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Rethinking Future Industrial Energy Systems

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Outline

1. Industrial Energy Consumption and Emissions
2. Future Industrial Energy Systems
3. Conceptual Design of Future Industrial Energy Systems
4. Case Study I
5. Energy and Society
6. Case Study II

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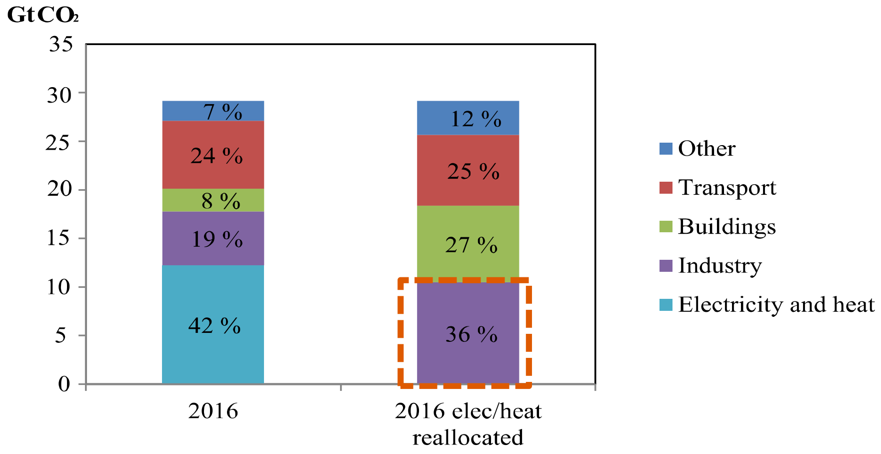
Industrial Emissions

✓ **Industry sector is the largest emitter of CO2 emissions**

In 2016, accounted for:

- 36 % of global GHG emissions

2/3 coming from a small number of **energy intensive industries**



Global CO_2 emissions by sector, 2016 [1]

✓ **Industrial Clusters mission (UK)**

- *Net-zero carbon industrial cluster* by **2040**
- At least one *low-carbon cluster* by **2030**

[1] OECD/IEA (2017). World Energy Outlook 2017.

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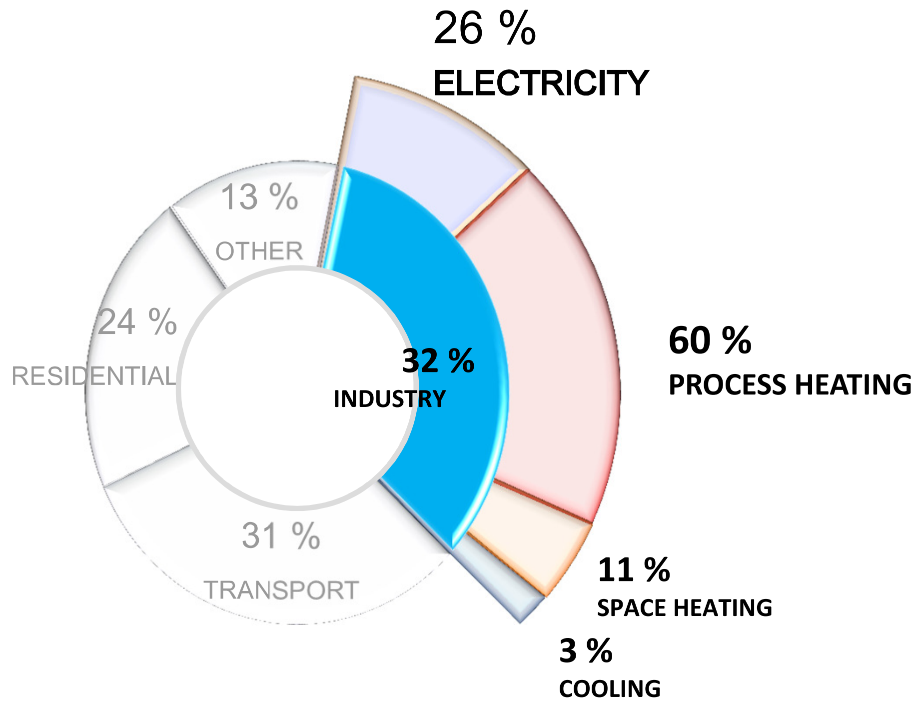
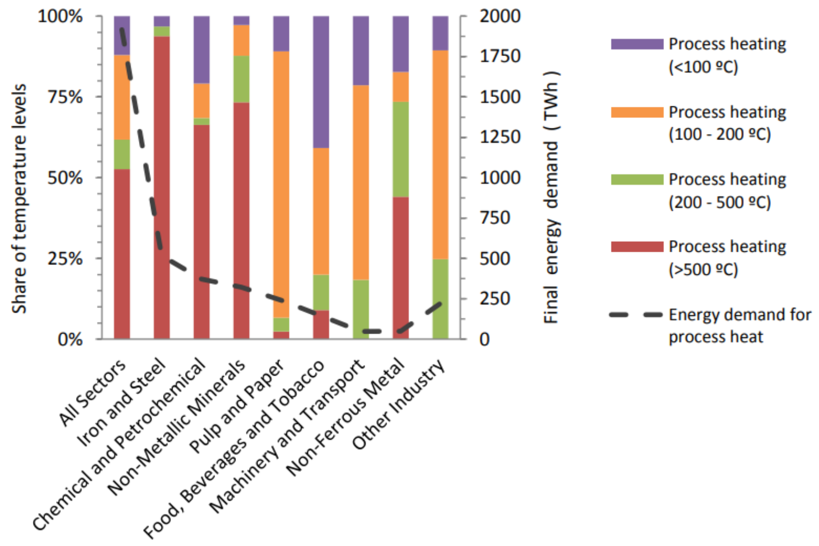
Energy Demand

Industry is the largest consumer of energy worldwide



Share and breakdown of energy demand , 2016 [2]



Energy demand for process heat by industrial sector 2012 [2]

- ✓ 69% of Industrial Emissions are from the Process Industries
  - Accounts for 2/3 of the industrial emissions

➢ **Process heating**

- ✓ ≈ 50% up to 500°C (mostly steam)
- ✓ Media:
  - Fired heat, steam, hot water

[2] OECD/IEA (2017). World Energy Outlook 2017.

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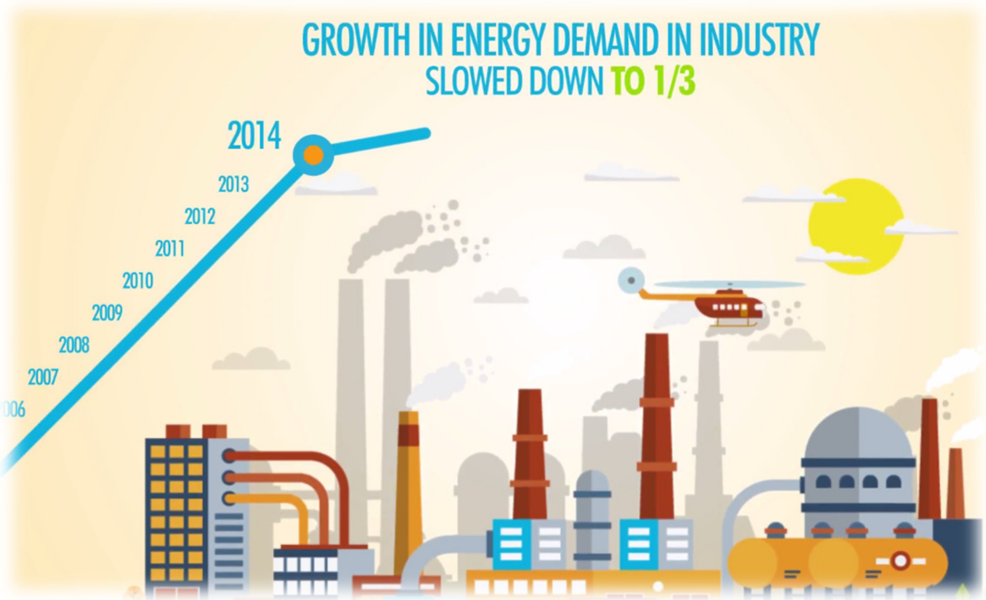
Industrial Energy Systems

Challenge of Global Energy Sustainability



Growth in industrial energy demand through the last years [3]

Energy efficiency first

In 2014, rate of increase of energy demand slowed down to 1/3

Remarkable, *but …*

The consumption will increase by 30% before 2040 [4]

Alone, not enough…

to reduce the increasing demand of fossil fuels and their associated environmental impact

[3] OECD/IEA (2017). World Energy Outlook 2017.

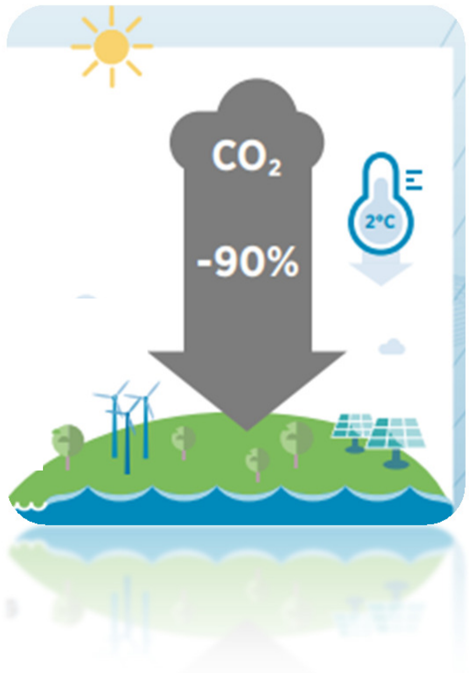
[4] Kempener, R. & Saygin, D. (2014). Renewable Energy in Manufacturing – A technology roadmap for REmap 2030. International Renewable Energy Agency (IRENA).

Industrial Energy Systems

Challenge of Global Energy Sustainability

Switch to **renewables + energy efficiency** is required to achieve:

- **90% of emissions reduction** needed by 2050
- Fulfill **Paris Agreement**
- Keep global temperature rise **below 2 °C**



Trend to move to a more *sustainable basis*

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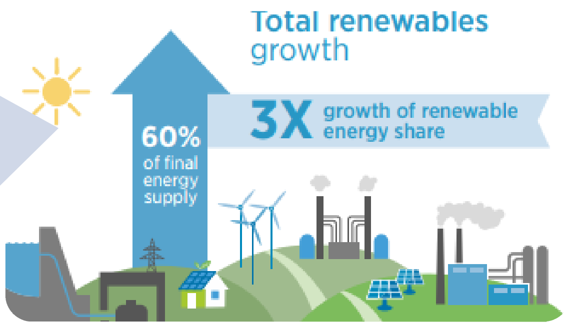
Current Situation

Renewable Energy Growth

Based on current plans and policies



By 2050

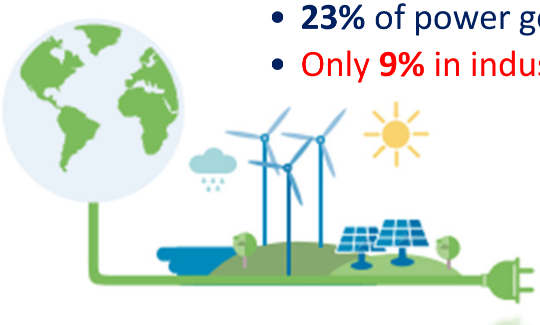
- **23*- 61%** of global energy demand**
- **37*- 82%**** of power generation
- **16*- 39%**** in Industry

By 2030

- **21*- 37%** of global energy demand**
- **13*- 23%**** in Industry

2015

- **19%** of global energy demand
- **23%** of power generation
- Only **9%** in industrial sector



Gives effective de-carbonisation

But..

- Cause frequent fluctuations in power supply
- Require additional electric generation capacity

* Based on current policies of G20 countries
** Accelerated implementation of renewables REmap

[5] IRENA (2017). Global Energy Transition Prospects and the Role of Renewables

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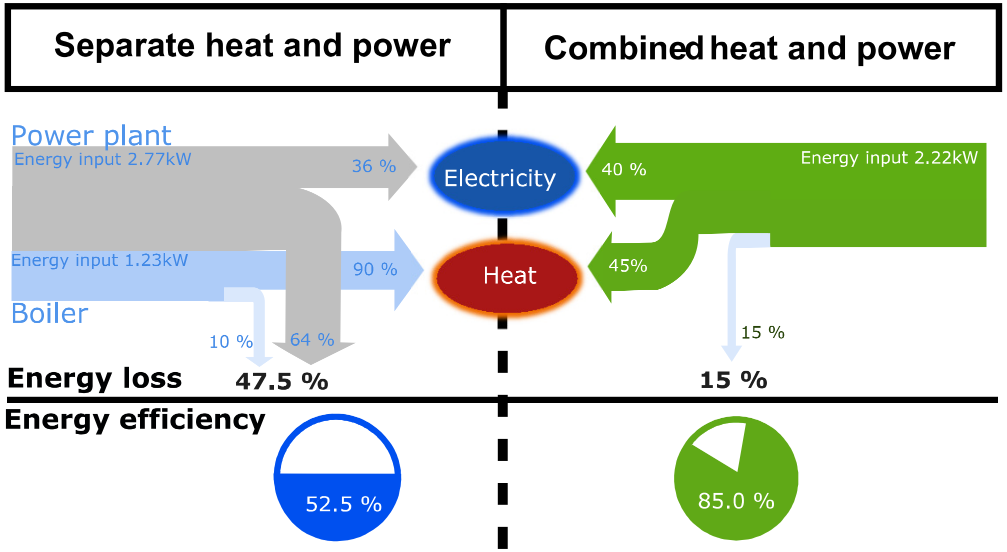
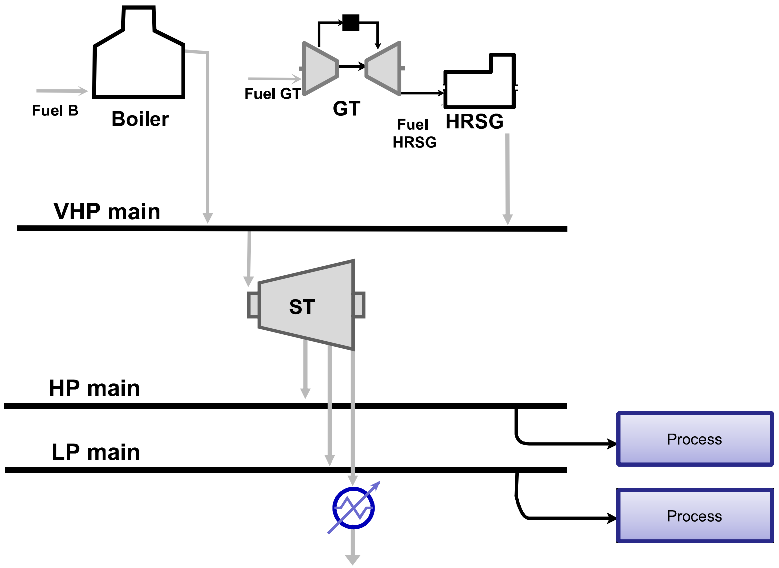
Cogeneration systems





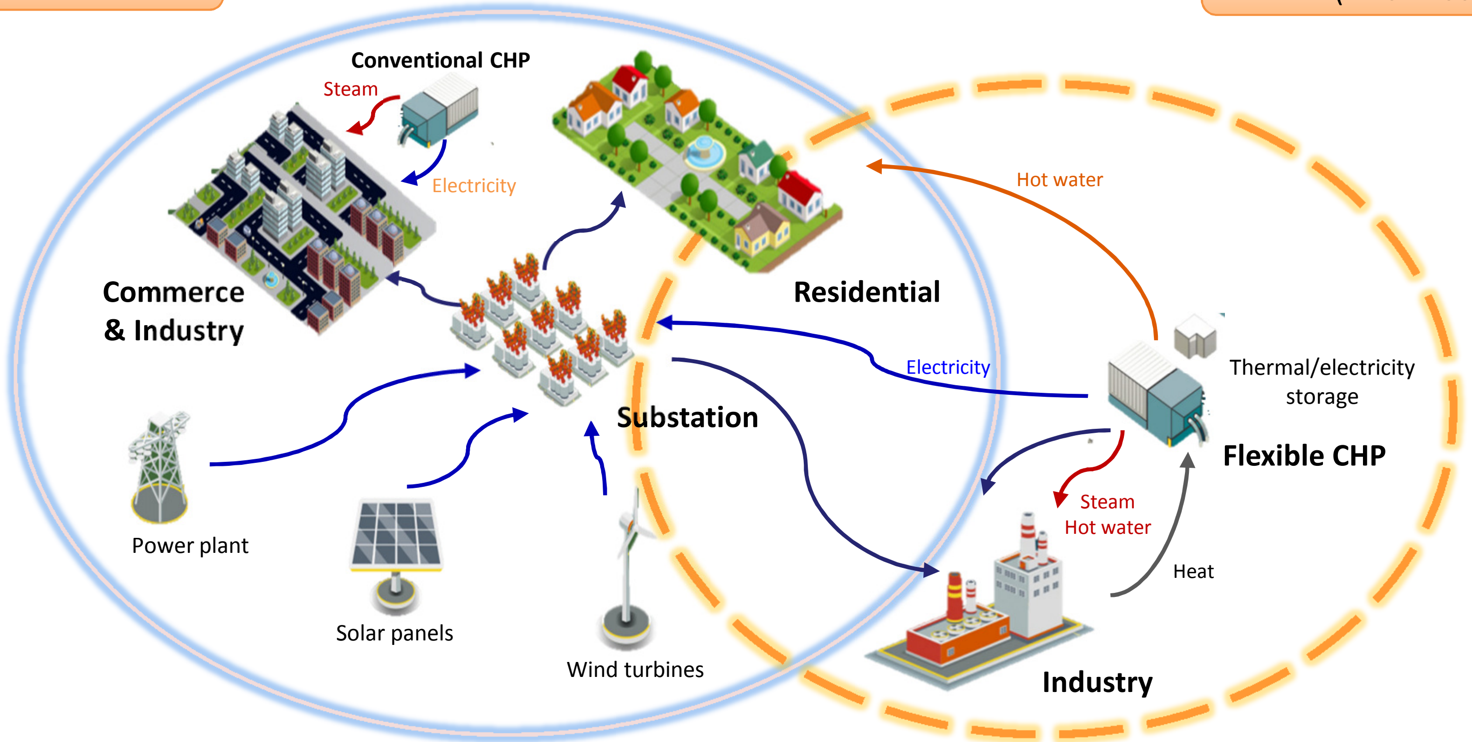
CHP can cut your energy use by more than 40 percent

Flexible CHP Systems

Characteristics

Distributed nature

Provide electricity to the grid (when needed)



Interact with the grid

Flexible CHP System concept [6]

Provide both thermal energy and electricity

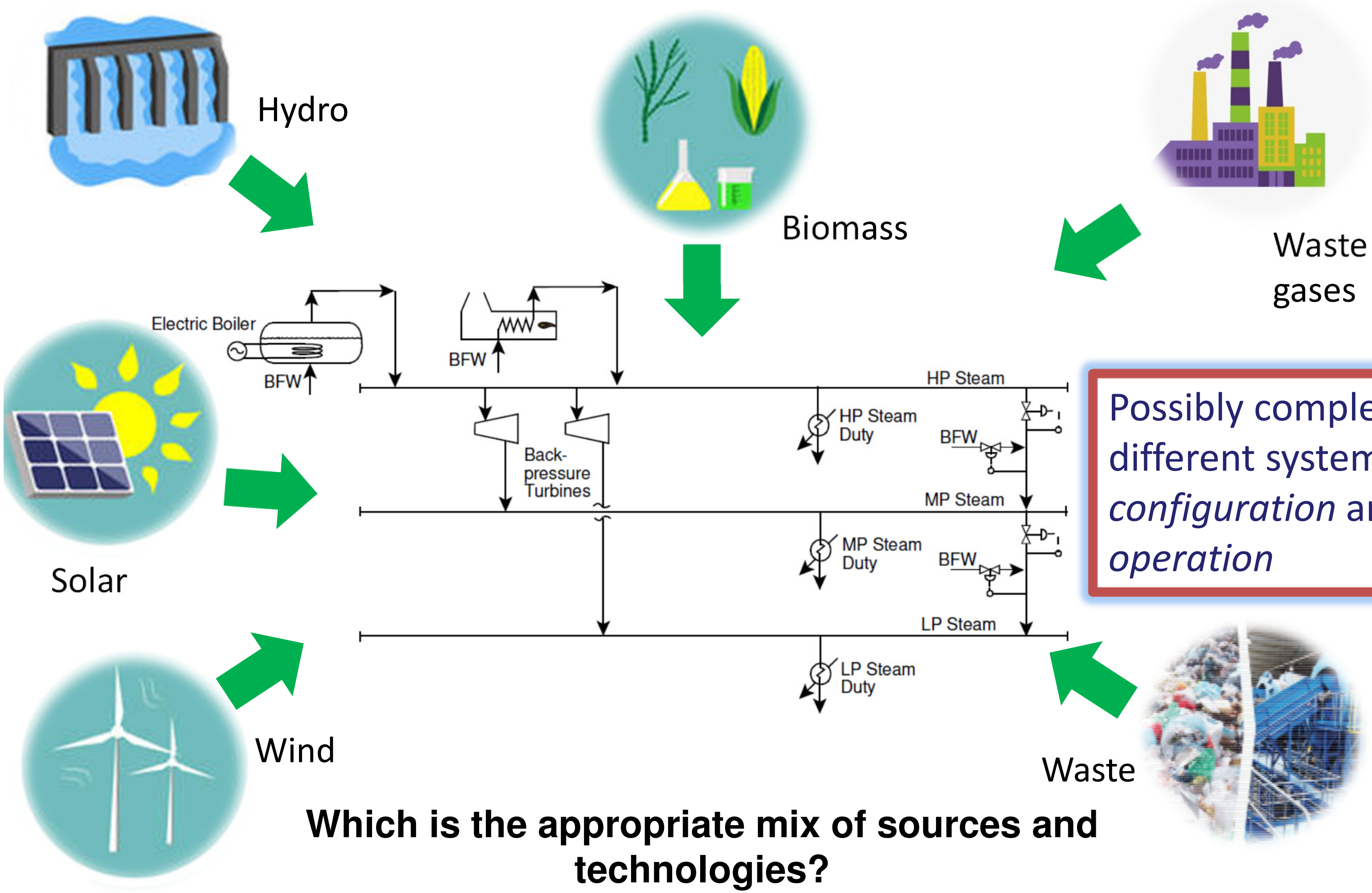
But..

Flexible CHP systems can provide these grid services

but little attention paid so far

[6] U.S. Department of Energy (2018). Flexible Combined Heat and Power (CHP) Systems

Integration of Renewables and Waste in Industrial Systems



Possibly completely different system *configuration* and *operation*

Which is the appropriate mix of sources and technologies?

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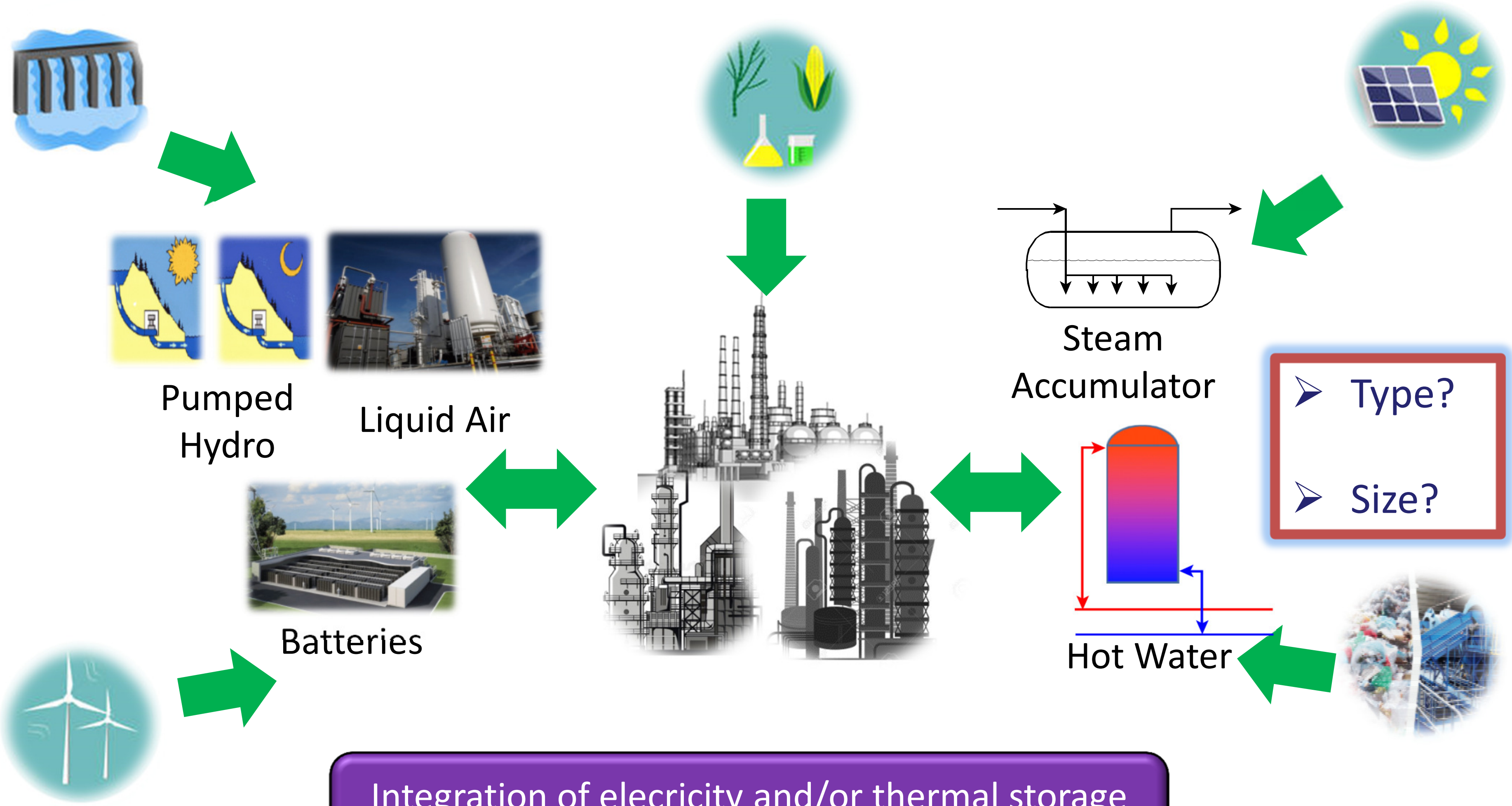
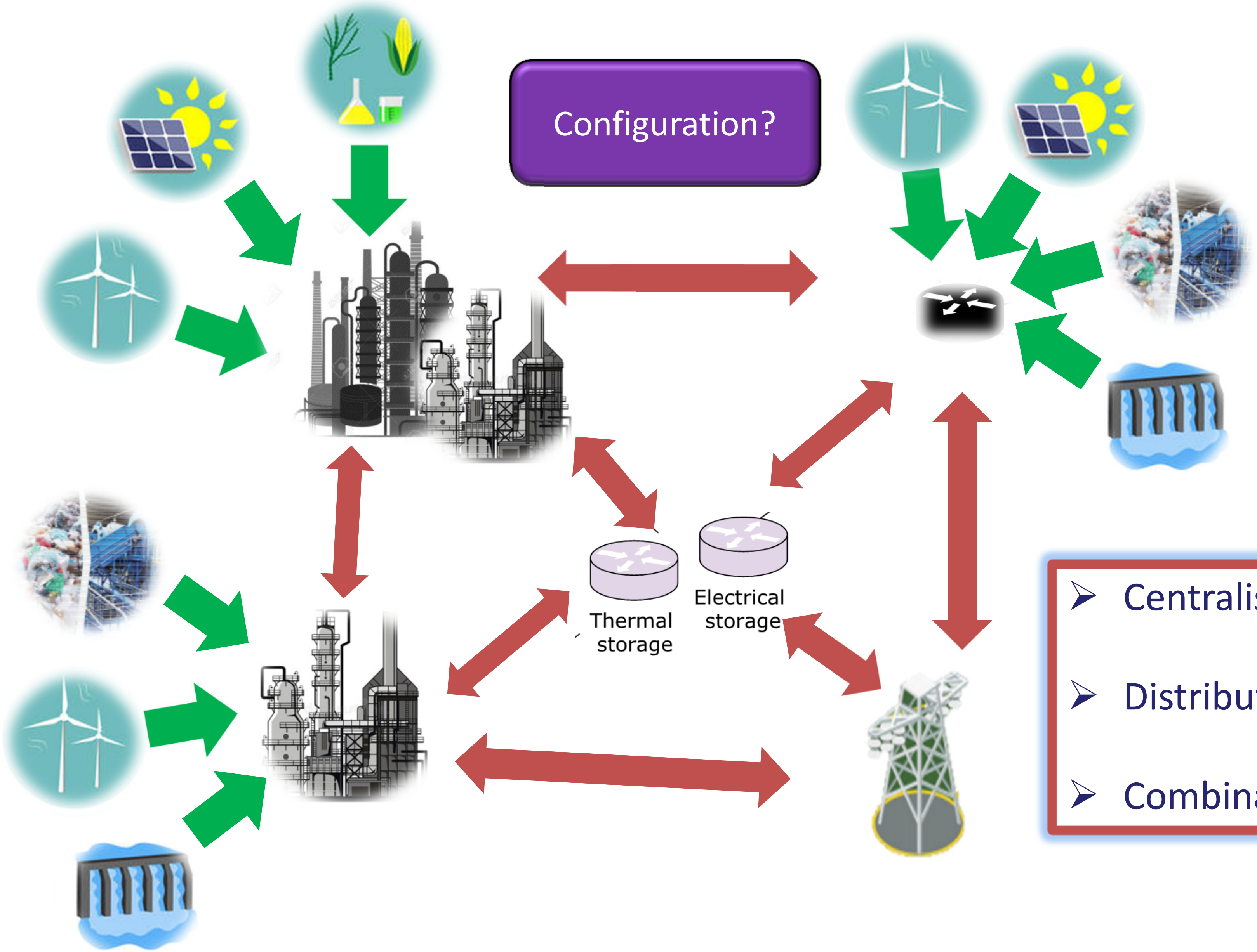
Integration of Energy Storage in Industrial Systems



Integration of elecricity and/or thermal storage storage?

Transition of the Utility System



- Centralised?
- Distributed?
- Combination?

Our Goal

- Fossil and renewable energy sources
- A full range of energy conversion technologies
- Steam and hot water storage
- Power storage

Site heating & cooling profiles →

Site power requirements →

Design and Optimization Framework

→ Design of (distributed) utility system

→ Utility system operating strategy

- Constraints on utility options
- **Time dependency** for utility options
- Life cycle costs
- **Sustainability constraints**

Use framework to develop road maps to **evolve** existing systems to future demands with a **sustainable basis**

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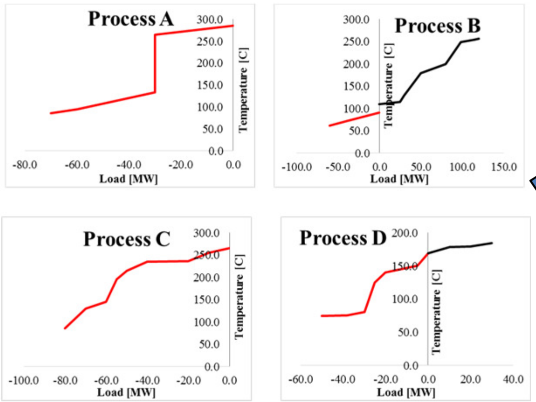
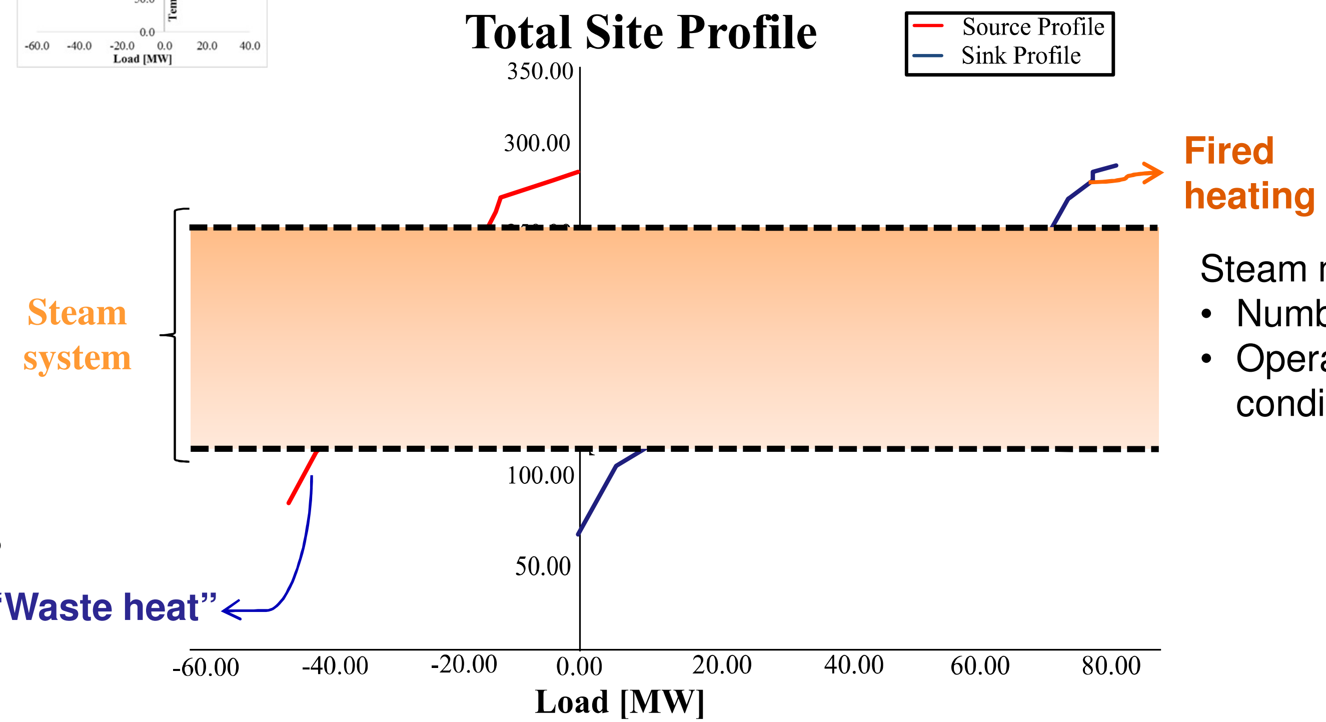
Utility System Components

Multiple Processes





Equipment

- type?
- fuel?
- size?
- load?

Cooling water ?
ORC ?
Hot water?

Furnace?
Hot oil circuit?

Steam mains

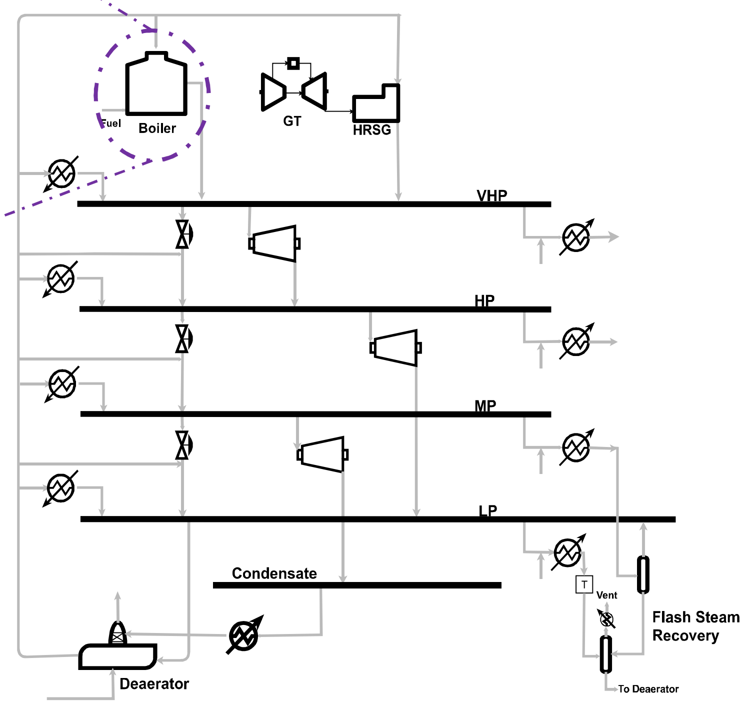
- Number?
- Operating conditions?

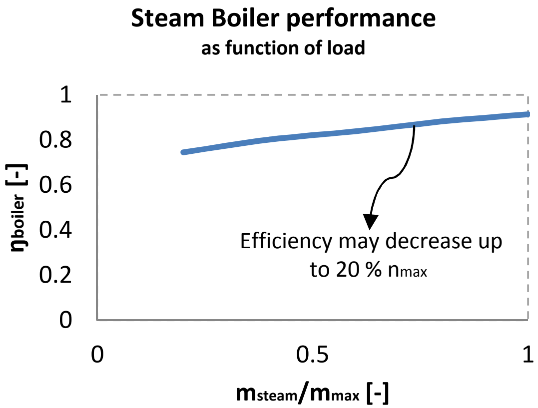
Modelling Utility System Components

Degrees of Freedom

Boilers

- Type of boilers
  Electric boilers,
  Biomass boilers,
  Waste heat recovery boilers
- Type of fuels
  Bio fuels, waste gases,
  natural gas, mixture
- Operating conditions
  Temperature, pressure
- Size, load





Models need to capture the effect of the **load** on the ***efficiency***

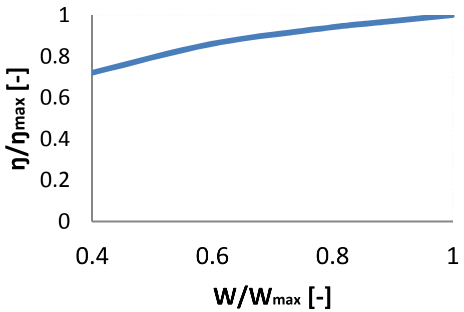
Modelling Utility Systems Components

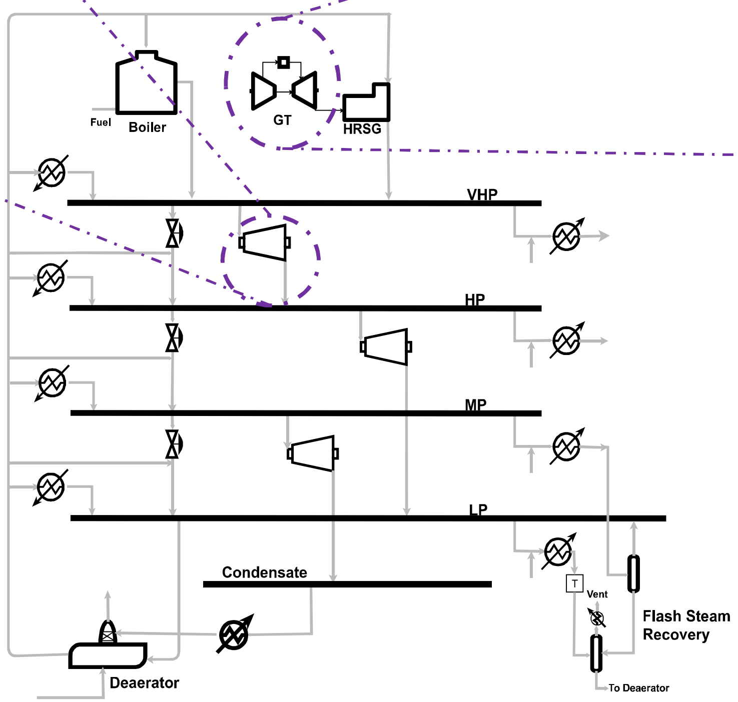
Degrees of Freedom

Steam Turbines

- Type
  (Condensing turbine,
  BP turbine, extracting turbine)
- Size, load
- Inlet and outlet conditions (T and P)

Steam turbine performance
as function of load

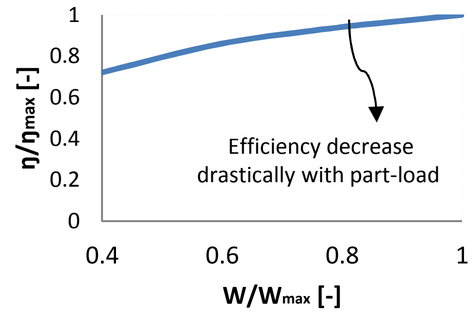




Gas Turbines

- Type of equipment
  (Industrial, Aero-derivative)
- Type of fuels -> NHV
  (Natural gas, syngas)
- Size, load

Gas turbine performance
as function of load



Modelling Utility Systems Components

Flexibility at the Design Stage

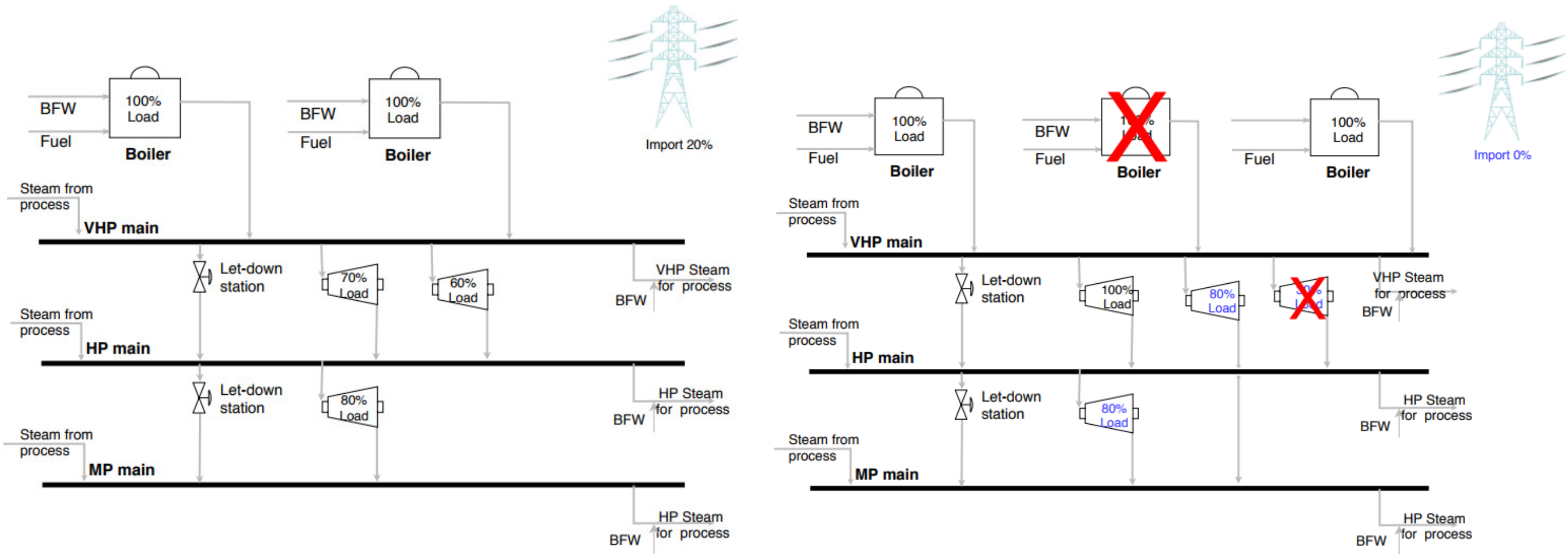
Number and Size of Units

Large units at part-load operation during most of the time – **Active redundancy**

or…

Several small units at full-load, one switched off – **Passive redundancy**

- Bigger size → more efficient ***but…*** partial-load → less efficient
- Fewer units → less expensive ***but…*** fewer units → less reliable



Modelling Utility Systems Components

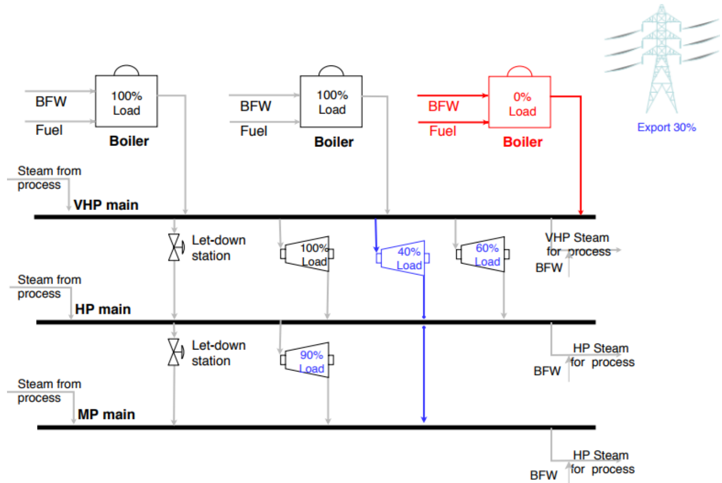
Flexibility at the Design Stage

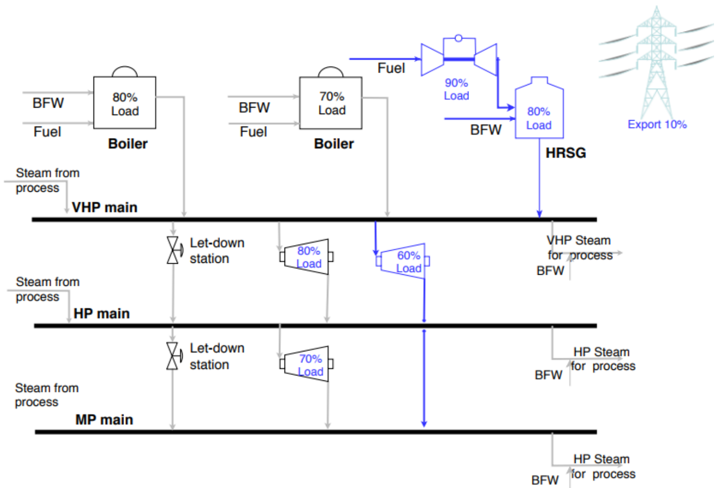
Type of Units

More units of the same type

or…

More units of the different types, but performing the same function





- Multiple design and operational degrees of freedom

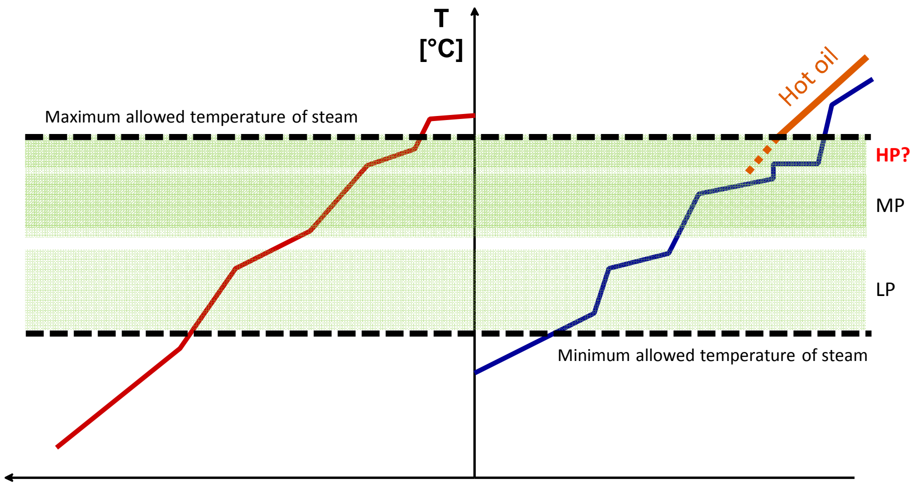
- Variables highly interrelated

Complex optimization

Process Integration in Utility Systems

Steam System

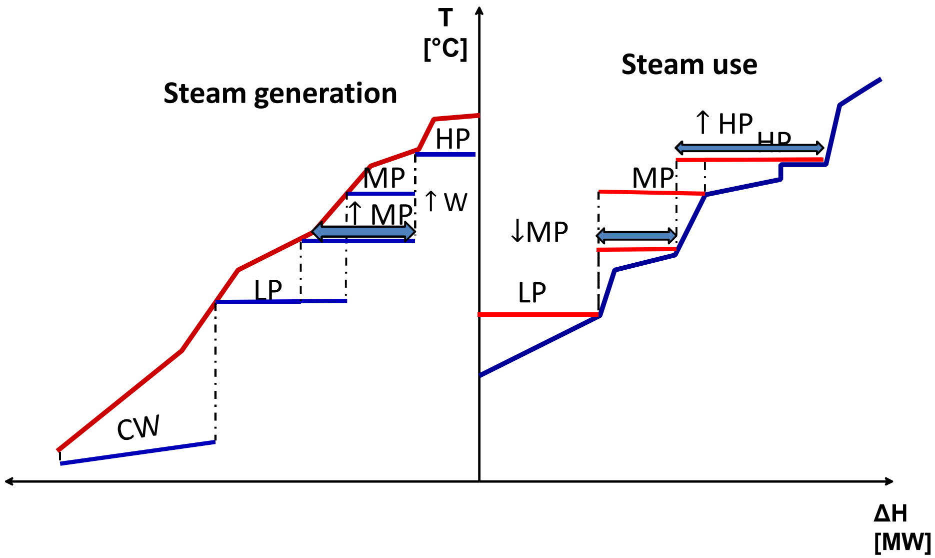
➢ **Steam mains**



Do we have the correct number of steam mains?

Do we have our steam mains at the correct pressure?

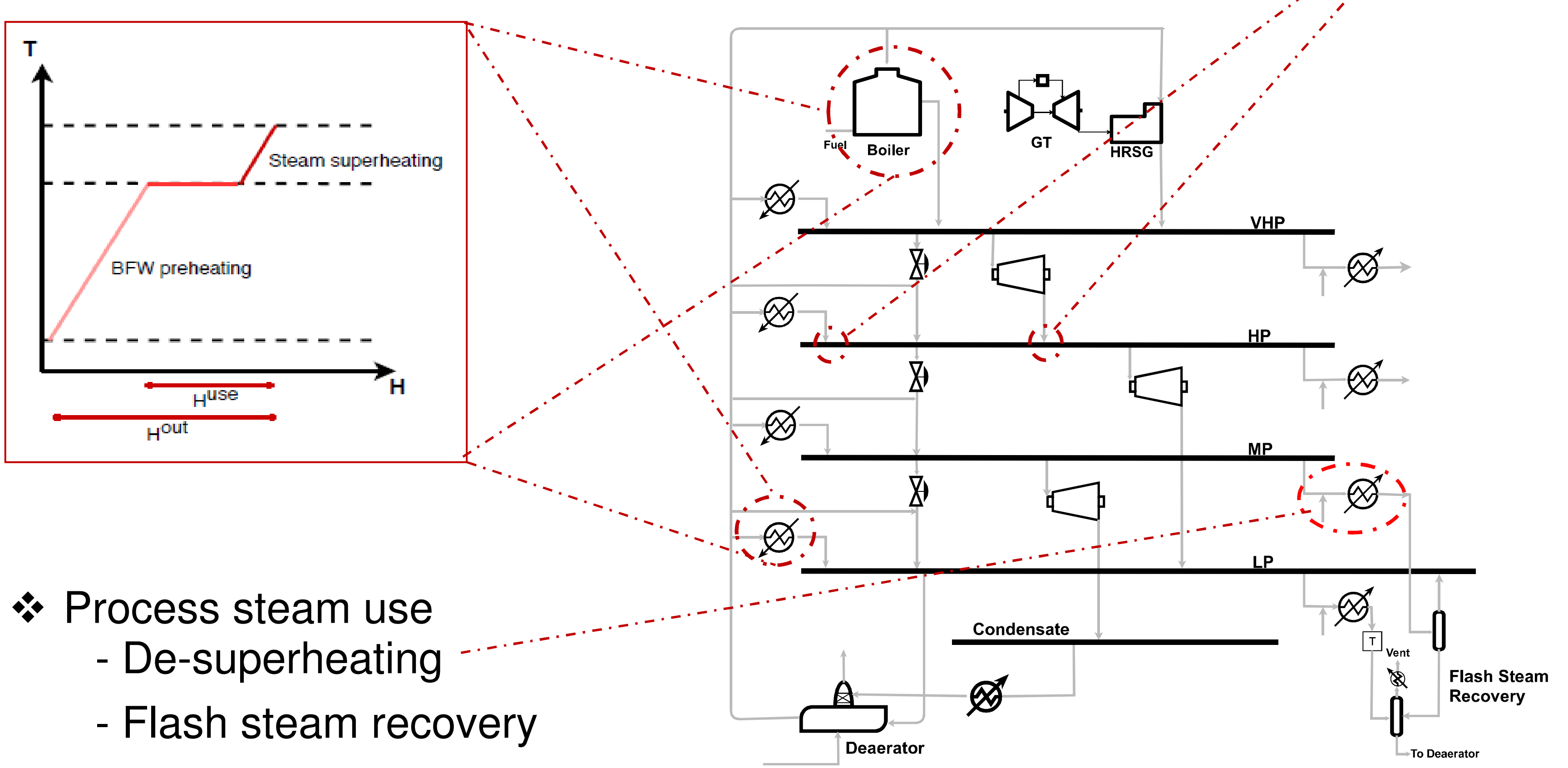
At saturated conditions?



Process Integration in Utility Systems

Steam System

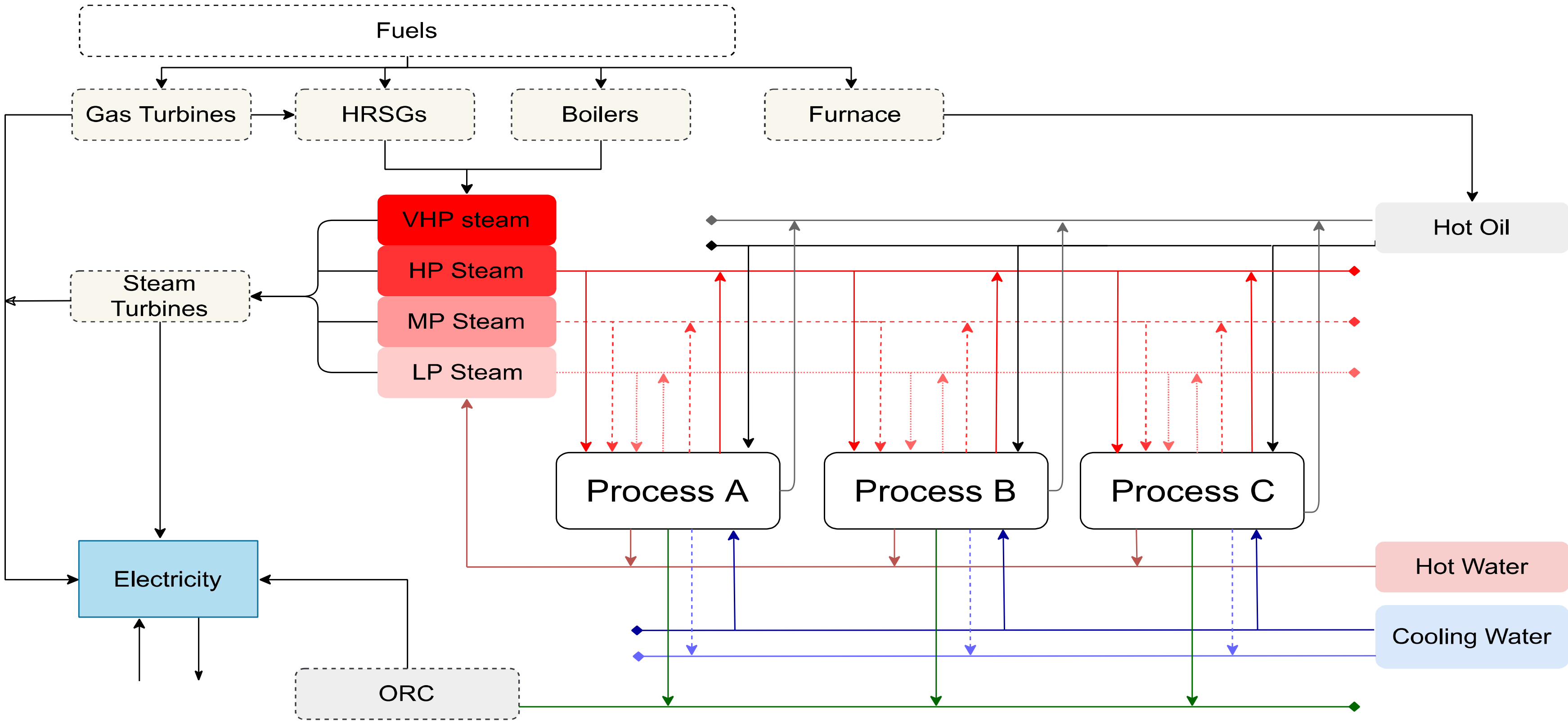
- ❖ Steam generation
  - Synthesis methods have previously only included the latent heat
  - Must include BFW preheating and superheating
- ❖ Non-isothermal mixing



- ❖ Process steam use
  - De-superheating
  - Flash steam recovery

Process Integration in Utility Systems

System Structure



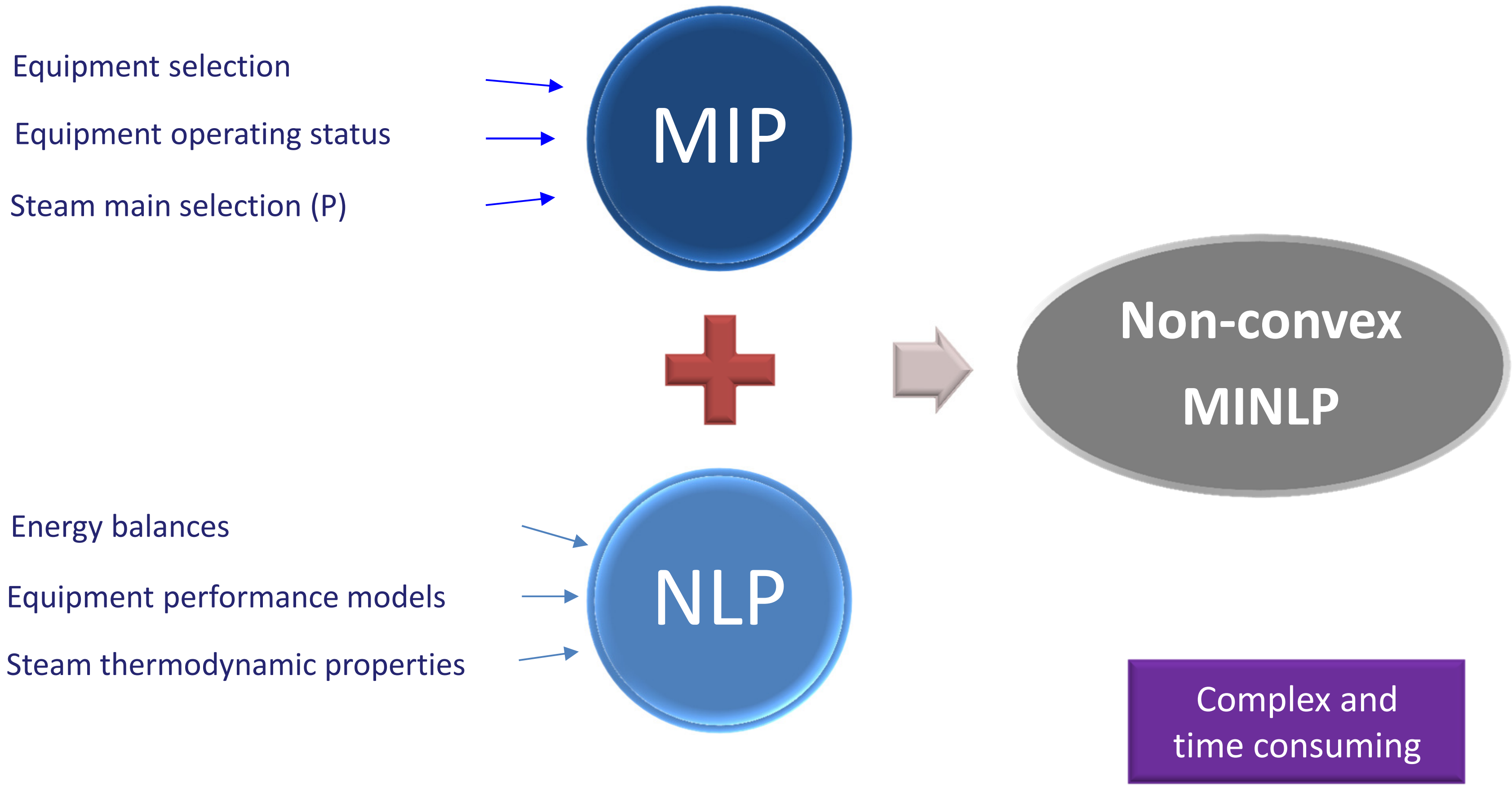
Optimize a superstructure including all structural options to obtain an energy system structure and optimum conditions

Process Integration in Utility Systems

Optimization

Problem Formulation

Utility system design with optimal steam main operating conditions involves:



Variation with time

Previously, the designs were based on **<u>nominal operating conditions</u>** of each process

BUT…

In the reality, operating conditions and the environmental conditions will **<u>vary significantly through time</u>**

Yearly mean demand →

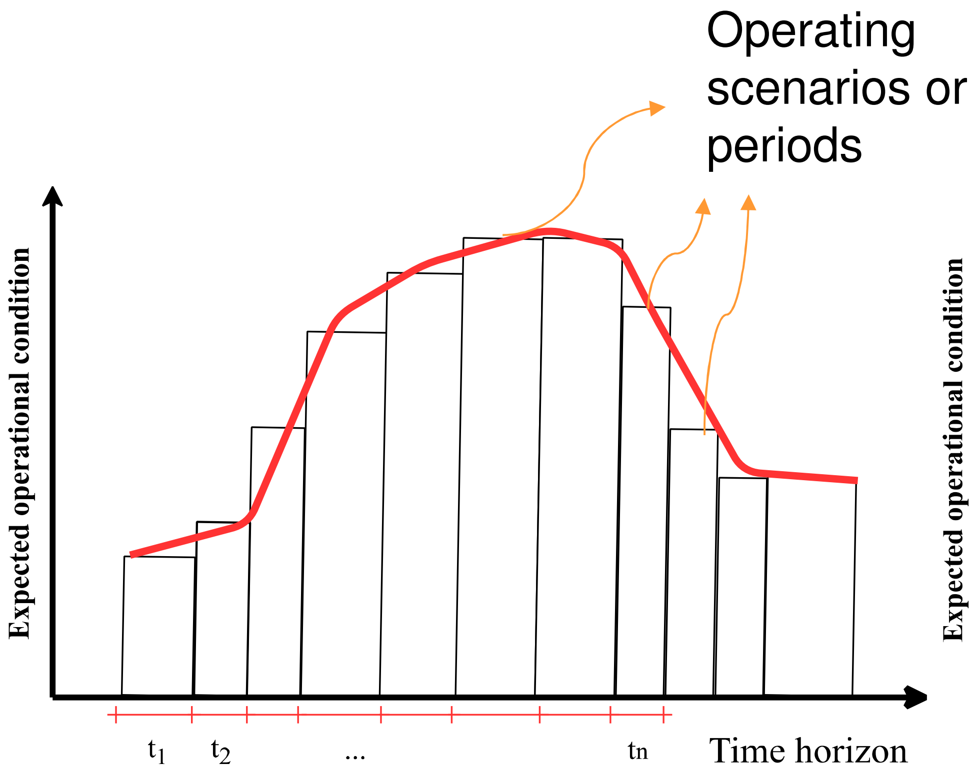
- May lead to suboptimal solutions (if they are feasible)
- Inaccurate economic evaluation

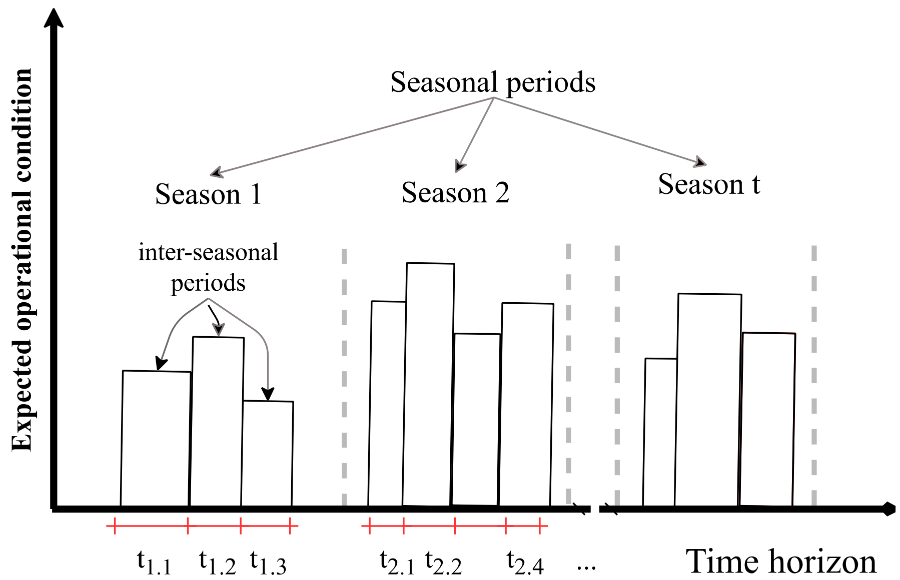
Variable demand →

- More resilient design but much more complex problem

Variation with time

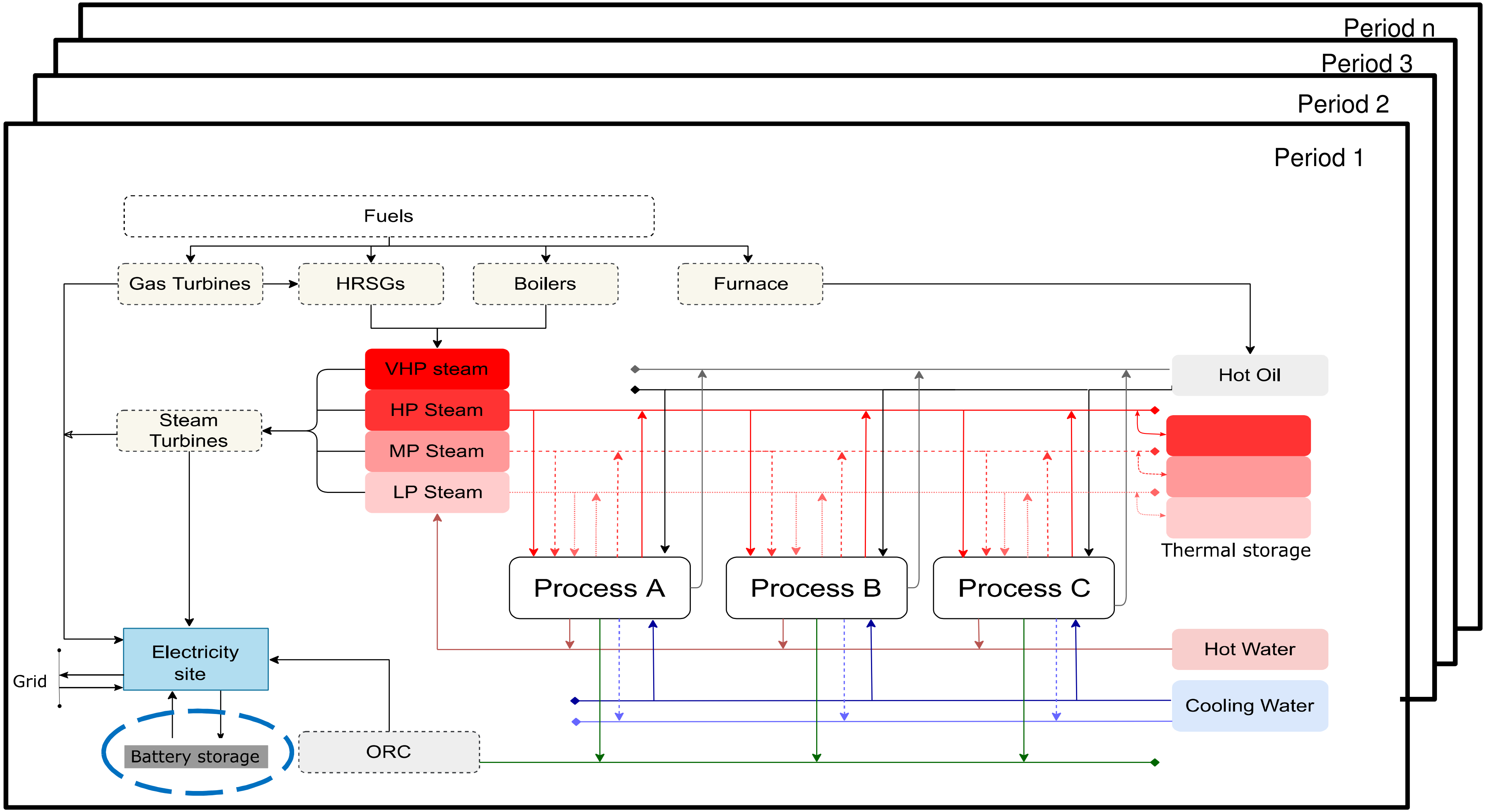
Multi-period approach





Various scenarios to represent different operating scenarios

Variation with time

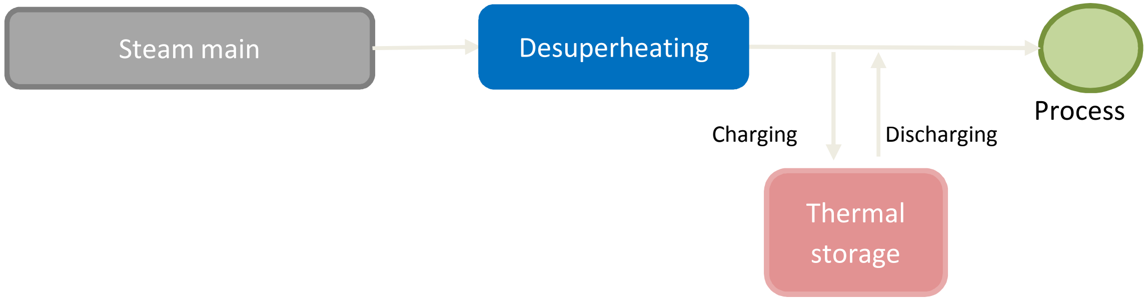


Synthesis of utility systems accounting for energy demand variation

Integration of Energy Storage

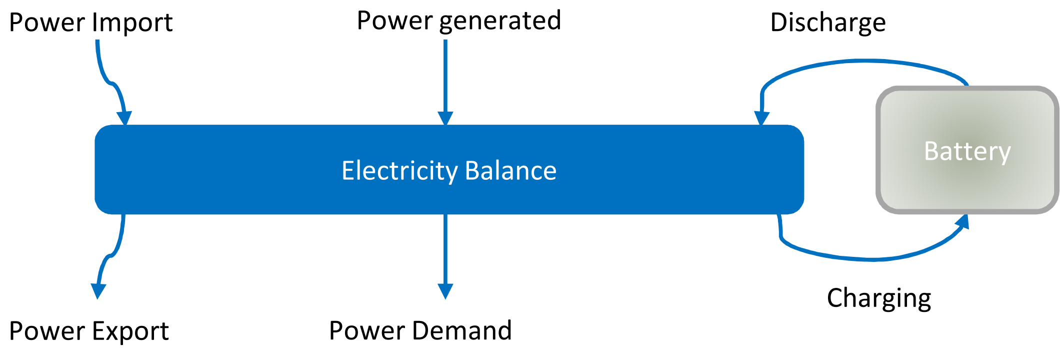
Thermal storage

- For steam:
  - Steam accumulators
  - Short-term storage (days)



Battery storage

- Different kind of batteries:
  - Li-ion
  - NaS
  - Lead-Acid
- Different efficiencies and costs
- Short-term storage (up to a week)



Methodology Overview

Optimisation

Decomposition

Two different approaches to the optimisation

	sMILP	Two-stage
Description	Sequence of MILP optimisation and simulation stages.	Master problem (rMINLP) followed by a non-linear sub problem
CPU time	Fastest (< 500 s)	Faster that commercial global solvers (< 1000 s) - BARON 10 times slower
Global optimality	Cannot be guaranteed	Guaranteed

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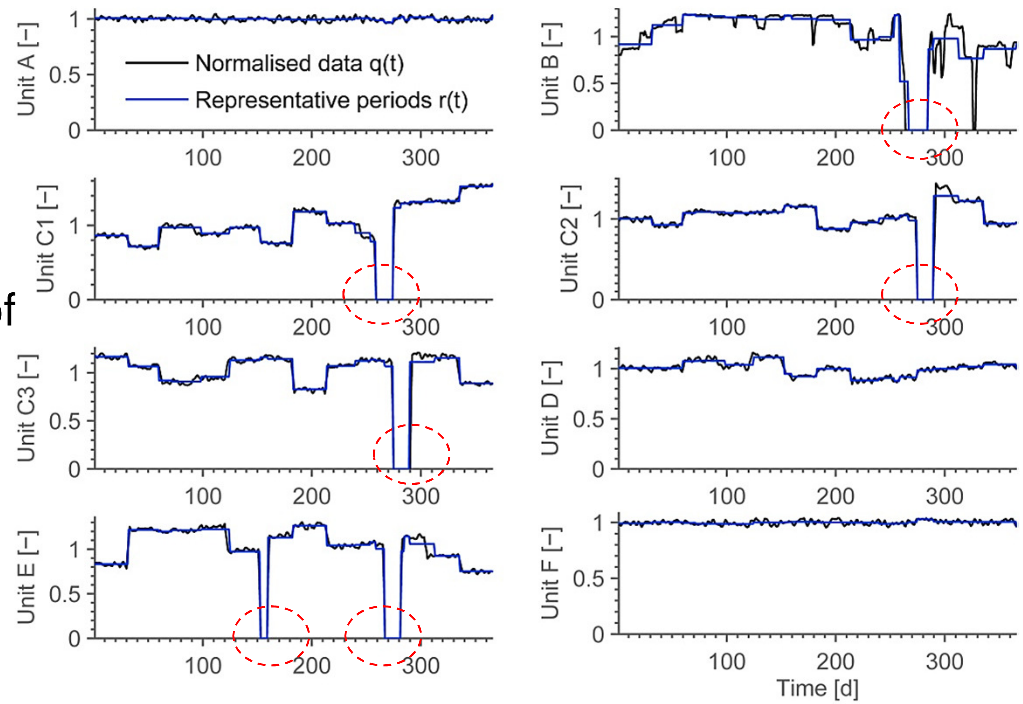
Case Study I

Demand Variation

Background

- A 6-plant chemical cluster
- Utility system to satisfy site thermal and electrical demand
- Electricity price fluctuations
- Semi-continuous processes
- Variation in the production profiles of the different units (including maintenance/shut down)



Production profiles of an Industrial Chemical Cluster across a year [7]

Constraints

- Utility temperature constraints.
- Equipment load and size.
- Max electricity import 1 MW
- Max electricity export 10 MW

[7] Bungener S., Hackl R., Eetvelde G.V., Harvey S., Marechal F. (2015) Multi-period analysis of heat integration measures in industrial clusters. Energy93 220-234

Case Study I

Design assumptions

Fuels price assumed to be constant across the year

Electricity price fluctuations:

- Across the day
  off-peak, peak and base
- Across the year
  winter, summer and mid-season

Variation of Industrial annual energy demand:

- Clustered in 20 periods in total each with 3 tariffs

Total periods: 60

2 scenarios are studied in order to analyse the effect of energy demand variation

Case	Considerations	Objective Function
Case A	Variable energy demand	TAC
Case B	Variable energy demand	CO_2 emissions

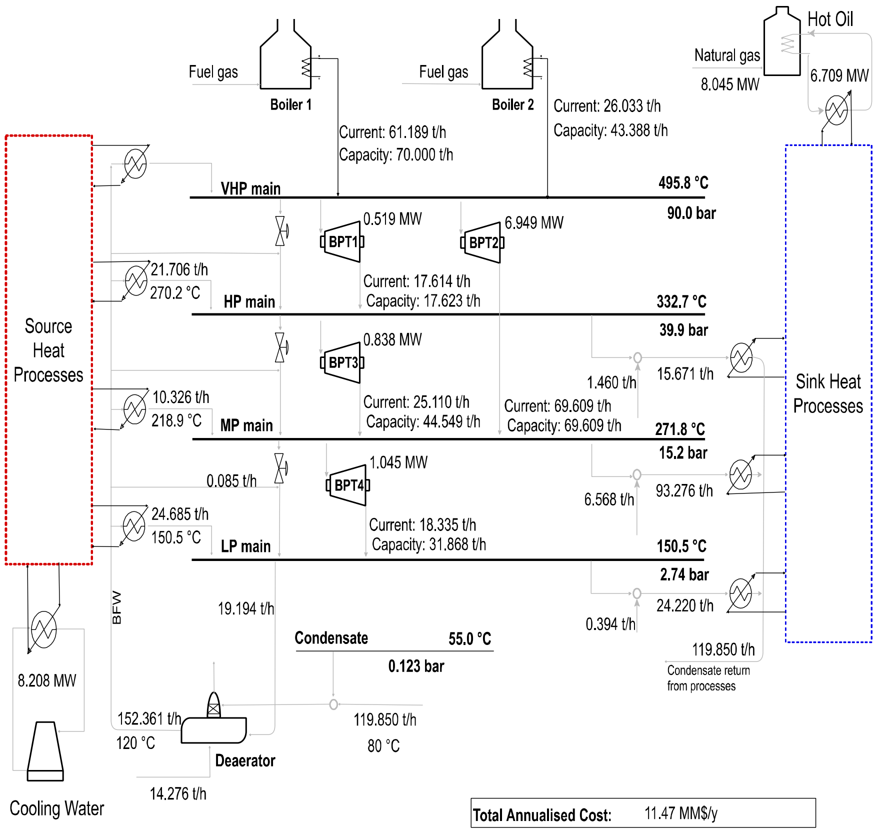
Electricity prices*	Off-Peak	Peak
Summer		
purchase (£/MWhel)	111.4	127.2
sale (£/MWhel)	81.7	96.4
Mid-season		
purchase (£/MWhel)	111.4	127.2
sale (£/MWhel)	81.7	96.4
Winter		
purchase (£/MWhel)	111.4	127.2
sale (£/MWhel)	81.7	96.4

*The consumed electricity, both purchased and produced, is subject to an excise tax which is calculated iteratively based on monthly consumption thresholds according to Testo Unico (2012).

Emissions factors [t CO_2/MWh]	
Grid	0.308
Fuel gas	0.485
Natural gas	0.331

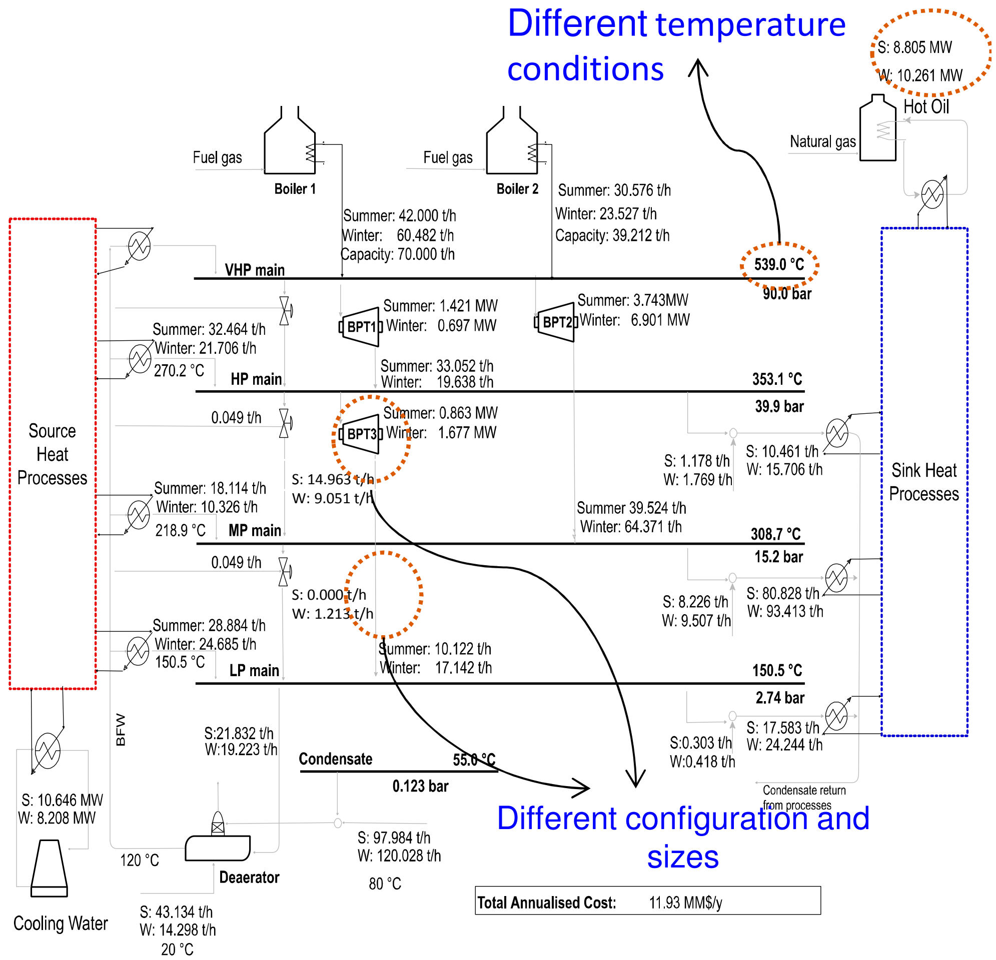
Case A: Variable Energy Demand

Comparison of the designs



Optimal design configuration

– nominal



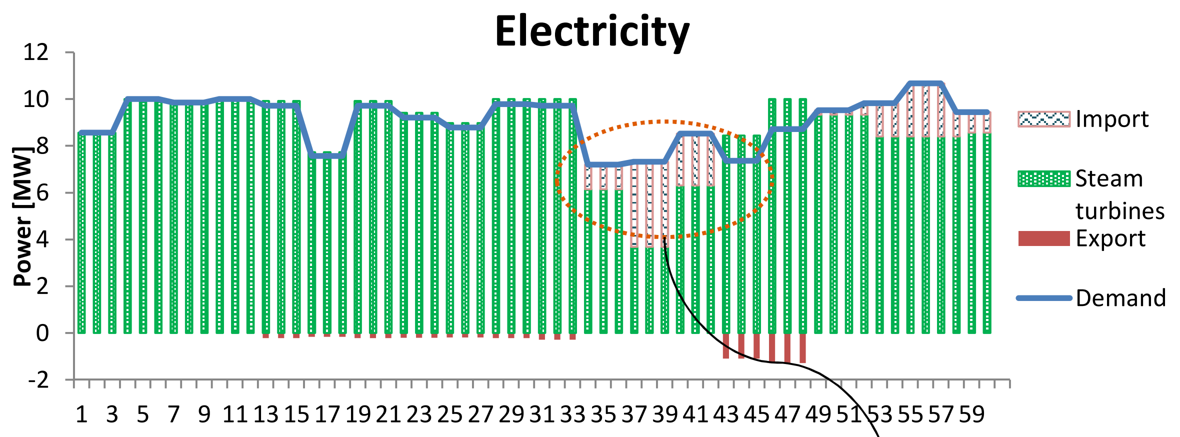
Optimal design configuration

– variable demand

Case A: Variable Energy Demand

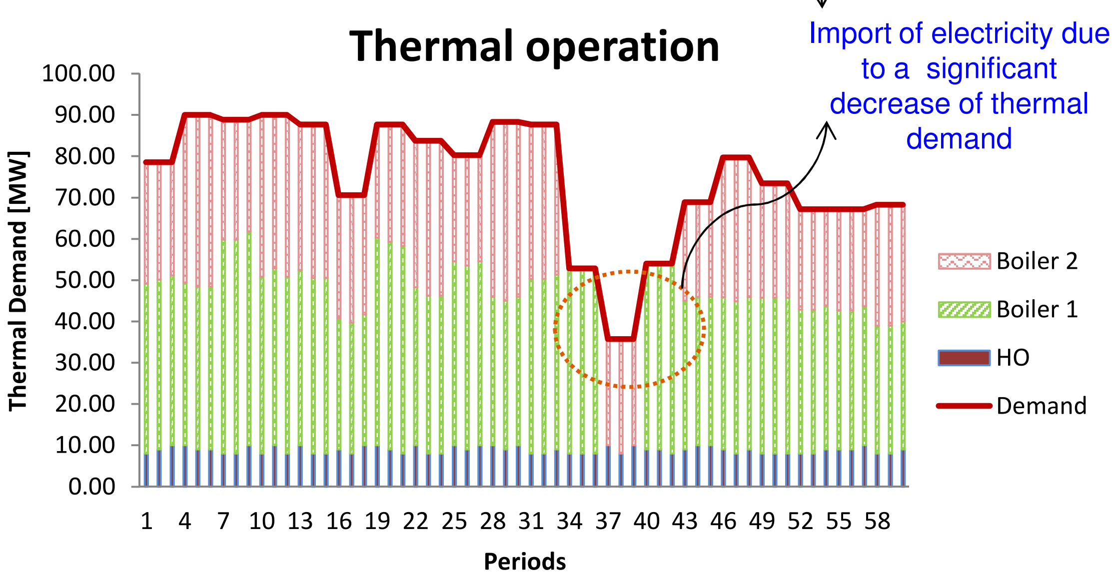
Electrical Operation

- Negative values represent export
- Electricity demand satisfied by 4 steam turbines



Thermal Operation

- Thermal demand satisfied by 2 boilers, and a hot oil circuit



Energy storage is not selected.

Design of a **flexible utility system** ***operating at optimal conditions*** may be more beneficial than including energy storage.

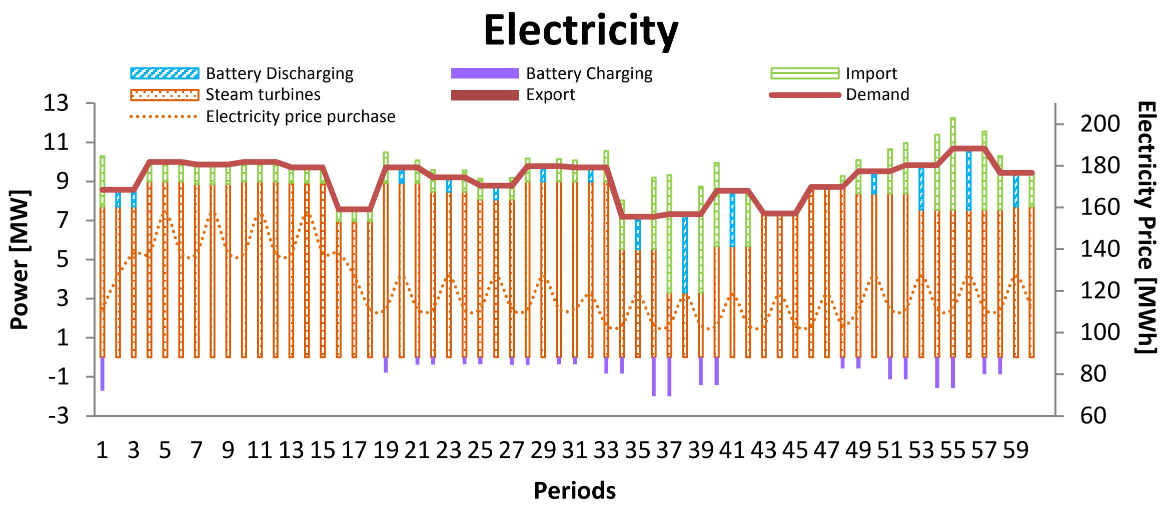
Case A: Variable Energy Demand Sensitivity Analysis

Difference Between Peak and Off-peak Electricity	40%	60%	80%	100%	230%
TAC (mm£/y)	13.81	13.92	14.04	14.14	14.24
Operating cost (mm£/y)	7.99	7.29	7.35	7.45	7.64
Capital cost (mm£/y)	6.81	6.63	6.69	6.58	6.60
Battery Capacity (MWh)	0.00	0.00	0.00	0.00	4.00

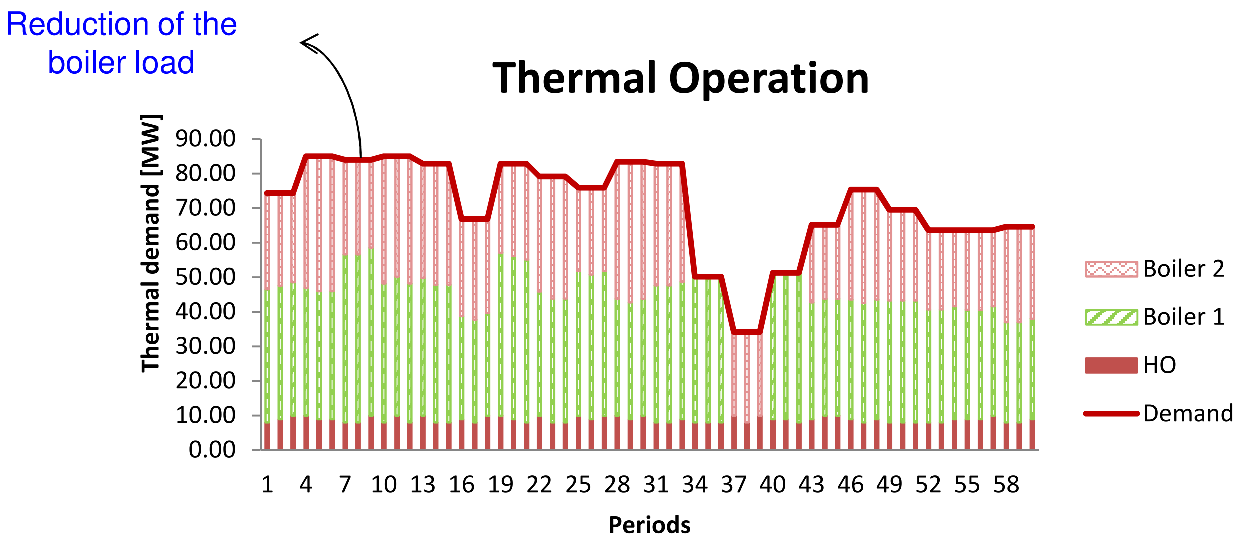
- Lead battery storage becomes economic when the difference between off-peak and peak prices of electricity is 2.3 times higher
- An analysis based on the spot market price of electricity price is recommended, to explore potential benefits of greater interaction with the grid (and a higher energy price fluctuation)

Case B: Minimum CO_2 Emissions

- Electricity import is favoured due to lower CO_2 emission factor of the grid



- Further analysis of trade-off between reduction of CO2 emissions and minimum TAC cost should be carried out



Energy storage becomes economically attractive when decarbonisation takes over TAC as objective function

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Case Study Summary

Case	Base Case	Case A	Case C
Objective function	min TAC	min TAC	min CO_2 emissions
Electricity price variation	N/A	-	-
Operating costs [m£/y]	6.64	6.80	9.65
Capital costs [m£/y]	4.83	5.13	8.70
CO_2 emissions [t/y]	153,866	138,855	**108,247**
TAC [m£/y]	11.47	11.93	**18.35**

- Utility system design based on nominal consumptions may lead to a lower capital cost. However, its energy efficiency is lower, leading to higher GHG emissions.

- Based on the current energy prices (fluctuations) and for a **grassroots design**, it is cheaper to alter the use of utility system components rather than incorporate energy storage.

- At significant fluctuations in electricity price, energy storage implementation has the potential to reduce the TAC cost of the utility system.

- Electricity storage has the potential to reduce the CO2 emissions of the utility system. However, there is a trade-off with the TAC required for that system.

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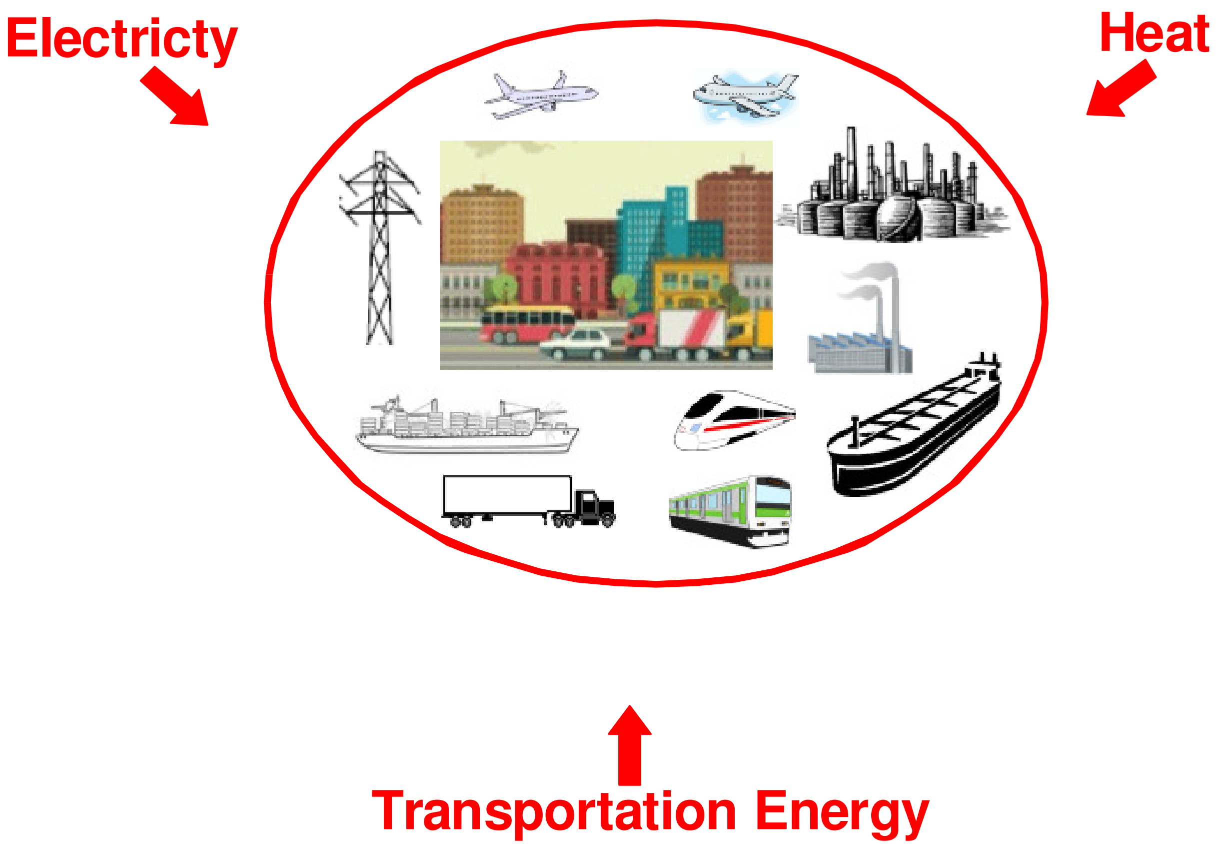
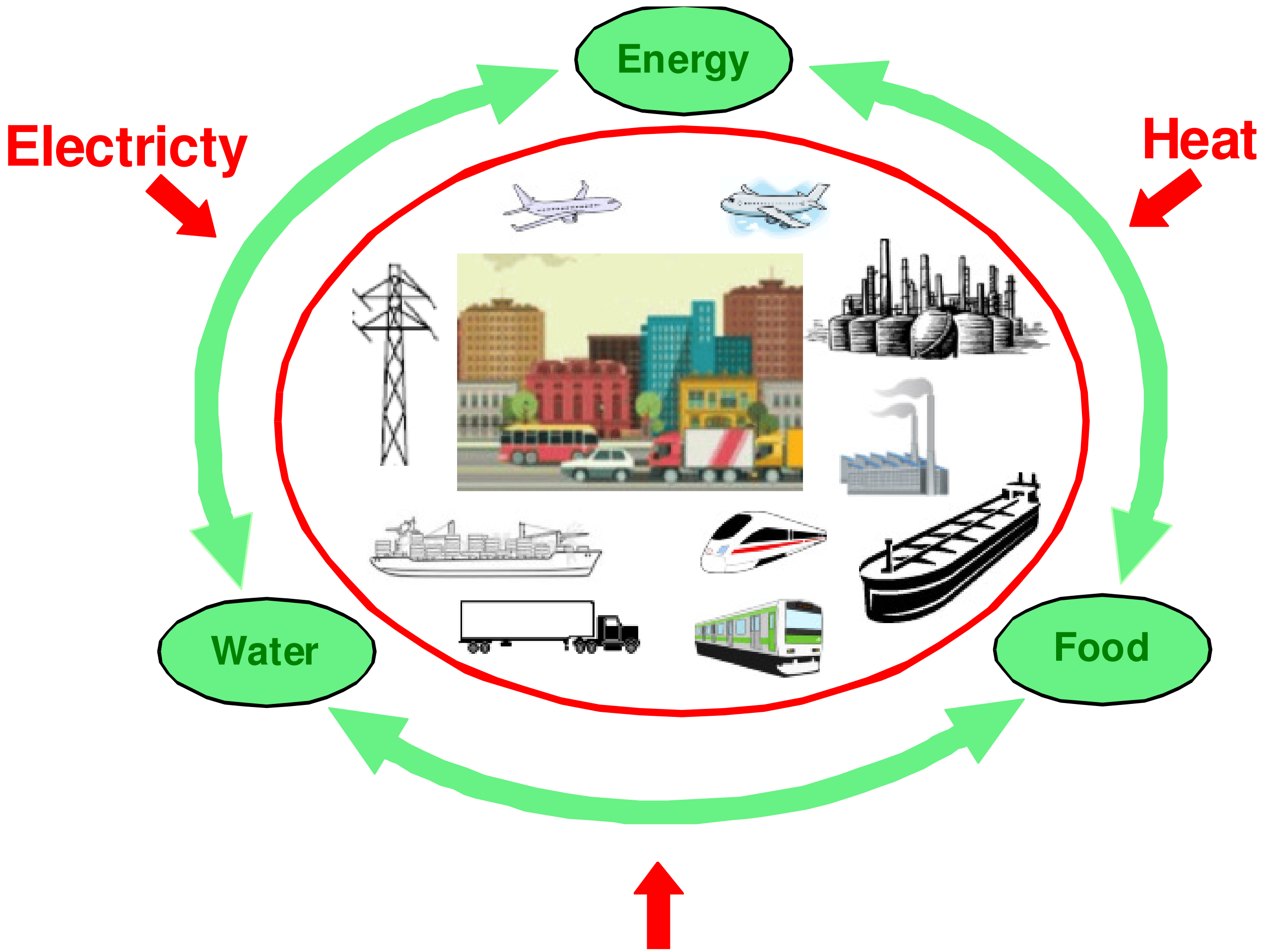
Energy and Society



- Society needs energy in the form of electricity, heat and transportation energy
- Supply of these needs has traditionally not been integrated

Energy and Society



Transportation Energy

BUT, this needs to be considered in the context of the

Energy-Food-Water Nexus

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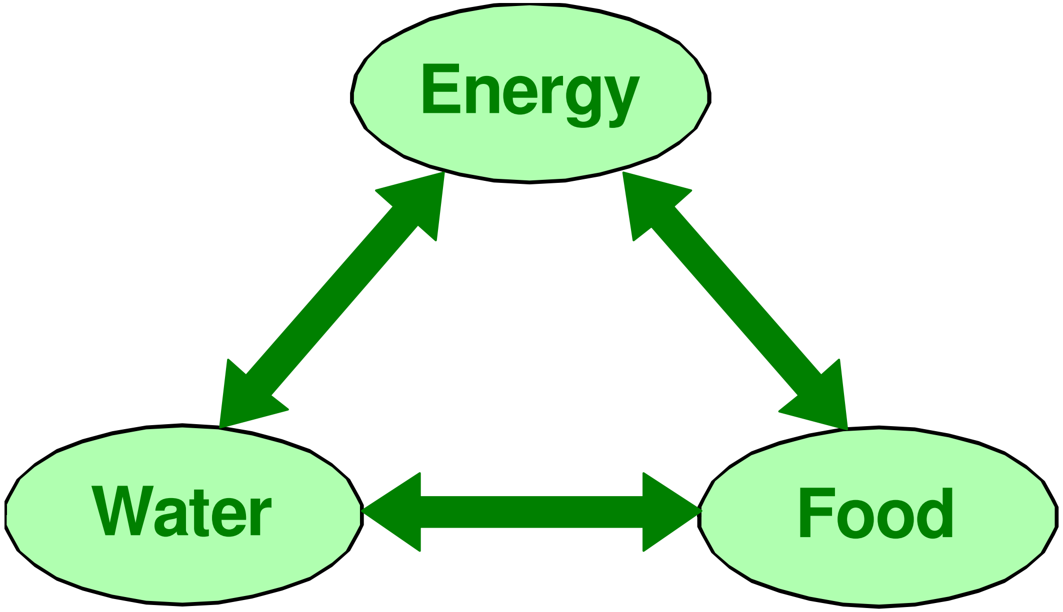
Energy-Water-Food Nexus

- Electricity generation consumes some 15% of global freshwater water withdrawals
- 18% of global energy is consumed for water extraction, treatment and distribution
- Food production accounts for 70% of water withdrawals and 30% of energy consumption globally
- These interrelationships among the energy, food and water (EFW) systems are known as the EFW nexus

1. International Energy Agency (2001). Water for Energy. www.worldenergyoutlook.org/resources/water-energynexus.
2. FAO (2011a) The state of the world's land and water resources for food and agriculture – Managing systems at risk. Food and Agriculture Organization of the United Nations, Rome and Earthscan, London.
3. FAO (2011b) Energy-smart for people and climate - Issue paper. Food and Agriculture Organization of the United Nations, Rome.

Energy-Water-Food Nexus



The security of the Energy-Water-Food nexus is a central challenge to the goal of sustainable development

Demand Reduction

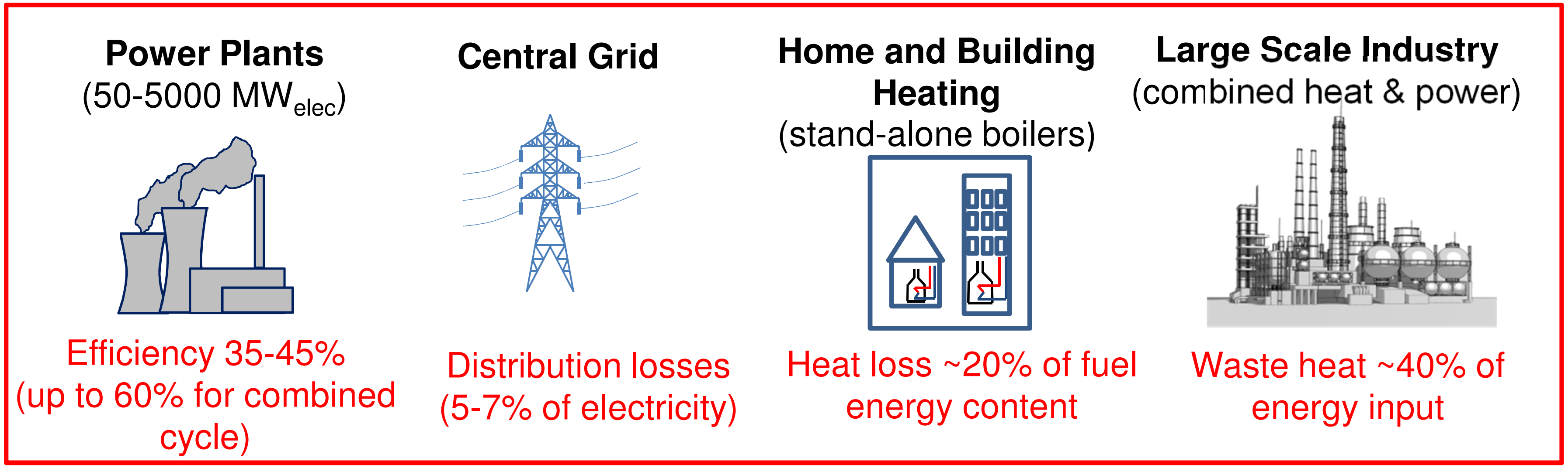
Domestic

Commercial

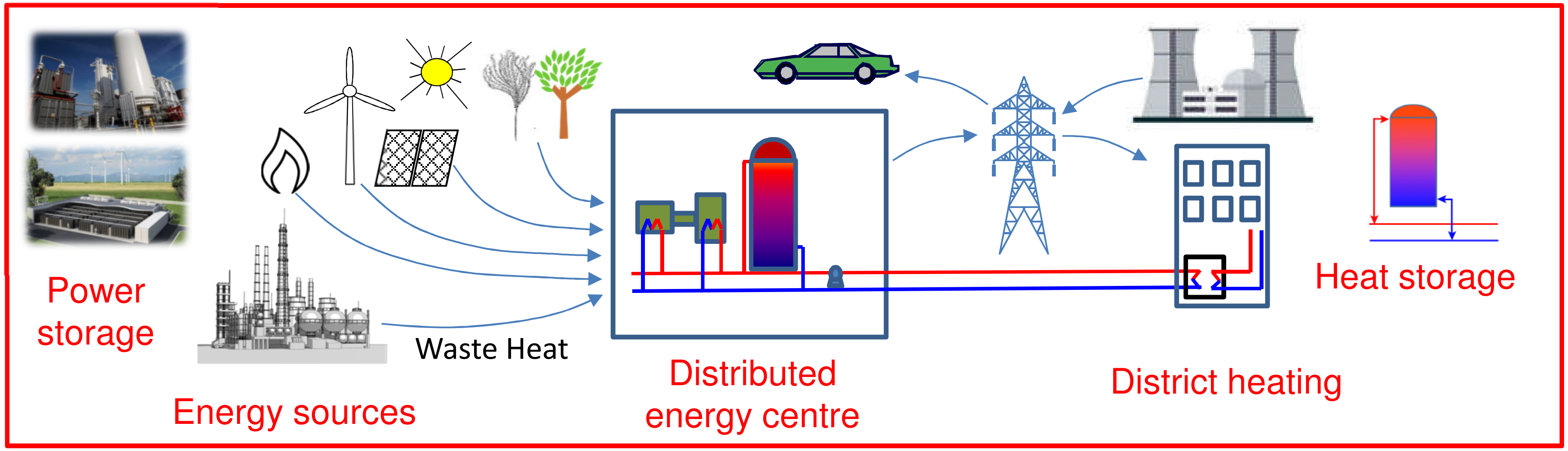
Industrial

Any sensible strategy starts with demand reduction!

Traditional Energy Supply Chain



Distributed Systems



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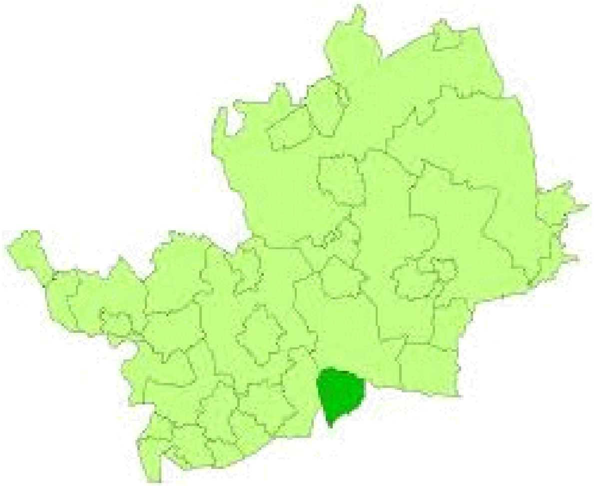
Solutions Must be Local

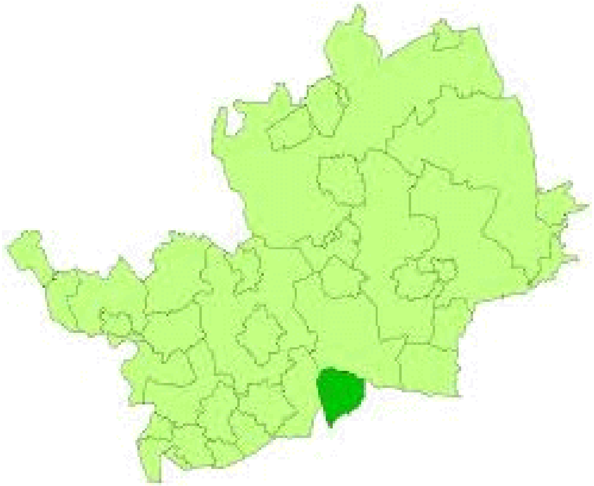
For a Geographic Region



- No one-size-fits-all solutions
- For example, solution for a city centre community will be different from the one required for a rural community
  - ➢ City centre community densely populated with domestic waste as a significant source of energy, etc
  - ➢ Rural community sparsely populated with agricultural waste as a significant source of energy, etc

Characteristic Zones

For a Geographic Region



- Divide a region into ‘characteristic zones’
- Exhaust the economic potential for demand reduction
- Apply solutions based on distributed energy systems

System Integration

BUT

How do we optimize the system integration?

.... Back to basics

PROBLEM

An enormous number of ways to integrate the systems!

BUT, also an *opportunity* for novel solutions through novel ways to integrate systems

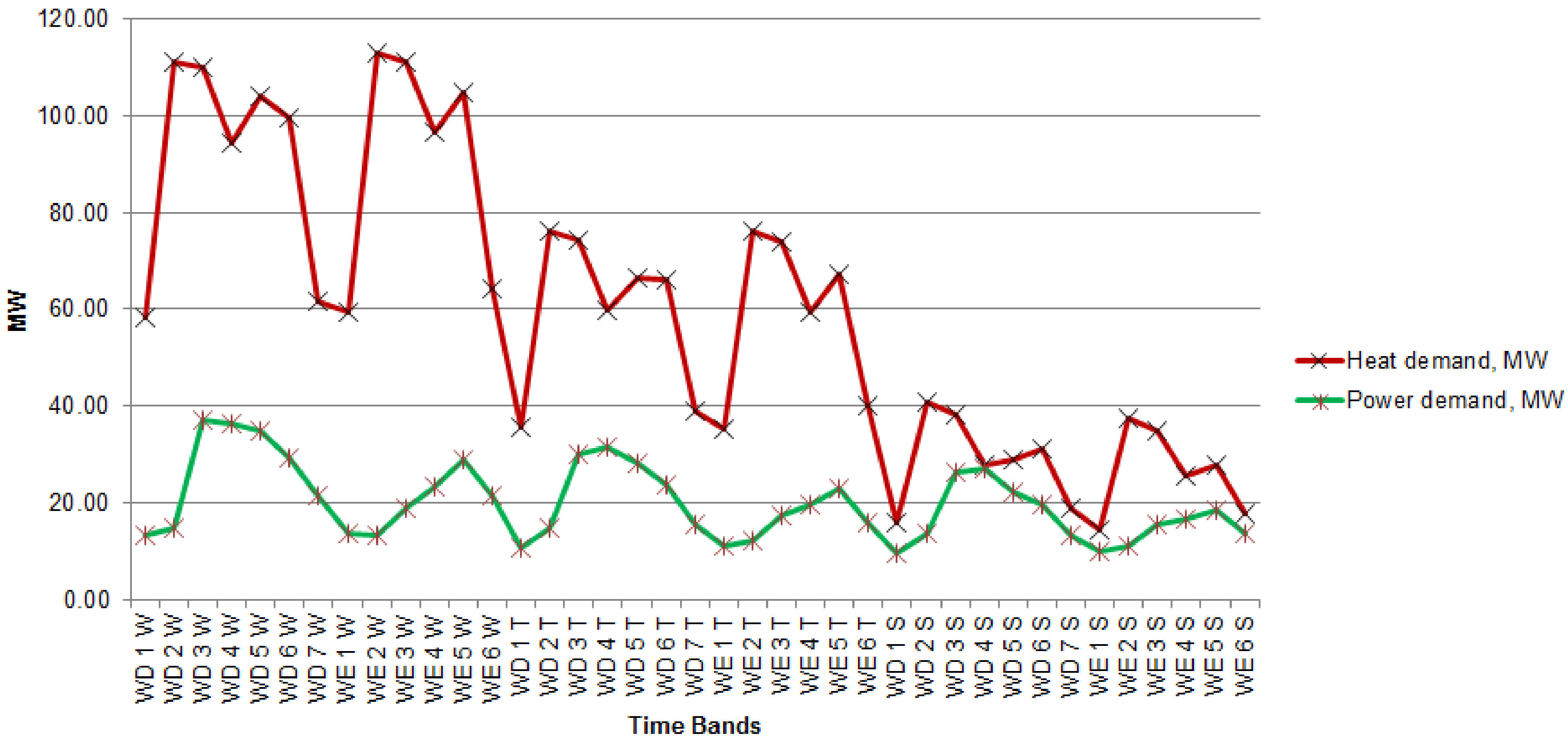
Let's look at an example…

Outline

1. Industrial Energy Consumption and Emissions
2. Future Industrial Energy Systems
3. Conceptual Design of Future Industrial Energy Systems
4. Case Study I
5. Energy and Society
6. **Case Study II**

Case Study II - Input

Thermal and electrical demand data of a particular Zone in the UK



39 bands selected based on thermal demand profile and electricity price tariff structure

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Case Study II - Input

Energy supply units (including CHPs and heat only units)

Technologies	Capacities available (MW)
1. Gas engines	0.375 1.12 2.02 3.86 4.44 5.917
2. Gas turbines	5.67 11.29 14.99
3. Fuel cells	0.4
4. Biodiesel engines	0.4 1.12 4.7
5. Land fill gas (LEG) engines	0.375 0.776 1.986
6. Diesel engines	0.4 1.12 4.7
7. Boilers	0.25 1.4 3.5 7 10 20
8. Solar heaters	0.1
9. Ground source heat pump	3.166 4.152
10.Heat Storage	

CHP units (1–6)

Heat only units (7–10)

Case Study II - Input

Present and future energy prices

<table>
<tr><th></th><th>2010</th><th>2020</th><th>2030</th><th>2040</th><th>2050</th></tr>
<tr><td>1. Natural gas price (p/kWh)</td><td>2.93</td><td>3.97</td><td colspan="3">4.05</td></tr>
<tr><td>2. Grid emission factor (kg/kWh)</td><td>0.485</td><td>0.370</td><td>0.210</td><td>0.040</td><td>0.020</td></tr>
<tr><td colspan="6">3. Electricity price (p/kWh)</td></tr>
<tr><td>Off peak</td><td>4.80</td><td>5.58</td><td colspan="3">9.14</td></tr>
<tr><td>Average price</td><td>6.80</td><td>7.91</td><td colspan="3">12.95</td></tr>
<tr><td>Peak</td><td>7.00</td><td>8.14</td><td colspan="3">13.33</td></tr>
</table>

Source:

Department of Energy and Climate Change, Interdepartmental Analysts' Group, Valuation of energy use and greenhouse gas (GHG) emissions, tool kit, 2012 <www.decc.gov.uk/en/content/cms/about/ec_social_res/iag_guidance/iag_guidance.aspx>

Case Study II - Solution

Model energy units

- Linear models for performance and cost against load
- Part-load performance linearised across different load ranges

Optimization model

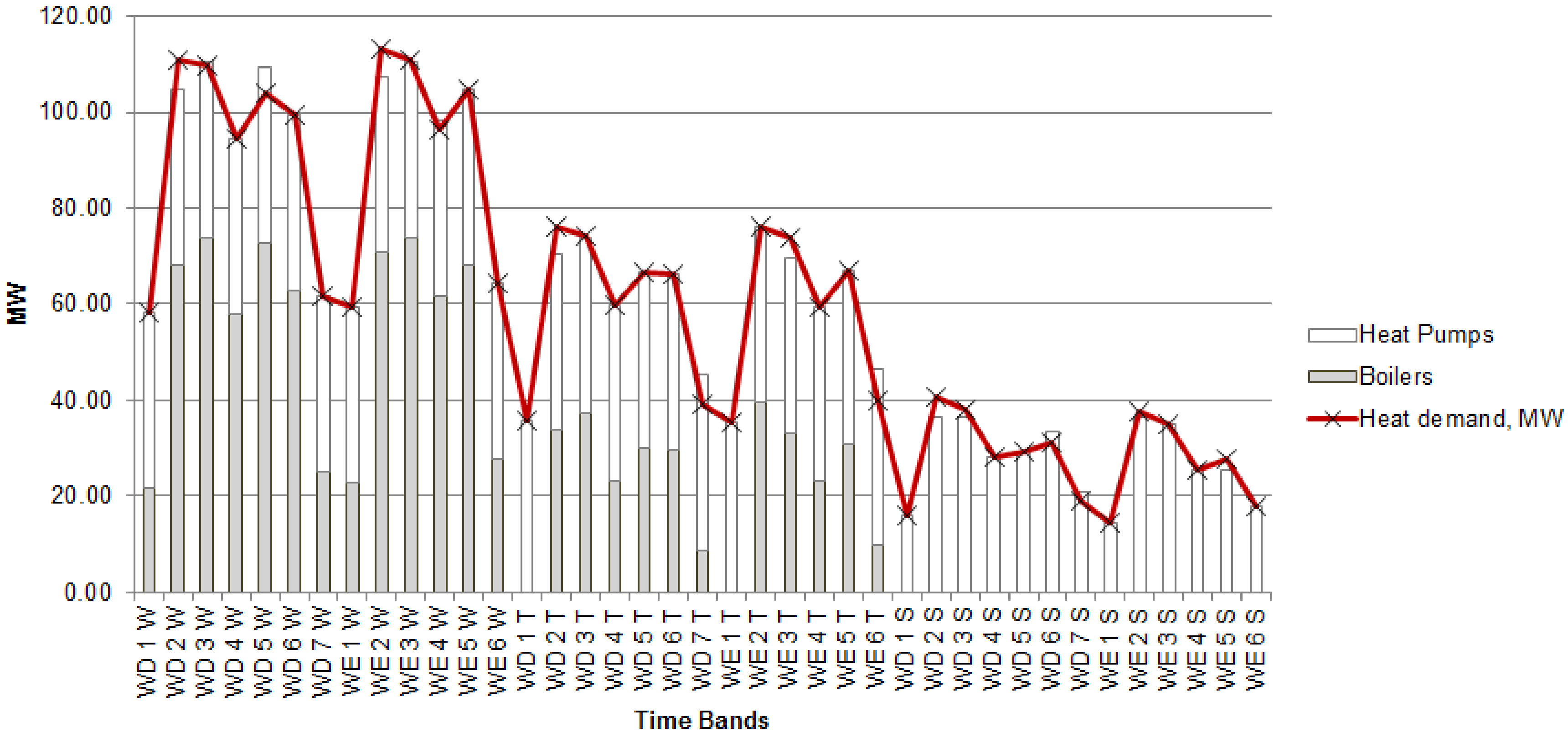
- Demand for power and heat discretized
- Choice of energy unit from integer variables
- Choice of part-load model for energy unit from integer variables
- CO_2 emissions can be taxed if appropriate
- Formulate as MILP

Constraints

- Maximum/minimum load on units
- Maximum CO_2 emissions

Case Study II - Scenario 1

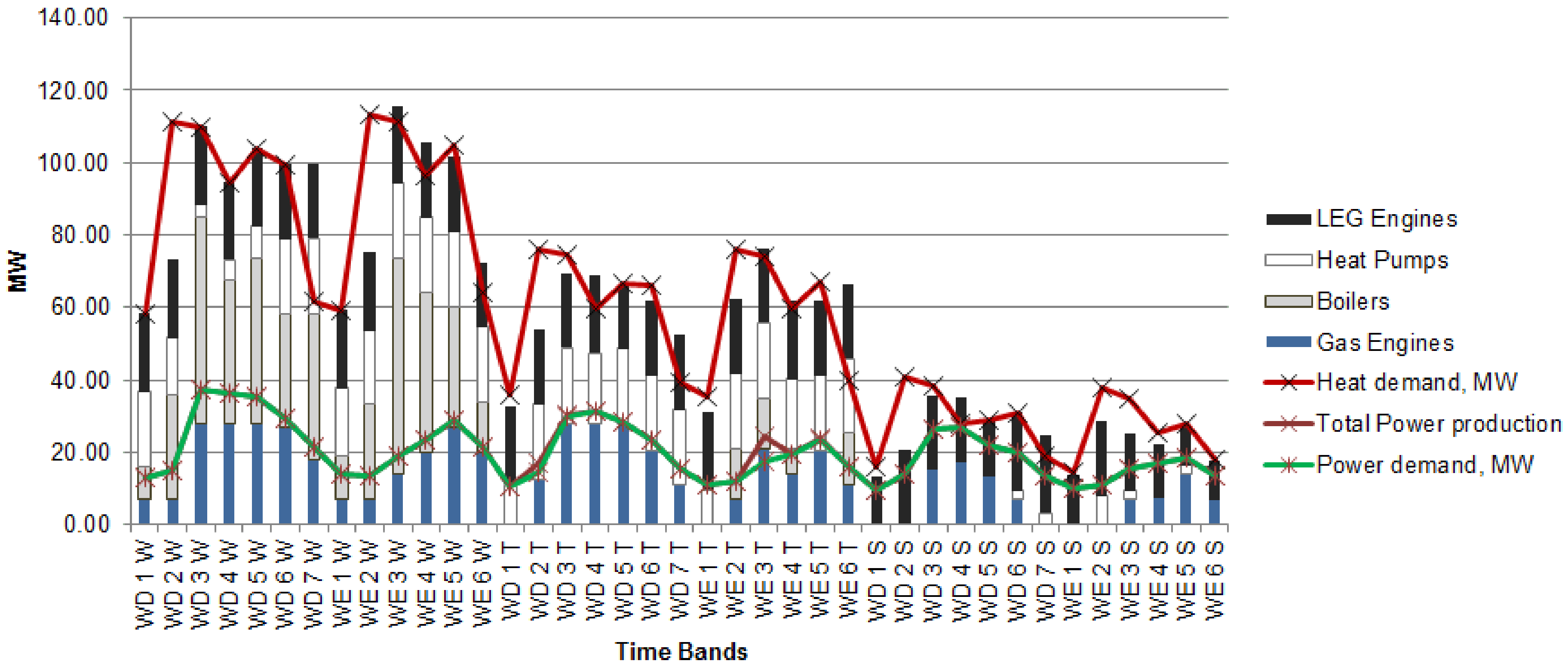
Scenario 1: Heating only DE centre (no cogeneration)



Thermal storage allowed with 24 hour balance

Case Study II - Scenario 2

Scenario 2: ‘Island’ style DE centre to satisfy both thermal and electrical demand

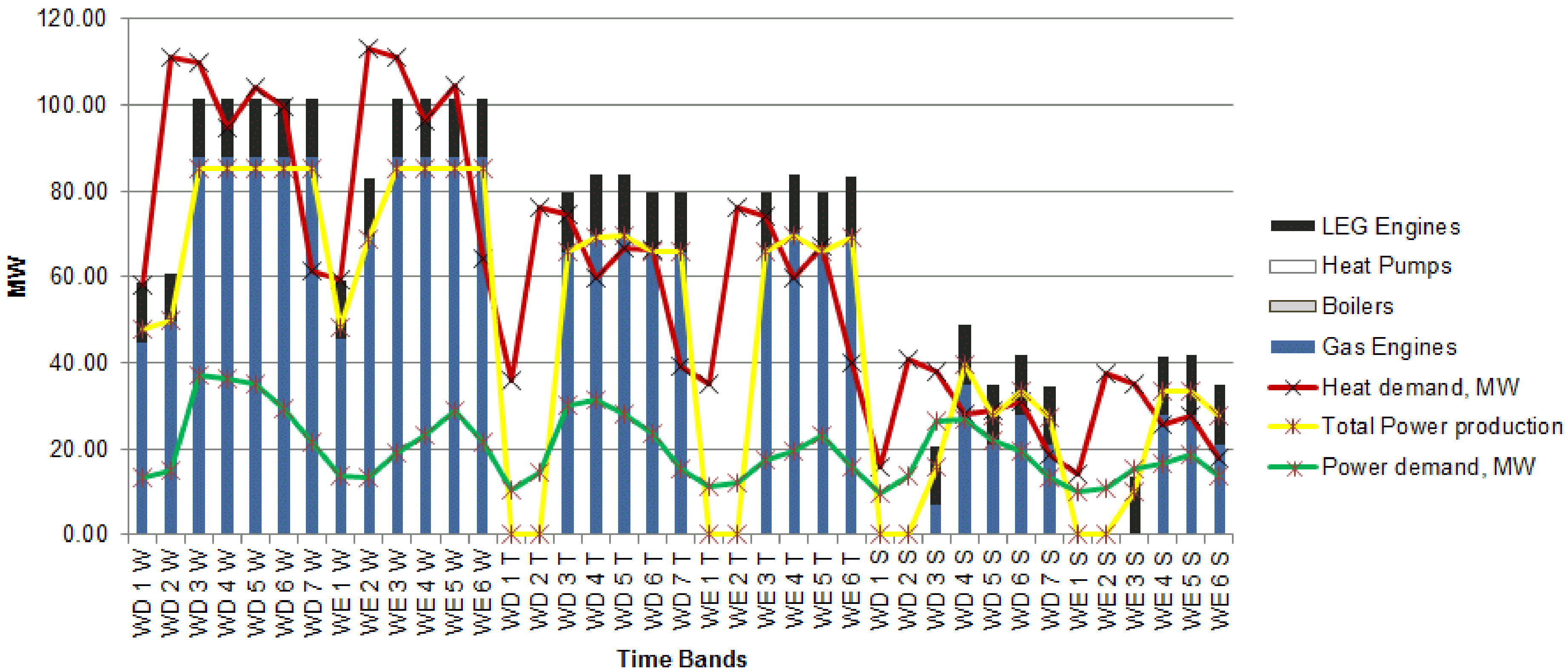


Thermal storage allowed with 24 hour balance

Case Study II - Scenario 3

Scenario 3: Supply heat and import/export electricity

- Electrical demand satisfied by producing on site or buying from the grid



Thermal storage allowed with 24 hour balance

Distributed Energy Systems

- Distributed energy applied across the UK for the domestic & commercial sectors will give CO_2 saving ~ 40%
  - Did not include industrial sector

    (missed opportunity for waste heat recovery)
  - Based on switch to DE based on current economics
  - No consideration of transportation energy
  - Only very limited renewables options included
  - No waste-to-energy
  - No power storage

http://www.eti.co.uk/wp-content/uploads/2014/03/ETI Macro Distributed Energy Report - 21 March 2013 2.pdf

Conclusions

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- Many potential sources of energy, each with their advantages and disadvantages
- The variability of energy demand creates challenges for supply.
- The security of the Energy-Water-Food nexus is a central challenge to the goal of sustainable development.
- Novel solutions can in principle be developed through the use of optimization applied to the needs of geographic regions.
- Novel solutions need to be sought through novel ways to integrate energy systems.

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Thanks for your attention

Any question?