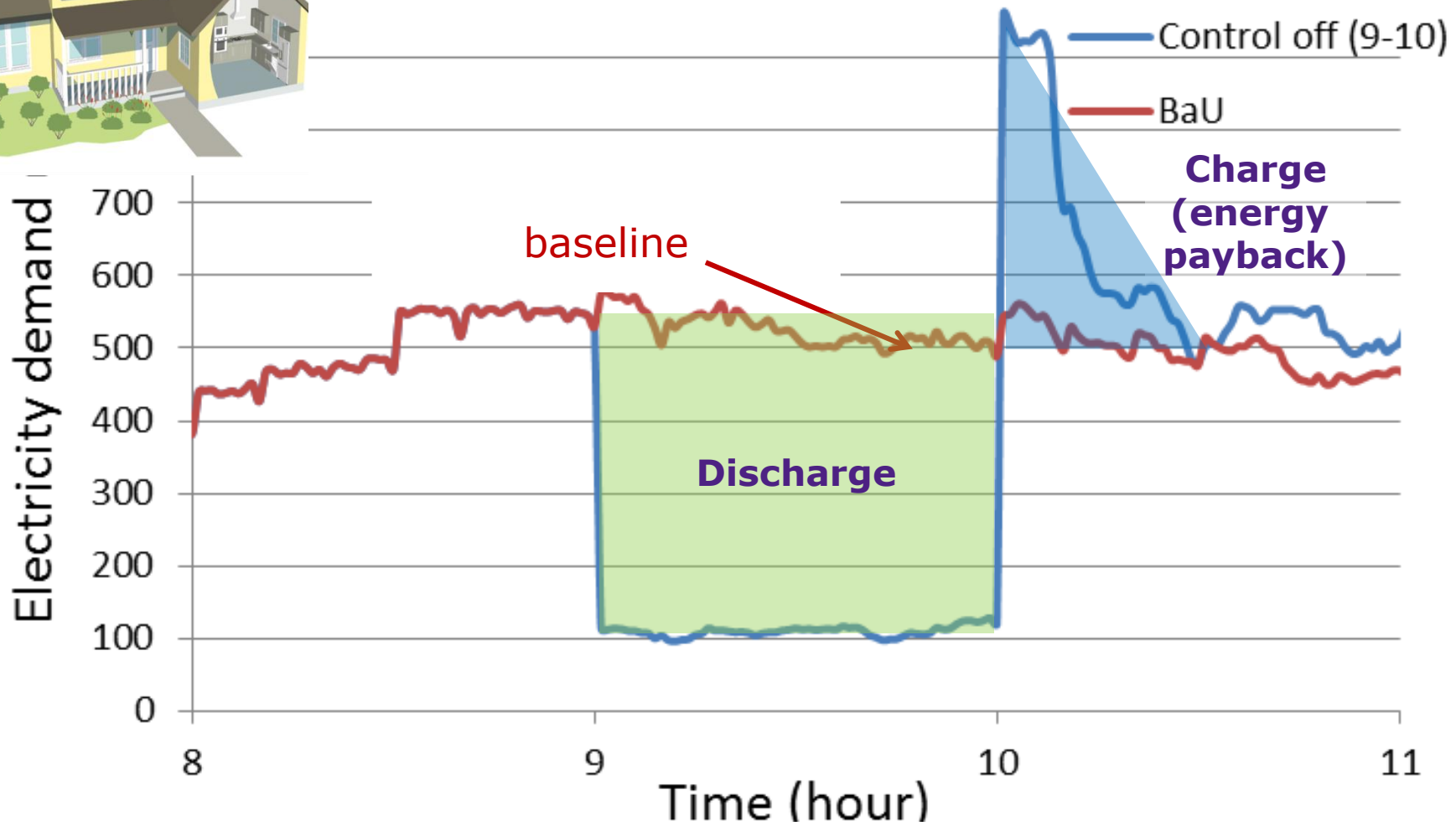
T. Capuder and P. Mancarella, "Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options," *Energy*, vol. 71, pp. 516–533, 2014

Virtual storage in buildings



N. Good, *et al.*, "High resolution modelling of multi-energy domestic demand profiles", *Applied Energy*, vol. 137, pp. 193–210, 1 January 2015

Comfort-to-power arbitrage via "virtual battery" flexibility

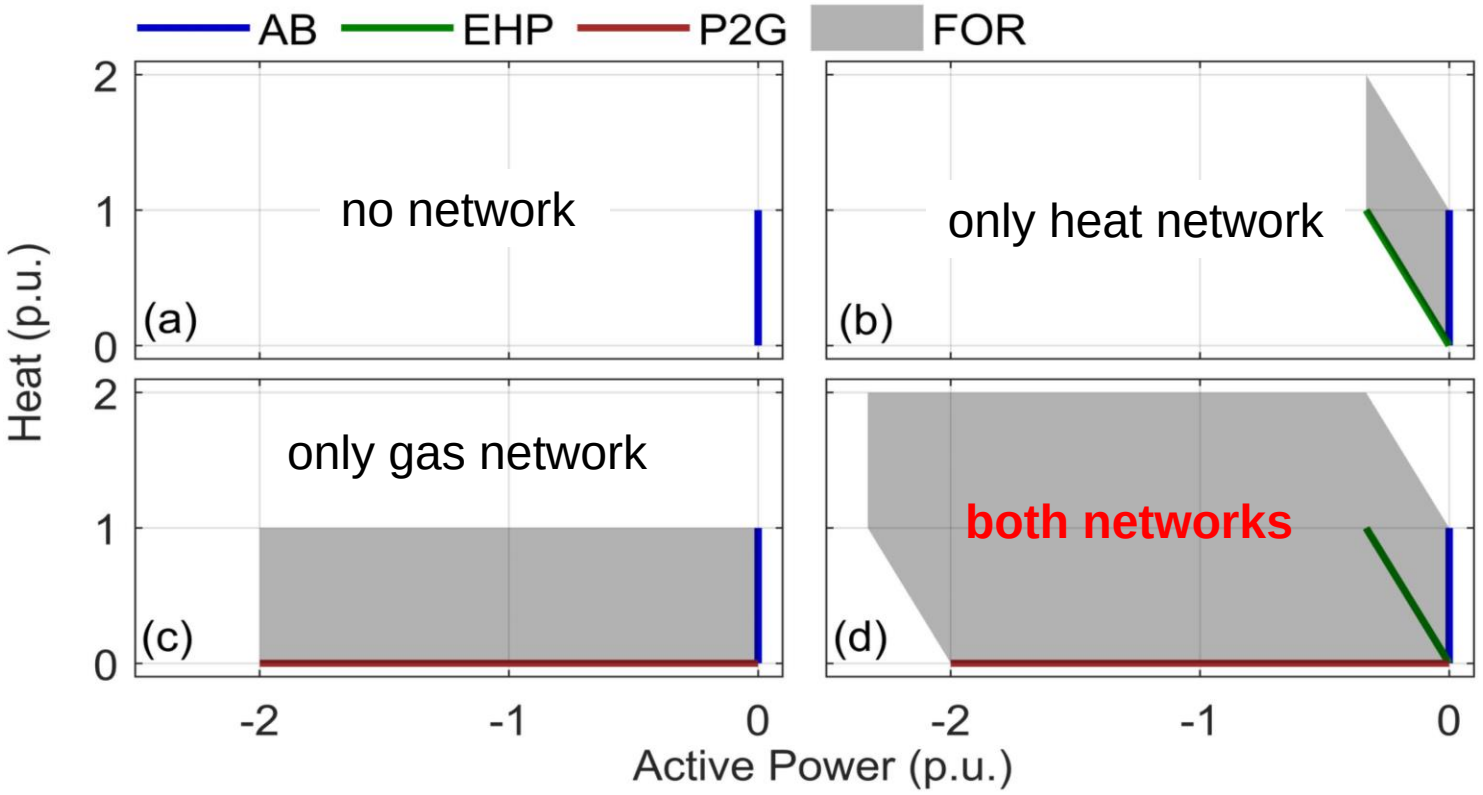


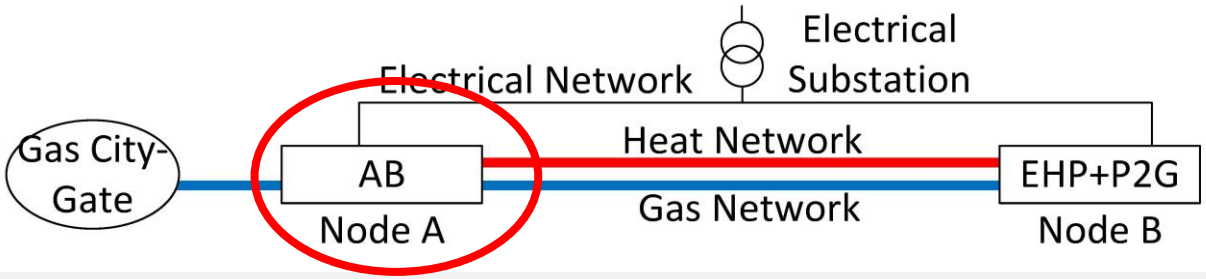
N. Good, *et al.*, "Optimization under uncertainty of thermal storage based flexible demand response with quantification of residential users' discomfort," *IEEE Trans. on Smart Grid*, vol. 6, no. 5, pp. 2333–2342, 2015

L. Zhang, *et al.*, "Building-to-grid flexibility: Modelling and assessment metrics for residential demand response from heat pump aggregations," *Applied Energy*, vol. 233–234, pp. 709–723, 2019

Multi-energy networks as enablers of grid flexibility

Node A FOR - *unconstrained* network case:

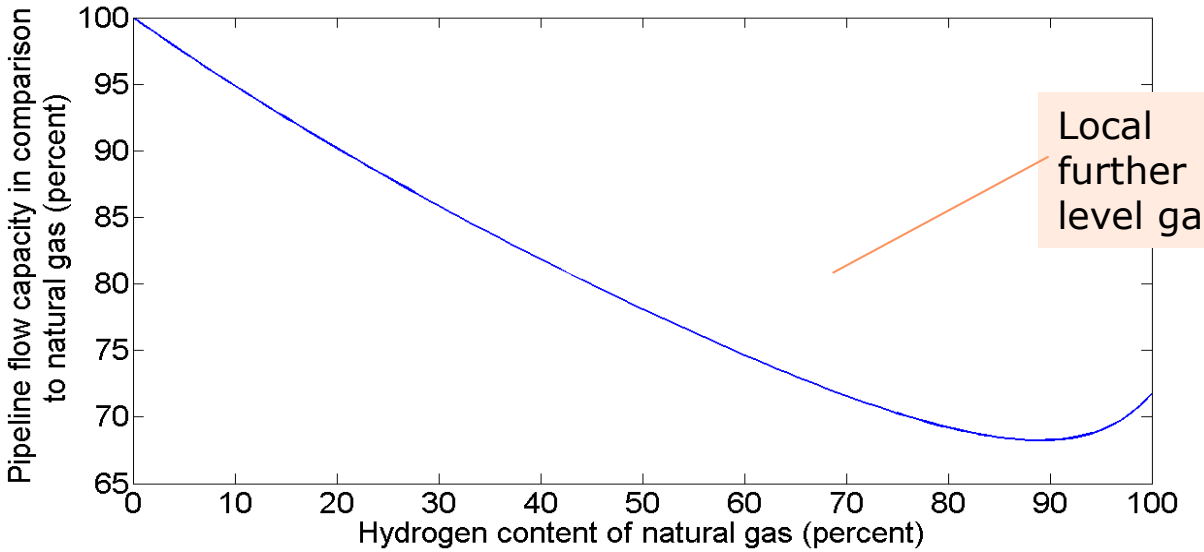




G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Network flexibility from embedded storage: Power-to-gas

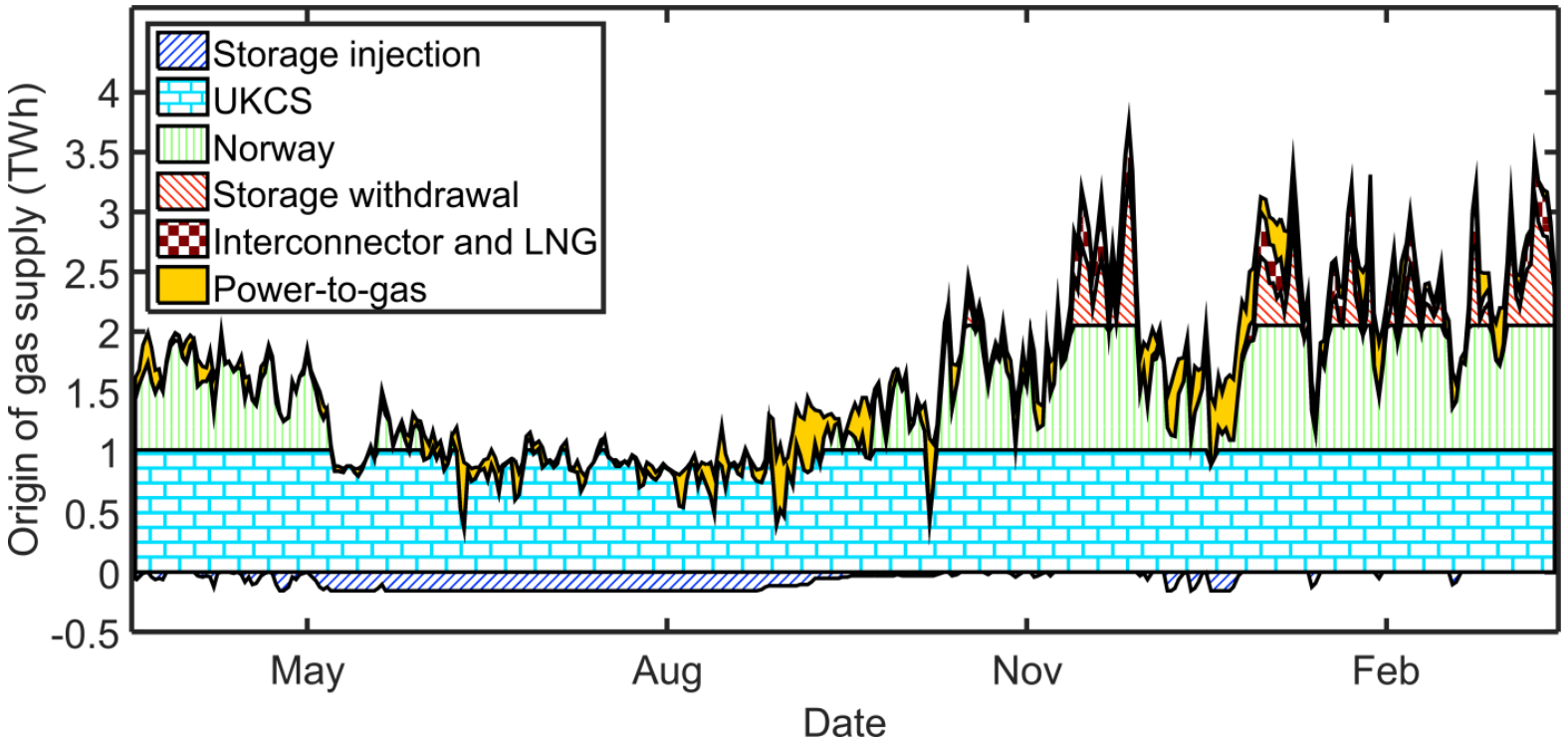
- Limits on the level of hydrogen in the gas network
  - Regulatory restrictions
  - Technical restrictions
  - Blending would be helped by upstream flow injection



Local injection may further require network-level gas flow validation

S. Clegg, P. Mancarella, "Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks", *IEEE Transactions on Sustainable Energy* 6 (4), pp.1234−1244, 2015

Power-to-gas with seasonal storage in the gas network



S. Clegg, P. Mancarella, "Storing renewables in the gas network: modelling of power-to-gas seasonal storage flexibility in low-carbon power systems", IET Generation, Transmission & Distribution, 10 (3), pp.566–575, 2015

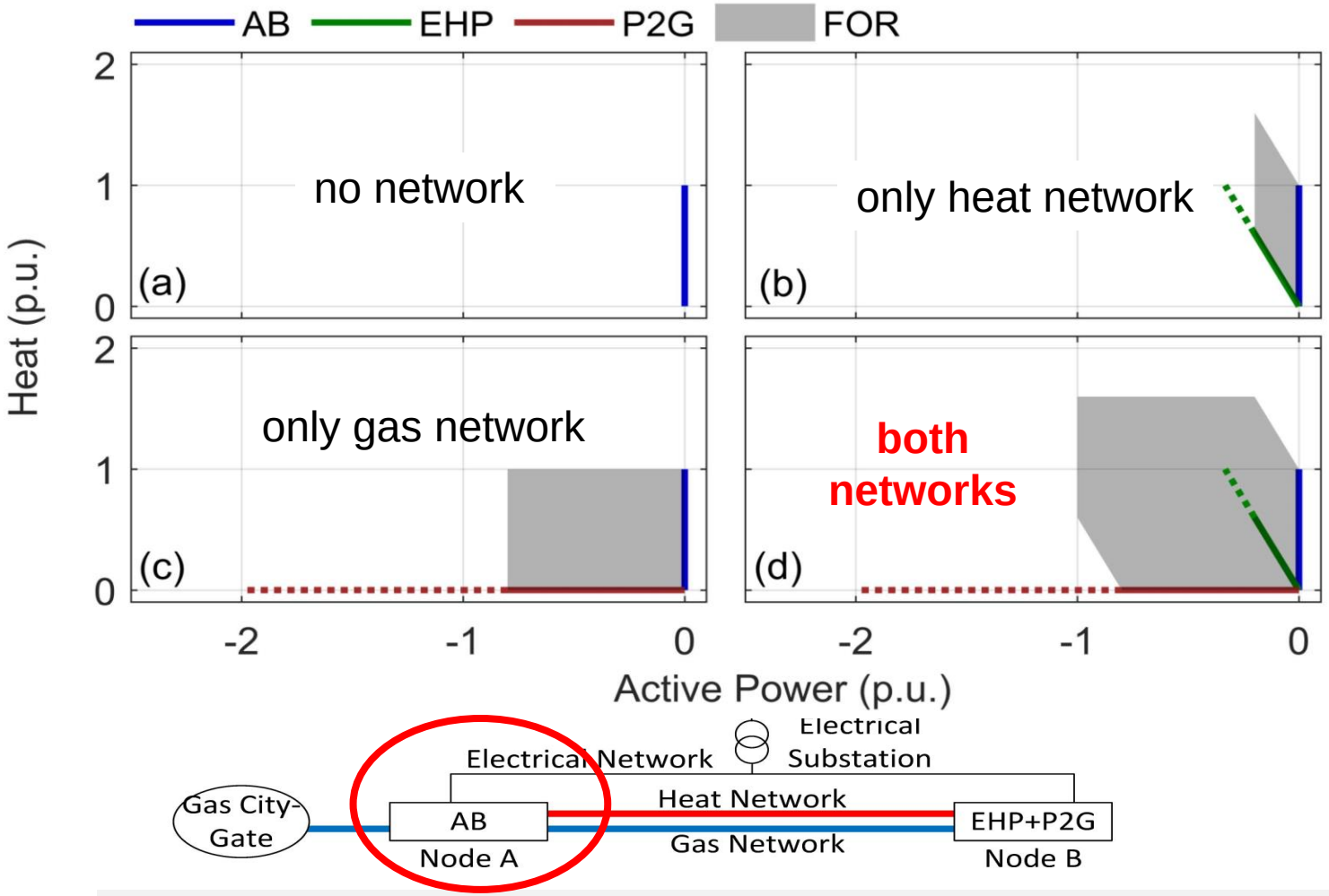
Multi-energy networks as constraints to grid flexibility

***Constrained* network case (0.4 p.u. for gas, 0.6 p.u. for heat):**

Node A FOR

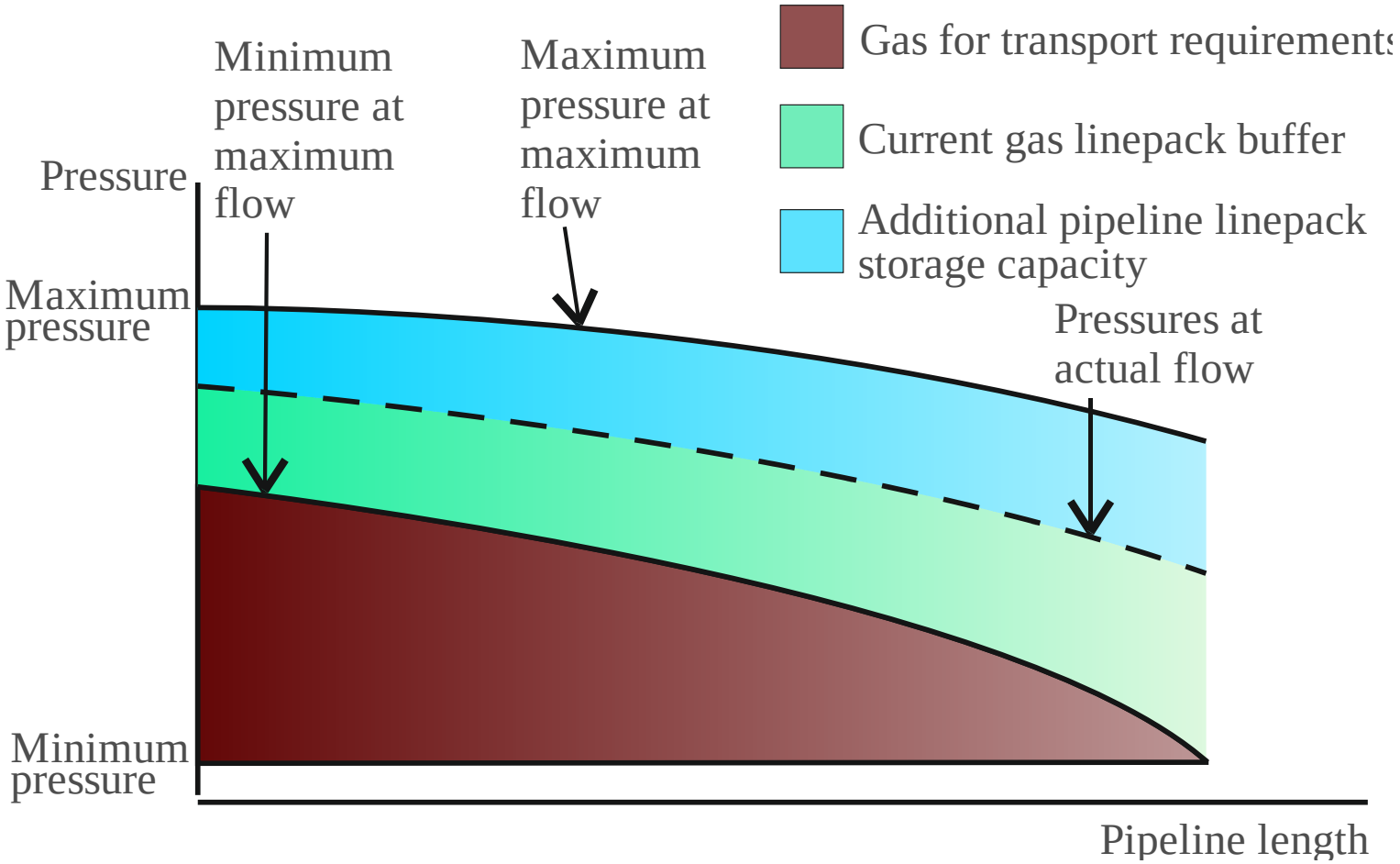
Solid lines: capacity that can be used for transfer

Dotted lines: capacity that is constrained due to networks



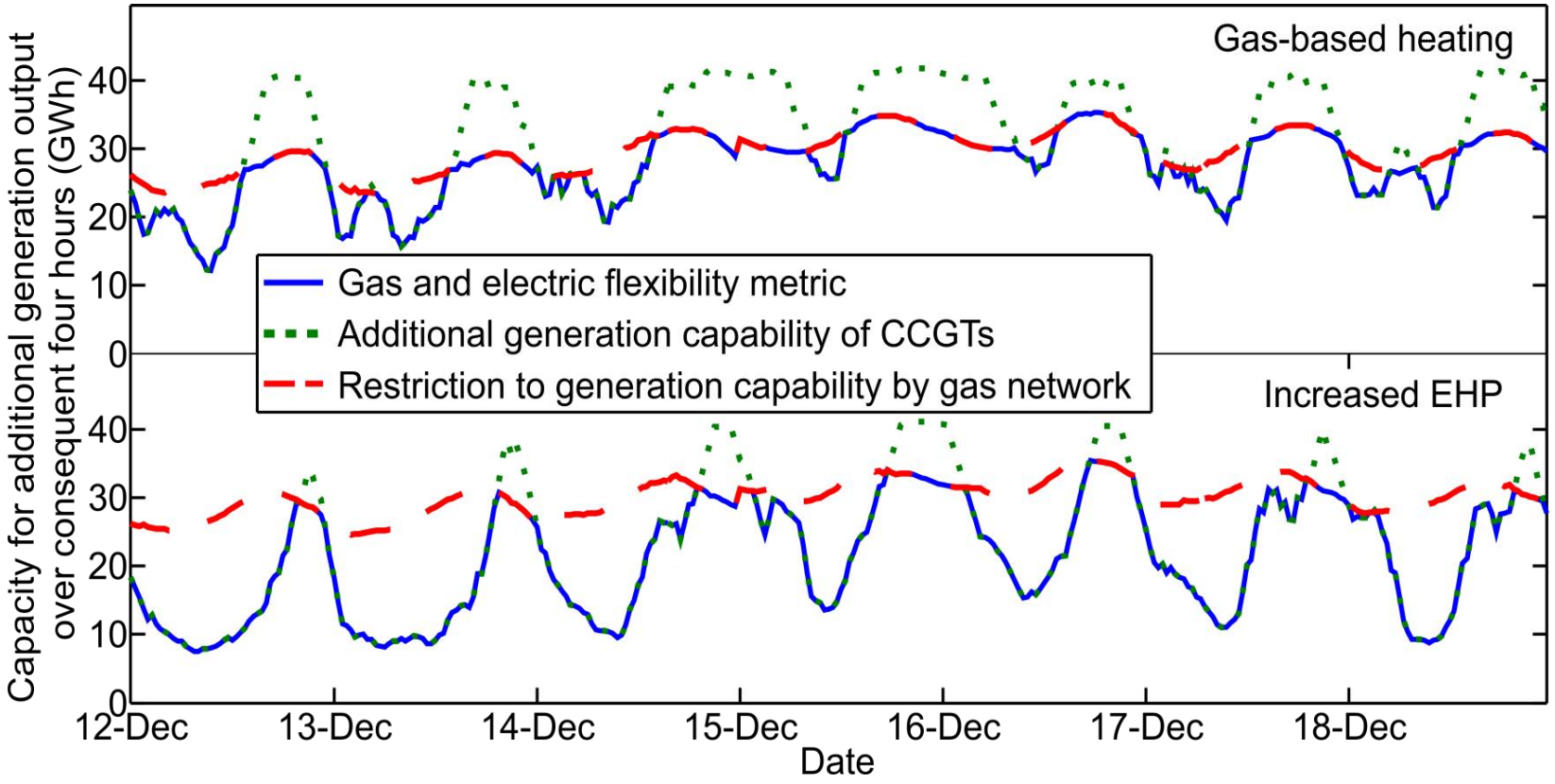
G. Chicco *et al.*, "Flexibility from distributed multienergy systems", *Proceedings of the IEEE*, 2020

Example: linepack in a gas pipeline



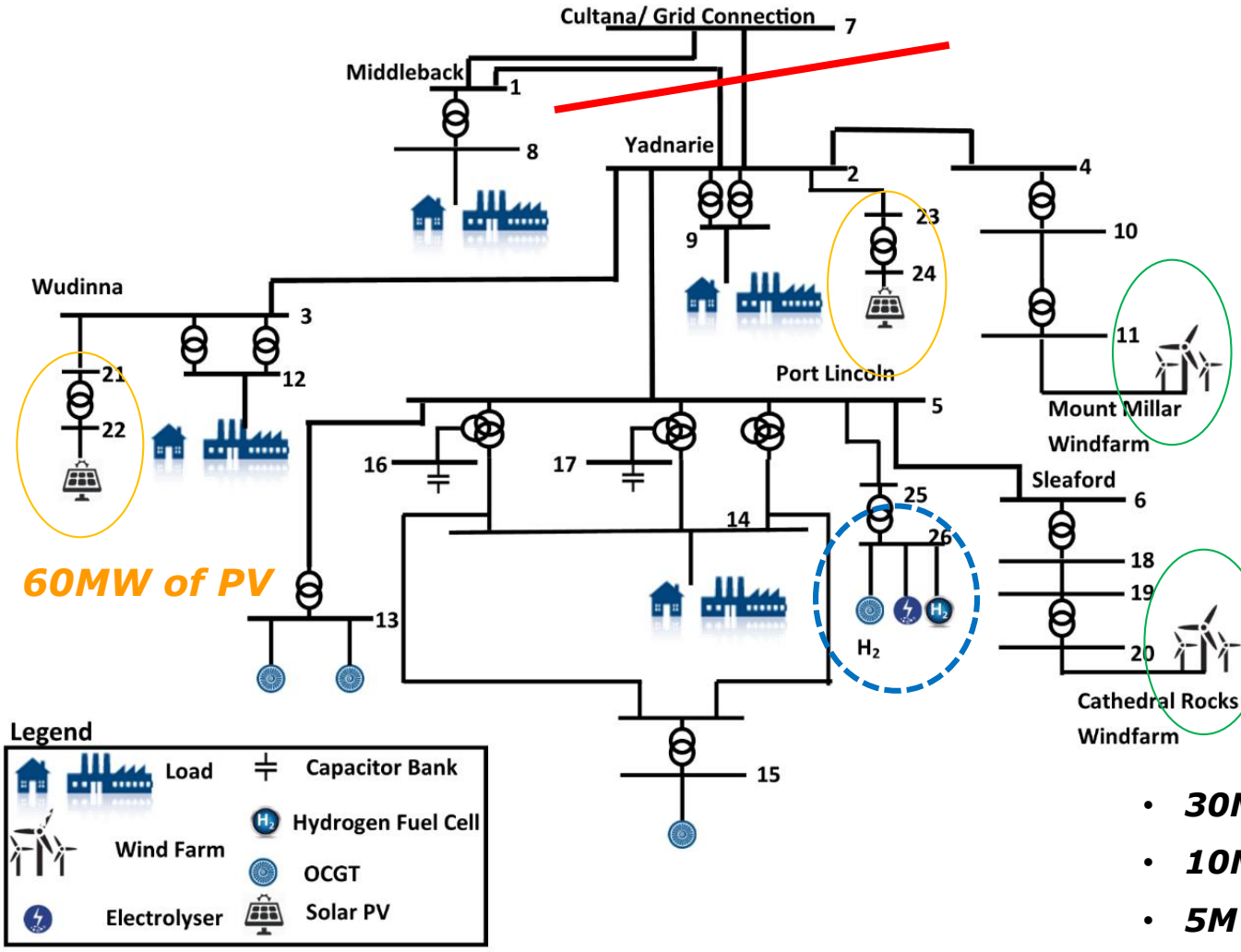
S. Clegg, P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems", IEEE Transactions on Sustainable Energy, 7 (2), pp.718–731, 2015

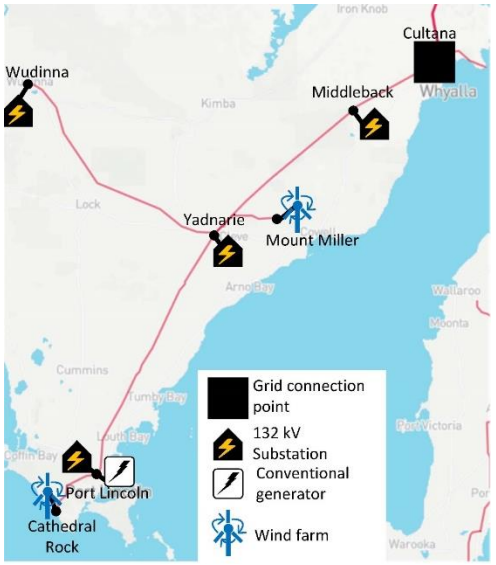
Integrated electricity and gas flexibility



S. Clegg, P. Mancarella, "Integrated Electrical and Gas Network Flexibility Assessment in Low-Carbon Multi-Energy Systems", IEEE Transactions on Sustainable Energy, 7 (2), pp.718–731, 2015.

Hydrogen-RES multi-energy VPP



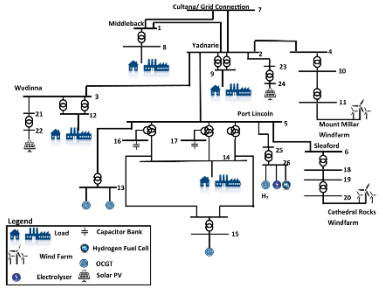


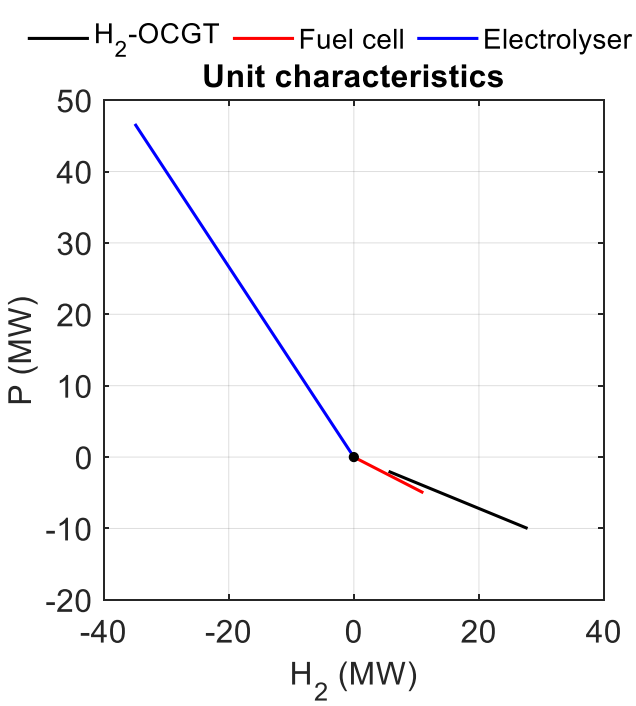
- ***60MW of PV***
- ***136MW of Wind***

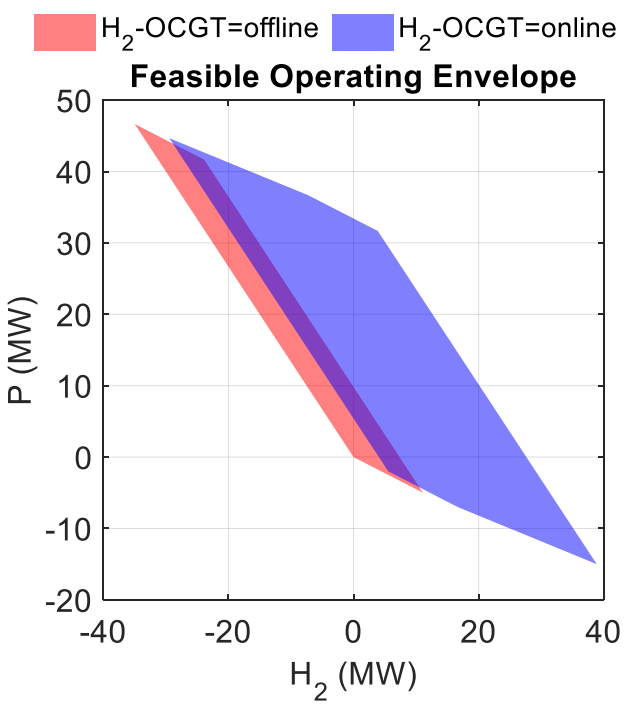
- ***30MW Electrolyser***
- ***10MW H2 OCGT***
- ***5MW Fuel Cell***
- ***100MWh of H2 Storage***
- ***73MW OCGT***

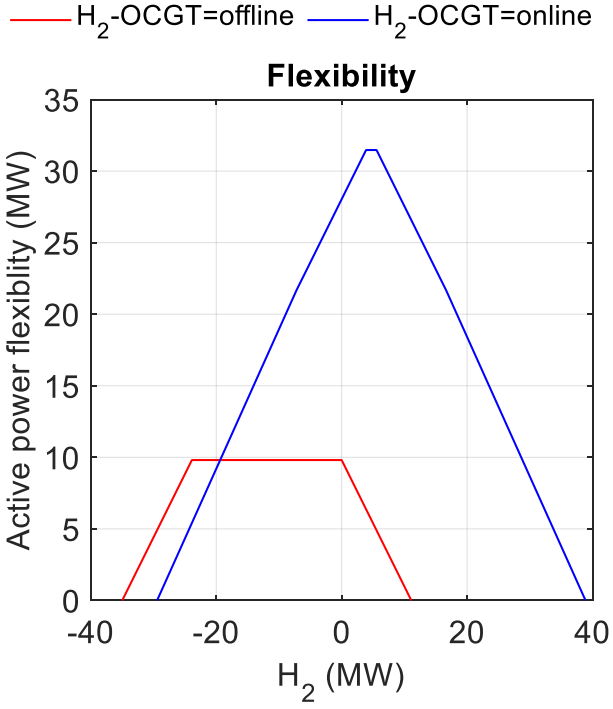
J. Naughton *et al.*, "Optimization of Multi-Energy Virtual Power Plants for Providing Multiple Market and Local Network Services", *Electric Power Syst. Research*, 2020

Multi-energy VPP flexibility



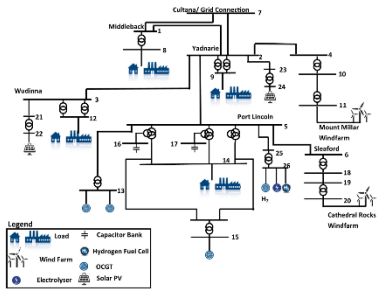


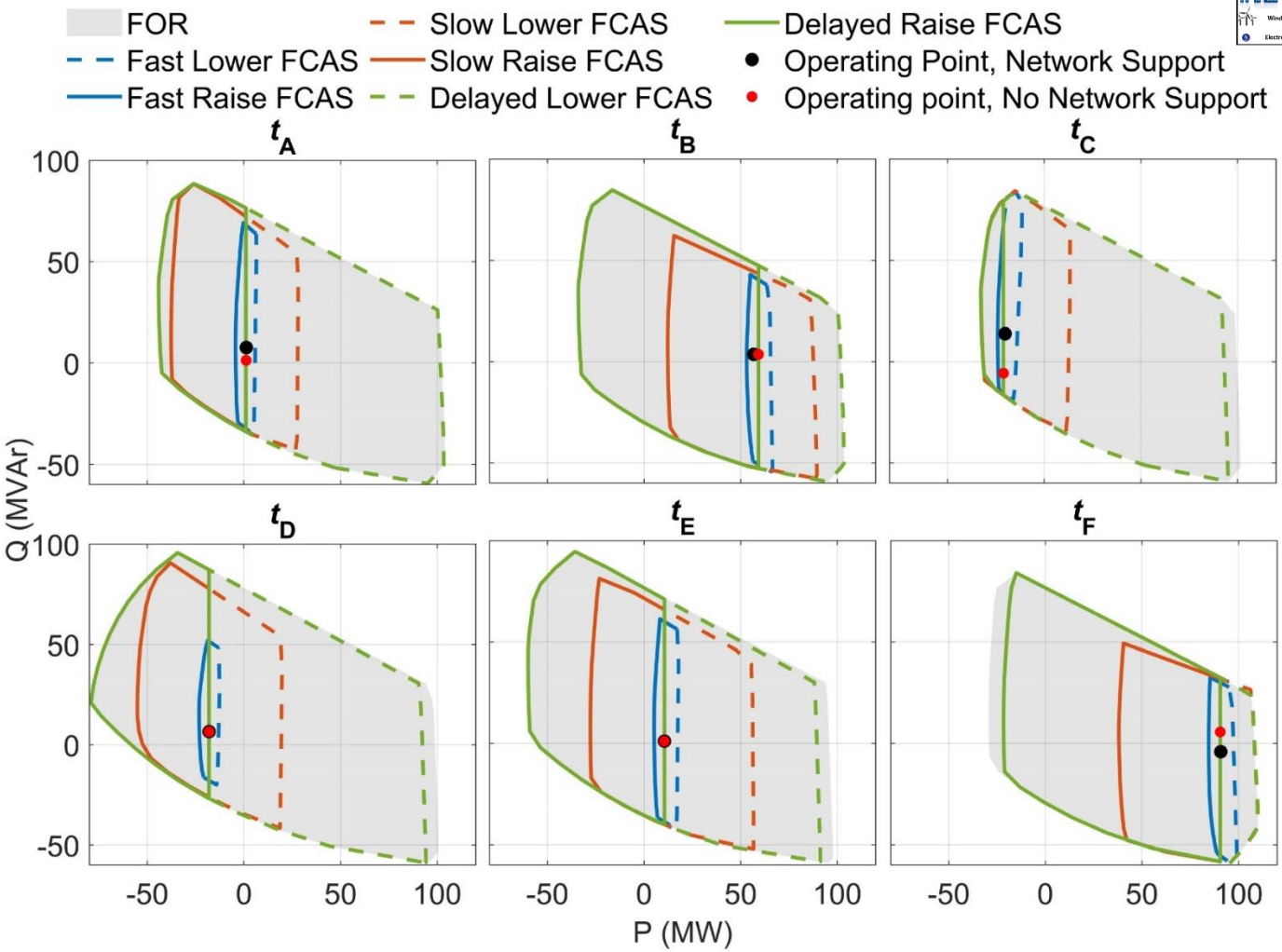




S. Riaz et al., "Flexibility and grid services from integrated electricity-hydrogen distributed energy systems", *Paris Cigre*, August 2020

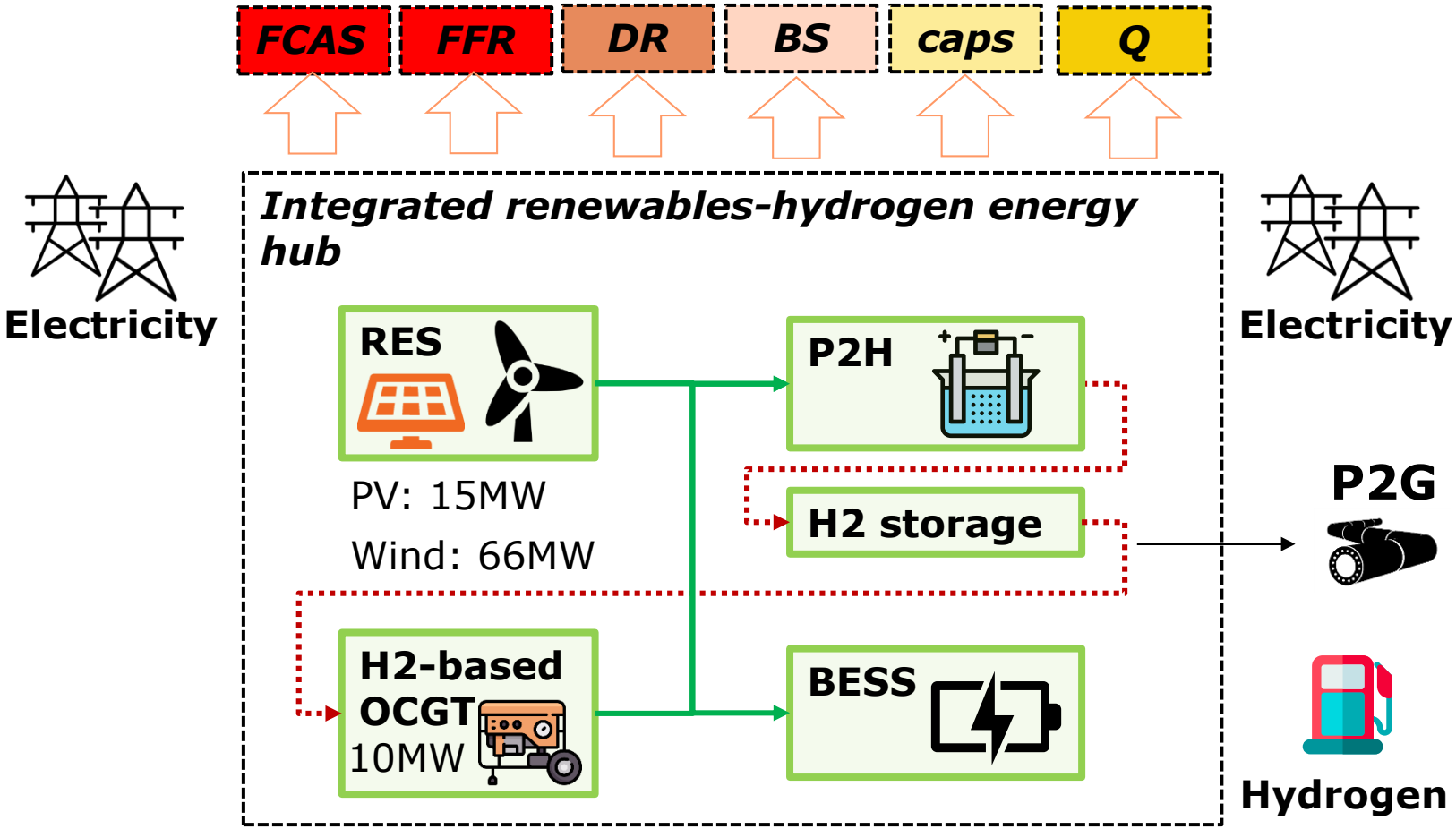
Multi-energy VPP flexibility and grid services maps



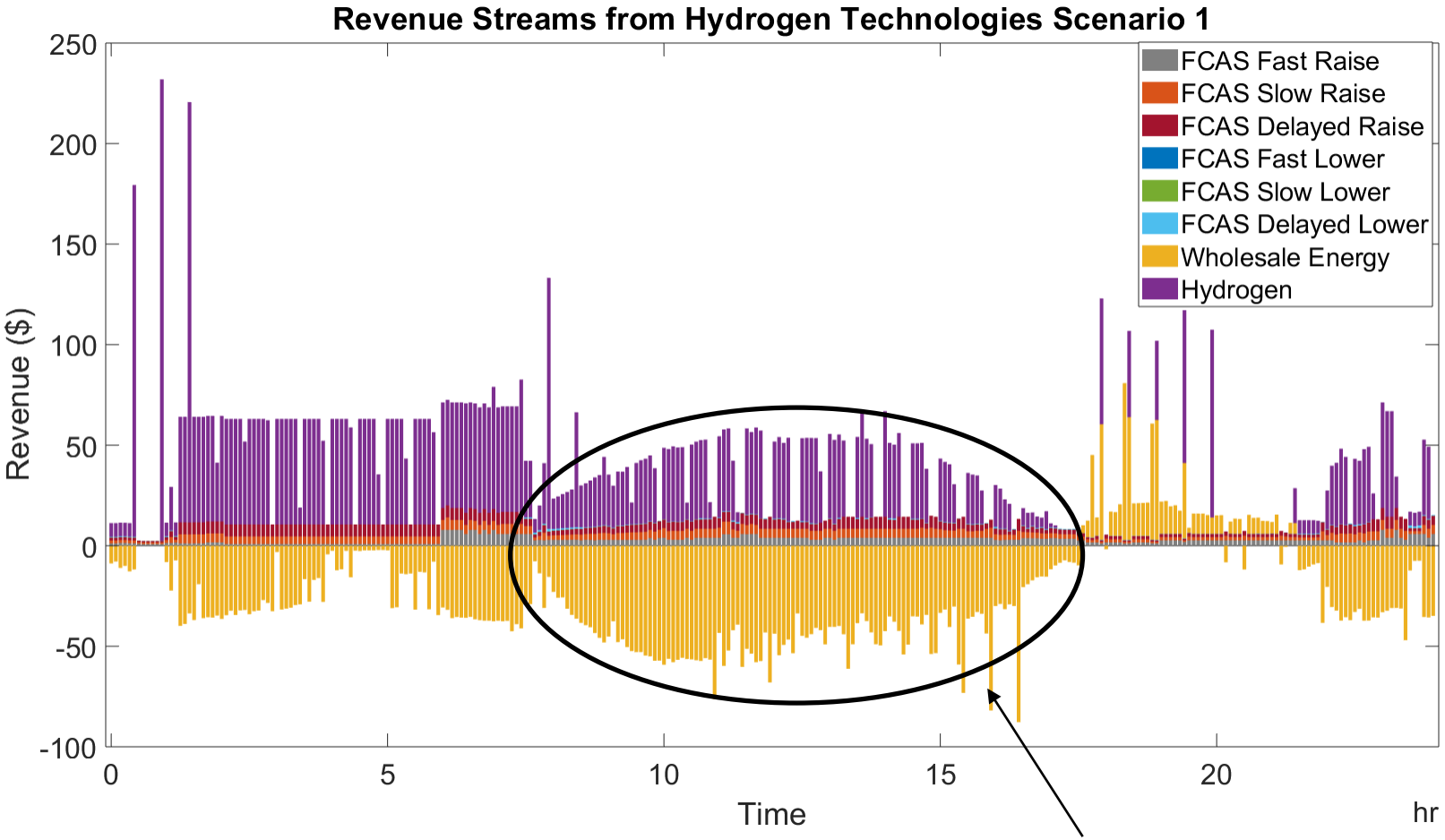


J. Naughton *et al.*, "Optimization of Multi-Energy Virtual Power Plants for Providing Multiple Market and Local Network Services", *Electric Power Syst. Research*, 2020

Integrated electricity, hydrogen, RES energy hub: flexibility and business cases



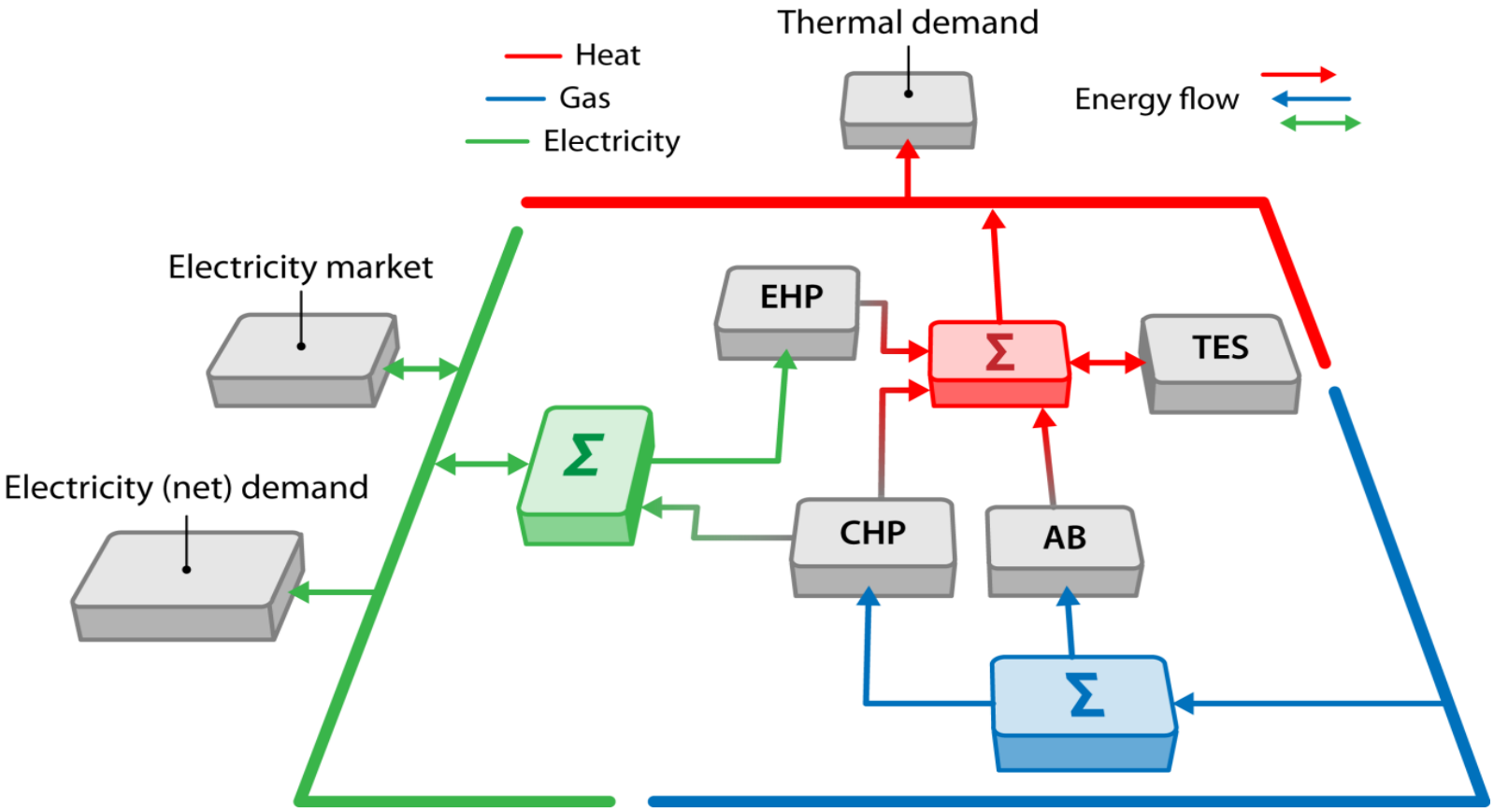
Security-constrained operation of hybrid energy hubs with multi-commodity markets



Note: Potential revenue from the FFR agreement *not* included

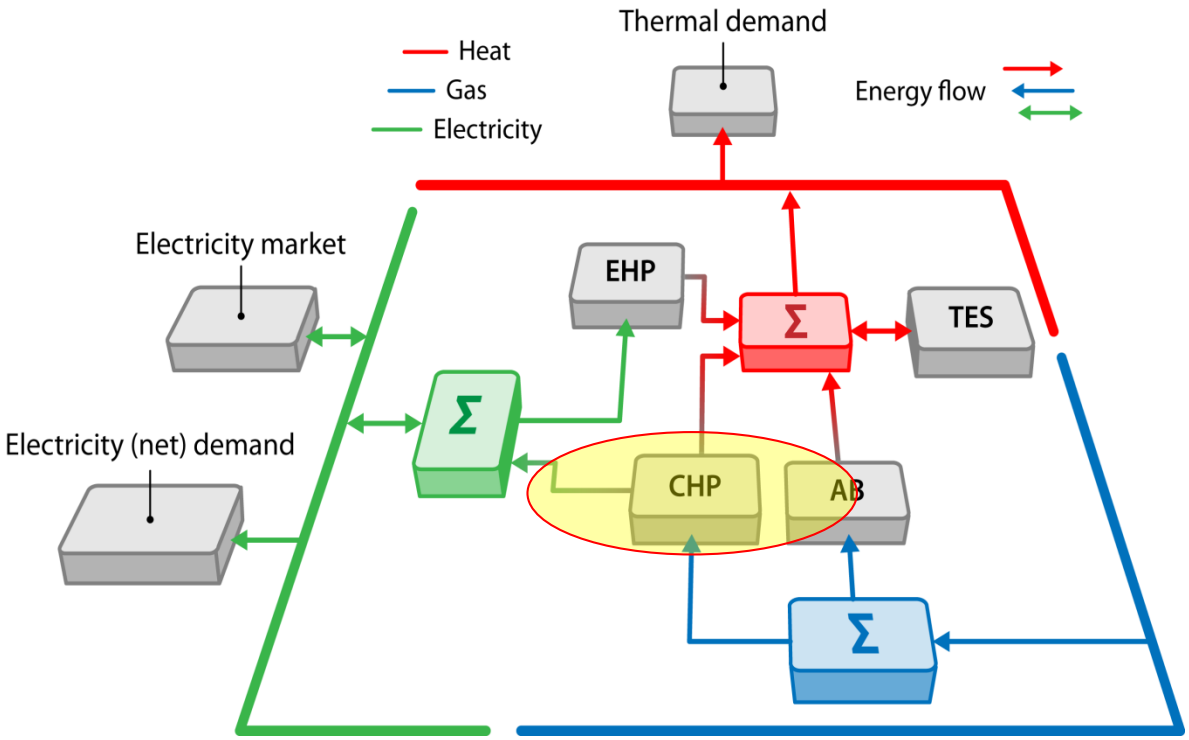
Hydrogen-based devices providing FFR for PV

Planning under uncertainty and MES



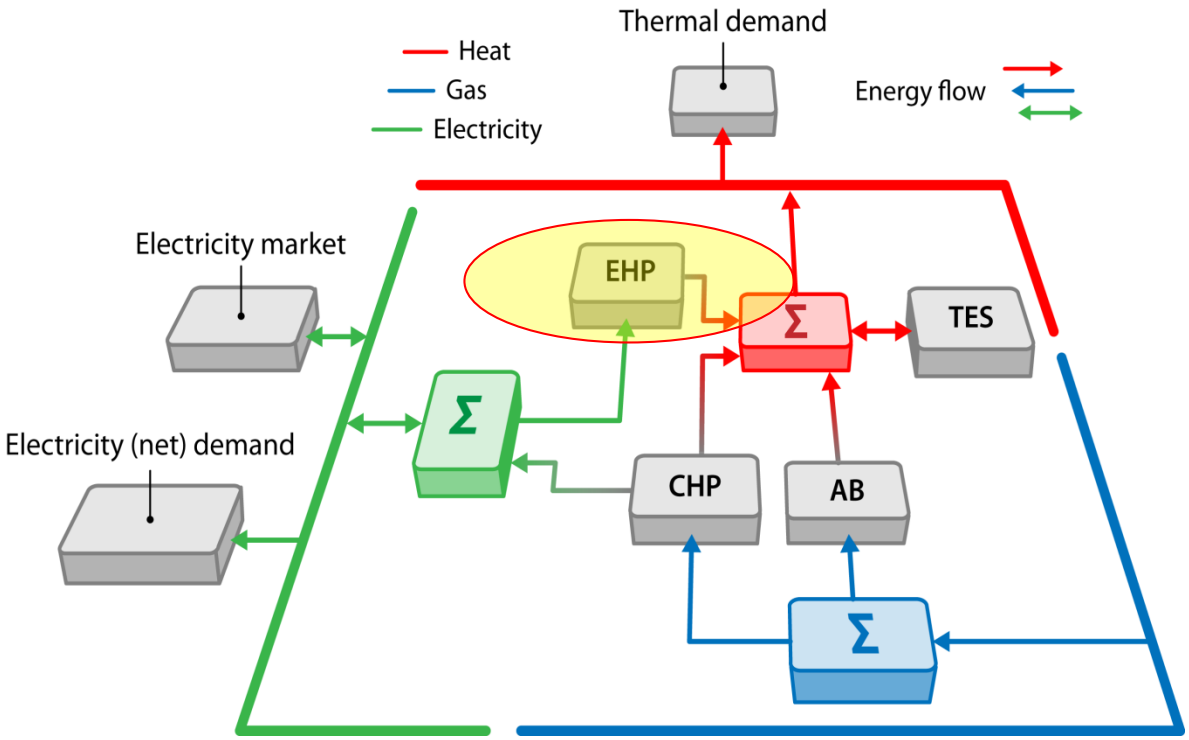
R. Moreno, A. Street, J.M. Arroyo, and P. Mancarella, "Planning Low-Carbon Electricity Systems under Uncertainty Considering Operational Flexibility and Smart Grid Technologies", *Philosophical Trans. Royal Society A*, June 2017

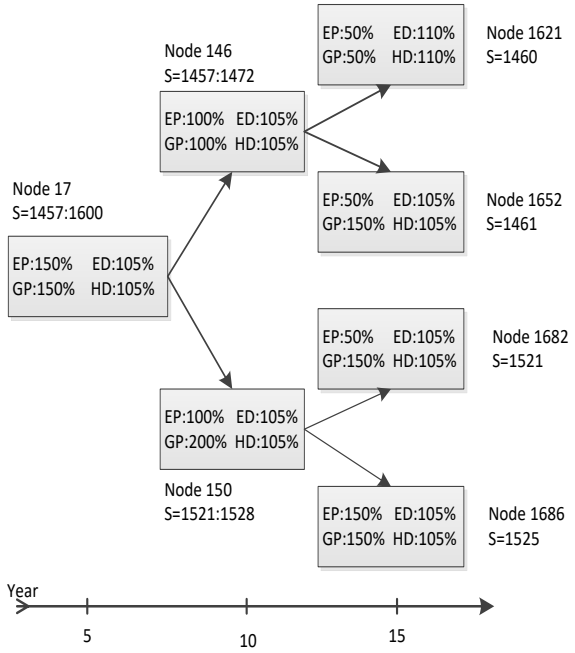
Planning for flexibility requires…



E.A. Martinez-Cesena, *et al*, Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty, *IEEE Transactions on Smart Grid,* 2016

… flexible planning methodologies

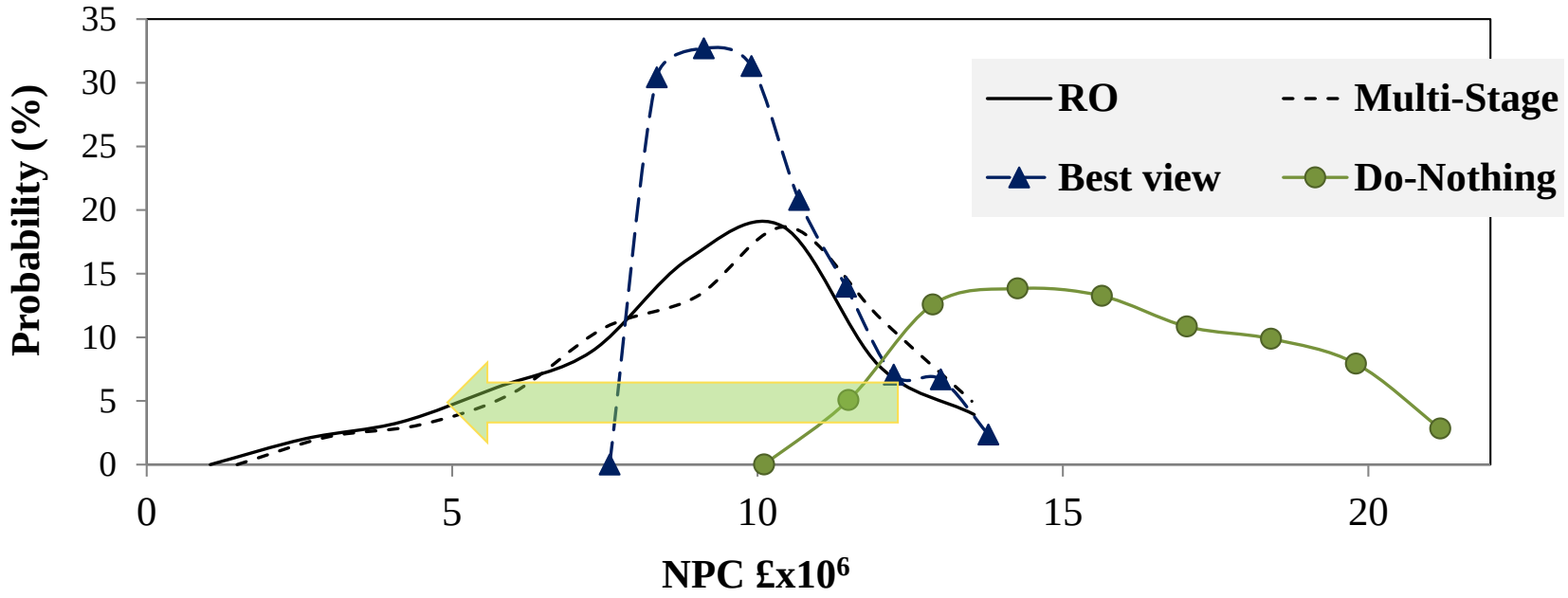




E.A. Martinez-Cesena, *et al*, Flexible Distributed Multi-Energy Generation System Expansion Planning under Uncertainty, *IEEE Transactions on Smart Grid,* 2016

Flexibility-in-planning fully exploits MES flexibility-in-operation

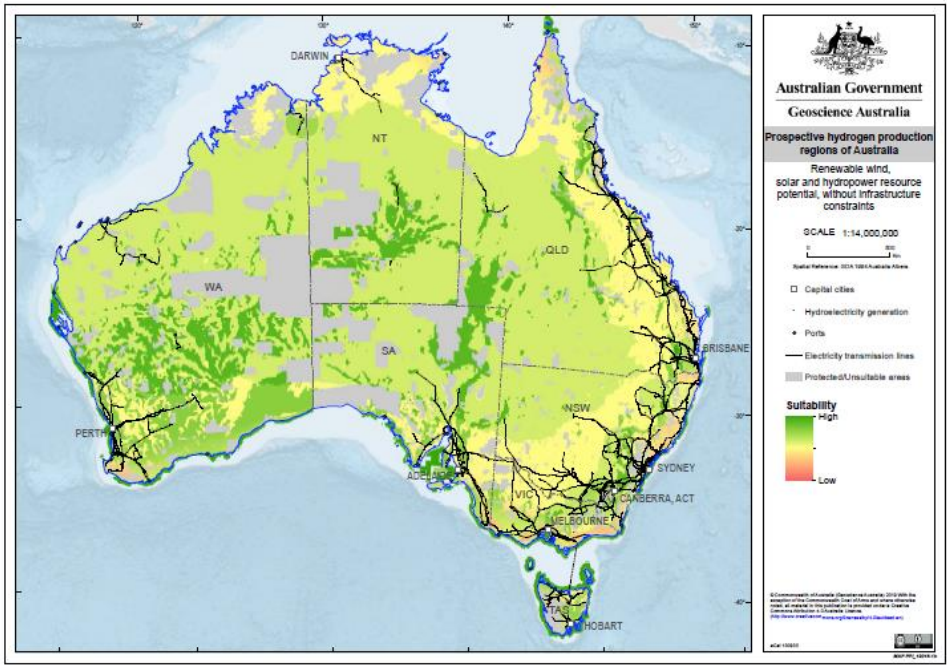
- The value of **flexible operation and investment** skews the expected economic performance of the DMES



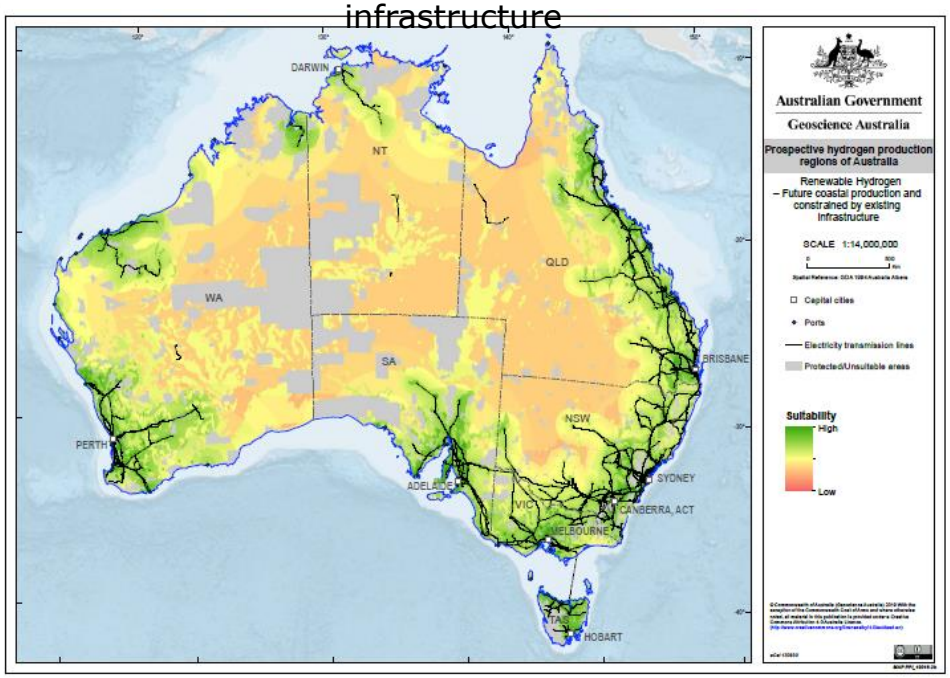
E. A. Martinez Cesena, T. Capuder and P. Mancarella, "Flexible distributed multienergy generation system expansion planning under uncertainty," IEEE Transactions on Smart Grid, 2016

Planning BIG:
The Australia's National Hydrogen Strategy and green hydrogen potential

Potential with no infrastructure constraints



Potential with consideration for access to water, ports, pipeline easements, and electricity infrastructure



Source: COAG Energy Council, Australia's National Hydrogen Strategy, November 2019

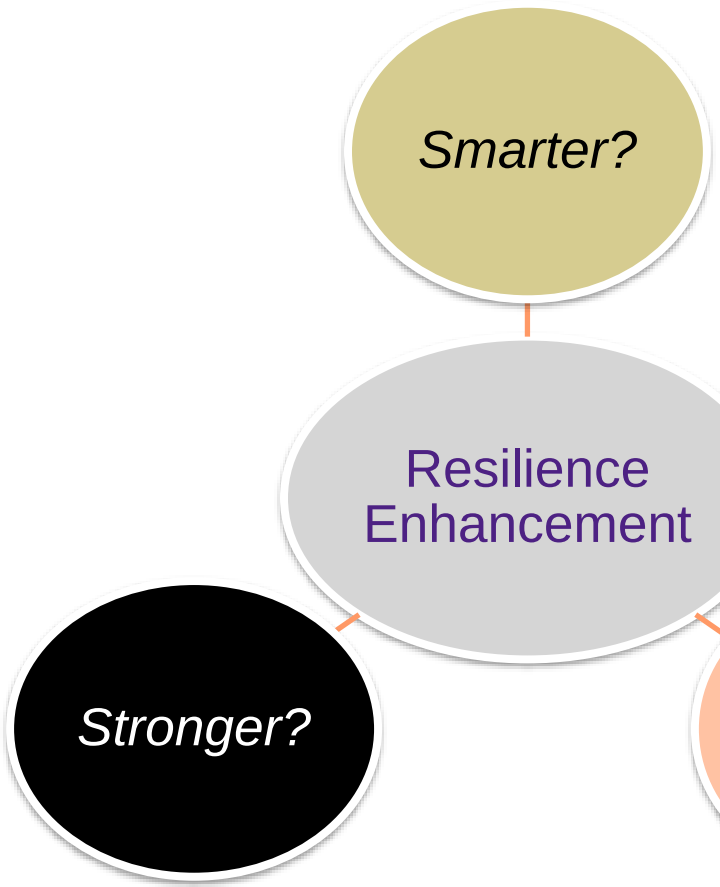
Australia Potential Exports of Hydrogen In the Next 20 Years

Scenario	Country	2025		2030		2040	
		PJ	'000 tonnes	PJ	000 tonnes	PJ	000 tonnes
Low hydrogen scenario	Japan	2.1	17.3	21.9	182.2	47.1	392.1
	Korea	1.0	8.0	4.8	40.1	12.9	107.4
	Singapore	0.04	0.3	0.5	3.9	1.5	12.5
	China	0.1	0.5	1.4	11.6	10.7	88.9
	Rest of the World	0.05	0.4	0.5	4.3	2.4	20.3
	Total	**3.2**	**26.5**	**29.1**	**242.1**	**74.6**	**621.3**
Medium hydrogen scenario	Japan	12.7	106.1	44.2	368.1	102.3	852.2
	Korea	2.9	23.9	9.4	78.1	28.1	233.6
	Singapore	0.2	2.1	0.9	7.4	2.7	22.6
	China	0.3	2.6	4.5	37.6	23.7	197.3
	Rest of the World	0.2	1.8	1.3	11.0	5.4	44.8
	Total	**16.4**	**136.5**	**60.3**	**502.1**	**162.2**	**1,350.4**
High hydrogen scenario	Japan	33.0	275.0	96.4	803.0	237.7	1,978.8
	Korea	6.4	53.0	20.1	167.4	68.4	569.5
	Singapore	0.5	4.2	1.8	15.1	7.5	62.5
	China	0.9	7.9	9.5	79.3	55.7	463.9
	Rest of the World	0.6	4.8	2.8	23.5	12.7	105.6
	Total	**41.4**	**344.8**	**130.7**	**1,088.4**	**382.0**	**3,180.4**

SOURCE: ACIL ALLEN ESTIMATES

How to plan for the black swan?

Planning for Resilience: The Resilience Trilemma



Make the network more responsive (e.g. faster restoration), self-adaptive, resourceful, etc.

Upgrade existing infrastructure, asset life extension, etc.

Build new infrastructure, e.g. transmission lines, substations, etc.

M. Panteli and P. Mancarella, The Grid: Stronger, Bigger, Smarter? Presenting a conceptual framework of power system resilience, *IEEE Power and Energy Magazine,* May/June 2015*, Invited Paper*.

Will more transmission enhance resilience?

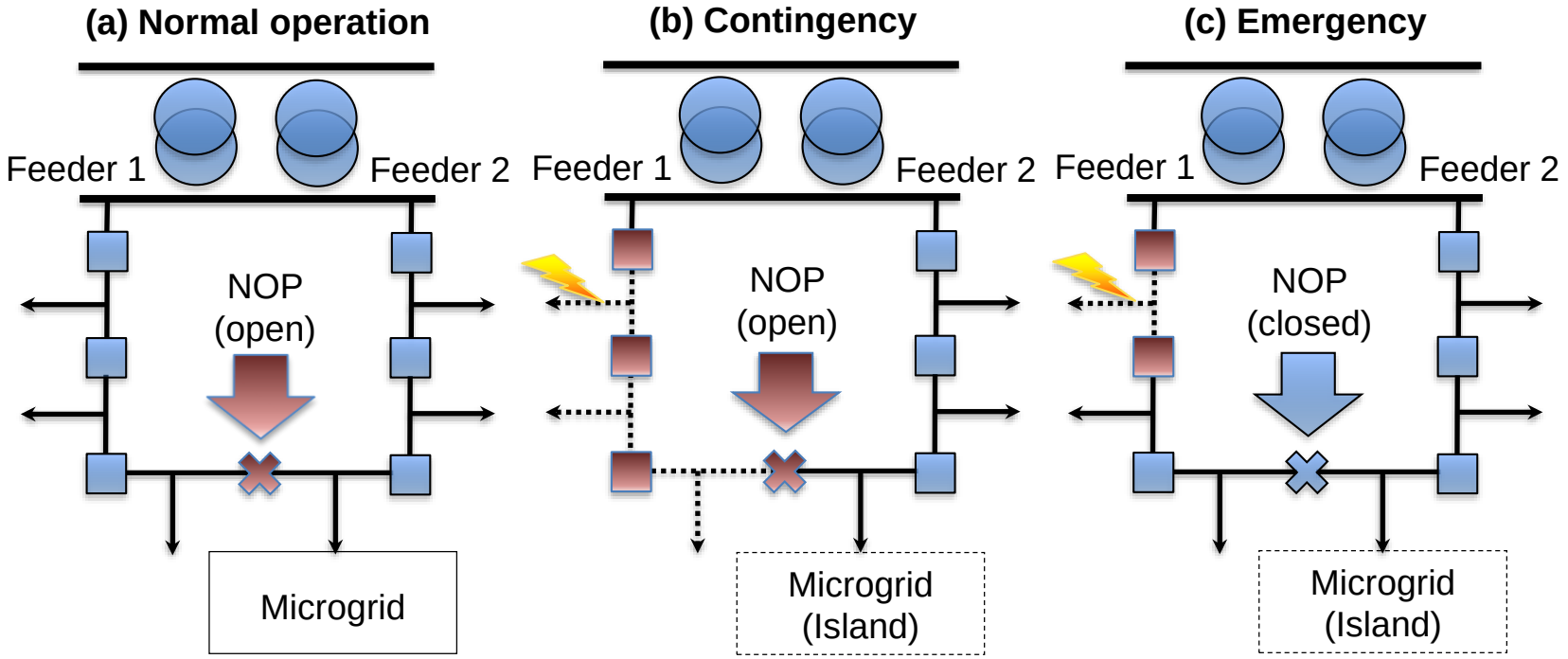
Why Investments Do Not Prevent Blackouts

The idea that increasing the capacity of the transmission network should improve the security of the system and reduce the probability of blackouts is intuitively appealing. However, this intuition does not withstand scrutiny.

Daniel Kirschen and Goran Strbac

D. Kirschen and G. Strbac, "Why investments do not prevent blackouts", *The Electricity Journal*, March 2004

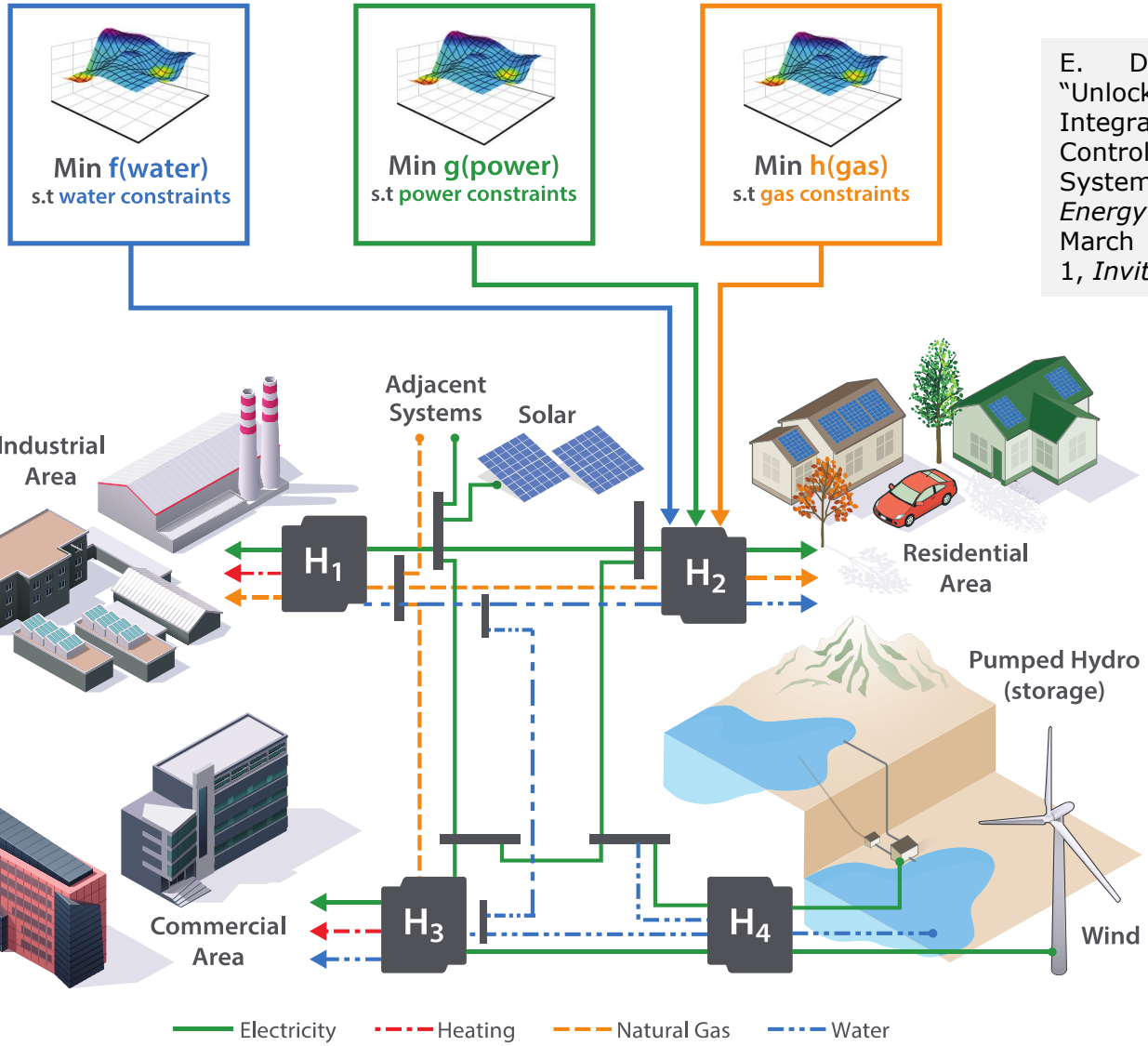
Flexibility and resilience from Multi-energy Microgrids



E. A. Martínez Ceseña, N. Good, A. L. A. Syrri, P. Mancarella, "Techno-economic and business case assessment of multi-energy microgrids with co-optimization of energy, reserve and reliability services," Applied Energy, 2017

T. Lagos, *et al.*, "Identifying Optimal Portfolios of Resilient Network Investments Against Natural Hazards, With Applications to Earthquakes", *IEEE Transactions on Power Systems*, *2020*

Next: Unlocking multi-energy flexibility via optimization, control, and integrated energy markets



E. Dall'Anese, *et al.*, "Unlocking Flexibility: Integrated Optimization and Control of Multienergy Systems", *IEEE Power and Energy Magazine*, January-March 2017, Vol. 15, Issue 1, *Invited Paper*

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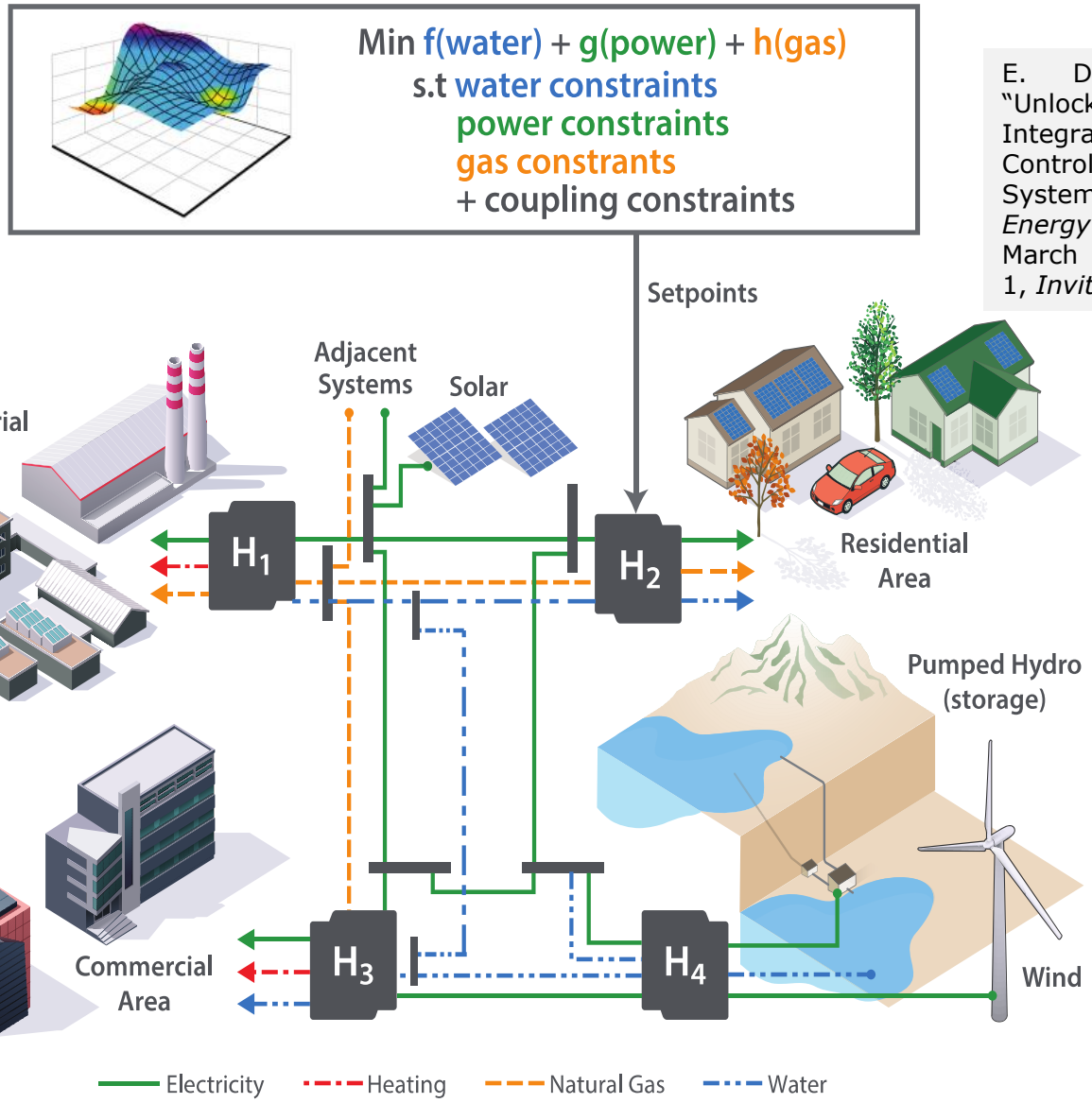

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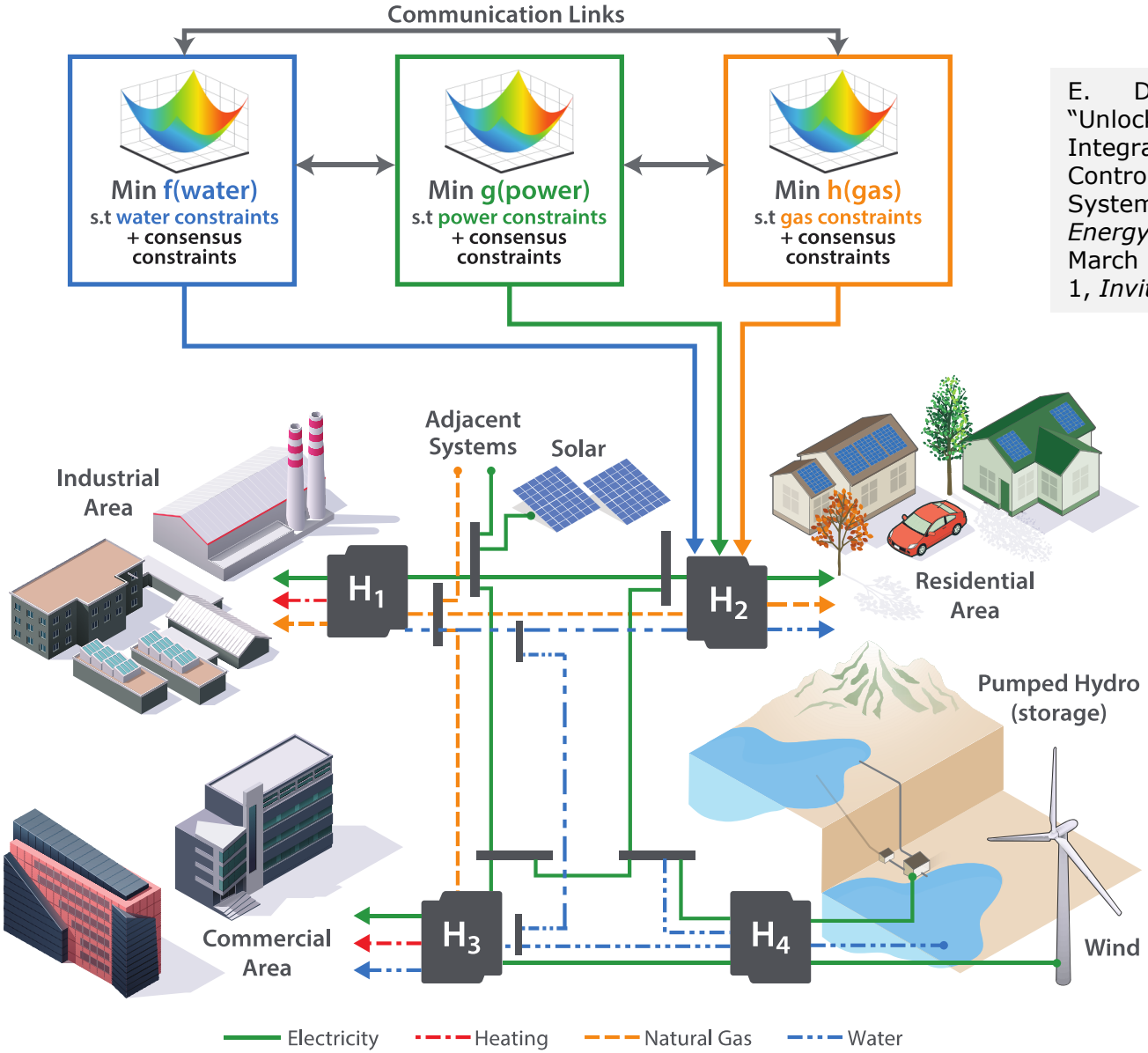

E. Dall'Anese, *et al.*, "Unlocking Flexibility: Integrated Optimization and Control of Multienergy Systems", *IEEE Power and Energy Magazine*, January-March 2017, Vol. 15, Issue 1, *Invited Paper*

Key remarks

- **Superior flexibility** can be harnessed from *multi-energy systems*
- Substantial grid flexibility can be unlocked at **relatively low cost** from other energy vectors
- MES have a key role to enable **local** and **system-level** flexibility and market participation in multiple commodities and grid services
  - Electricity and heat, gas, hydrogen
  - Frequency response, reactive support, etc.
  - Resilience services
- **Scalability** of MES flexibility concepts (building, district, city, region, country)
- Synergy between **flexibility-in-operation** and **flexibility-in-planning** to hedge against investment uncertainty and risk
- Regulatory, market, and policy framework to create the right price signals to optimally deploy flexibility across MES

Back to the future

"Water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.

Someday the coal-rooms of steamers and the tenders of locomotives will, instead of coal, be stored with these two condensed gases, which will burn in the furnaces with enormous calorific power."

Jules Verne, "The Mysterious Island",1874

"For the anxious, progress towards a hydrogen future is too slow. But look back a few decades from now and history will record the hydrogen industry as an overnight success"

Dr Alan Finkel, Chief Scientist of Australia, November 2019

Source: COAG Energy Council, Australia's National Hydrogen Strategy, November 2019

Acknowledgments

- My research teams in Melbourne and Manchester
- The Victorian Government and *veski* for my *veski* Innovation Fellowship
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- The UK EPSRC (MY-STORE and TERSE projects)
- The UK-Chile Newton-Picarte "*Disaster management and resilience in electric power systems*" project
    - Project awarded a 2018 international Newton Prize
- The European Commission for the support provided throughout the years via ADDRESS, COOPERATE, DIMMER, ATTEST, EUniversal projects

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Flexibility and grid services from multi-energy systems

Pierluigi Mancarella

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