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Smart Grids and Sustainable Electricity Systems

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Introduction to Smart Grids

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Introduction to Smart Grids and Sustainable Electricity Systems

DR ALESSANDRA PARISIO

Outline of the course: Lecturers

- Lecturers:
  - Dr Alessandra Parisio (AP)
    - Engineering Building A, 5th floor
      alessandra.parisio@manchester.ac.uk
  - Dr Haiyu Li (HL)
    - Engineering Building A, 5th floor
      haiyu.li@manchester.ac.uk

Something about myself

- **PhD in Automatic Control**

  University of Sannio (Italy) and Swiss Federal Institute of Technology (ETH, Switzerland)

- **Post Doc at the Department of Automatic Control**

  Royal Institute of Technology (KTH, Sweden)

- **Reader at Power & Energy Division**

  Department of Electrical and Electronic Engineering, The University of Manchester, UK

Main research interests

Energy management systems under uncertainty, model predictive control, stochastic constrained control and distributed optimisation for power systems.

Outline of the course: Aims

- Explore the main concepts behind smart grids and low-carbon networks, two prominent changes in power systems
- Assess and calculate the impact of the integration of low-carbon technologies into the grid
- Explain environmental concerns as well as the technical economic and social (the energy quadrilemma)

Outline of the course: sections (AP)

1. Introduction to Smart Grids
   - Definition of smart grid, its main features, challenges and opportunities.
2. Integration of low carbon technologies
   - Main aspects of power system planning, operation and economics.
   - Impact of the integration of low-carbon technologies, and in particular renewable energy sources, on the way power systems are planned and operated.
   - Model the generators through efficiency and emission factors.
3. Generation and demand flexibility in low carbon electricity systems: challenges and opportunities
   - Key technologies that are flexibility sources in a smart grid.
   - Description of how the flexibility is related to the energy market, short-term operational and long-term planning aspects.
   - Use of flexibility to support and decarbonise the power grid. Multi-energy networks and microgrids.

Outline of the course: sections (HL)

4. Introduction to Electricity Distribution Networks
   - Overall structure of electric distribution networks and their main components, including voltage levels, network configuration, load profiles/characteristics, low voltage network design and voltage drop calculation.
5. Impact of Low Carbon Technologies on Distribution Networks
   - Main aspects of low carbon technologies, including electric vehicles, photovoltaic, and other technologies (storages, heat pumps, smart appliances).
   - Impacts low carbon technologies on network voltage rise/drop issues as well as the network power flow capability.
6. Integration of Low Carbon Technologies - Technical Challenges and Methods
   - Technical issues of low carbon technology integration, in particular their impact on distribution network operation, protection and control.
   - Active Network Management techniques and maximization of the integration of low carbon technologies into distribution network.

Outline of the course: tutorials

- Impact of renewable energy sources on the power system operation.
- Modelling of generation technologies through efficiencies and emission factors
- Quantification of the potential energy savings associated to given production plants.
- Impact of distributed generation, electric vehicles, heat pumps on distribution networks
- Active network management

Outline of the course: assessment

- Blackboard-submitted (Turnitin-checked) coursework report, including lab-based results and studies (**20%**).
- Three-hour laboratory session on - Wednesday **17th April**, 9:00-12:00, Engineering A_1A.011+1A.016 Computer clusters 1&2
- Deadline for report submission: **24th April**
- Exam (**80%**)

Industrial guest lectures

- Jacobs, 10th April, 15:00 – 16:00.

Energy webpage

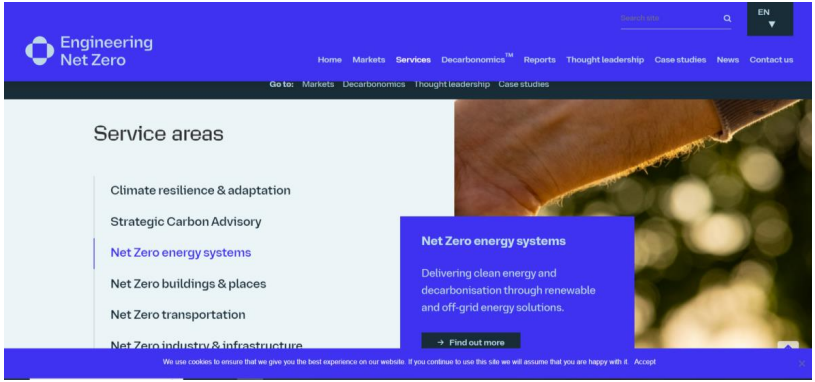
Energy

Building a more sustainable future for everyone

Industrial guest lectures

- AtkinsRéalis, 15th April, Stopford Building Theatre 1, 12:00 – 13:30.

[Engineering Net Zero webpage]



You will be able to

- Describe what is meant by smart grids
- Explain the key planning and operational issues of low carbon electricity systems
- Evaluate the economic and environmental potential benefits of low carbon electricity systems
- Describe and compare a variety of different distribution networks
- Calculate the impact of adding low carbon technologies and use active management systems to maximise their penetration

Suggested reads

- Bollen, “The Smart Grid”, Morgan and Claypool, 2011
  - High level concepts on the Smart Grid
- Kirschen & Strbac, Fundamentals of Power System Economics, Wiley, 2004
  - Introduction to power systems (may be useful for REaCT)
- Jenkins, Ekanayake and Strbac, “Distributed Generation”, IET
  - Models and analysis of the impact of DG
- Masters, “Renewable and efficient electric power systems”, Wiley, 2004
  - Fundamentals of renewable energy technologies
- Mancarella, “An overview of concepts and evaluation models”, Energy, 2014
  - Review of multi-energy generation

Further reads

- BEIS ad Ofgem, “Transitioning to a net zero energy system Smart Systems and Flexibility Plan 2021”
- G. Dileep, “A survey on smart grid technologies and applications”, Renewable Energy, Volume 146, 2020
- N. Shaukat, et al., “A survey on electric vehicle transportation within smart grid system”, Renewable and Sustainable Energy Reviews, Volume 81, Part 1, 2018
- Catarina Araya Cardoso et al., “Making demand side response happen: A review of barriers in commercial and public organisations”, Energy Research & Social Science, 2020

Unit Evaluation Survey

Please do give us your feedback on your studies here at Manchester (both what's gone well and what's gone not so well)

Examples of what has been changed based on feedback

- More tutorials and exercises
- More convenient schedule of laboratory sessions
- Additional teaching material focusing on the coursework

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Introduction to Smart Grids

Dr Alessandra Parisio

Questions to start with

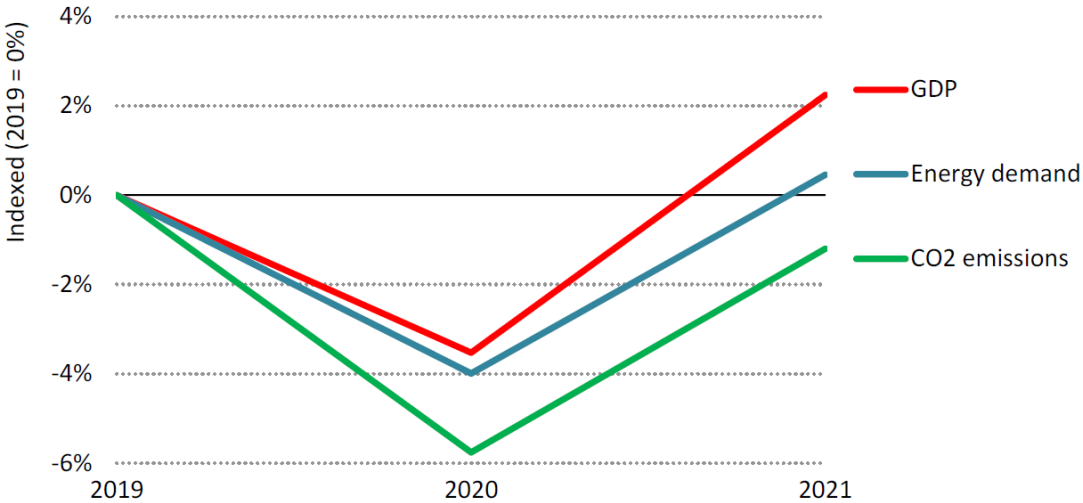
What is a *smart grid* and why we need it?

My definition of a smart grid

The use of *information processing, communication and control* in the power grid to:

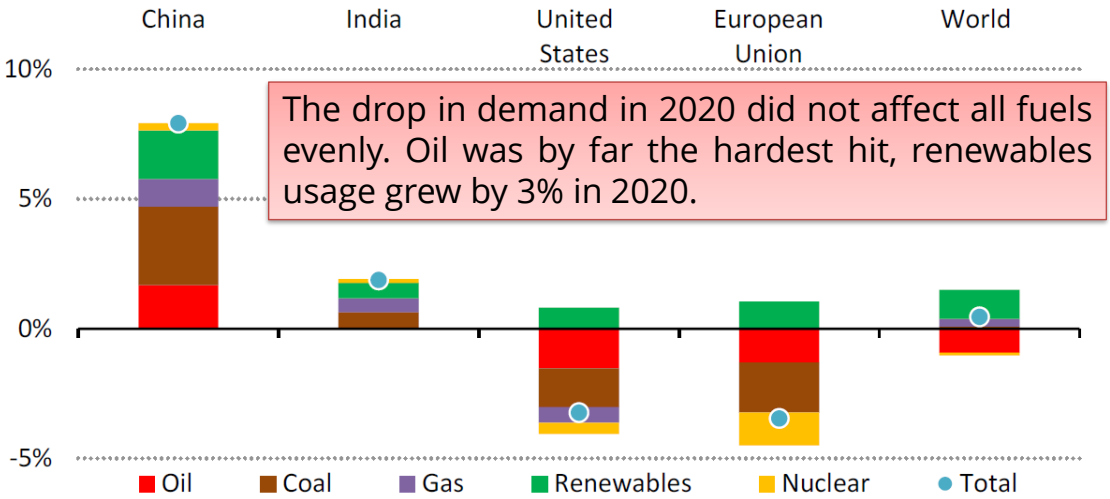
- enable informed participation by consumers
- accommodate all generation and storage options
- optimise asset utilisation and operating efficiency
- minimise costs and emissions
- provide resiliency to disturbances

Evolution of global GDP, total primary energy demand, and energy-related CO_2 emissions, relative to 2019



International Energy Agency (IEA), Global Energy Review 2021 (https://www.iea.org)

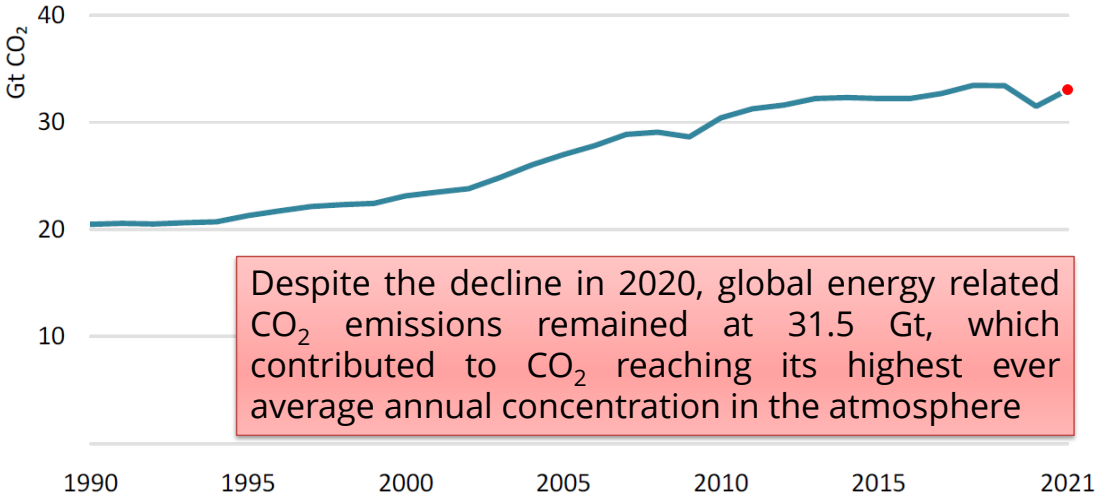
Change of primary energy demand by region and by fuel in 2021 relative to 2019



The drop in demand in 2020 did not affect all fuels evenly. Oil was by far the hardest hit, renewables usage grew by 3% in 2020.

International Energy Agency (IEA), Global Energy Review 2021 (https://www.iea.org)

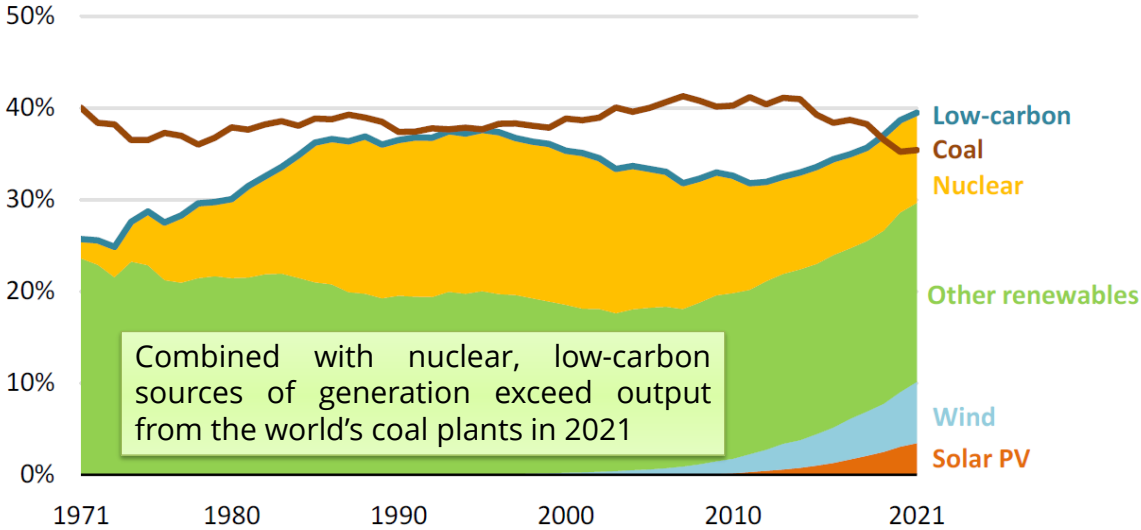
Global energy-related CO2 emissions, 1990-2021



Despite the decline in 2020, global energy related CO_2 emissions remained at 31.5 Gt, which contributed to CO_2 reaching its highest ever average annual concentration in the atmosphere

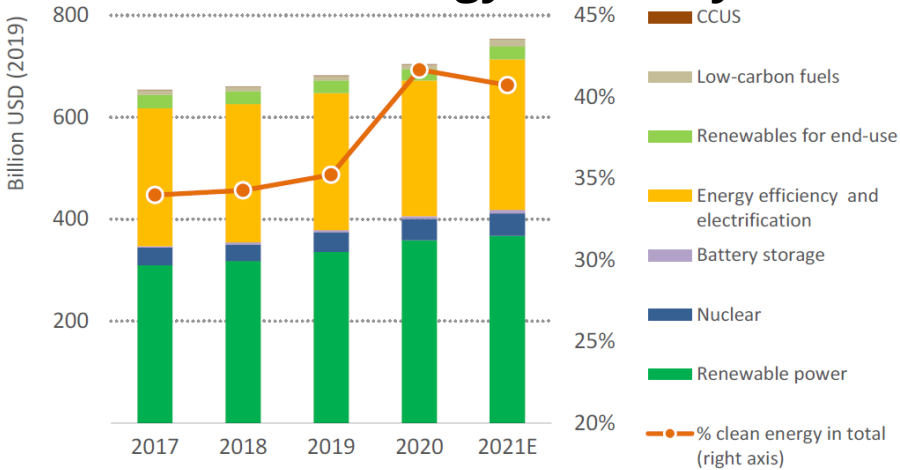
International Energy Agency (IEA), Global Energy Review 2021 (https://www.iea.org)

Share of low-carbon sources and coal in world electricity generation, 1971-2021



International Energy Agency (IEA), Global Energy Review 2021 (https://www.iea.org)

Global investment in clean energy and energy efficiency, 2017-2021



Getting the world on track for 1.5 °C requires a surge in annual investment in clean energy projects and infrastructure to nearly USD 4 trillion by 2030.

Clean energy investment is on a moderate upswing, but remains far short of what will be required to avoid severe impacts from climate change

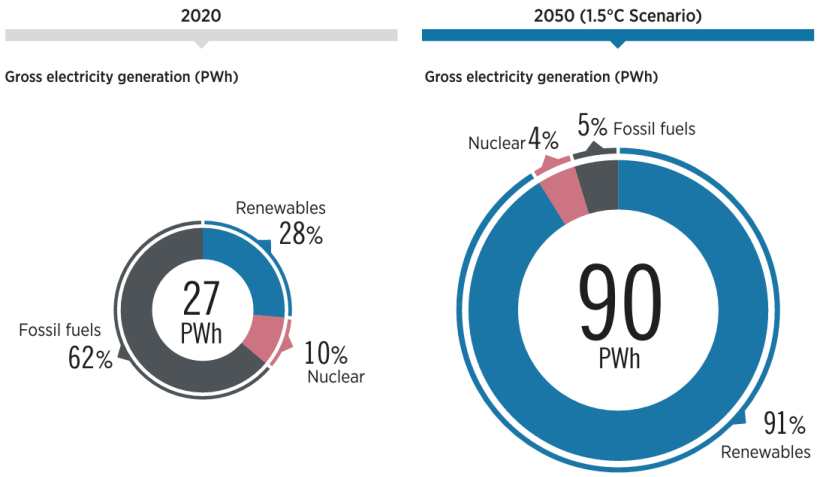
International Energy Agency (IEA), World Energy Investment, 2021 (https://www.iea.org)

Power generation

The **Planned Energy Scenario (PES)** is the primary reference case for this study, providing a perspective on energy system developments based on governments' current energy plans and other planned targets and policies, including Nationally Determined Contributions (NDCs) under the Paris Agreement.

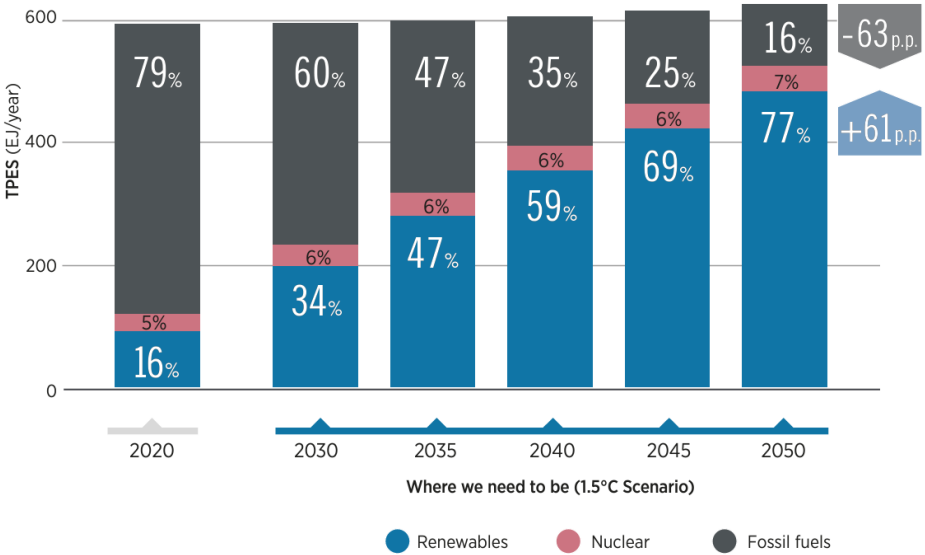
The **1.5°C Scenario (1.5-S)** describes an energy transition pathway aligned with the 1.5°C climate ambition – that is, to limit global average temperature increase by the end of the present century to 1.5°C, relative to pre-industrial levels. It prioritises readily available technology solutions, which can be scaled up at the necessary pace for the 1.5°C goal.

Power generation needs to more than triple by 2050 in the 1.5°C Scenario



IRENA (International Renewable Energy Agency), *World Energy Transitions Outlook*, 2023

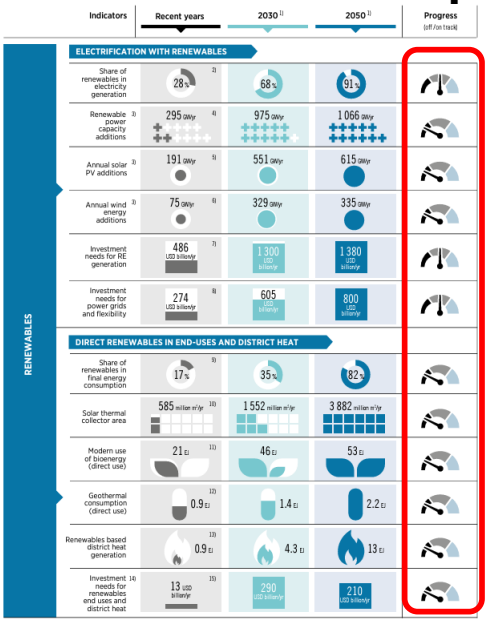
Total primary energy supply by energy carrier group



Achieving this level of renewable energy penetration is critical to meeting global climate goals and would require significant investment and policy support, as well as continued innovation.

IRENA (International Renewable Energy Agency), *World Energy Transitions Outlook*, 2023

Tracking progress of key energy system components to achieve the 1.5°C Scenario



Every year, the gap between what is achieved and what is required continues to grow.

Significant acceleration is needed across energy sectors and technologies, from deeper end-use electrification of transport and heat, to direct renewable use, energy efficiency and infrastructure additions

IRENA (International Renewable Energy Agency), *World Energy Transitions Outlook*, 2023

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Tracking progress of key energy system components to achieve the 1.5°C Scenario

	Indicators	Recent years	2030 [1]	2050 [1]	Progress (off / on track)
ENERGY EFFICIENCY	Energy intensity improvement rate	1.7 %/yr [16]	3.3 %/yr	2.8 %/yr	
	Investment needs for energy conservation and efficiency [17]	295 USD billion/yr [18]	1780 USD billion/yr	1525 USD billion/yr	
ELECTRIFICATION	Share of direct electricity in final energy consumption	22 % [19]	29 %	51 %	
	Passenger electric cars on the road	10.5 million [20]	360 million	2 180 million	
	Investments needs for charging infrastructure of EV's and EV adoption support	30 USD billion/yr [21]	137 USD billion/yr	364 USD billion/yr	
	Investment needs for heat pumps	64 USD billion/yr [22]	237 USD billion/yr	230 USD billion/yr	
HYDROGEN	Clean hydrogen production	0.7 Mt/yr [23]	125 Mt/yr [24]	523 Mt/yr [25]	
	Electrolyser capacity	0.5 GW [26]	428 GW	5 722 GW	
	Investment needs for clean hydrogen and derivatives infrastructure [27]	1.1 USD billion/yr [28]	100 USD billion/yr	170 USD billion/yr	
CCS AND BECCS	CCS/U - emissions abated	0.04 $GtCO_2$ captured/yr [29]	1.4 $GtCO_2$ captured/yr	3.2 $GtCO_2$ captured/yr	
	BECCS and others to abate total emissions	0.002 $GtCO_2$ captured/yr [30]	0.8 $GtCO_2$ captured/yr	3.8 $GtCO_2$ captured/yr	
	Investment needs for carbon removal and infrastructure	6.4 USD billion/yr [31]	38 USD billion/yr	107 USD billion/yr	

IRENA (International Renewable Energy Agency), *World Energy Transitions Outlook*, 2023

Why do we need to change?

Can't we just keep on doing business as usual?

The International Energy Agency has estimated that

- Global CO_2 emissions rebound by nearly 5% in 2021, approaching the 2018-2019 peak

Science is clear: 45% of global greenhouse gas emissions from 2010 levels must be reduced by 2030. Unfortunately, the recent trends show that we are on the wrong path, and we need to change the course now.

IEA, Global Energy Review 2021 and IRENA, *World Energy Transitions Outlook*, 2021

Summary

Future power system will be driven by *economics*, *security* plus *sustainability* issues

Key features of a smart grid are:

- use of *Information and Communication Technology and Control*
- energy consumer involvement

Future power systems have to integrate:

- active, responsive demand and demand side technologies
- renewable and distributed generation

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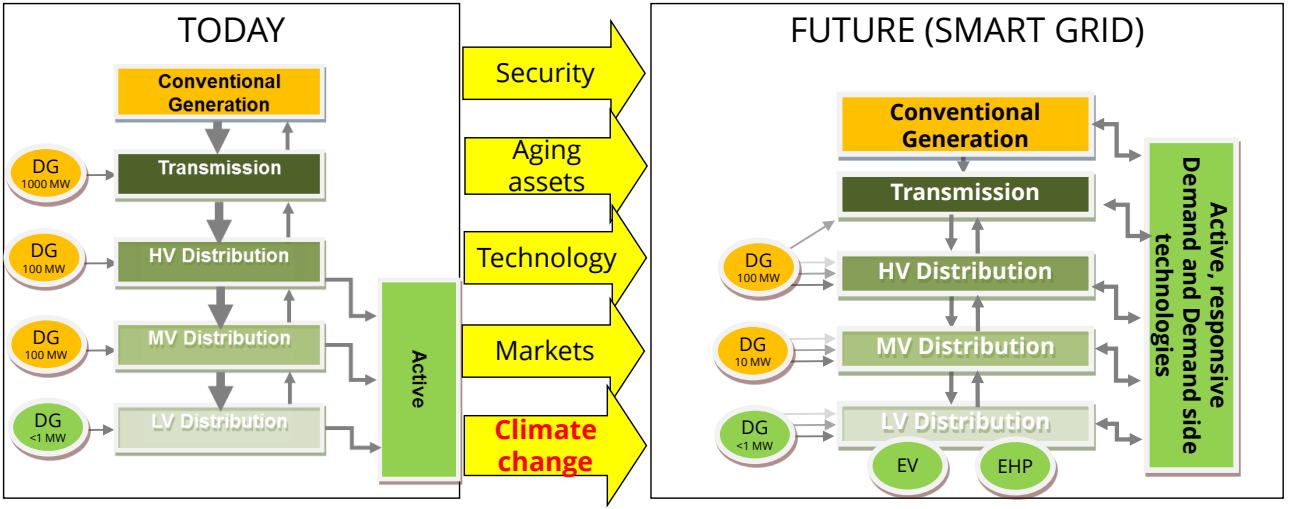
Introduction to Smart Grids

Dr Alessandra Parisio

The Smart Grid and drivers for change

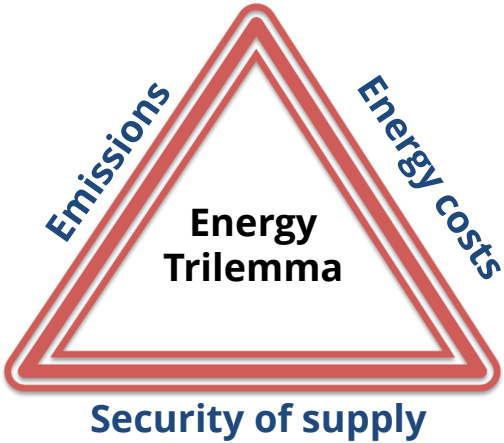


Sustainable energy

Sustainable energy means provision of energy that *meets the needs of the present without compromising the ability of future generations to meet their needs*

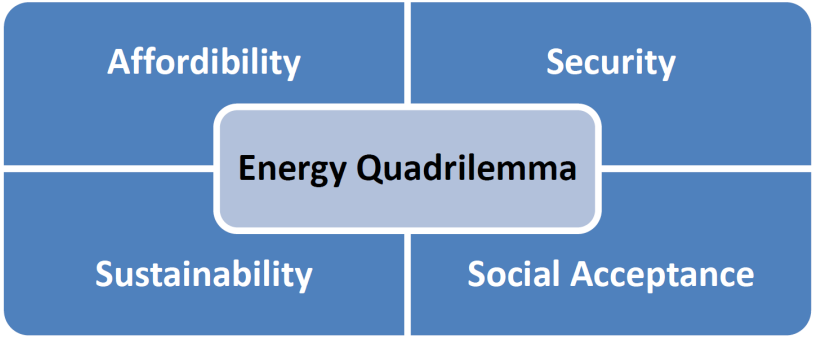
Source: REEEP 2008 - Glossary of Terms in Sustainable Energy Regulation, www.reeep.org.

The energy trilemma



Targets	Smart grid
Costs	Free digitalised market
Emissions	• Energy efficiency • Renewables integration
Security of supply	• Diversified mix • Self-reliability

The energy quadrilemma



A major challenge in the transition to a low-carbon future is to determine appropriate infrastructure for the provision of affordable, secure and sustainable energy services without compromising social acceptance – the so-called ‘energy quadrilemma’

UK targets

- Existing target under the Paris agreement: 80% reduction of CO_2 levels from 1990 levels by 2050 (40% up to 2018)
- ***Net Zero*** emissions law signed in June 2019: bring all greenhouse gas emissions to net zero by 2050
- Net zero means any emissions would be balanced by schemes to offset an equivalent amount of greenhouse gases from the atmosphere (e.g., planting trees or carbon capture and storage)

The future of power systems: Challenges, trends, and upcoming paradigms

Lopes, João Abel Peças, et al.

"The future of power systems: Challenges, trends, and upcoming paradigms."

Wiley Interdisciplinary Reviews: Energy and Environment (2019)

Sources

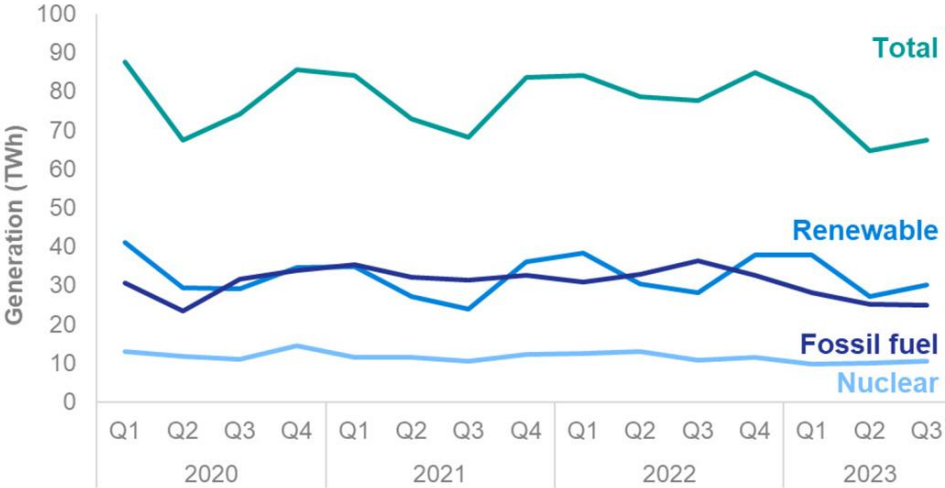
- **European Commission** Quarterly Report on European Electricity Markets Volume
- **Deloitte** 2022 Power and Utilities Industry Outlook
- **IEA** Global Energy Review 2021
- **IEA** World Energy Investment 2021
- **IEA** World Energy Outlook 2021
- **IRENA** World Energy Transitions Outlook 2021

Low-carbon technologies

Produce power with lower amounts of carbon dioxide emissions than conventional power plants

- *Renewable technologies*
- *Carbon capture and storage*
- *Combined Cycle Gas Turbine*
- *Nuclear, …*

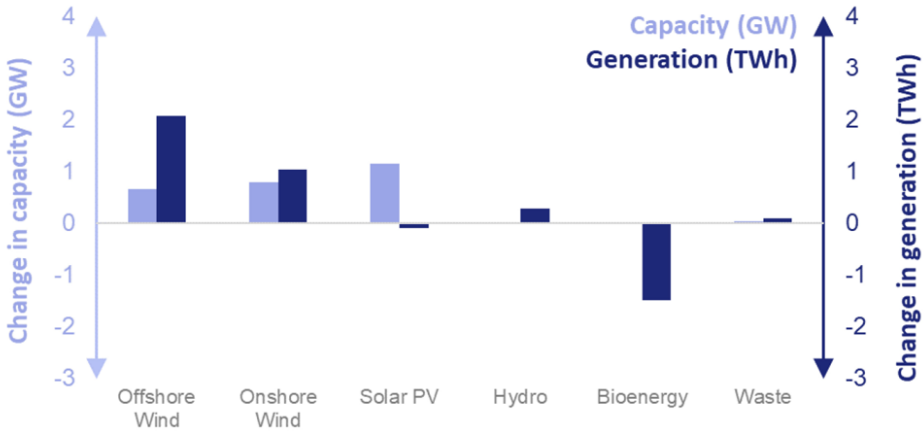
Electricity generated, by fuel type, in UK



Quarter 3 of 2023 saw total electricity generation of 67.5 TWh, 13 per cent decrease compared to Quarter 3 2022.

Renewable electricity generation was 30.1 TWh in Quarter 3 2023, 6.8 per cent higher than the same period in 2022.

Change in renewable generation and capacity between 2022 and 2023 in UK

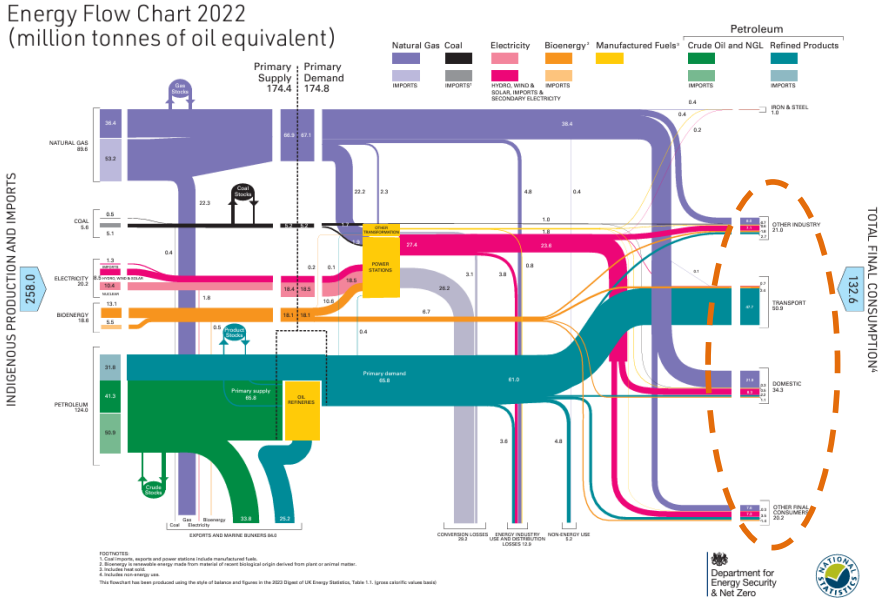


Record wind generation (driven by the highest wind speeds for a third quarter since 2016).

Small decrease in PV generation, because lower sun hours.

Energy Trends December 2023 Department for Business, Energy and Industrial Strategy

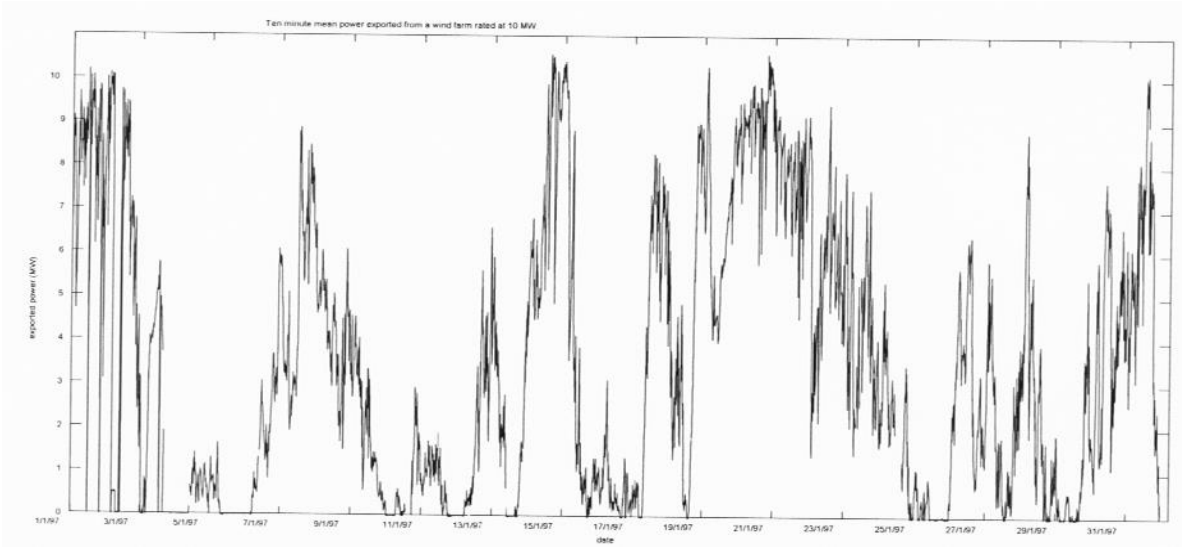
It’s not only about electricity - UK



© Crown copyright Department for Business, Energy and Industrial Strategy– Energy flow chart 2022

Wind (and solar): are they the solution?

Can we trust this?



Ten minute-mean real power exported from a 10MW wind farm over a month

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Where we are

- Future power system will be driven by *economics*, *security* plus *sustainability* issues
- Key features of a smart grid are:
  - use of *Information and Communication Technology and Control*
  - energy consumer involvement
- Future power systems have to integrate:
  - active, responsive demand and demand side technologies
  - renewable and distributed generation
- It's not only about electricity – interaction with heat and transport sectors
- Wind and solar: are they the solution?

Outline: impact on…

- Long term security
  - Generation adequacy
  - Capacity credit of wind
- Short term security
  - Balancing
  - Spinning and standing reserve
- Power system operation
- Energy market

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Low-carbon technologies

Produce power with lower amounts of carbon dioxide emissions than conventional power plants

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- *Combined Cycle Gas Turbine*
- *Nuclear, …*

Impact on…

- Energy market
- Long term security
  - Generation adequacy
  - Capacity credit of wind
- Short term security
  - Balancing
  - Spinning and standing reserve
- Power system operation

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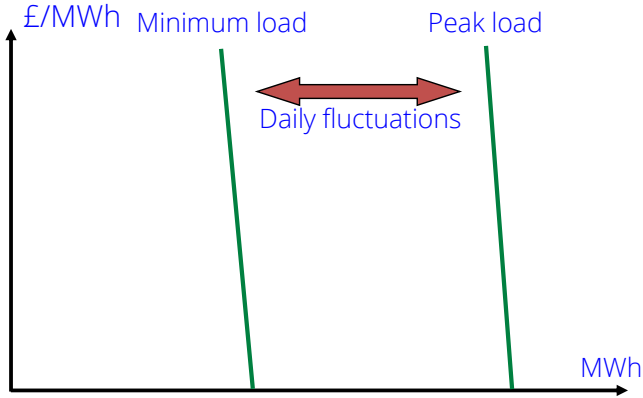
Impact on the energy market

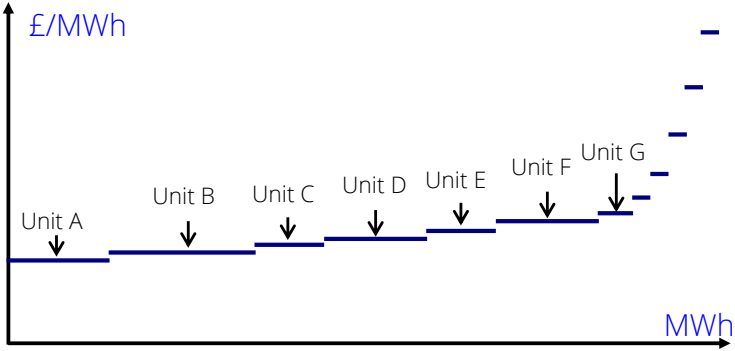
Demand curves for electricity

- Cheapest electricity is at minimum load (typically during nights)
- Most expensive electricity is at peak loads (typically 18:00 to 19:30 in the UK)
- Very low elasticity of the demand for electricity in the short-term



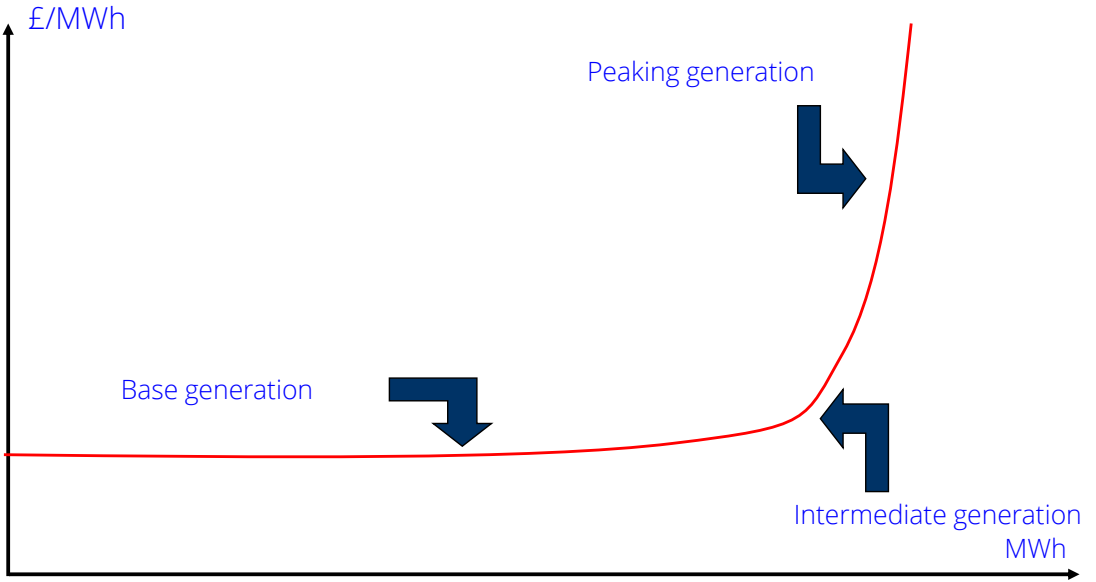
Supply curve for electricity

- In a centralised market, the supply curve is built by ranking the offers made by the generators
- An offer specifies the quantity that the generator is willing to sell at a given price

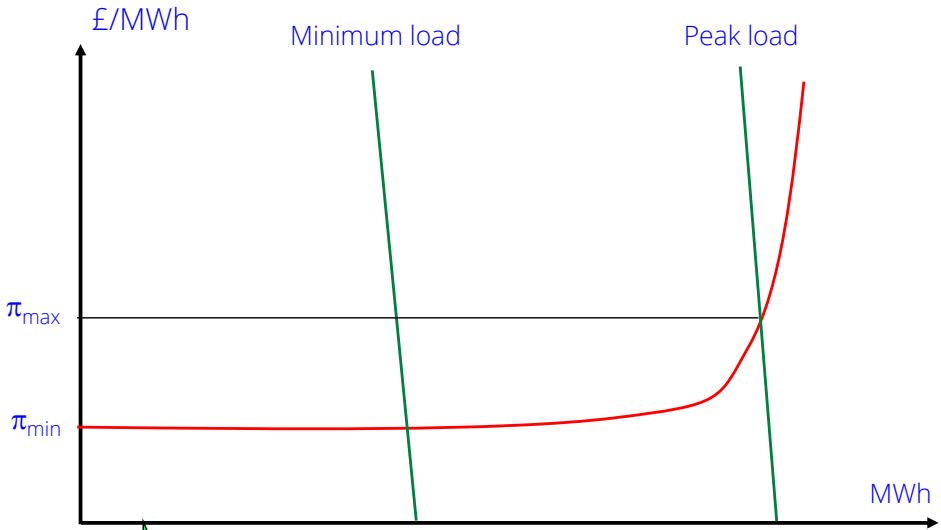


- How should a generator bid to maximize its profit?
- It depends on **how much competition it has**!

Supply curve for electricity



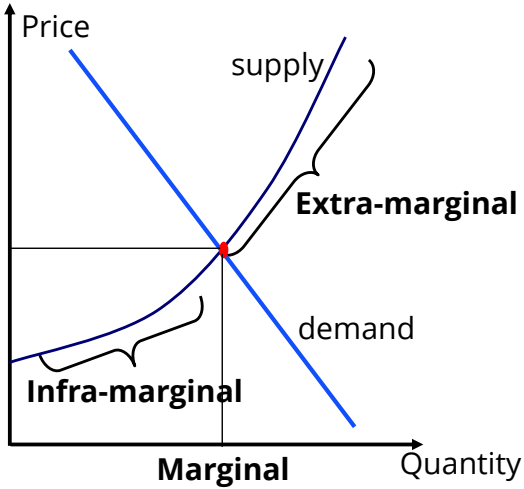
Supply and demand for electricity



Cost - price of electricity fluctuates during the day

Producers

- ***Marginal producer***:
  - Sells this last unit
  - Gets exactly its bid
- **Infra-marginal producers**:
  - Get paid more than their bid
  - Collect economic profit
- **Extra-marginal producers**:
  - Sell nothing



Why trade all energy at the MBP?

- Why not pay the generators what they bid (*marginal bidding price*)?
  - Cheaper generators would not want to “leave money on the table”
  - Would try to guess the MBP and bid close to it
  - Occasional mistakes - get left out of the schedule (overall efficiency cost as less efficient generators would be dispatched)
  - Increased uncertainty - increase in price
  - Marginal bidding price would make the supply curve very flat and no money would actually be saved

Profit of an infra-marginal producer

- Selling at marginal cost covers the variable cost of production
- The difference between the market price and the marginal cost must pay for the fixed costs:
  - No-load cost, startup cost
  - Cost of building the plant
  - Interest payments for the bank, dividends for the shareholders
- A plant must therefore be infra-marginal often enough to cover its fixed costs

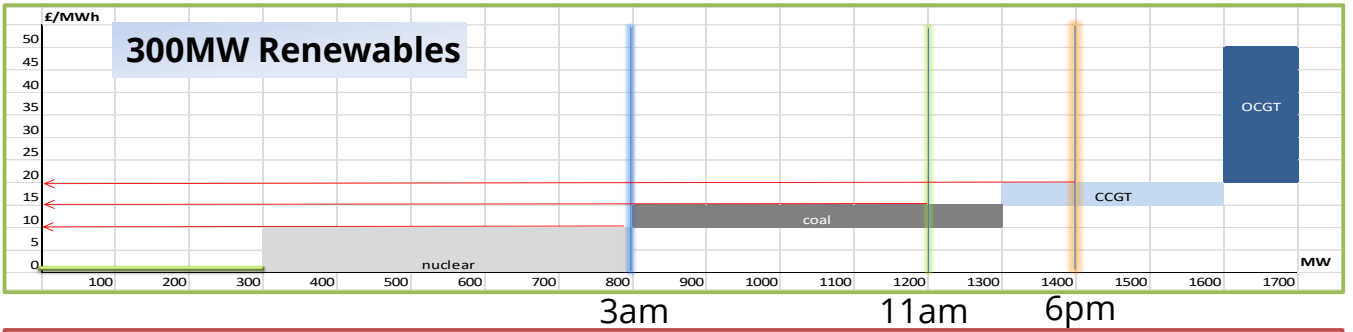
Profit of a marginal producer

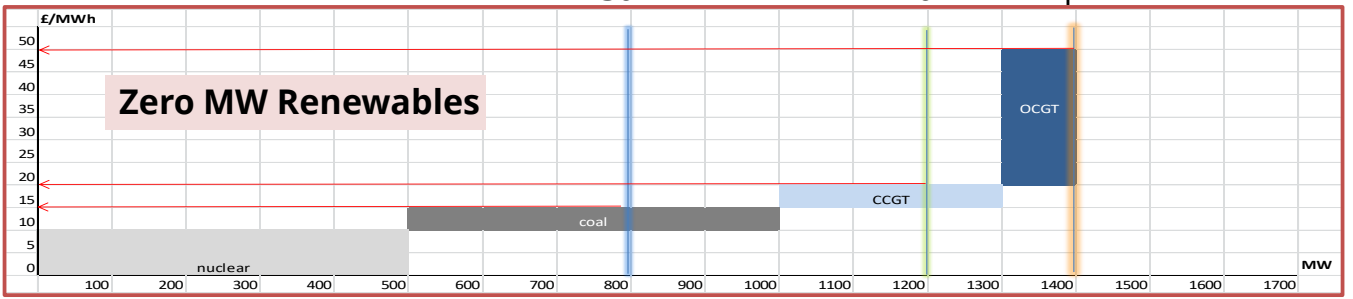
- If a marginal generator bids at its marginal cost, it makes no economic profit
  - Covers only its variable cost of production, not its fixed cost
- Generators that are too often marginal or just below marginal will not recover their fixed costs if they bid at their marginal cost of production
  - They must **include part of their fixed costs in their offer price**
  - Their offer price is therefore **higher than their marginal cost**
  - They can do it because **competition is not perfect** when the load is high because most generators are already producing

Effect of variable sources

- Generation from renewable sources is variable
- Market prices become **more variable and volatile**
- Power from variable generation might need to be **curtailed**
- Base load producers might be **unable to cover their costs**

A market sketch with renewables



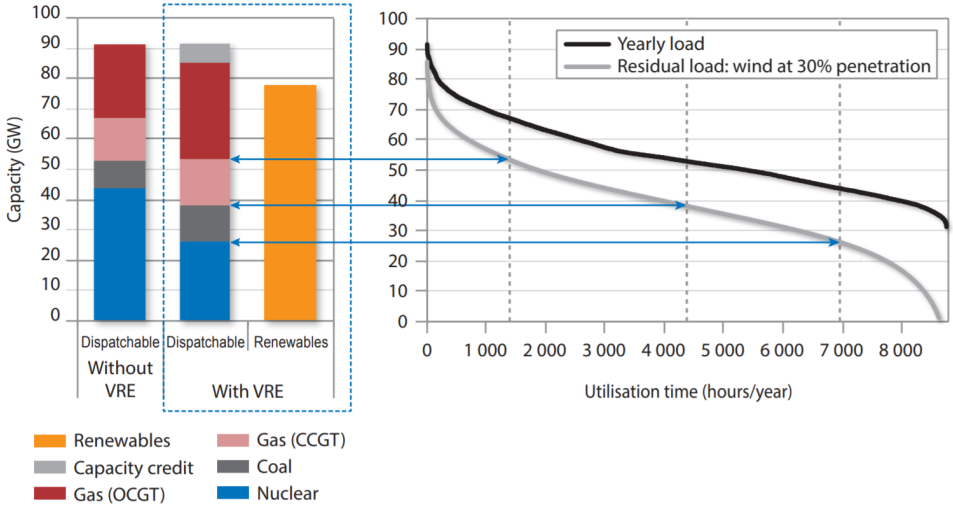


Capacity factor

<u>Capacity factor</u> : energy produced by a generator as a percentage of that which would be achieved if the generator were to operate at maximum output 100% of the time

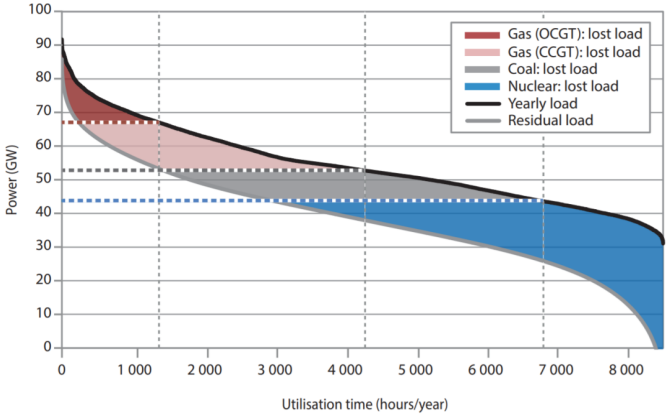
- Capacity factors of base load thermal generators ~ 85%
- Capacity factors of wind turbines ~ 20% - 40%

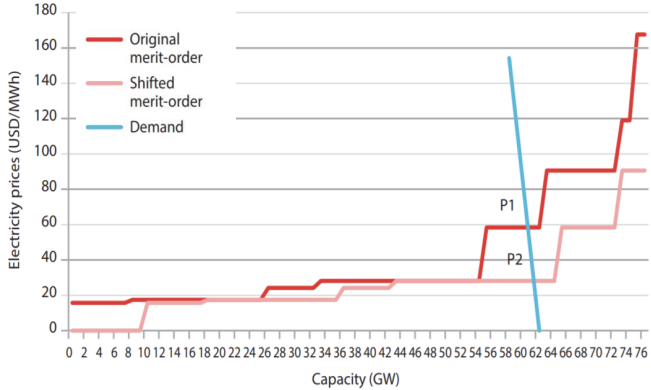
Generation mix with wind



Source: © OECD/IEA 2015 *Projected Costs of Generating Electricity*, IEA Publishing. Licence: www.iea.org/t&c. Available at: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf

Prices and capacity factors reduction





The production losses for peaking plants can reach up to 80% of the level expected in the absence of variable renewable generation.

Source: © OECD/IEA 2015 *Projected Costs of Generating Electricity*, IEA Publishing.

Supply-demand balance – market perspective

- ***Day-ahead market - EPEX SPOT***

✓ (Forecast) supply and demand curves submitted for each settlement period of the following day

✓ EPEX SPOT - day-ahead auction

✓ Development of demand and supply completely determined by members themselves

✓ Market members: production and distribution companies, large consumers, industrial end-users and traders

Supply-demand balance – market perspective

- ***Balancing mechanism***

  ✓ Real-time balancing through re-declarations of generation planning and bidding on an intraday market where bids are selected and activated in real time

- ***Financial imbalance settlement*** between physical and contractual positions. It generally takes place the following day and spreads fairly the incomes and costs among the actors

Balancing market

- Balance load and generation, maintains the **security** of the system
- Use of available reserves in order to keep the frequency at 50±0.5 Hz
- Run by National Grid
- System operator's tasks
  - Use competitive *offers and bids* for generation adjustments
  - Determine a cost-reflective spot price
- Not a true market because price is not set through interactions of buyers and sellers

Bids and Offers in the Balancing Mechanism

- Balancing mechanism starts 1 hour before real-time when all other transactions are completed => this so called '**Gate Closure**'
- The Balancing Mechanism allows different Parties to submit
  - **Offers** to sell energy (by *increasing generation* or *decreasing consumption*) to the system
  - **Bids** to buy energy (by *decreasing generation* or *increasing consumption*) from the system
- If a Party has under-generated or over-consumed compared to its contracted volume, it will have to buy at **System Buy Price**
- If a Party has over-generated or under-consumed compared to its contracted volume, it will have to sell at **System Sell Price**

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Renewables in the Balancing Mechanism

- Increasing amounts of variable renewable generation will reduce the availability of traditional balancing resources which tends to increase the cost of maintaining system security
- The development of intraday markets with gate closure times which are close to real time facilitate the participation of RES in markets
- Ofgem has granted *Limejump* in 2018 (and other aggregators) access to the balancing market via its virtual power plant, thus allowing both renewable and distributed energy generators to compete

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Flexible services

- Local flexibility services are an important component of the UK's net zero transition - by releasing power back to the grid at times of high demand, and storing it during times of lower demand, local flexibility services unlock additional capacity and support the connection of more low-carbon technology like wind power.
- In 2023, electricity network companies tendered a record 4.6GW of capacity on Great Britain's local flexibility markets last year, with 2GW contracted.
- More than 70% of the contracted flexibility is made up of low-carbon technologies, such as stored energy, solar and biofuel.

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Smart Grids and Sustainable Electricity Systems

Industrial guest lecture

- Jacobs, 10th April, 15:00 – 16:00, in Kilburn Building, TH_1.4.

Energy webpage

Energy

Building a more sustainable future for everyone

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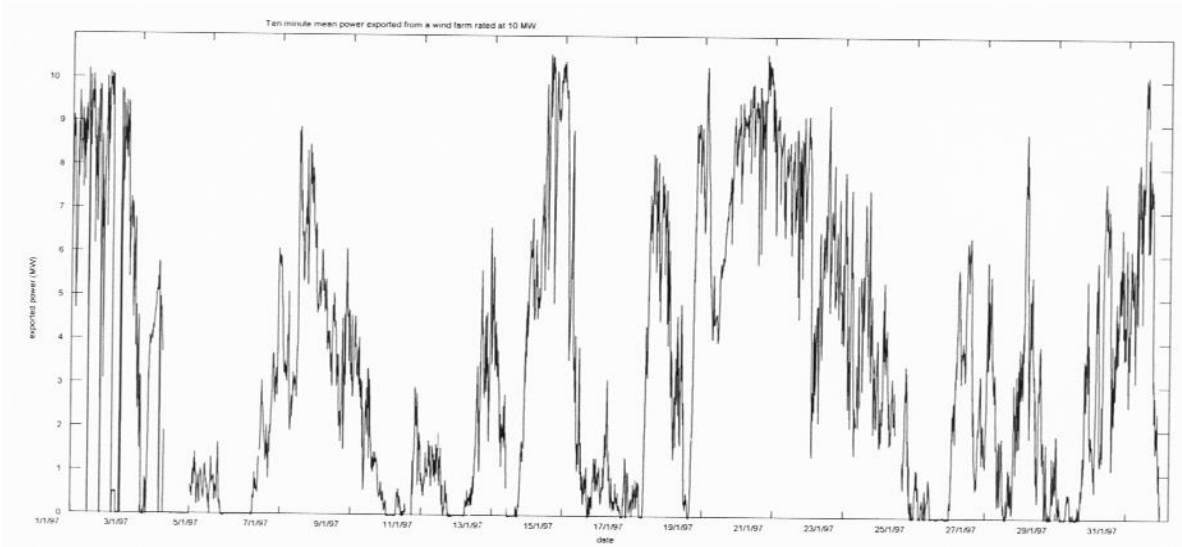
Where we are

- Future power system will be driven by *economics*, *security* plus *sustainability* issues
- Key features of a smart grid are:
  - use of *Information and Communication Technology and Control*
  - energy consumer involvement
- Future power systems have to integrate:
  - active, responsive demand and demand side technologies
  - renewable and distributed generation
- It's not only about electricity – interaction with heat and transport sectors
- Wind and solar: are they the solution?

Can we trust this?



Ten minute-mean real power exported from a 10MW wind farm over a month

Outline: impact on…

- Energy market
- Long term security
  - Generation adequacy
  - Capacity credit of wind
- Short term security
  - Balancing
  - Spinning and standing reserve
- Power system operation

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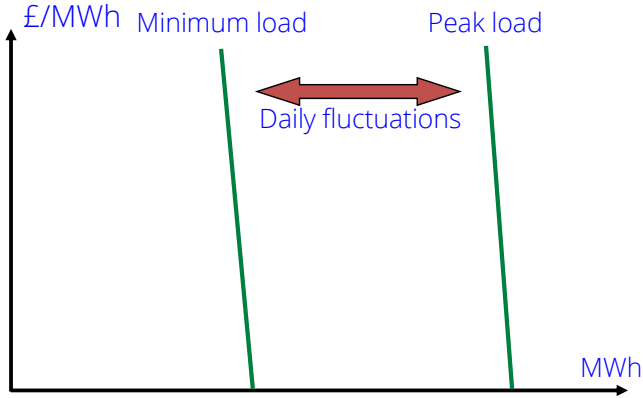
Impact on the energy market

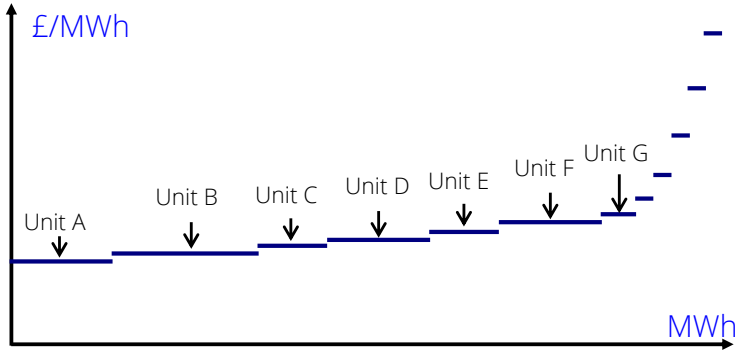
Demand curve for electricity

- Cheapest electricity is at minimum load (typically during nights)
- Most expensive electricity is at peak loads (typically 18:00 to 19:30 in the UK)
- Very low elasticity of the demand for electricity in the short-term

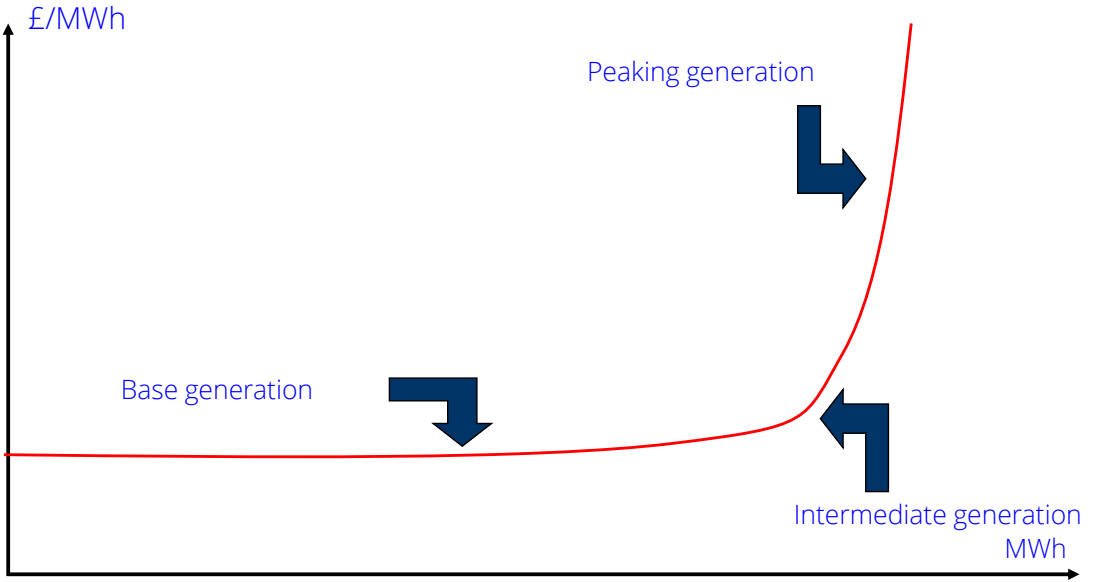


Supply curve for electricity

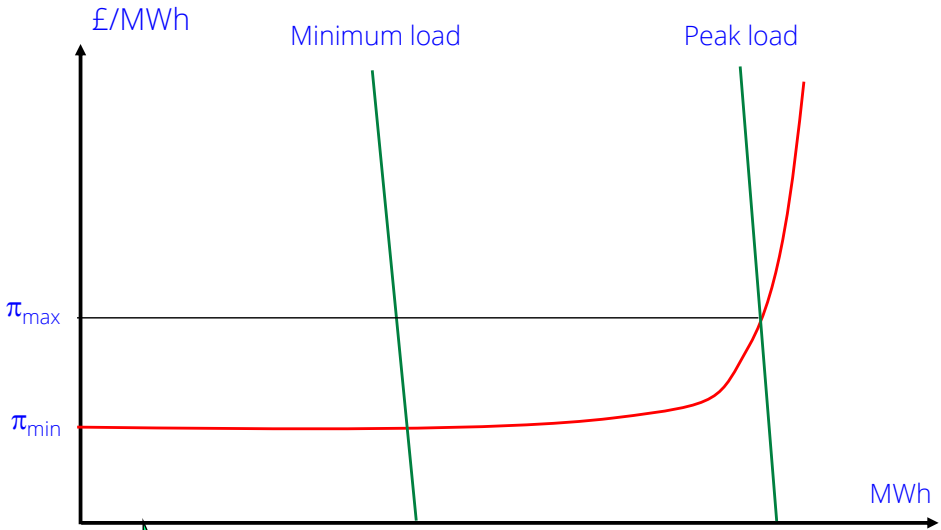
- An offer specifies the quantity that the generator is willing to sell at a given price



Supply curve for electricity



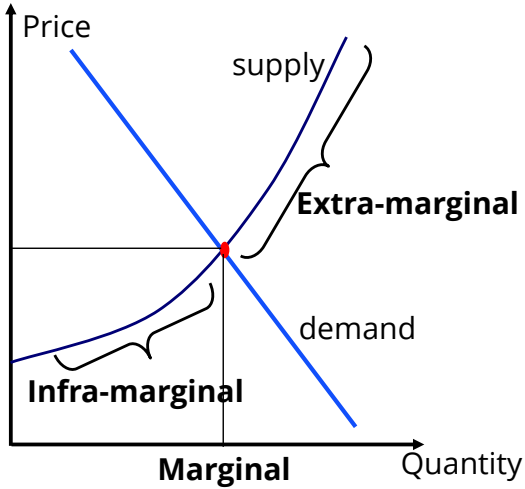
Supply and demand for electricity



Cost - price of electricity fluctuates during the day

Producers

- ***Marginal producer***:
  - Sells this last unit
  - Gets exactly its bid
- **Infra-marginal producers**:
  - Get paid more than their bid
  - Collect economic profit
- **Extra-marginal producers**:
  - Sell nothing



Why trade all energy at the MBP?

- Why not pay the generators what they bid (*marginal bidding price*)?
  - Cheaper generators would not want to “leave money on the table”
  - Would try to guess the MBP and bid close to it
  - Occasional mistakes - get left out of the schedule (overall efficiency cost as less efficient generators would be dispatched)
  - Increased uncertainty - increase in price
  - Marginal bidding price would make the supply curve very flat and no money would actually be saved

Profit of an infra-marginal producer

- Selling at marginal cost covers the variable cost of production
- The difference between the market price and the marginal cost must pay for the fixed costs:
  - No-load cost, startup cost
  - Cost of building the plant
  - Interest payments for the bank, dividends for the shareholders
- *A plant must therefore be infra-marginal often enough to cover its fixed costs*

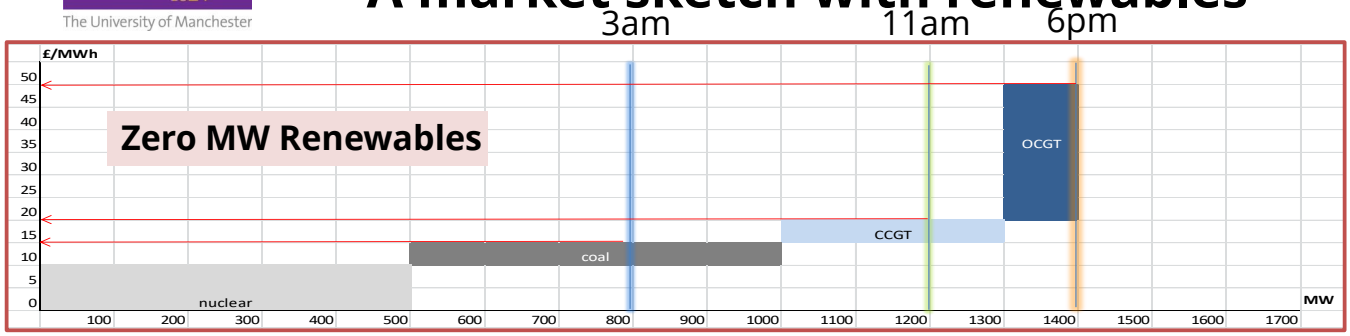
Profit of a marginal producer

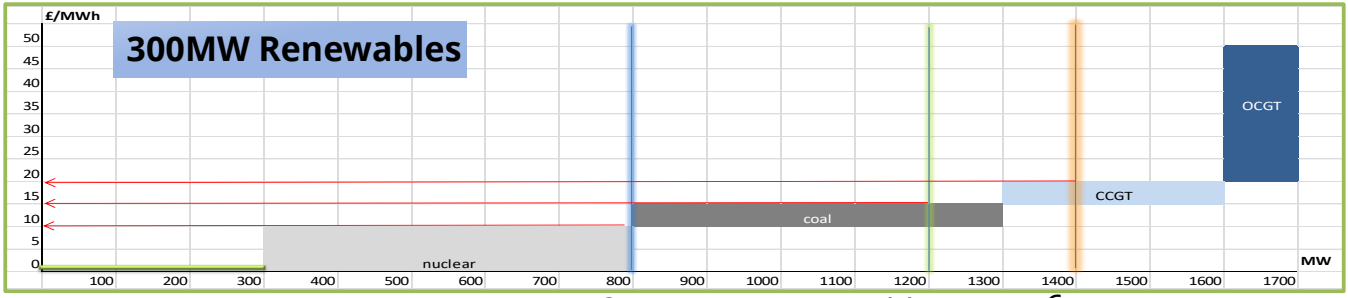
- If a marginal generator bids at its marginal cost, it makes no economic profit
  - Covers only its variable cost of production, not its fixed cost
- Generators that are too often marginal or just below marginal will not recover their fixed costs if they bid at their marginal cost of production
  - They must **include part of their fixed costs in their offer price**
  - Their offer price is therefore **higher than their marginal cost**
  - They can do it because **competition is not perfect** when the load is high because most generators are already producing

Effect of variable sources

- Generation from renewable sources is variable
- Market prices become **more variable and volatile**
- Power from variable generation might need to be **curtailed**
- Base load producers might be **unable to cover their costs**

A market sketch with renewables

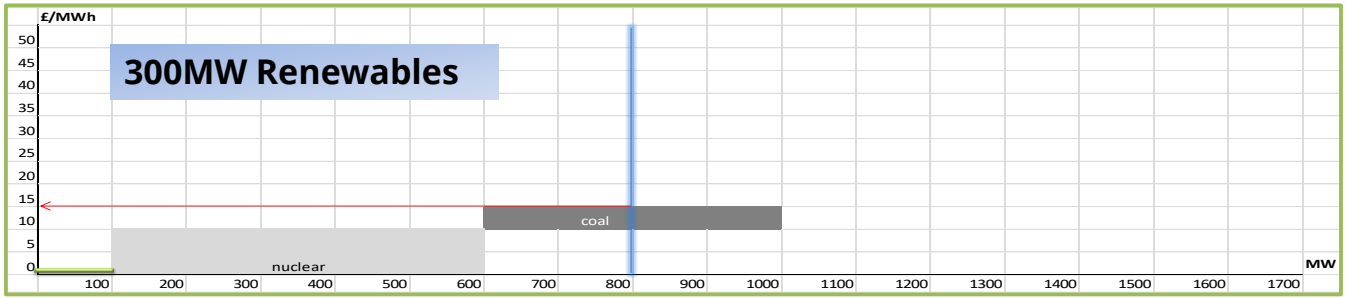




Impact of generator constraints

- Minimum uptimes for nuclear (24h) and coal (5h)
- Nuclear and coal have been online for the previous 12 hours and 3 hours, respectively

Minimum load condition (800 MW)



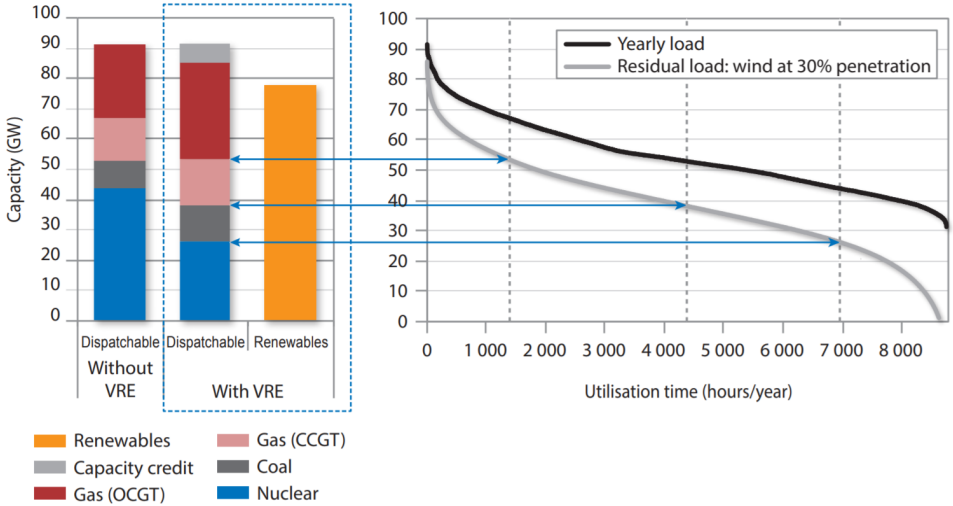
What happens to 200MW of RES?

Capacity factor

<u>Capacity factor</u> : energy produced by a generator as a percentage of that which would be achieved if the generator were to operate at maximum output 100% of the time

- Capacity factors of base load thermal generators ~ 85%
- Capacity factors of wind turbines ~ 20% - 40%

Generation mix with wind



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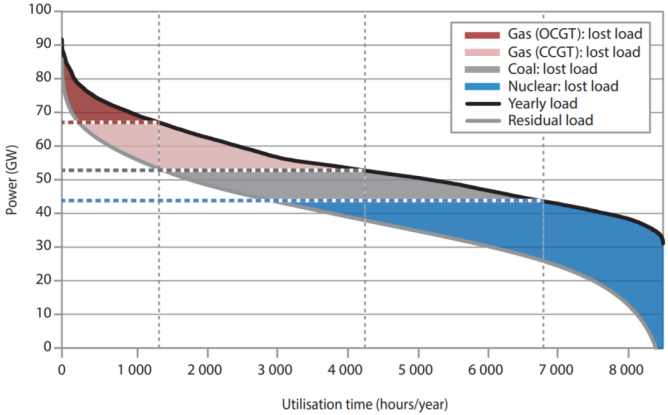
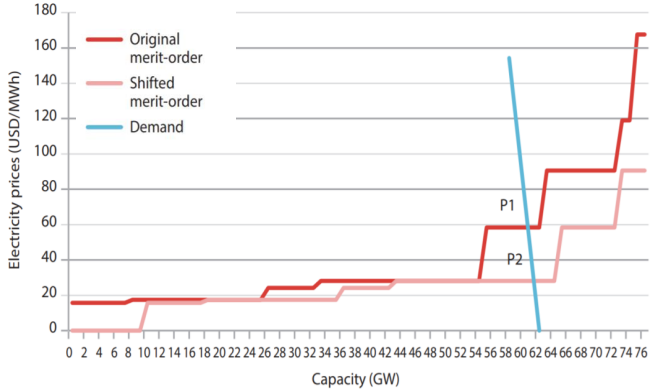
Prices and capacity factors reduction





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- ***Balancing mechanism - Balance load and generation, maintains the security of the system***

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  - ✓ Run by National Grid - Use competitive *offers and bids* for generation adjustments

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Flexible services

- Local flexibility services: releasing power back to the grid at times of high demand, and storing it during times of lower demand.
- To unlock additional capacity and support the connection of more low-carbon technology like wind power.
- UK Flexible Power initiative
- In 2023, electricity network companies tendered 4.6GW of capacity on Great Britain's local flexibility markets, with 2GW contracted.
- More than 70% of the contracted flexibility is made up of low-carbon technologies, such as stored energy, solar and biofuel.

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Impact on the long-term security

What is meant by variable generation

Variable renewable energy is a renewable energy source that is non-dispatchable due to its fluctuating nature, like wind power and solar power, as opposed to a controllable renewable energy source such as hydroelectricity, or biomass

How intermittent is conventional thermal generation?

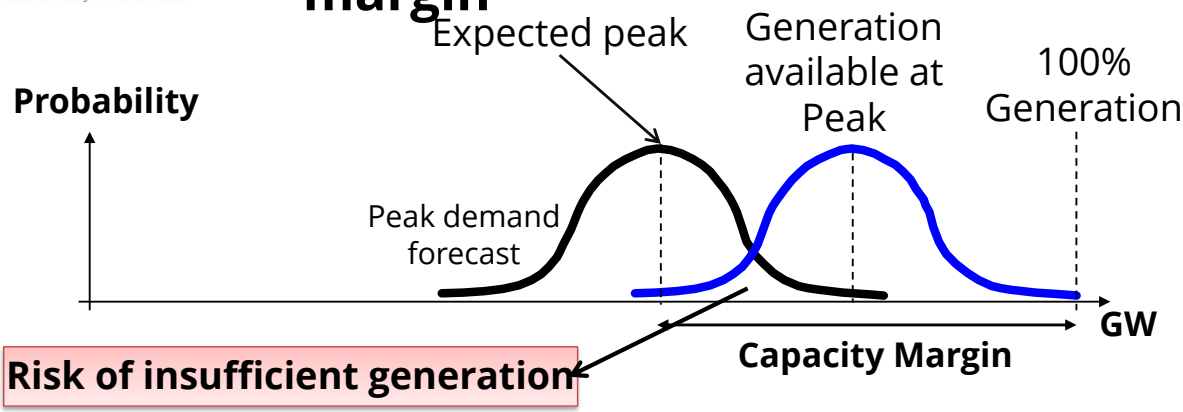
Long-term security

- *Generation adequacy*: capability to meet demand with a certain level of reliability of supply

- **LOLP (Loss of Load Probability)** widely used:
  - Probability of peak demand exceeding available generation

- How do I assess the adequacy of conventional generation?
  - Excess installed capacity above expected peak demand (*capacity margin*)

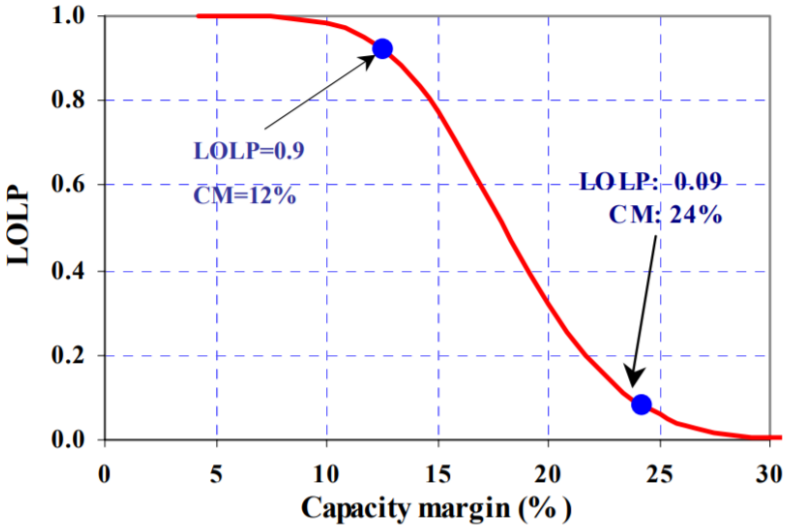
Determining the capacity margin



- The higher the margin, the lower the LOLP
- Generation capacity **adequate** if LOLP meets threshold level

R. Billinton and R.N. Allan, Reliability evaluation of power systems, Springer, 1996

LOLP versus capacity margin



Source: Nedic, D., Shakoor, A., Strbac, G., Black, M., Watson, J. and Mitchell, C.(2005). *Security Assessment of Future UK Electricity Scenarios*.

Capacity credit

<u>Capacity credit</u> (or capacity value): measure of the amount of load that can be served on an electricity system by variable plants with no increase in the LOLP or other similar index.

Determinants of capacity credit

- Degree of *correlation* between *demand peaks and variable output*
- Range of variable outputs (higher *diversity*)
- *Average level* of output
  - A higher level of average output over peak periods will tend to increase capacity credit

Capacity credit of…

- PV in the UK
- PV in California
- Wind in the UK

Capacity credit of variable generation

- Capacity credit (in % of installed capacity) reduces with wind penetration level
- For low penetration, capacity credit approaches capacity factor
- A diverse profile (large spread area) exhibits higher capacity credit than non-diverse profile (e.g., wind farms concentrated in small area)

Capacity credit

<u>Capacity credit</u> (or capacity value): measure of the amount of load that can be served on an electricity system by variable plants with no increase in the LOLP or other similar index.

Capacity credit (in % of installed capacity) reduces with penetration level

Simplified example

LOAD PEAK = 55 GW

INSTALLED CAPACITY = 60 GW

1

10% PENETRATION → 5.5 GW (55 · 0.1 GW)

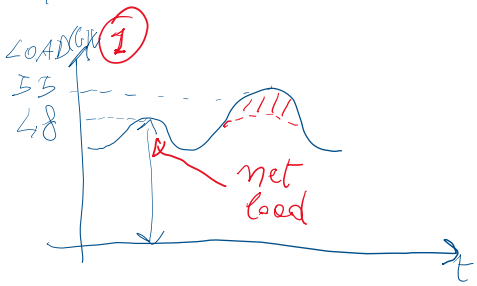
40% CAPACITY CREDIT → 0.4 · 5.5 = 2.2 GW of CG dismissed → 57.8 GW

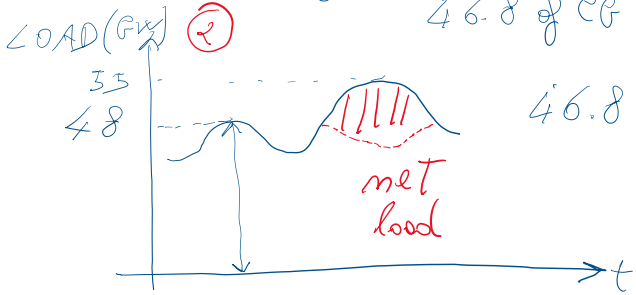
2

60% PENETRATION → 33 GW of VRE

40% CAPACITY CREDIT → 13.2 GW of CG dismismissed → 46.8 of CG available

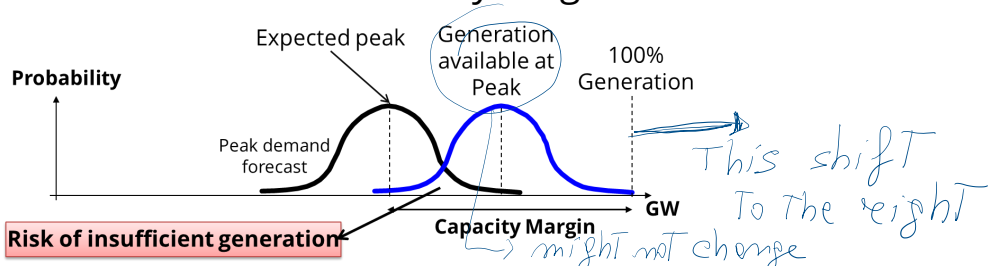
46.8 < 48 GW





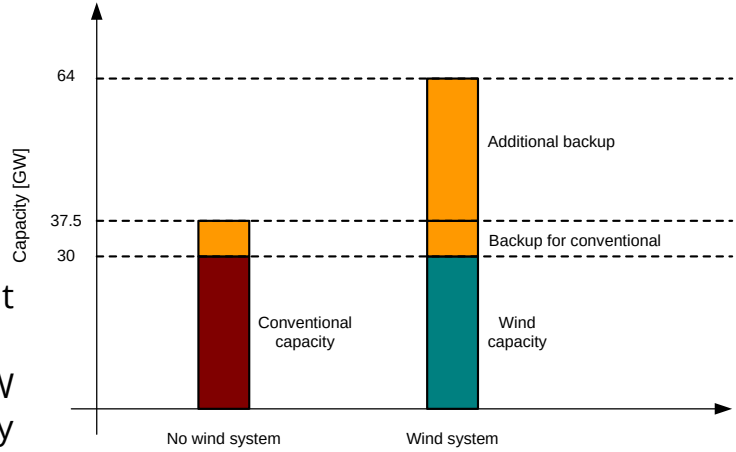
Implication of wind capacity credit

- Wind may displace a significant amount of energy produced by large conventional plant, but relatively small capacity
- It will therefore be necessary to retain a significant proportion of conventional plant to ensure that the security of supply is maintained
- Thus, wind rich systems will feature an increasingly large generation capacity margin which exceeds demand by a significant amount



Implications of wind capacity credit

- 30 GW peak demand
- Capacity margin of 25% without wind (7.5 GW)
- 30 GW wind displaces 3.5 GW conventional plant (~12% capacity credit)
- 30 GW wind requires 34 GW backup (capacity margin)



Necessary to retain a significant proportion of conventional plant to ensure that the security of supply

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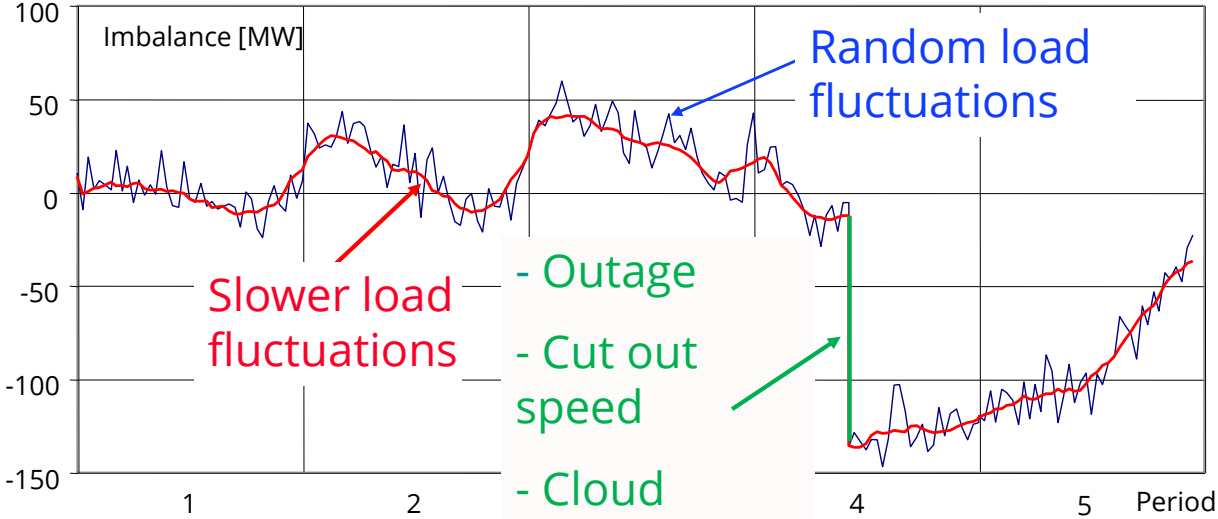
Impact on the short-term security

Balancing production-consumption

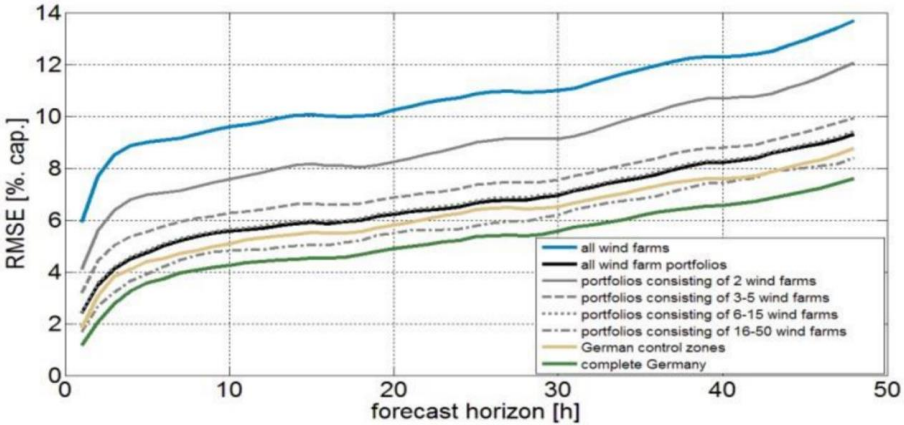
- If production = consumption, frequency remains constant
- UK National Grid has to maintain the frequency within *statutory* (49.5Hz-50.5Hz) and *operational* limits (49.8Hz-50.2Hz)
- In practice:
  - Constant fluctuations in the load
  - Inaccurate control of the generation
  - Sudden outages of generators and interconnectors
  - **Uncertainty in output from variable generation**

Example of imbalances



- Outage
- Cut out speed
- Cloud transients?

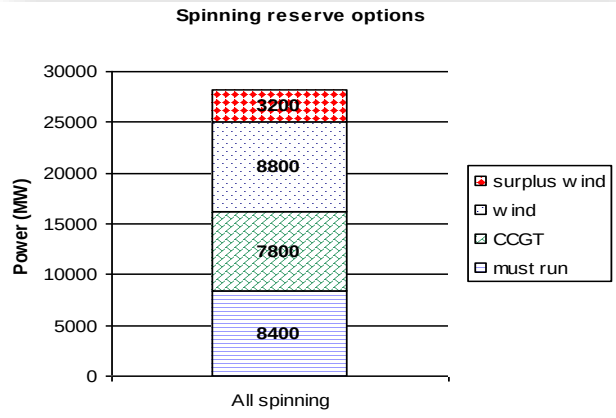
Wind is difficult to forecast

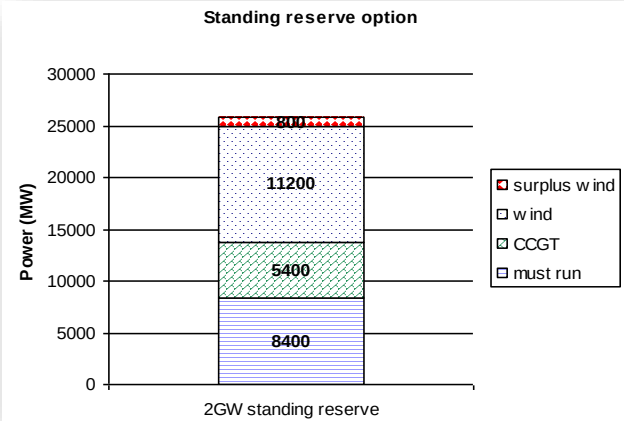


How much reserve would you schedule if there was no wind?

Source: Dobschinski, J., How good is my forecast? Comparability of wind power forecast errors, Proceedings of the 13th International Workshop on LargeScale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, November 2014, Berlin, 2014

Reserve options





Any other option?

Example

30 GW of wind power capacity need to be connected into a power system in which demand varies between a minimum of 30 GW and a maximum of 70 GW. The power system generation mix is composed of 10 GW of inflexible nuclear plant, 10 GW of inflexible coal plant, and 30 GW of flexible Combined Cycle Gas Turbine (CCGT) units with characteristics given in the following table:

Technology	Capacity	Minimum stable generation (MSG)
	[MW]	[MW]
CCGT	500	200

Example

For a specific hour, the system operator decides to schedule 6 GW of reserve to cover the uncertainty in wind power when its expected output is 20 GW. Reserve will be provided by part-loaded CCGT operating as spinning reserve.

- What is the minimum number of CCGT units that need to run to provide the required reserve?

Each unit can provide (500 - 200) = 300MW of reserve, hence 20 units are needed to provide the overall reserve required.

- What is their total output?

Each unit produces its MSG while spinning to provide reserve, hence the total output is 4GW.

Example

For a specific hour, the system operator decides to schedule 6 GW of reserve to cover the uncertainty in wind power when its expected output is 20 GW. Reserve will be provided by part-loaded CCGT operating as spinning reserve.

- What is the output of wind that may need to be curtailed when demand is highest and lowest, respectively?

The “must-run” generation (MRG) is equal to the total of the inflexible plant (20GW) plus the output due to spinning reserve, hence MRG = 24GW.

If wind output is 20 GW, there is an overall generation (excluding the flexible one) of 44GW.

When demand is 70 GW, no curtailment is therefore needed, and other CCGT units cover the remaining 26 GW of load.

In contrast, when demand is only 30 GW, 14 GW of wind needs to be curtailed as everything else is Must Run Generation.

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Impact on power system operation

Power system operation

Short-term operation is how to run the system, considering security first and then economics but…

…in a smart grid the ***environmental*** aspect is to be taken into account, along with

- Renewable generation ***forecast*** and ***uncertainty*** modelling
- ***Flexible and distributed generation*** technologies (e.g., CHP, CCGT)
- ***New loads*** (e.g., heat pumps, electric vehicles)
- ***Consumers with embedded generation and flexible loads***
- ***Interaction with other energy sectors*** (e.g., heat)
- …

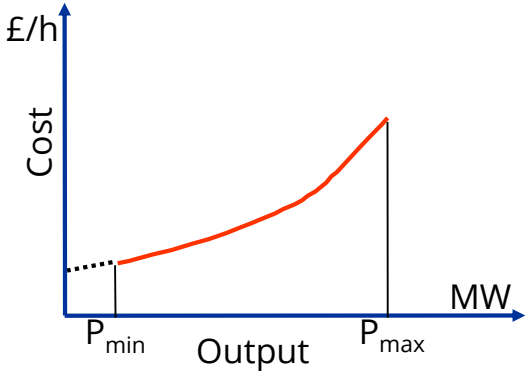
Problem Formulation

Minimise running costs

subject to:

- Power balance: $\sum_i P_i = L$
- Unit minimum stable generation
- Unit maximum capacity

Generation Cost Curve



Derivative of the cost curve

- In **£/MWh**
- **Cost of the next MWh**

Merit order economic dispatch

Optimal Power Flow

- Generating units and loads are not all connected to the same bus
- The Economic Dispatch can result in unacceptable flows or voltages into network
- Optimal Power Flow includes
  - Power flow equations
  - Inequality constraints: network operating limits (line flows, voltages) and limit on decision variables
- Challenges: nonlinear and large-scale optimisation problem

Power Flow Equations

$$P_k^I - \sum_{i=1}^{N} V_k V_i [G_{ki} \cos(\theta_k - \theta_i) + B_{ki} \sin(\theta_k - \theta_i)] = 0$$

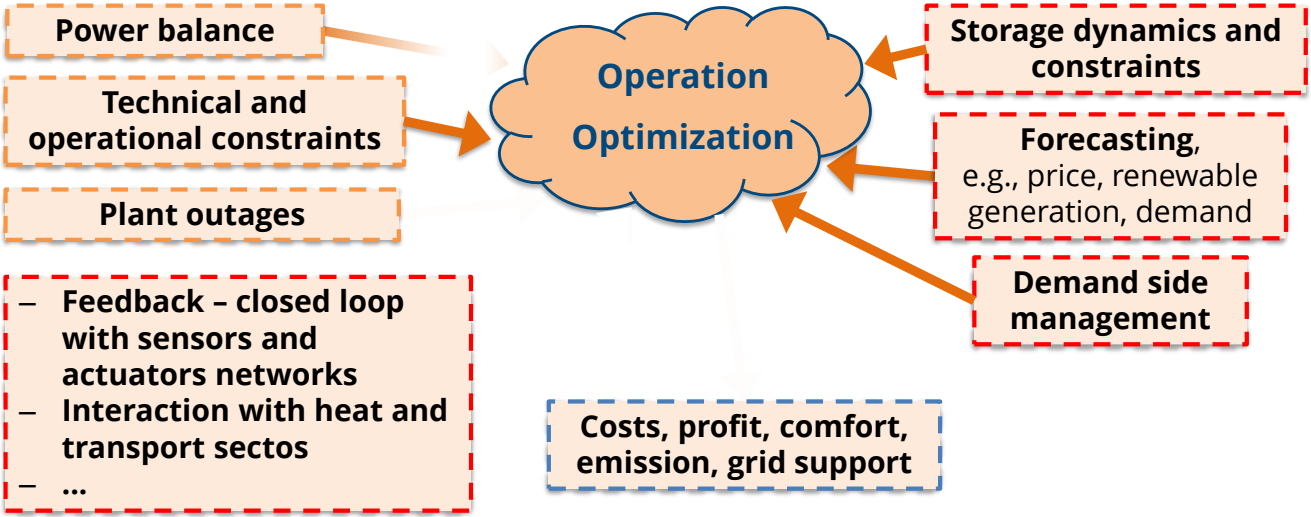
$$Q_k^I - \sum_{i=1}^{N} V_k V_i [G_{ki} \sin(\theta_k - \theta_i) - B_{ki} \cos(\theta_k - \theta_i)] = 0$$

- Set of non-linear simultaneous equations
- Need a simple linear relation for fast and intuitive analysis
- DC power flow provides such a relation but requires a number of approximations

Challenges in future power systems

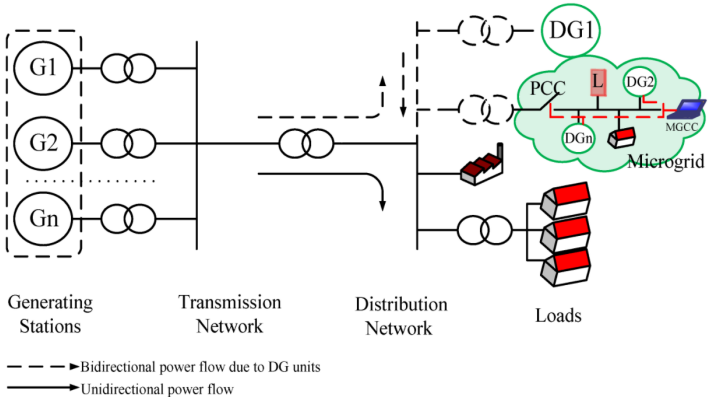
- Uncertainties considered in the traditional unit commitment
  - Plant (generators, lines, transformers, etc.) outages
  - Errors in demand forecast
- Uncertainties handled through requirements on spinning reserve at convenient network locations
- Additional uncertainties in smart grids
  - Renewable generation (e.g., wind and solar)
  - User behaviour (e.g., new loads, costumers' owned generation, demand-side management)
  - Interaction with the other energy sectors

Smart grids: operational challenges



Microgrid operation management

The microgrid concept assumes a cluster of loads and distributed generators (DGs) operating as a single controllable system that provides both electricity and heat to its local area



Microgrid components:

- Distributed Generators (DGs)
- Loads
- Storage equipment (batteries, capacitors, flywheels)
- Microgrid Controller
- Point of Common Coupling (PCC) to the utility grid

Examples of real-world microgrids

Grid-Connected Microgrids

- **IKEA Store Microgrid**, New York, USA, integrates solar panels, energy storage systems, and advanced controls.
- **General Motors' Factory Microgrid**, Michigan, USA, integrates solar panels, energy storage, and advanced control systems.
- **Smart Community Microgrid**, California, USA, integrates solar panels, battery storage, and smart energy management systems in a neighbourhood.

They provide backup during power outages and flexibility in energy management, allowing the facility to optimise energy consumption and reduce peak demand charges.

Examples of real-world microgrids

Standalone (islanded) microgrids

- **Kodiak Island, Alaska, USA,** is a hybrid microgrid integrating wind and hydroelectric power with battery energy storage. It now supplies over 99% of its electricity from renewable sources.
- **Ta'u Island, American Samoa,** located in the South Pacific, consists of over 5,300 solar panels and 60 Tesla Powerpacks, enabling the island to meet nearly 100% of its electricity demand from solar energy.
- **Necker Island, British Virgin Islands,** integrates solar panels, wind turbines, and a state-of-the-art energy storage system.

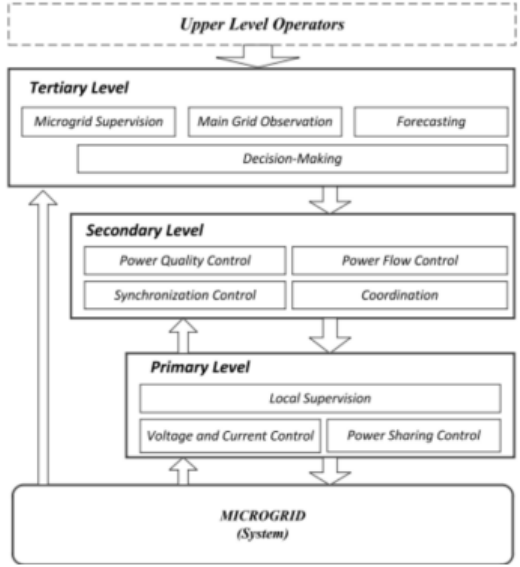
Self-sufficient energy systems operating independently from the main utility grid.

Microgrid control structure

- **Primary control**: stabilisation of frequency and voltage

- **Secondary control**: compensation of steady state deviations

- **Tertiary control**: economic optimisation and energy management



Meng et al., Review on Control of DC Microgrids and Multiple Microgrid Clusters, IEEE Journal of Emerging and Selected Topics in Power Electronics, Sept. 2017

Microgrid Operation Optimisation

Objective:

- Optimise microgrid operations over a planning horizon to fulfill a time-varying demand subject to operational constraints while minimizing a cost function

The **Microgrid Operation Optimisation** includes

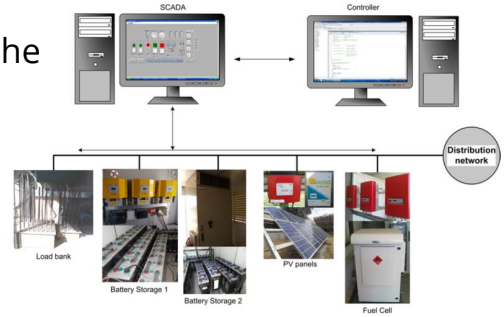
- Unit Commitment (UC)
- Economic Dispatch (ED)
- Optimal scheduling of storage operations
- Demand side policies (curtailment options)
- When and how much energy should be purchased/sold from/to the utility grid

Source: A. Parisio, E. Rikos, L. Glielmo, "A Model Predictive Control Approach to Microgrid Operation Optimization', IEEE Transactions on Control System Technology, September 2014. Available at https://ieeexplore.ieee.org/document/6705582/ (via CC BY 3.0)

Experimental Results

Experiments of 6 hours were run at Center for Renewable Energy Sources and Saving (CRES), Pikermi-Athens, Greece.

- Grid-connected microgrid 3-phase power line to the public grid
- 15 minutes sampling time
- Two PV generators with 1.1 and 4.4 kWp
- Battery with 40 kWh total capacity
- Loads of 13 kW maximum
- 2 kW micro-CHP, 5kW fuel cell



Without high-level control: **total cost of 27.43€**
MPC-MILP with 6-hours prediction horizon:**19.6 € (28.5% saving)**
MPC-MILP with 18-hours prediction horizon:**17.9 € (34.7 % saving)**

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Smart Grids and Sustainable Electricity Systems

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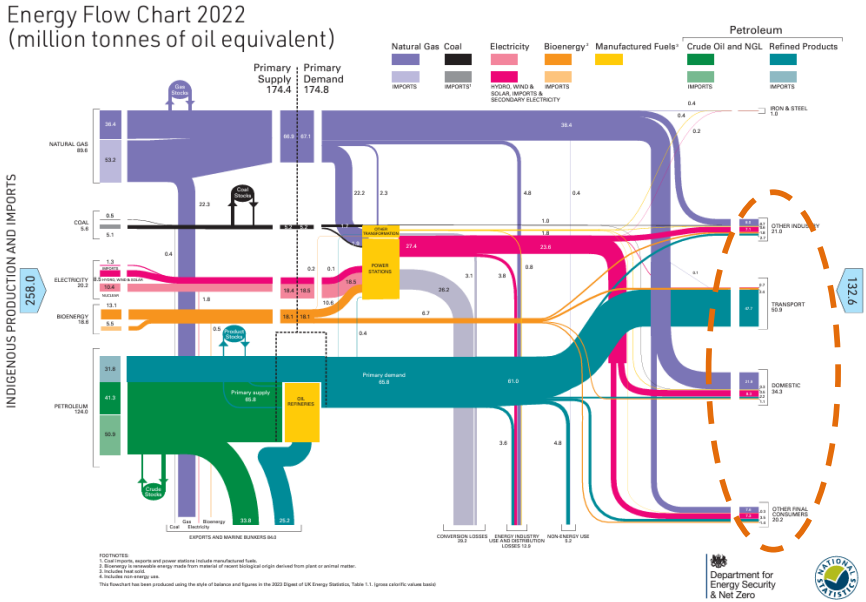
Decarbonisation of heat and transport

Dr Alessandra Parisio

It’s not only about electricity - UK



© Crown copyright Department for Business, Energy and Industrial Strategy– Energy flow chart 2022

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Decarbonisation of heat

An alternative to gas boilers

- An Electric Heap Pump (EHP) is a device that transfers heat from a *heat source* (at lower temperature) to a *heat sink* (at higher temperature)

- EHPs can operate during both heating (in winter) and cooling (summer)

Coefficient of performance

- The performance of an EHP is measured through its ***Coefficient Of Performance*** (COP) for heating

$$COP = \frac{Q}{W}$$

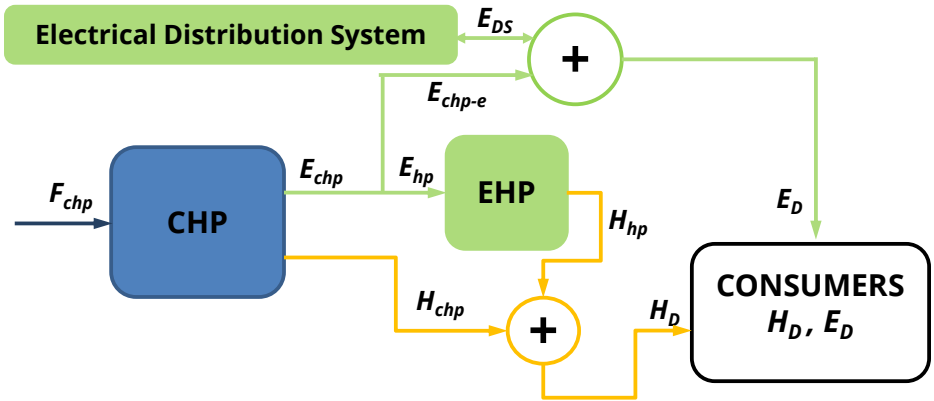
  - **Q**: output heat
  - **W**: input electricity

and ***Energy Efficiency Ratio*** (EER) for cooling

$$EER = \frac{R}{W}$$

  - **R**: output cooling
  - **W**: input electricity

Flexibility of P2H schemes



E_D: electrical demand

H_D: heat demand

F_{chp}: CHP fuel input

E_{chp}: CHP electrical output

E_{hp}: EHP electrical input

H_{hp}: EHP heat output

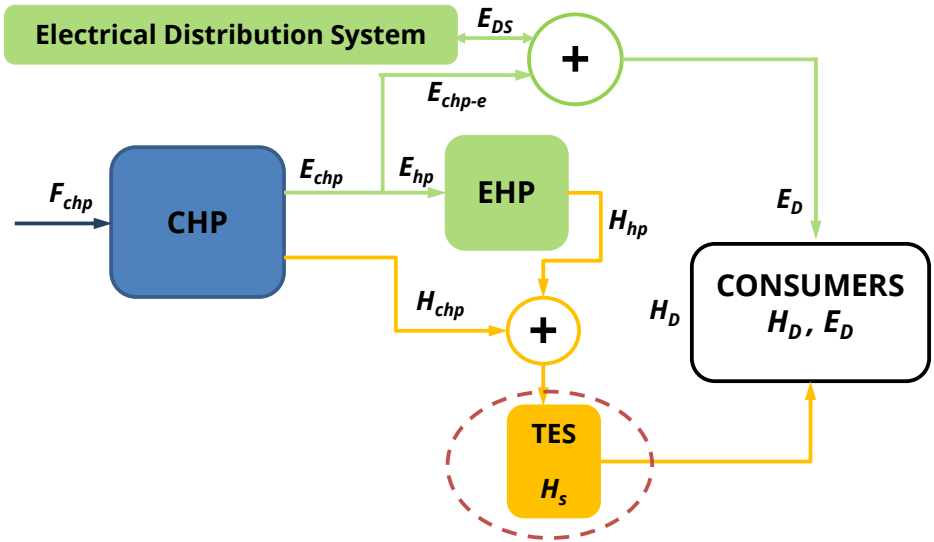
H_{chp}: CHP heat output

E_{chp-e}: share of the CHP electrical output to the consumers or to the distribution system

E_{DS}: electrical power exchanged with the distribution system

Is there any device you would add?

Flexibility of P2H schemes



E_D: electrical demand

H_D: heat demand

F_{chp}: CHP fuel input

E_{chp}: CHP electrical output

E_{hp}: EHP electrical input

H_{hp}: EHP heat output

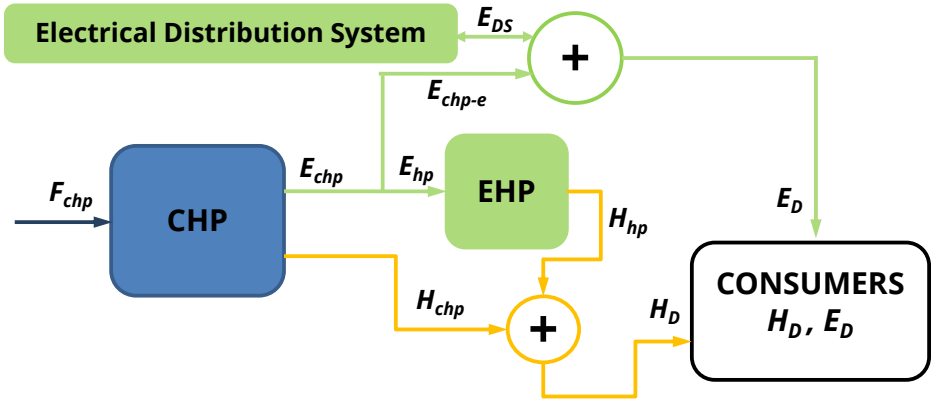
H_{chp}: CHP heat output

H_s: TES energy stored

E_{chp-e}: share of the CHP electrical output to the consumers or to the distribution system

E_{DS}: electrical power exchanged with the distribution system

At a given hour



E_D: 700 kW

H_D: 1500 kW

F_{chp}: ?

E_{chp}: ?

E_{hp}: ?

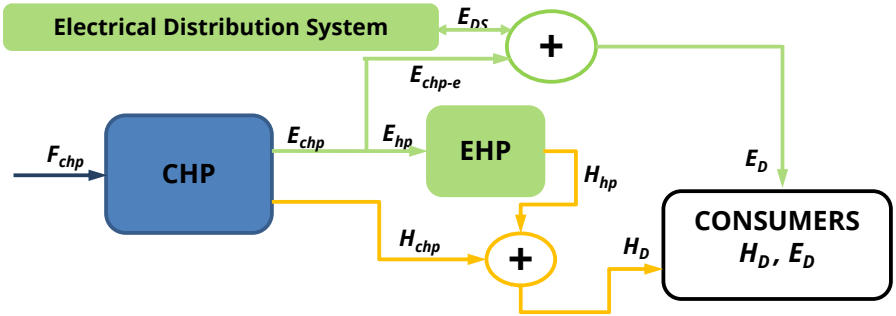
H_{hp}: ?

H_{chp}: ?

E_{DS}: ?

- The CHP has an electrical efficiency of 30 % and a thermal efficiency of 40 %, and its maximum heat output is 1400 kW.
- The EHP has a Coefficient of Performance (COP) of 3, and its maximum heat output is 800 kW.
- CHP is operated so as to cover 80% of the heat demand, whilst the EHP satisfies the remaining 20%.

At a given hour



E_D: 700 kW

H_D: 1500 kW

F_{chp}: ?

E_{chp}: ?

E_{hp}: ?

H_{hp}: ?

H_{chp}: ?

E_{DS}: ?

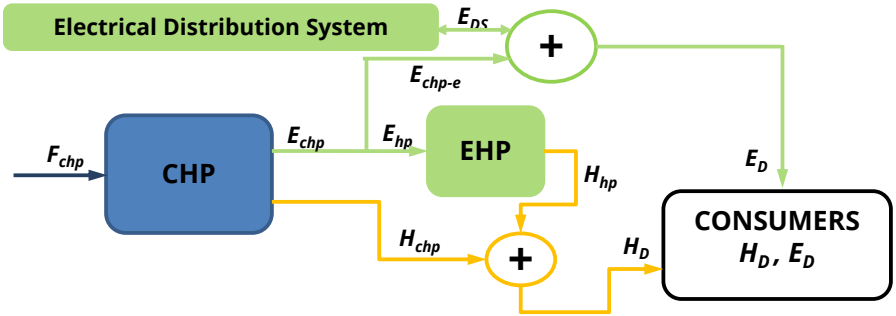
Heat energy balance:

- $H_D = H_{hp} + H_{chp}$, H_{hp} =0.2*1500 = 300 kW, H_{chp} =0.8*1500 = 1200 kW

Electrical energy balance:

- $E_D = E_{DS} + E_{chp-e} = E_{DS} + E_{chp} - E_{hp} = E_{DS} + (\eta_e / \eta_h * H_{chp}) - H_{hp} /COP = E_{DS} + [(0.3/ 0.4) * 1200] – 300/3$ ->
- -> $700 = E_{DS} + 0.75 * 1200 – 100$ -> $800 = E_{DS} + 900$ -> E_{DS} = - 100 kW

At a given hour



E_D: 700 kW

H_D: 1500 kW

F_{chp}: ?

E_{chp}: ?

E_{hp}: ?

H_{hp}: ?

H_{chp}: ?

E_{DS}: ?

- E_{hp} = 300/3 = 100 kW
- F_{chp} = 1200/ 0.4 = 3000 kW
- E_{chp} = (1200/ 0.4) * 0.3 = 900 kW

Is this enough? Can we optimise (e.g., optimal share of the heat load covered by EHP that minimizes the costs)?

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Decarbonisation of transport

Electric vehicle technologies

- Battery electric vehicles (BEVs)
- Fuel Cell powered Electric Vehicles (FCEVs)
- Hybrid Electric Vehicles (HEVs)

Trade-offs

Hydrogen fuel cell vehicle

Starts at: €60,000

Range: 320-405km/200-250 miles

Time to refuel: 3-4 minutes

Electric vehicle

Starts at: €21,000

Range: 160-500km/100-310 miles

Time to refuel: 30 minutes to 12 hours

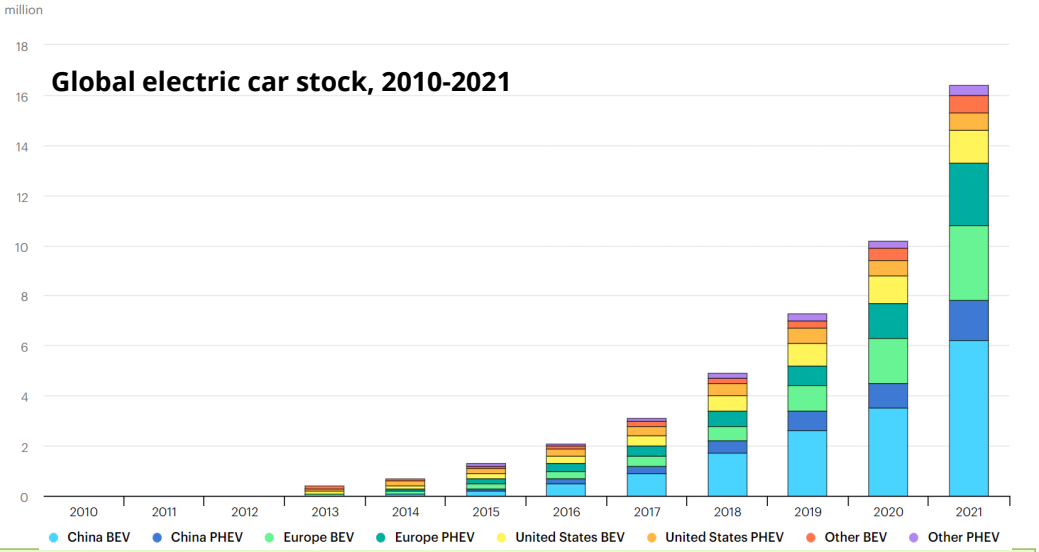
Petrol or diesel vehicle

Starts at: €8,000

Range: 480-640km/300-400 miles

Time to refuel: 2-3 minutes

Electric vehicles deployment



Over 16.5 million electric cars were on the road in 2021, a tripling in just three years

International Energy Agency, Global EV Outlook 2022

Example

At a given hour, the electricity demand for a power system is equal to 25 GW. The power system is given in the table below.

Generation type	Installed capacity	Average electrical efficiency	Average fuel cost
	[GW]	[%]	[£/MWh]
Base load nuclear	5	35	10
Flexible gas	10	45	30
Flexible coal	20	40	15
Transmission and distribution electrical losses with respect to peak demand			10%

SUPPLY = DEMAND + 0.1 · DEMAND

Example

- Calculate the total hourly cost when supplying the given electricity load, assuming that the bulk electricity system is optimally dispatched according to an economic priority list.

Calculate the average electricity cost for the different power plants

Source	Installed capacity	Average electrical efficiency	Average fuel cost	Average electricity cost
	[GW]	[%]	[£/MWh]	[£/MWh]
Base load nuclear	5	35	10	28.6
Flexible gas	10	45	30	66.7
Flexible coal	20	40	15	37.5

Nuclear -> Coal -> Gas as the merit order list

Example

Considering 10% losses -> total electrical load = 27.5 GW (25 + 0.1*25) and the merit order list is as follows: 5 GW Nuclear -> 20 GW Coal -> 2.5 GW Gas

and the relevant electrical load costs are

5,000 MW x 28.57 £/MWh + 20,000 MW x 37.47 £/MWh + 2,500 MW x 66.7 £/MWh = 1,059,524 £/h

- Repeat the calculations in the case that a fleet of 1 million of battery electric vehicles is added to the electrical load. Assume that the electric vehicle charging at the given hour will increase their travelling range by 15 km and that their batteries consume 0.3 kWh/km.

Example

The new load added by EV can be quickly calculated as

EV load = 1,000,000 x 0.3 x 15 = 4.5 GW

so that the electrical peak load to serve, including losses, is equal to

New total load = (25+4.5)*(1+10%)= 32.5 GW

The merit order list in this case yields

5 GW Nuclear -> 20 GW Coal -> 7.5 GW Gas

5,000 MW x 28.57 £/MWh + 20,000 MW x 37.47 £/MWh + 7,500 MW x 66.7 £/MWh = 1,392,857 £/h (~24% higher)

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Efficiencies and emission factors

Modelling low-carbon technologies

- Efficiency performance

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100 \qquad 0 < \eta < 100 \ \%$$

- Emission factor
  - Fuel-related emission factor
  - Output-related emission factor

Energy performance assessment

Electricity

- Produced in a fuel power plant with ***electrical efficiency***

$$\eta_e = \frac{W}{F_W}$$

W ← useful electricity output

F_W ← fuel input

Heat

- Produced in a fuel boiler with ***thermal efficiency***

$$\eta_t = \frac{Q_u}{F_Q}$$

Q_u ← useful heat output

F_Q ← fuel input

Output-related emission factor

Efficiency (% or p.u.)

$$\eta_X = \frac{X}{F}$$

Fuel emission factor (g/kWh)

$$m_{CO_2}^F = \mu_{CO_2}^F \cdot F \qquad \mu_{CO_2}^F = \frac{m_{CO_2}^F}{F}$$

Output emission factor (g/kWh)

$$m_{CO_2}^X = \mu_{CO_2}^X \cdot X$$

$$\boxed{\mu_{CO_2}^X = \mu_{CO_2}^F / \eta_X}$$

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Smart Grids and Sustainable Electricity Systems

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Flexibility in smart grids

Dr Alessandra Parisio

What is flexibility?

- *Flexibility* describes the system ability to cope with events that may cause imbalances between supply and demand at different time frames while maintaining the system reliability in a cost effective manner
- Flexibility is measured in terms of MW available for ramping up/down over time
- New sources of flexibility are needed in a smart grid

Flexibility requirements

- Sustain upward or downward ramp
- Respond for a defined period of time
- Change ramp directions quickly
- React quickly and meet expected operating levels
- Start with short notice from a zero or low-electricity operating level
- Start and stop multiple times per day
- Accurately forecast operating capability

Flexibility in traditional power systems

Flexibility is provided by power plants running at less than full capacity. The quality of such a reserve is determined by

- *Capacity*: How much imbalance will the resource be able to compensate, both in terms of power and energy
- *Length of reserve period*: How long is the unit committed to provide reserve
- *Activation time*: How fast can the reserve be activated

Sources of flexibility in smart grids

- Dispatchable power plants (e.g., DG, CCGT, CHP)
- Demand-side management (e.g., demand response, energy efficiency, balancing services)
- Energy storage facilities
- Interconnection with adjacent markets

Flexibility in the distribution system/demand flexibility

- Availability of energy storage also in forms of energy other than electricity (e.g., thermal)
- Difference in time constants between electricity and other processes such as heating or cooling
- User flexibility in the net consumption/generation profile

Need of distributed optimisation and control strategies at various time scales

Demand-Side Management (DSM)

Demand-side management refers to technologies, actions and programmes on the demand-side of energy metres that seek to manage or decrease energy consumption, in order to reduce total energy system expenditures or contribute to the achievement of policy objectives such as emissions reduction or balancing supply and demand

Categories of DSM

- Energy Efficiency
- Demand Response
- On-site generation and storage

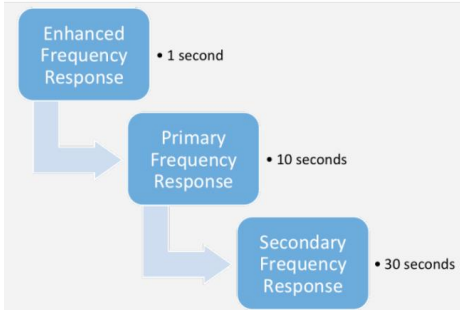
Advantages of DR provision of ancillary services

- Larger number of participants increases competition and lowers cost
- Better utilization of resources, e.g.,
    - Providing reserve with interruptible loads rather than partly loaded thermal generating units
    - Particularly important if proportion of generation from renewable sources increases
- Flexible demand may be a more reliable provider
  - Large number of small demand-side providers

EFR battery project

10MW installation near Sheffield to provide Enhanced Frequency Response (EFR) services to the grid

- ✓ More than 1,000 lithium-ion batteries divided into racks
- ✓ Battery + biomass plant (wood) produce power for 40,000 homes
- ✓ *Discharge power to the network when frequency falls or withdrawing power if supply is greater than demand*



National Grid ESO. Other case studies at http://powerresponsive.com/case-studies/

Power Potential project

- Trial in South East England begun in January 2019
- Battery storage, wind farms, solar PV and synchronous generation involved
- Generate up to an extra 4GW
- If this works and extended to further 59 sites, savings could total £12m by 2050
- Distributed Energy Resources can help solve transmission voltage problems

National Grid ESO, https://www.nationalgrideso.com/innovation/projects/power-potential

London Underground

Demand Side Reserve (DSR) run by National Grid *to offer 55MW of demand reduction*

- ✓ The Tube is the biggest power consumer in London, and has the largest private power network in the country
- ✓ DSR makes use of our own stand-alone emergency back-up supply at the Greenwich Power Station

http://powerresponsive.com/on-track-to-support-demand-side-response-2/

Colchester Hospital University NHS Foundation Trust

Aggregator *KiWi Power* to provide demand response for National Grid

- ✓ Export capacity of 2MW
- ✓ Under DSR, generators are used at times when the system requires it via KiWi Power
- ✓ Payback for the cost of the backup generators was two to three months
- ✓ Over £100,000 of annual revenue

http://powerresponsive.com/nhs-trust-benefits-from-demand-side-response/

Challenges for flexible demand

- Lack of adequate ICT infrastructure as yet (smart meters and controllers/actuators)
- Lack of understanding and quantification of the system benefits of demand response
- Increased complexity of system operation
- Inappropriate market structure and lack of incentives
- Need for storage (heat, dishes, clothes)
- People being reluctant to accept comfort level changes for relatively small savings

National ESO: Roadmap to 2025

	2020	2025 (LW)	What could this mean for markets?
Supply side			• These new low-carbon sources should provide cost effective power. But they will also change the characteristics of how the system behaves in terms of greater unpredictability. Our markets will therefore need to be efficient for cleaner low carbon technology and smaller decentralised providers. This means that markets will need to attribute more value to speed of service response, and enable decisions for market outcomes closer to real time operation.
Renewable generation (%)	38%	75%	
Offshore wind	9.5GW	24.7GW	
Solar	13GW	19GW	
Interconnector capacity	4.75GW	17.9GW	
Demand side			• Vast amounts of new potential flexibility will connect to the system, from a variety of sources including EVs and batteries. Markets across both transmission and distribution need to be co-ordinated and co-optimise to recognise the whole electricity system value that these assets can deliver. • The nature of the changing energy mix on the system will change how we use the system. This will result in ESO markets needing to evolve in order to work efficiently for the changing profile of demand across different profiles.
BEVs of total cars	0.3%	9%	
Battery storage	1GW	>4GW	
Residential heat pumps	162k	1.86m	
Transmission demand summer Sunday pm	18.8GW	14.5GW	
Transmission peak demand	46.2 GW	38.7GW	

Leading the Way (LW) scenario, which assumes that GB would decarbonises rapidly with high levels of investment in world-leading decarbonisation technologies.

National Grid ESO, *Markets Roadmap to 2025*, 2021

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National Grid ESO, *Markets Roadmap to 2025*, 2021

2020 UK response market: services

- The auction trial is an innovation project which is procuring Low Frequency Static (LFS) and Dynamic Low High (DLH) frequency products through the EPEX SPOT Auction Platform on a weekly basis (i.e., static is where an agreed amount of energy is delivered if the system frequency hits a certain trigger point e.g. 49.7Hz. Dynamic is where output rises and falls automatically in line with the system frequency).
- Dynamic Containment (DC)
- Firm Frequency Response (to be dismissed)
- Mandatory Frequency Response (MFR)
- Enhanced Frequency Response (EFR)

National Grid ESO, *Markets Roadmap to 2025*, 2021

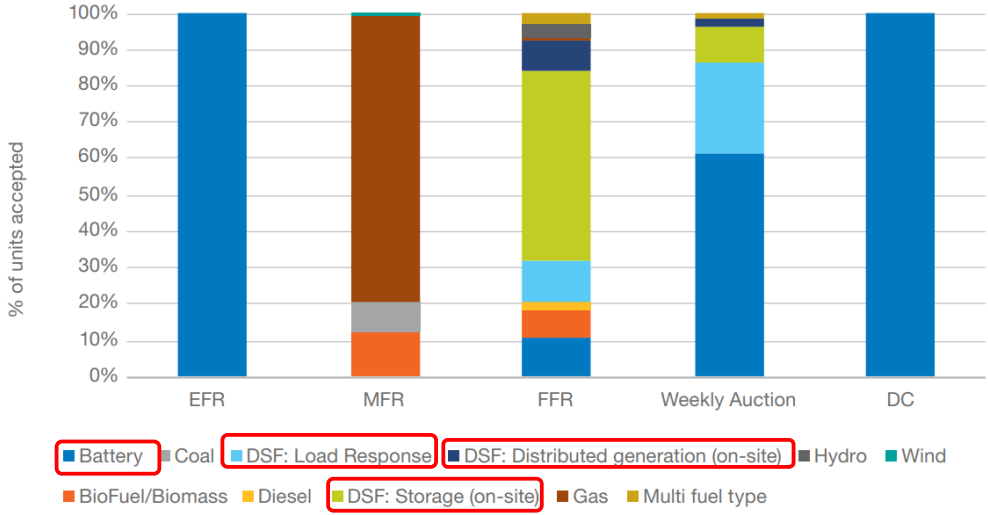
New frequency services (NG ESO)

- Response – pre-fault services to manage frequency close to 50 Hz and post fault services to ensure we can contain the frequency following a fault, which have to be faster to ensure that the frequency is contained.
- Reserve – manually activated and can be used to move frequency back towards 50Hz following the activation of response.

Frequency service	System need	Requirement
Dynamic Regulation and Dynamic Moderation	**Regulate** steady-state frequency within the statutory limits of +/-0.5Hz	up to 300MW each
Dynamic Containment	**Contain** the frequency for events within standards	up to 1,400MW
Quick Reserve	**Recover** frequency to the statutory range (+/-0.5Hz) within 60 seconds	up to 1,400MW
Slow Reserve	**Restore** frequency to the operational range (+/-0.2Hz) within 15 minutes	up to 1,400MW

National Grid ESO, *Markets Roadmap to 2025*, 2021

2020 UK response market



By 2025 there will be greater volumes of distribution connected generation and aggregated capacity participating in response markets, including emerging flexibility providers such as Vehicle to Grid (V2G) and residential DSR.

National Grid ESO, *Markets Roadmap to 2025*, 2021

Residential flexible demand

- Cold appliances
- Wet appliances
- Home computing
- Lighting
- Cooking
- Consumer electronic

Possible appliance classification

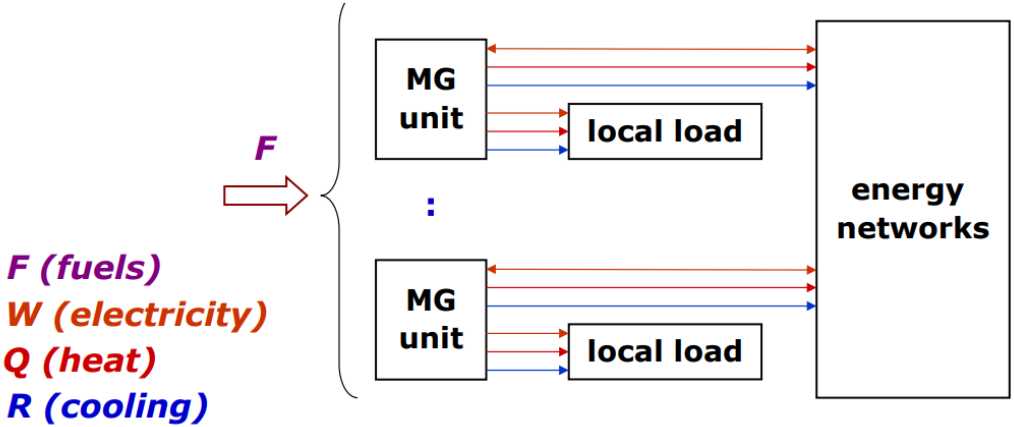
- **Deferrable** load may be classified into:
  - → *Non-flexible*, which has a predefined profile that cannot be altered during operation time, such as Washing Machine
  - → *Flexible,* such as electrical vehicle
- **Curtailable** load may be classified into:
  - → *Partially curtailable*, such as air conditioning, whose power consumption can be controlled according to its temperature set point
  - → *Fully curtailable*, according to the consumer priorities, meaning that these appliances can be switched off without the need of re-turned them on later (for example, light bulbs)

How about…

	Deferrable		Curtailable	
	Nonflexible	Flexible	Partially	Fully
TV				
Playstation				
Microwave oven				
Kettle				
Hob				
Oven				
Laptop				
Water heater				
Dishwasher				
Storage heater				
…				

Multi-generation energy systems

A multi-generation energy system is structured as a set of multi-generation units supplied by the relevant fuel and connected to the energy networks



Separate Production system

Electricity

- Produced in a fuel <u>power plant</u> with ***electrical efficiency***

$$\eta_e = \frac{W}{F_W}$$

useful electricity output

fuel input

Heat

- Produced in a fuel <u>boiler</u> with ***thermal efficiency***

$$\eta_t = \frac{Q_u}{F_Q}$$

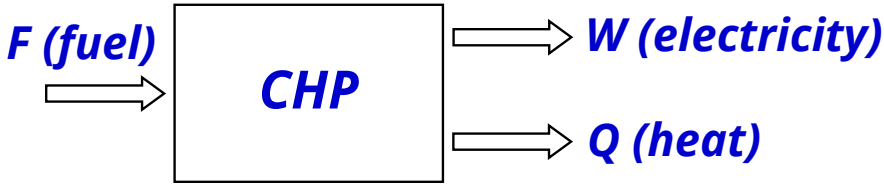
useful heat output

fuel input

Cogeneration

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

- *simultaneous production* of electricity and heat from fuel
- **higher overall energy efficiency (80-90%)**
- **lower CO_2 emissions** (also depending on the fuel utilised)

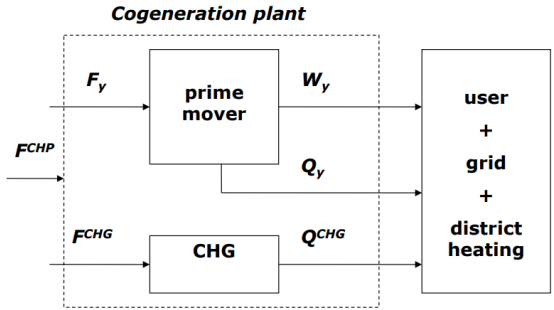


- Heat networks aggregating several different users can enhance CHP deployment

Cogeneration components

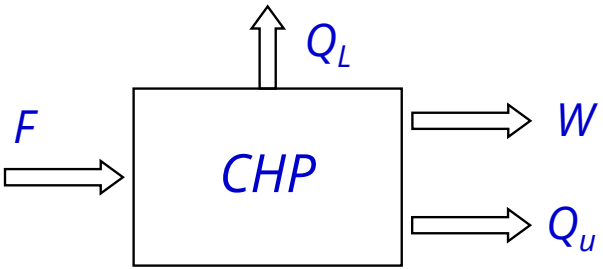
– a ***Cogenerator prime mover***: for instance a gas-fed Internal Combustion Engine (ICE) or a Microturbine (MT)

– a ***Combustion Heat Generator*** (CHG) group, usually boilers in back-up or peak shaving operation mode (The regenerative system of the electric thermal storage boiler used for peak shaving in the power plant can ensure the auxiliary units of the electric boiler to participate in deep peak shaving in summer)



F (fuel); W (electricity); Q (heat)

CHP efficiencies



- *F = fuel thermal input*
- *W = electricity output*
- *Q_u = useful heat*
- *Q_L = heat losses*

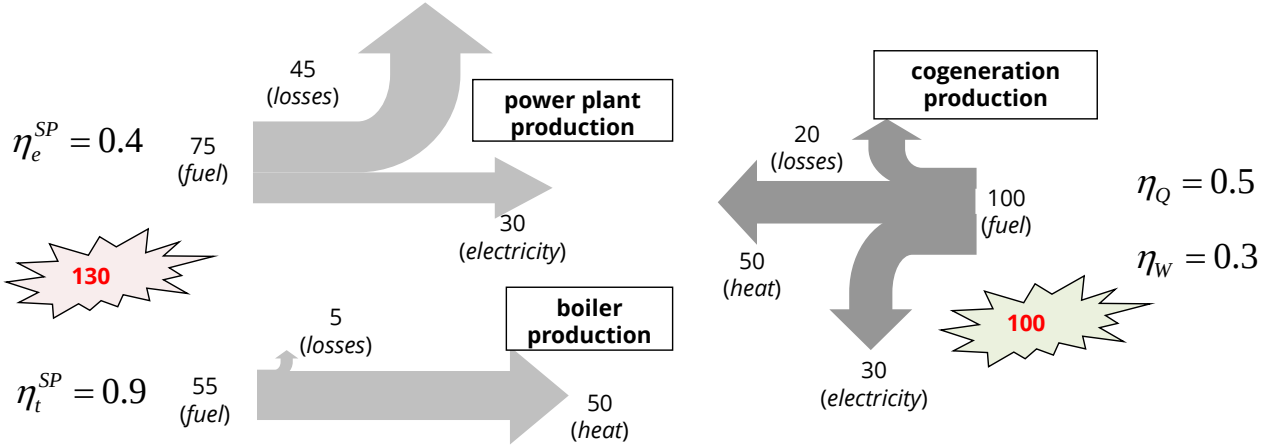
Electrical efficiency

$$\eta_W = \frac{W}{F}$$

Thermal efficiency

$$\eta_Q = \frac{Q_u}{F}$$

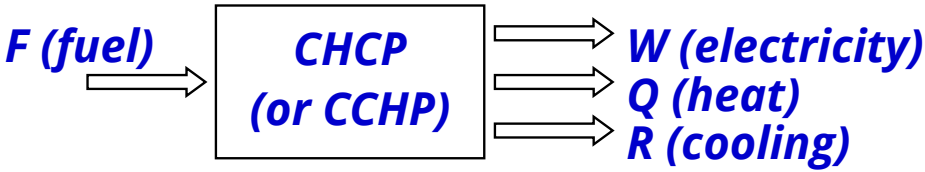
A Cogeneration Sankey diagram



Cogeneration Primary Energy Saving (TPES) = (130-100)/130 = 23%

Trigeneration

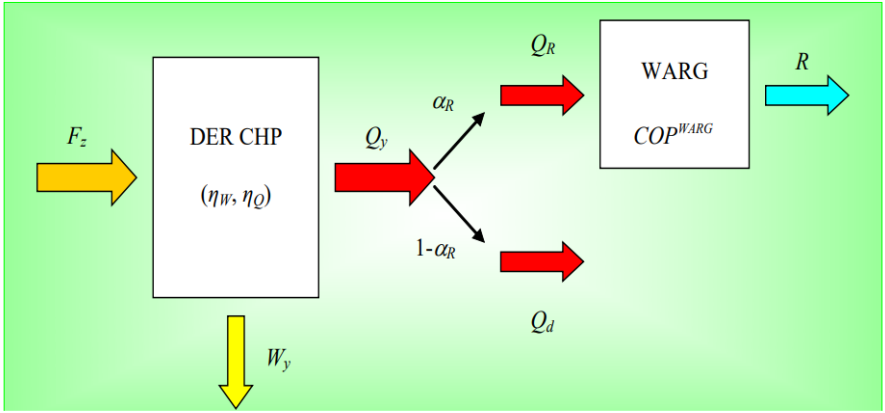
Trigeneration is simultaneous production of electricity, heat and cooling power from a single fuel source



- ***CHCP*** = Combined Heat and Cooling Power
- ***CCHP*** = Combined Cooling Heat and Power
- ***Extension*** of cogeneration
- Classical **seasonal thermal load patterns** for several applications: **heating** in wintertime, **cooling** in summertime

Classical trigeneration black-box model

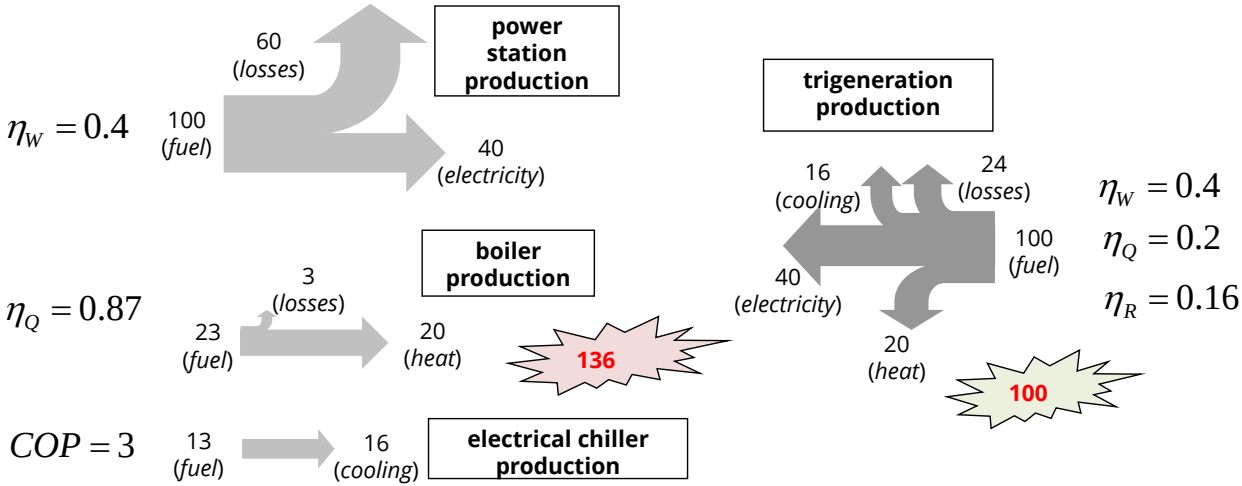
- **CHP + WARG** (Water Absorption Refrigerator group)
- **Absorption group**, fed by hot water or steam produced in cogeneration to generate cooling



Q_R = thermal input to the WARG to produce the cooling power R

α_R = heat-to-cooling ***dispatch factor***

A Trigeneration Sankey diagram



Trigeneration Primary Energy Saving (TPES) = (136-100)/136 = 26%

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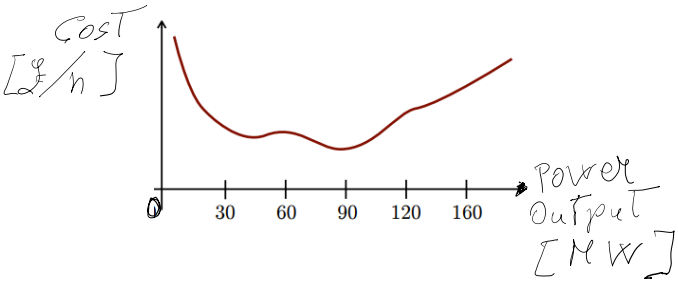
Smart Grids and Sustainable Electricity Systems

Background on optimization

Optimization = assign values to a set of decision variables so to optimize a certain objective function

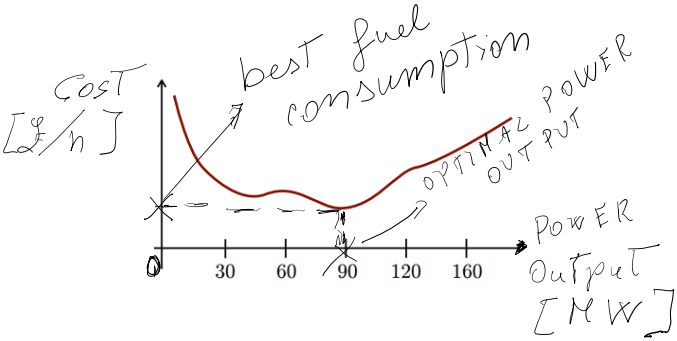
Example: Which is the best power output to minimize fuel consumption?



©2023 A. Bemporad - Numerical Optimization

Background on optimization

Optimization = assign values to a set of decision variables so to optimize a certain objective function



optimization variable: power output

cost function to minimize: fuel consumption

parameters of the decision problem: plant type, efficiency, UP and DOWN times,....

Background on optimization

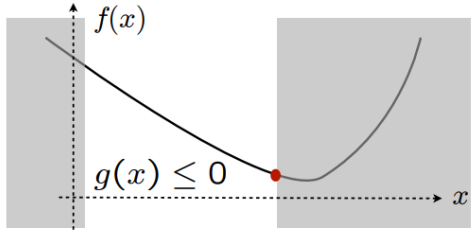
$$\min_x f(x)$$

- The **objective function** $f : \mathbb{R}^n \to \mathbb{R}$ models our goal: minimize (or maximize) some quantity.
- The **optimization vector** $x \in \mathbb{R}^n$ is the vector of **optimization variables** (or **unknowns**) x_i to be decided optimally.

Most often the problem is difficult to solve by inspection
Use a numerical solver implementing an optimization algorithm

Constrained optimization

$$\begin{aligned} \min_x \quad & f(x) \\ \text{s.t.} \quad & g(x) \leq 0 \\ & h(x) = 0 \end{aligned}$$



- The (in)equalities define the feasible set $\mathcal{X}$ of admissible variables

$$\mathcal{X} = \{x \in \mathbb{R}^n : \; g(x) \leq 0, \; h(x) = 0\}$$

- Further constraints may restrict $\mathcal{X}$, for example:
  $x \in \{0,1\}^n$ (x = **binary vector**)
  $x \in \mathcal{Z}^n$ (x = **integer vector**)

$$g : \mathbb{R}^n \to \mathbb{R}^m, \; h : \mathbb{R}^n \to \mathbb{R}^p$$

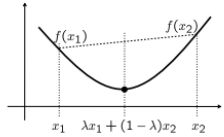
$$g(x) = \begin{bmatrix} g_1(x_1, x_2, \ldots, x_n) \\ \vdots \\ g_m(x_1, x_2, \ldots, x_n) \end{bmatrix}$$

$$h(x) = \begin{bmatrix} h_1(x_1, x_2, \ldots, x_n) \\ \vdots \\ h_p(x_1, x_2, \ldots, x_n) \end{bmatrix}$$

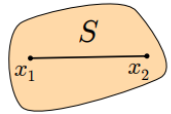
Convex optimization

The optimization problem

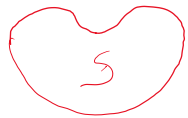
$$\begin{aligned} \min \quad & f(x) \\ \text{s.t.} \quad & x \in S \end{aligned}$$



is a **convex optimization problem** if S is a convex set and $f : S \to \mathbb{R}$ is a convex function



- Often S is defined by **linear equality constraints** $Ax = b$ and **convex inequality constraints** $g(x) \leq 0, g : \mathbb{R}^n \to \mathbb{R}^m$ convex
- Every local solution is also a global one
- Efficient solution algorithms exist
- Often occurring in many problems in engineering, economics, and science



Discrete optimization

- In some problems the optimization variables can only take integer values. We call $x \in \mathbb{Z}$ an **integrality constraint**

- A special case is $x \in \{0, 1\}$ (**binary constraint**)

- When all variables are integer (or binary) the problem is an **integer programming** problem (a special case of **discrete optimization**)

- In a **mixed integer programming** (MIP) problem some of the variables are real ($x_i \in \mathbb{R}$), some are discrete/binary ($x_i \in \mathbb{Z}$ or $x_i \in \{0, 1\}$)

Optimization problems with integer variables are more difficult to solve

Optimization algorithms

- An **optimization algorithm** is a procedure to find an optimizer x^* of a given optimization problem $\min_{x \in \mathcal{X}} f(x)$
- It is usually iterative: starting from an **initial guess** x^0 of x it generates a sequence x^k of "iterates", with hopefully $x^N \approx x^*$ after N iterations
- Good optimization algorithms should possess the following properties:
  - **Efficiency** = do not require excessive **CPU time/flops** and **memory** allocation
  - **Robustness** = perform well on a wide variety of problems in their class, for all reasonable values of the initial guess x^0
  - **Accuracy** = find a solution close to the optimal one, in spite of **roundoff errors** due to finite precision arithmetic (**numerical robustness**)
- The above are often conflicting properties

Optimization model

- An **optimization model** is a mathematical model that captures the objective function to minimize and the constraints imposed on the optimization variables
- It is a **quantitative** model, the decision problem must be formulated as a set of mathematical relations involving the optimization variables
- Optimization models, as all mathematical models, are never an exact representation of reality but a **good approximation** of it
- There are usually many different models for the same real problem

Optimization modeling is an art

Modelling languages for optimization problems

- **AMPL** (A Modeling Language for Mathematical Programming) most used modeling language, supports several solvers
- **GAMS** (General Algebraic Modeling System) is one of the first modeling languages
- **CVX**/**CVXPY**/**Convex.jl** Convex problem modeling in MATLAB/ python / julia
- **YALMIP** MATLAB-based modeling language
- **PYOMO** python -based modeling language
- **PYTHON-MIP** python -based modeling language for mixed-integer linear programming
- **JuMP** A modeling language for linear, quadratic, and nonlinear constrained optimization problems embedded in julia

Formulating an optimization model

1. Talk to the domain expert to **understand** the problem we want to solve
2. Single out the optimization **variables** x_i (what are we able to decide?) and the
   domain (real, binary, integer)
3. Treat the remaining variables as **parameters** (=data that affect the problem bu
   are not part of the decision process)
4. Translate the objective(s) into a **cost function** of x to minimize (or maximize)
5. Are there **constraints** on the decision variables ? If yes, translate them into
   (in)equalities involving x
6. Make sure we have all the required **data** available

Economic dispatch

- What are we able to decide?

Power to dispatch

- What are the parameters?

Running costs, load, MSG and maximum capacity, committed generators

- What is the performance criteria?

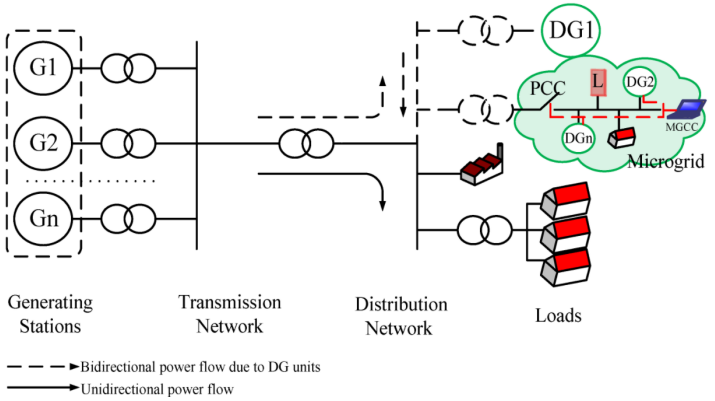
Minimise costs

- Are there constraints on the decision variables?

Bounds on the amount of power dispatch, power balance

Microgrid operation management

The microgrid concept assumes a cluster of loads and distributed generators (DGs) operating as a single controllable system that provides both electricity and heat to its local area



Microgrid components:

- Distributed Generators (DGs)
- Loads
- Storage equipment (batteries, capacitors, flywheels)
- Microgrid Controller
- Point of Common Coupling (PCC) to the utility grid

Microgrid Operation Optimization

Objective:

- Optimize microgrid operations over a planning horizon to fulfill a time-varying demand subject to operational constraints while minimizing a cost function

The **Microgrid Operation Optimization** includes

- Unit Commitment (UC)
- Economic Dispatch (ED)
- Optimal scheduling of storage operations
- Demand side policies (curtailment options)
- When and how much energy should be purchased/sold from/to the utility grid

Source: A. Parisio, E. Rikos, L. Glielmo, "A Model Predictive Control Approach to Microgrid Operation Optimization', IEEE Transactions on Control System Technology, September 2014. Available at https://ieeexplore.ieee.org/document/6705582/ (via CC BY 3.0)

Microgrid Operation Optimization

- What are we able to decide?

Power to dispatch, units to commit, storage operation (when to charge/discharge and by how much), load curtailment, power exchange with the grid

- What are the parameters?

Generation costs, MSG and maximum capacities, storage efficiencies, emission factors...

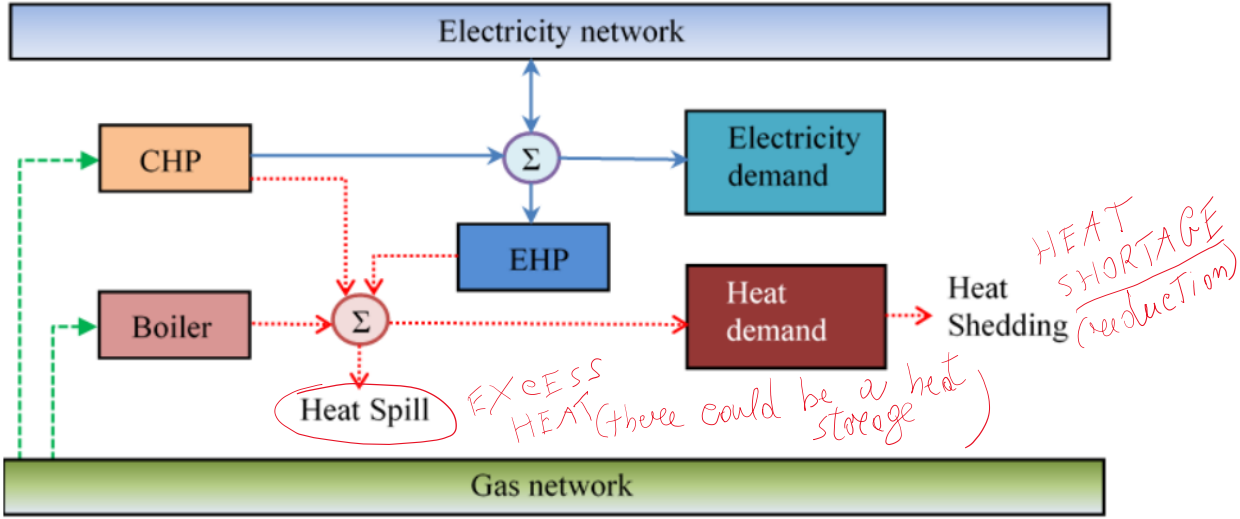
- What is the performance criteria?

Minimise costs,...

- Are there constraints on the decision variables?

Technical and operational limits of the energy resources, power balance, curtailment limits,...

Multi-energy systems



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Energy management problem

- What are we able to decide?

Time varying gas amount to buy, electricity to buy/sell, when to use the heat pump and the CHP,...

- What are the parameters?

Gas and electricity costs, device efficiencies and capacities, energy demands....

- What is the performance criteria?

Minimise costs

- Are there constraints on the decision variables?

Bounds on the amount of power to buy/sell, ramp-rate limits, power balance....

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Multi-energy systems (MES) - Examples

Source

Tutorial on Multi-Energy Systems (MES) (with Phyton code) available at:

https://gitlab.com/cesenia/mes-tutorial-basic-concepts

Look *only* at:

- Multi-energy generation systems - Example with gas boiler
- Multi-energy generation systems - Example with cogeneration
- Multi-energy generation systems - Case studies

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Results

https://gitlab.com/cesenia/mes-tutorial-basic-concepts

Test Binder-Jupyter public

Use the link below to run this jupyter notebook:

launch binder

File Edit View Run Kernel Tabs Settings Help

Filter files by name

/

Name	Last Modified
Figures	2 months ago
environment.yml	2 months ago
Integrated networks modelling - Electricity examples.ipynb	2 months ago
Integrated networks modelling - Electricity.ipynb	2 months ago
Multi energy districts - Examples.ipynb	2 months ago
Multi energy districts - Model.ipynb	2 months ago
Multi-energy generation systems - Example with cogeneration.ipynb	32 minutes ago
Multi-energy generation systems - Example with gas boiler.ipynb	24 minutes ago
Multi-energy generation systems - General formulation example_size.ipy...	2 months ago
Multi-energy generation systems - General formulation.ipynb	2 months ago
README.md	2 months ago

Launcher | Multi-energy generation syst | Multi-energy generation syst | Multi-energy generation syst

Download GitLab Binder Markdown No Kernel

[33]:
```
results = pyo.SolverFactory('glpk').solve(model)
print(results)
```

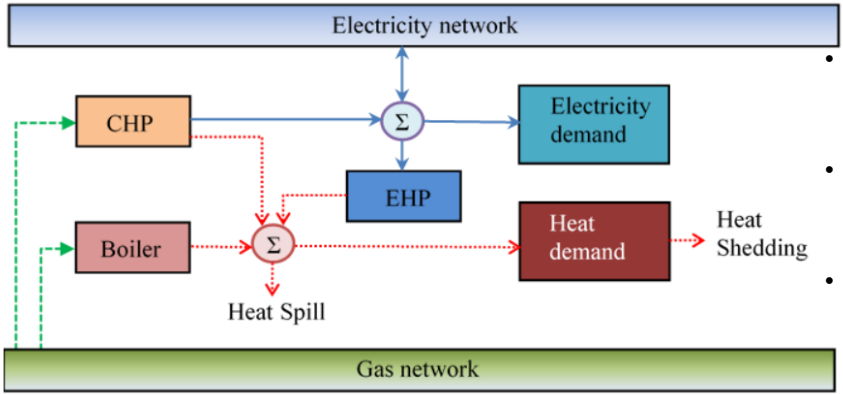
```
Problem:
- Name: unknown
  Lower bound: 2.32647058823529
  Upper bound: 2.32647058823529
  Number of objectives: 1
  Number of constraints: 26
  Number of variables: 21
  Number of nonzeros: 36
  Sense: minimize
Solver:
- Status: ok
  Termination condition: optimal
  Statistics:
    Branch and bound:
      Number of bounded subproblems: 0
      Number of created subproblems: 0
  Error rc: 0
  Time: 0.025510787963867188
Solution:
- number of solutions: 0
  number of solutions displayed: 0
```

The information above does not provide many insights about the model, so two methods to visualize the result are created. The firs method, presented below, is to present selected variables (the gas consumption of the boiler is not included as it is the same as the gas import) in a bar chart.

[34]:
```
def plot_MES_boiler(model):
    import matplotlib.pyplot as plt

    plt.figure(figsize=(15,4))
    plt.bar([0, 1, 2, 3, 4], [y.value for y in model.Electricity_Import.values()],
            label='Electricity import', width=0.15)
    plt.bar([0.15, 1.15, 2.15, 3.15, 4.15], [y.value for y in
                                             model.Boiler_Heat_Output.values()],
            label='Boiler heat output', width=0.15)
    plt.bar([0.30, 1.30, 2.30, 3.30, 4.30], [y.value for y in model.Gas_Import.values()],
            label='Gas import', width=0.15)
    plt.grid()
    plt.legend()
    plt.xlabel('Period')
```

MES with CHP – flexible MES

Flow diagram of MES with CHP



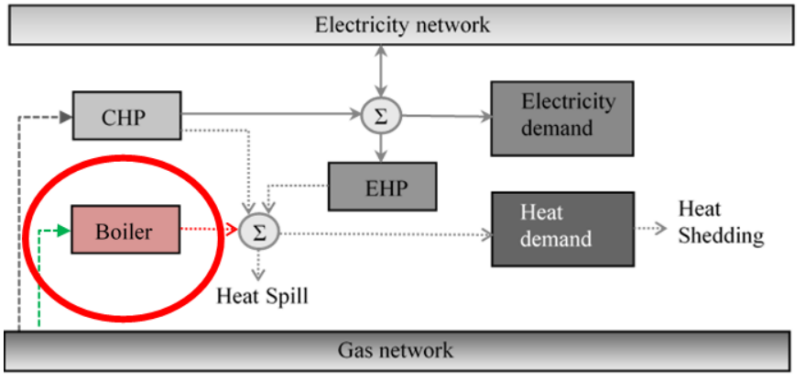
- **CHP:** consumes gas to produce heat and electricity
- **EHP**: consumes electricity to produce heat
- **Gas boiler**: consumes gas to produce heat

Boiler, Combined Heat and Power (CHP) and Electric Heat Pump (EHP) are DERs

Heat *shedding* and *spilling* allowed -> flexibility

How to minimize the energy costs of this MES?

Boiler model



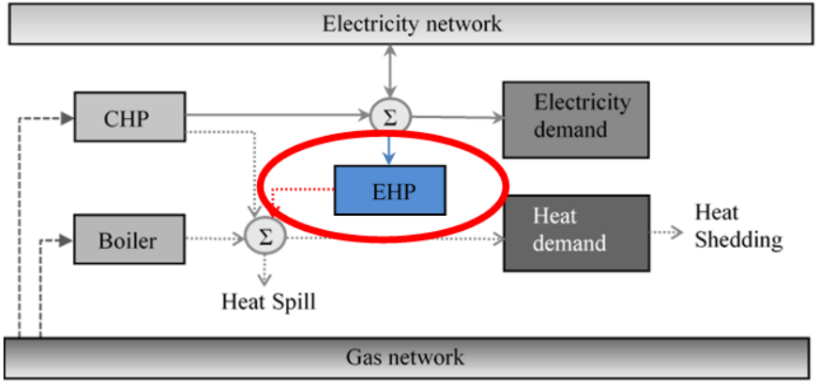
Parameters?

Optimization variables?

$$Boiler_Heat_Output_{period} \leq Boiler_Heat_Capacity$$

$$Boiler_Heat_Output_{period} = Boiler_Gas_Input_{period} \times Boiler_Heat_Efficiency_{period}$$

EHP model



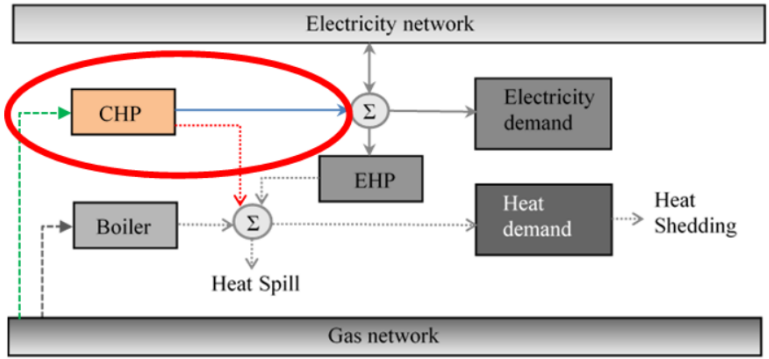
Parameters?

Optimisation variables?

$$EHP_Heat_Output_{period} \leq EHP_Heat_Capacity$$

$$EHP_Heat_Output_{period} = EHP_Electricity_Input_{period} \times EHP_Efficiency_{period}$$

CHP model



Parameters?

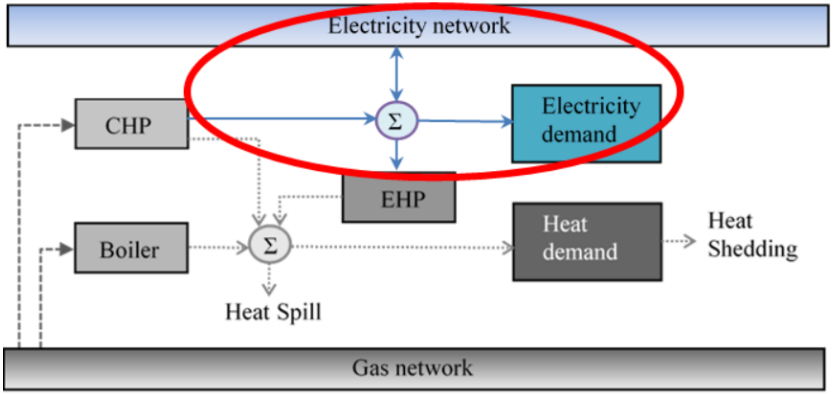
Optimisation variables?

$$CHP_Heat_Output_{period} \leq CHP_Heat_Capacity_{period}$$

$$CHP_Electricity_Output_{period} = CHP_Gas_Input_{period} \times CHP_Electricity_Efficiency_{period}$$

$$CHP_Heat_Output_{period} = CHP_Gas_Input_{period} \times CHP_Heat_Efficiency_{period}$$

Electricity balance

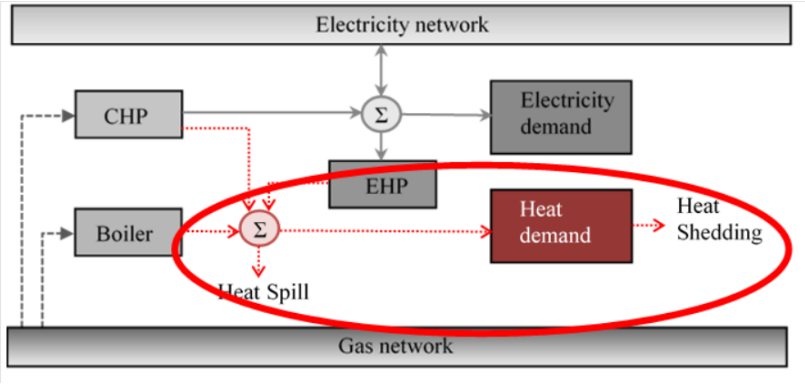


Parameters?

Optimisation variables?

$$Electricity_Demand_{period} + EHP_Electricity_Input_{period} + Electricity_Export_{period} = Electricity_Import_{period} + CHP_Electricity_Output_{period}$$

Heat balance

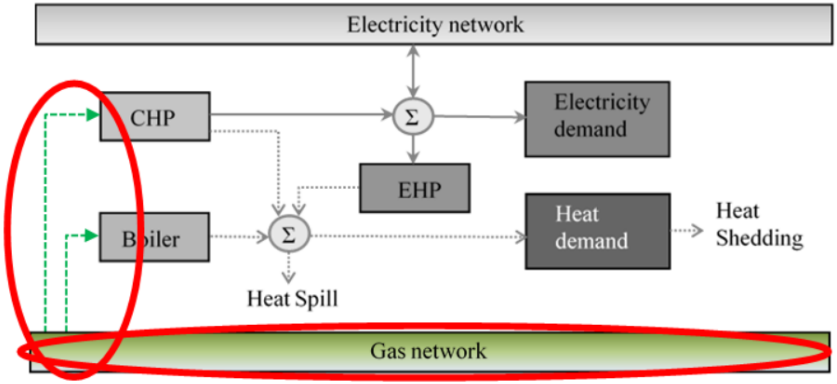


Parameters?

Optimisation variables?

$$Heat_Demand_{period} + Heat_Spill_{period} = Boiler_Heat_Output_{period} + CHP_Heat_Output_{period} + EHP_Heat_Output_{period} + Heat_Shedding_{Period}$$

Gas balance



Parameters?

Optimisation variables?

$$CHP_Gas_Input_{period} + Boiler_Gas_Input_{period} = Gas_Import_{period}$$

Objective function

Cost minimisation

$$
\begin{aligned}
&Minimise: \\
&\sum_{period} \Big(Electricity_Importperiod \times Electricity_Import_Price_{period} && + \\
&\quad Gas_Import_{period} && \times Gas_Import_Price_{period} && - \\
&\quad Electricity_Export_{period} && \times Electricity_Export_Price_{period} && + \\
&\quad Heat_Spill_{period} && \times Heat_Spill_Penalty_{period} && + \\
&\quad Heat_Shedding_{period} && \times Heat_Shedding_Penalty_{period} \Big) \times dt
\end{aligned}
$$

Period (dt) = 1h

Constraints

Boiler constraints:

$$Boiler_Heat_Output_{period} \leq Boiler_Heat_Capacity$$

$$Boiler_Heat_Output_{period} = Boiler_Gas_Input_{period} \times Boiler_Heat_Efficiency_{period}$$

EHP constraints:

$$EHP_Electricity_Output_{period} \leq EHP_Heat_Capacity$$

$$EHP_Heat_Output_{period} = EHP_Electricity_Input_{period} \times EHP_Efficiency_{period}$$

CHP constraints:

$$CHP_Heat_Output_{period} \leq CHP_Heat_Capacity_{period}$$

$$CHP_Electricity_Output_{period} = CHP_Gas_Input_{period} \times CHP_Electricity_Efficiency_{period}$$

$$CHP_Heat_Output_{period} = CHP_Gas_Input_{period} \times CHP_Heat_Efficiency_{period}$$

Energy balance constraints:

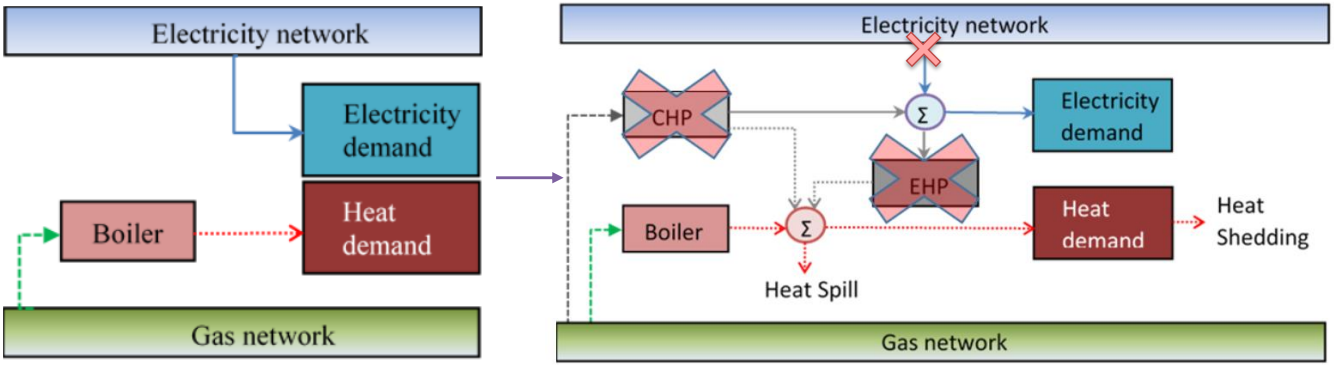
$$Electricity_Demand_{period} + EHP_Electricity_Input_{period} + Electricity_Export_{period} = Electricity_Import_{period} + CHP_Electricity_Output_{period}$$

$$CHP_Gas_Input_{period} + Boiler_Gas_Input_{period} = Gas_Import_{period}$$

$$Heat_Demand_{period} + Heat_Spill_{period} = Boiler_Heat_Output_{period} + CHP_Heat_Output_{period} + EHP_Heat_Output_{period} + Heat_Shedding_{Period}$$

for each period – all nonnegative optimization variables

Inflexible MES -> Flexible MES



MANCHESTER 1824
The University of Manchester

Inflexible MES

```
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(3)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 5  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 0  # Setting capacity to zero [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 0  # Setting capacity to zero [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.15, 0.20, 0.25]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```

Results – problem parameters

```
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 5  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 5  # [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 5  # [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.01, 0.5, 0.01]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```

Heat demand reduction are penalised because of the user discomfort

Results – impact of DERs

```python
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(3)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 5  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 0  # Setting capacity to zero [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 0  # Setting capacity to zero [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.15, 0.20, 0.25]  # [£/kW
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kW
model.Gas_Import_Price = [0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```

Costs: 1.29 £

```python
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(3)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 5  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 5  # Adding EHP capacity [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 0  # Setting capacity to zero [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.15, 0.20, 0.25]  # [£/kW
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kW
model.Gas_Import_Price = [0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```

Costs: 1.24 £
EHP more used than boiler

```python
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(3)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 5  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 5  # [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 5  # [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.15, 0.20, 0.25]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```

Costs: 0.77 £
CHP mostly used
40% cost savings wrt to the case with only boiler

Results

```
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]
```

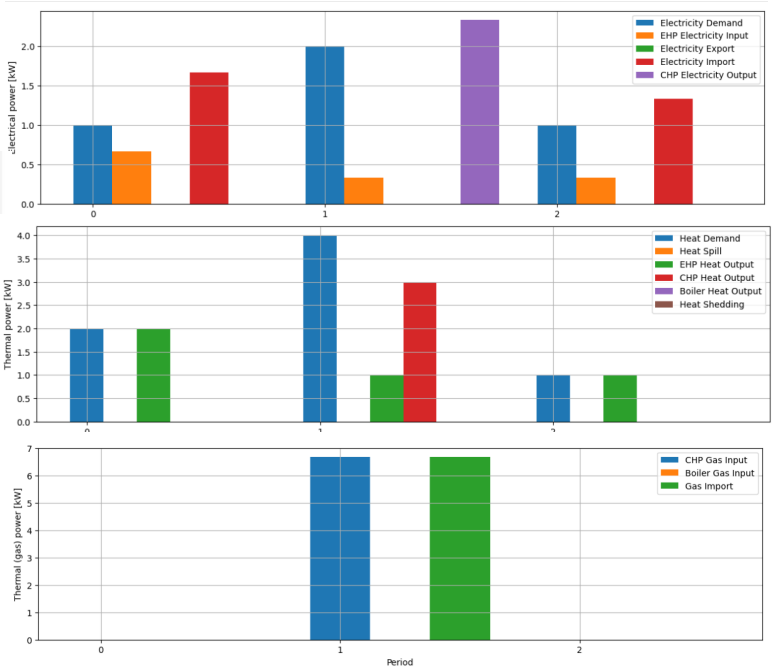
```
model.Electricity_Import_Price = [0.01, 0.5, 0.01]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06]  # [£/kWh]
```

3 periods, only boiler -> Costs: 1.51 [£]

3 periods, with boiler, EHP, CHP -> Costs: 0.49 [£] (67.5% cost saving)

CHP and EHP used during peak electricity prices and energy demands in period 2

Boiler not used



Do not consider Sankey diagrams and flexibility areas

Results

```
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]
```

```
model.Electricity_Import_Price = [0.1, 0.5, 0.1]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.03, 0.03, 0.03]  # [£/kWh]
```

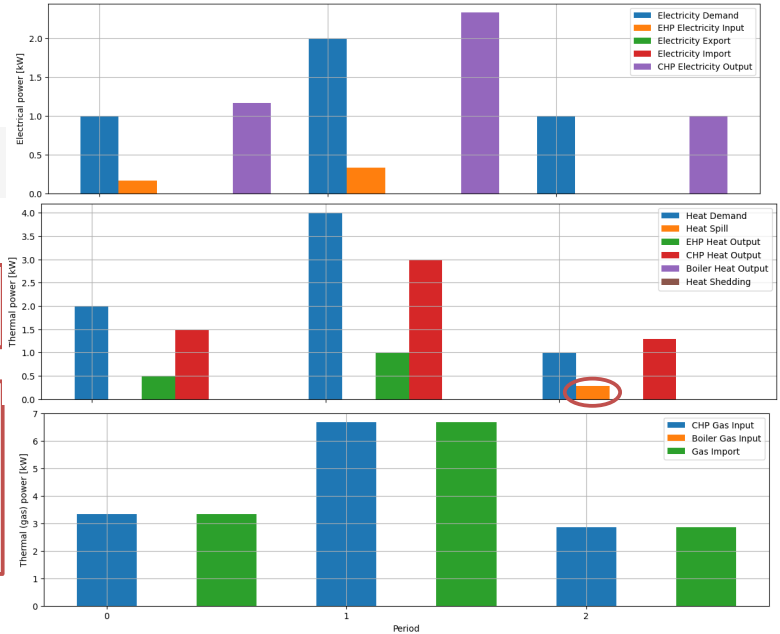
Higher electricity price and lower gas price

Costs: 0.39 £

CHP mostly used, EHP little used, when heat demand is higher, no electricity imported.

Boiler not used

Heat spill because of higher than demanded CHP heat output and heat spill not penalized.



Results

```
model.Electricity_Demand = [1, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 1]  # [kW]
```

```
model.Electricity_Import_Price = [0.1, 0.5, 0.1]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.03, 0.03, 0.03]  # [£/kWh]
```

Higher electricity price and lower gas price

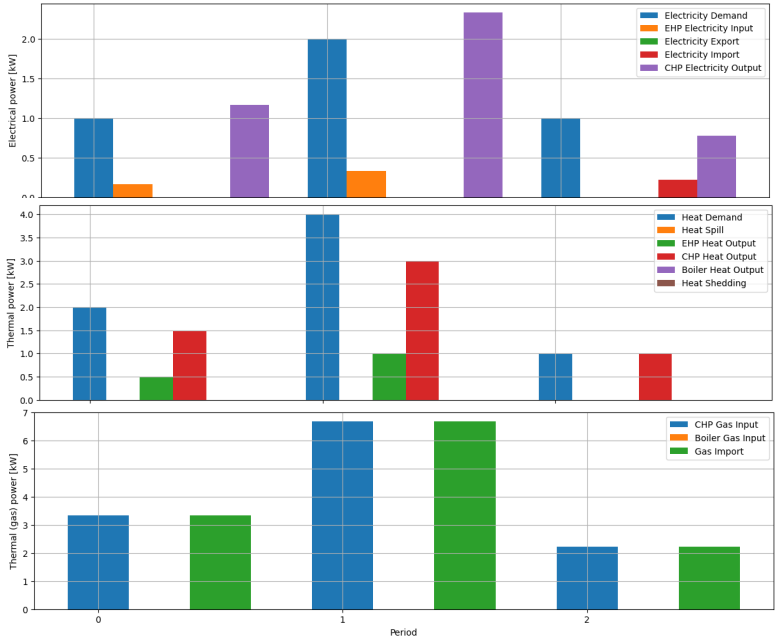
Costs: 0.39 £

CHP mostly used, EHP little used, when heat demand is higher, no electricity imported.

Boiler not used

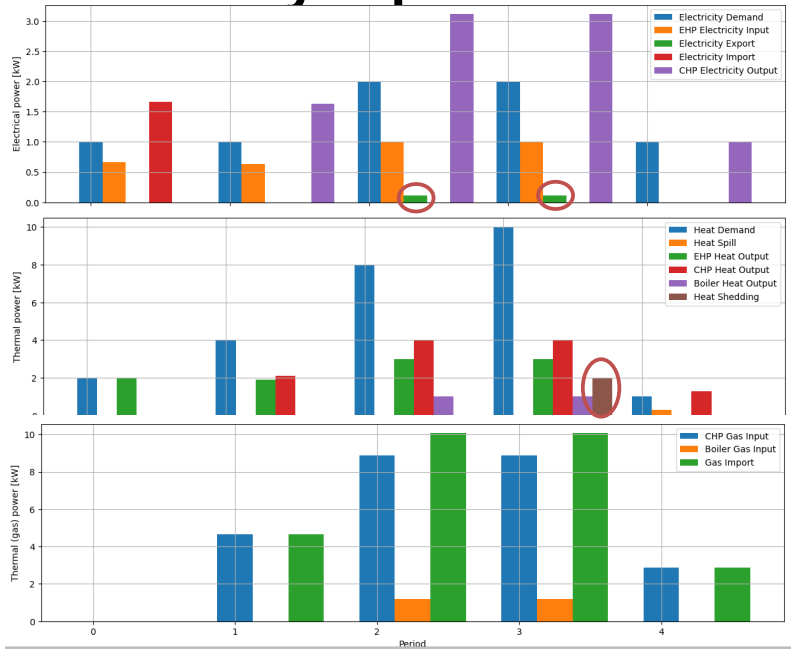
If heat spill penalised, electricity imported during period 3 and no heat spill

Same energy costs



Results – electricity export

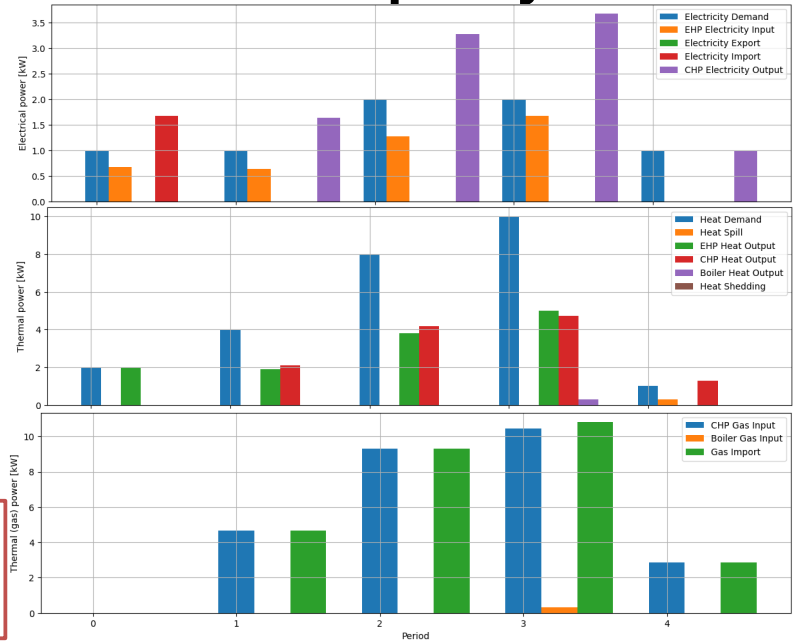
```
model = pyo.ConcreteModel()
model.Set_Periods = range(5)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 1, 2, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 8, 10, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 1  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 3  # [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 4  # [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.10, 0.15, 0.20, 0.30, 0.20]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```



- **Costs: 11.82 £ (because heat shedding costs, 10 £)**
- **Periods 2 and 3: why CHP electricity output greater than electricity demand?**
- **Period 3: why heat shedding is applied instead of increasing CHP production and the electricity export or using EHP or Boiler?**

Results – increased capacity

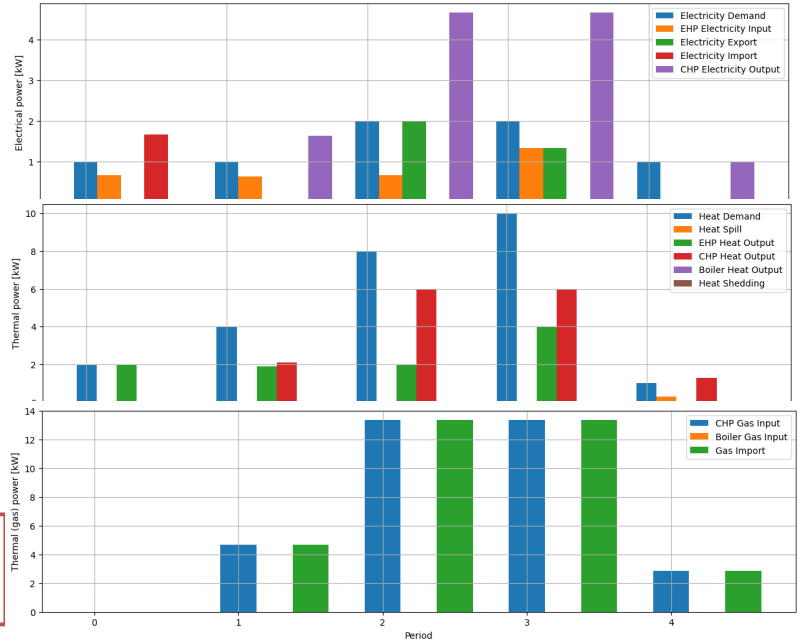
```
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(5)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 1, 2, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 8, 10, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 2  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 5  # [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 6  # [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.10, 0.15, 0.20, 0.30, 0.20]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.01, 0.01, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```



- **Costs: 1.83 £**
- **No need for heat shedding**
- **No electricity export anymore**

Results – electricity export price

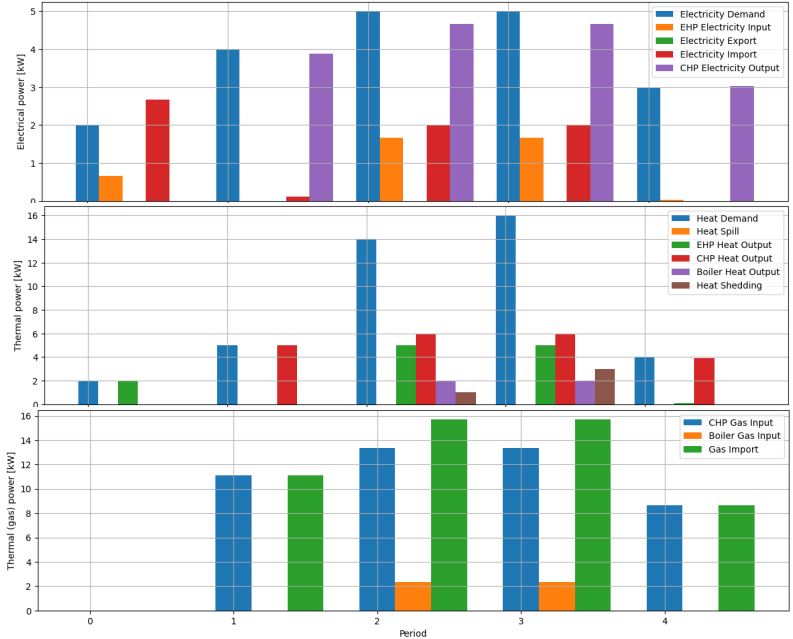
```python
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(5)
model.dt = 1

# Demands
model.Electricity_Demand = [1, 1, 2, 2, 1]  # [kW]
model.Heat_Demand = [2, 4, 8, 10, 1]  # [kW]

# DER
model.Boiler_Heat_Capacity = 2  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 5  # [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 6  # [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.10, 0.15, 0.20, 0.30, 0.20]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.2, 0.2, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```



- **Costs: 1.55 £**
- **Significantly increased electricity export price during periods 2 and 3**

Results – increased demand

```python
# Setting pyomo model and number of periods to optimise
model = pyo.ConcreteModel()
model.Set_Periods = range(5)
model.dt = 1

# Demands
model.Electricity_Demand = [2, 4, 5, 5, 3]  # [kW]
model.Heat_Demand = [2, 5, 14, 16, 4]  # [kW]

# DER
model.Boiler_Heat_Capacity = 2  # [kW]
model.Boiler_Heat_Efficiency = 0.85  # [pu]

model.EHP_Heat_Capacity = 5  # [kW]
model.EHP_Heat_Efficiency = 3  # [pu]

model.CHP_Heat_Capacity = 6  # [kW]
model.CHP_Electricity_Efficiency = 0.35  # [pu]
model.CHP_Heat_Efficiency = 0.45  # [pu]

# Prices and penalties
model.Electricity_Import_Price = [0.10, 0.15, 0.20, 0.30, 0.20]  # [£/kWh]
model.Electricity_Export_Price = [0.01, 0.01, 0.2, 0.2, 0.01]  # [£/kWh]
model.Gas_Import_Price = [0.06, 0.06, 0.06, 0.06, 0.06]  # [£/kWh]

model.Heat_Spill_Penalty = [0, 0, 0, 0, 0]  # [£/kWh]
model.Heat_Shedding_Penalty = [5, 5, 5, 5, 5]  # [£/kWh]
```



- **Costs: 24.35 £ (because heat shedding costs, 20 £, during periods 2 and 3)**
- **No electricity export and during periods 2 and 3, also electricity import is needed**