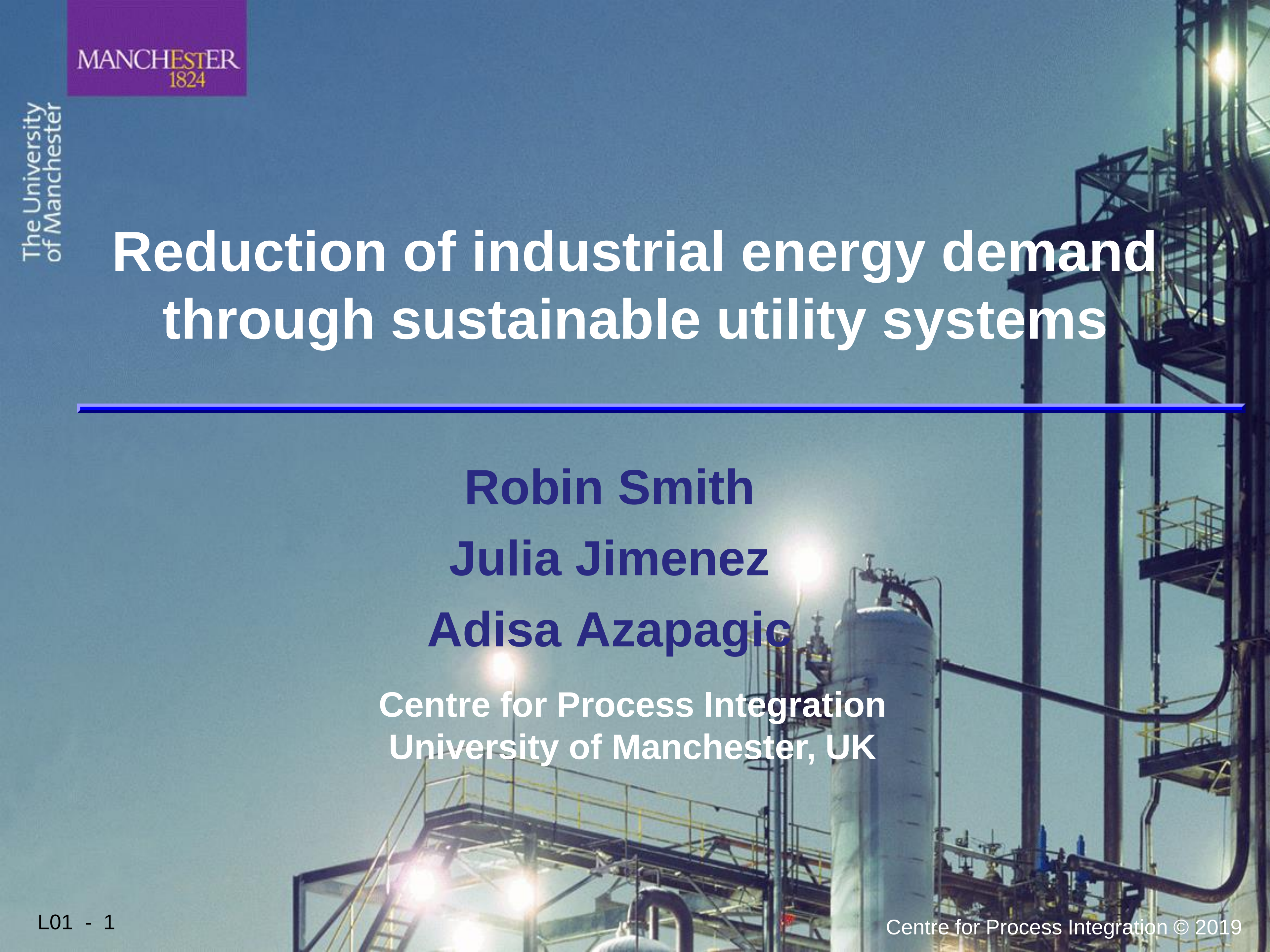

Reduction of industrial energy demand through sustainable utility systems

Robin Smith

Julia Jimenez

Adisa Azapagic

Centre for Process Integration
University of Manchester, UK

Outline

PART I – Robin Smith

1. Background
2. Future Utility Systems
3. Transition of the Utility System
4. Summary

PART II – Julia Jimenez

1. Project Objectives
2. Cogeneration targeting
3. Design of utility systems
4. Methodology
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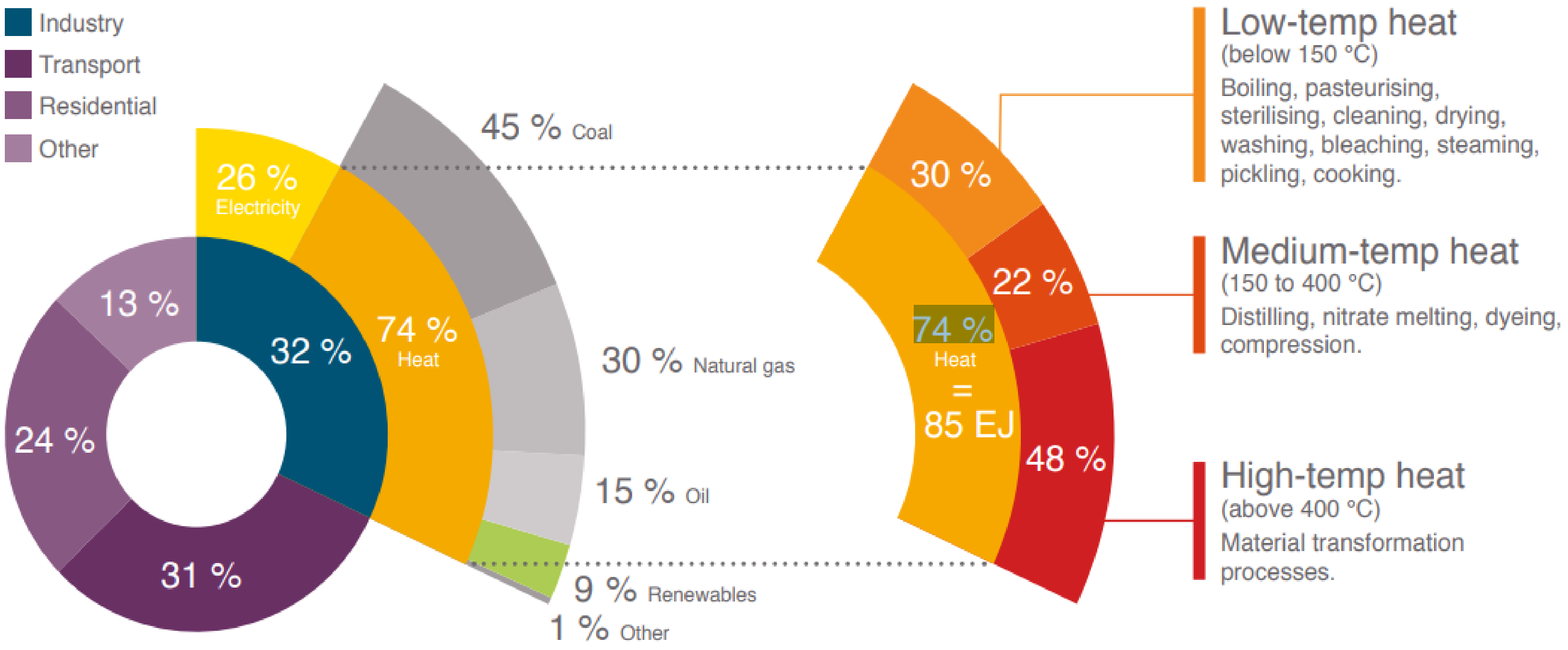
Industrial Energy Systems

One of the major final energy consuming sectors…

ENORMOUS GLOBAL HEAT DEMAND IN INDUSTRY

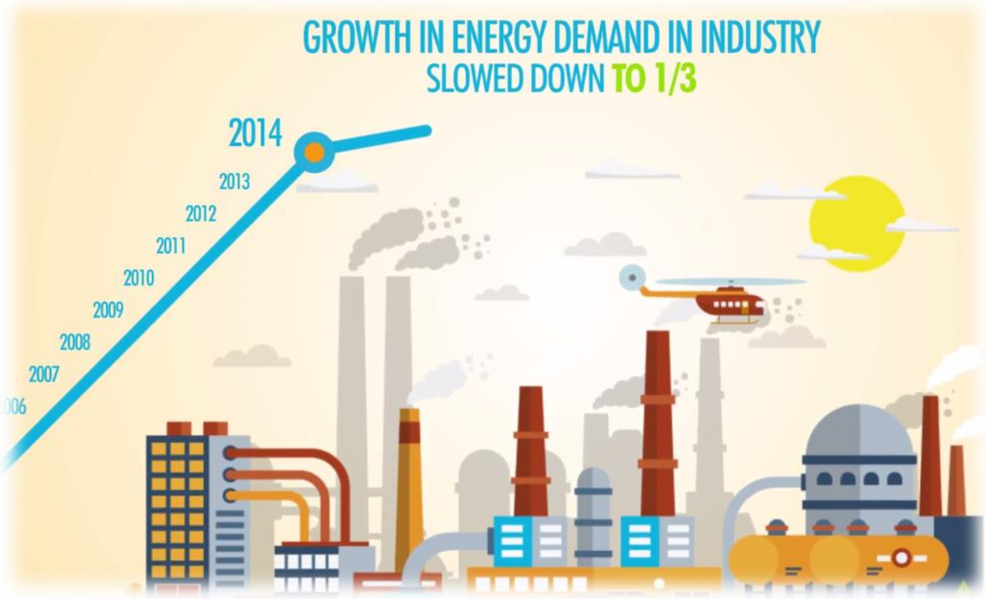


Solar Payback (2017). Solar Heat for Industry, based on IEA statistics and calculations by IRENA. In: Ministry, G. F. E. (ed.). Germany.

…and its share will rise

Industrial Energy Systems

Challenge of Global Energy Sustainability



OECD/IEA (2017). World Energy Outlook 2017.

Energy efficiency first principle

In 2014, energy demand slowed down to 1/3

Remarkable, *but …*

the consumption will increase by 30% before 2040

Alone, not enough…

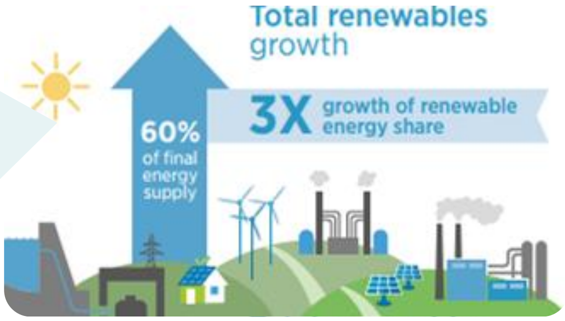
to reduce the increasing demand of fossil fuels and their associated environmental impact.

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

Industrial Energy Systems

Renewable Energy Growth

Based on current plans and policies



By 2050

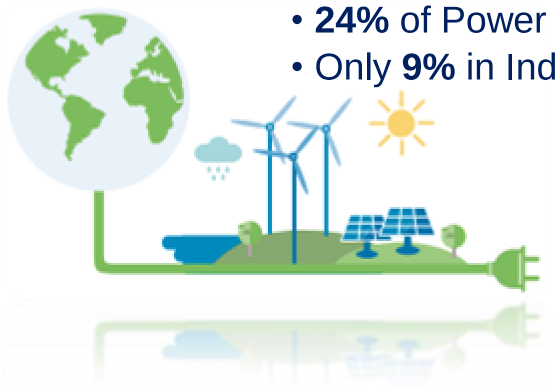
- **60% of final energy supply**
  - **78%** of electricity supply
  - **39%** in Industry

By 2030

- **27% of final energy supply**
- **27%- 34%** in Industry

Current Situation

- **19%** of final energy supply
  - **24%** of Power generation
  - Only **9%** in Industrial sector

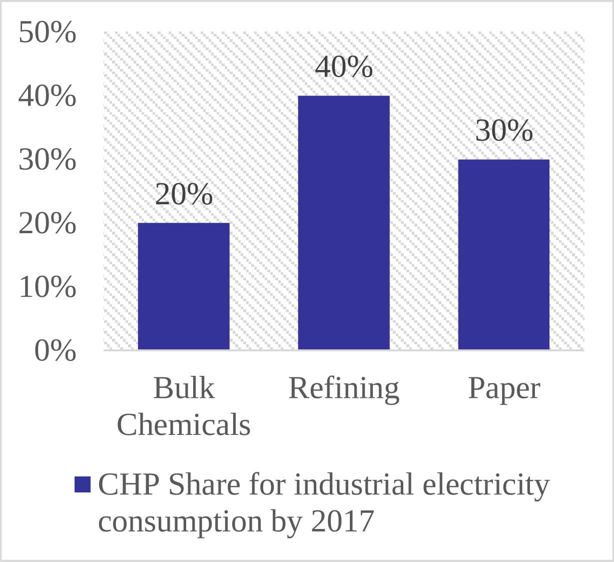


Increasing amount of energy from renewable sources

Industrial Energy Systems

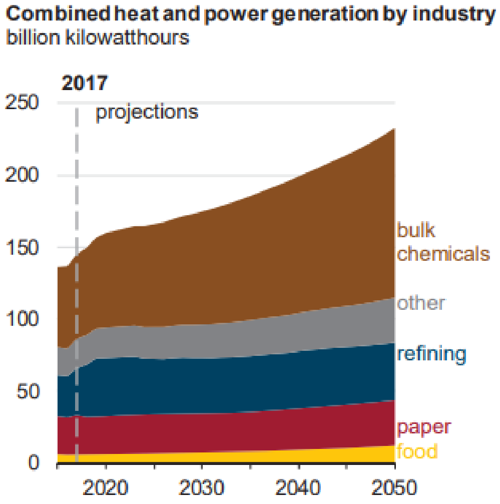
- Energy-intensive industries account for about 65% of total industrial energy consumption
- Industrial CHP is commonly used in large, steam-intensive industries

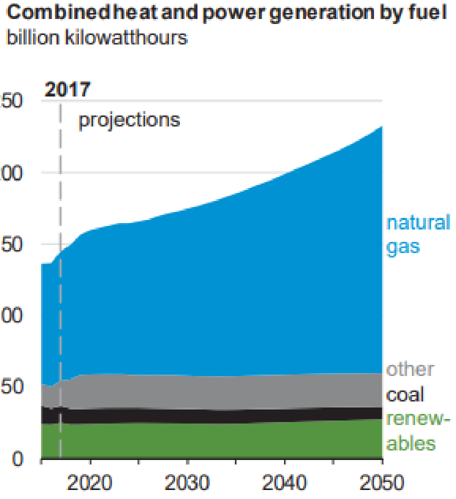
2017



Industrial combined heat and power use grows

Projection


Combined heat and power generation by industry
billion kilowatthours


Combined heat and power generation by fuel
billion kilowatthours

EIA (2018), *Annual Energy Outlook 2018 with projections to 2050,* Retrieved from https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf

PART I

1. Background
2. **Future Utility Systems**
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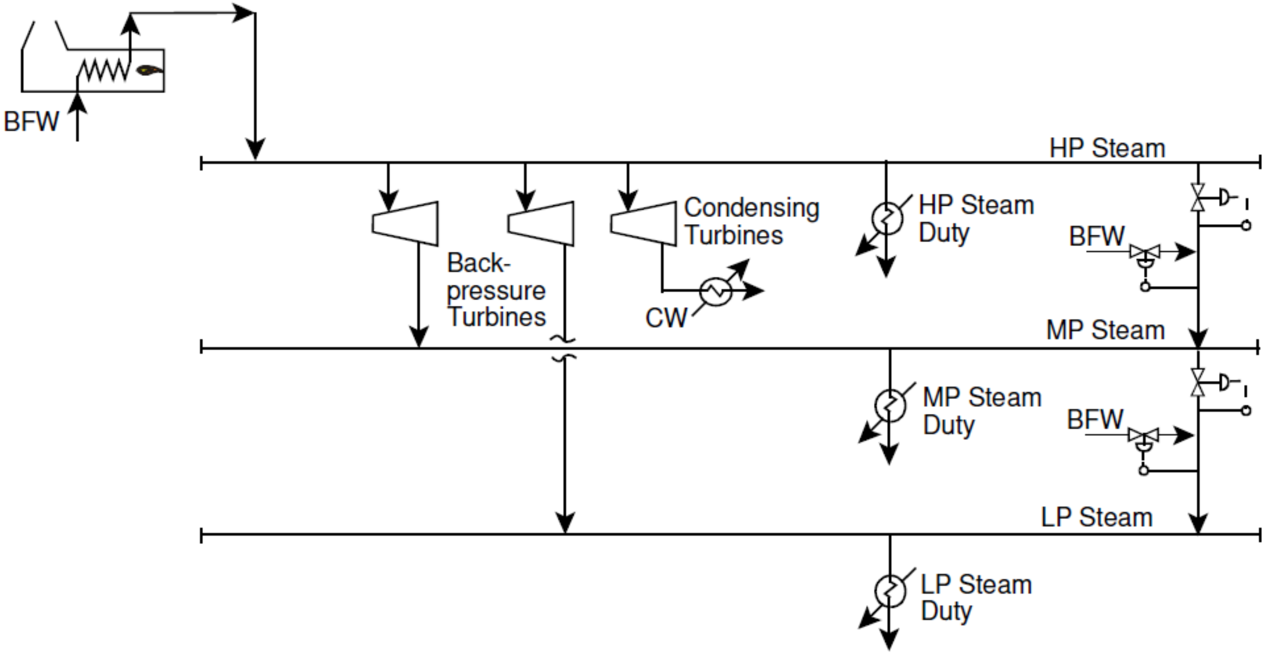
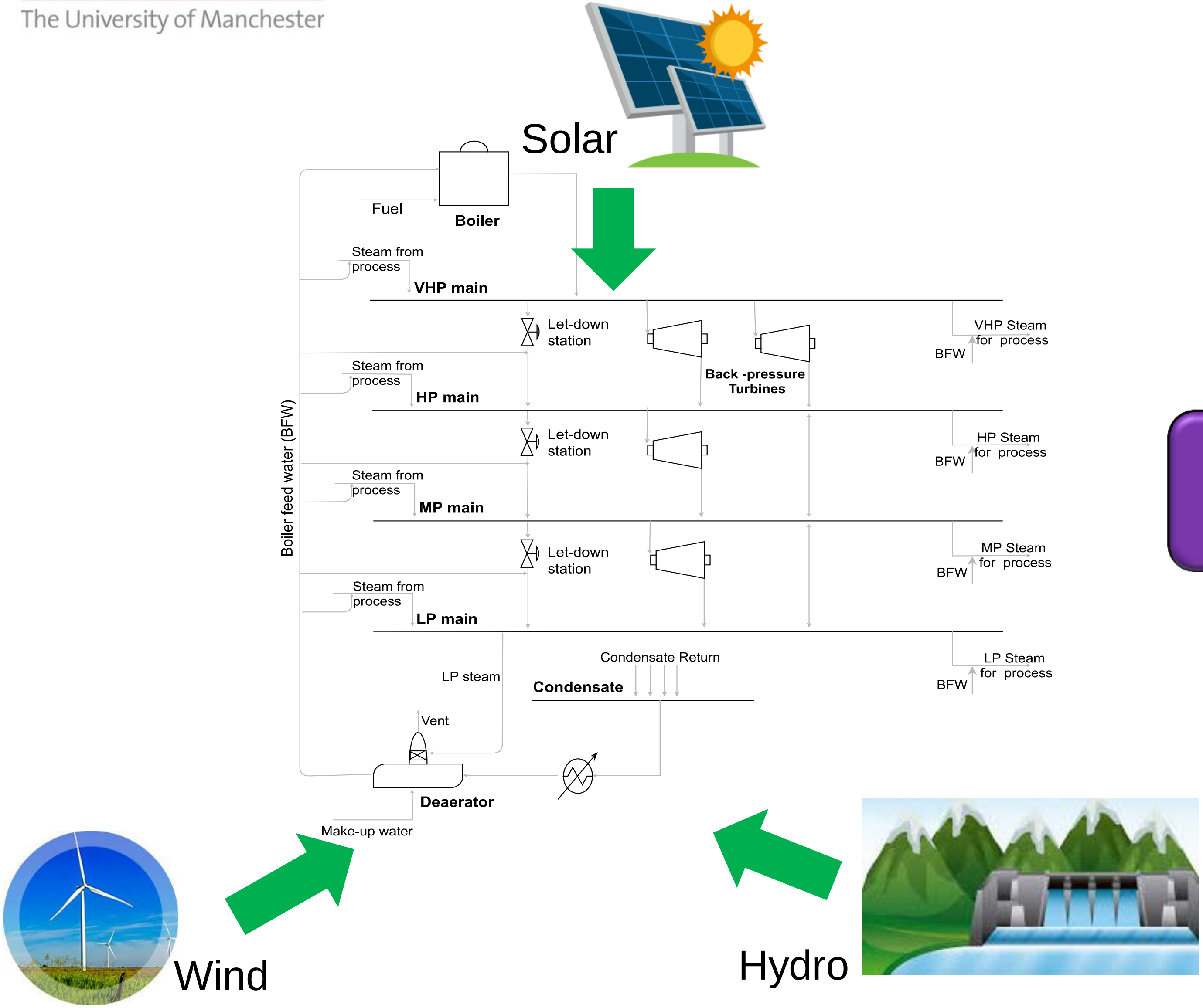
Utility systems of the future



We need to become more energy efficient, but also:

- Phase out fossil fuels and phase in renewables (including waste to energy)
- Move to a more *sustainable basis* for process industry energy systems
- Design and optimization to be based on the *full life cycle* implications of *integrated systems*

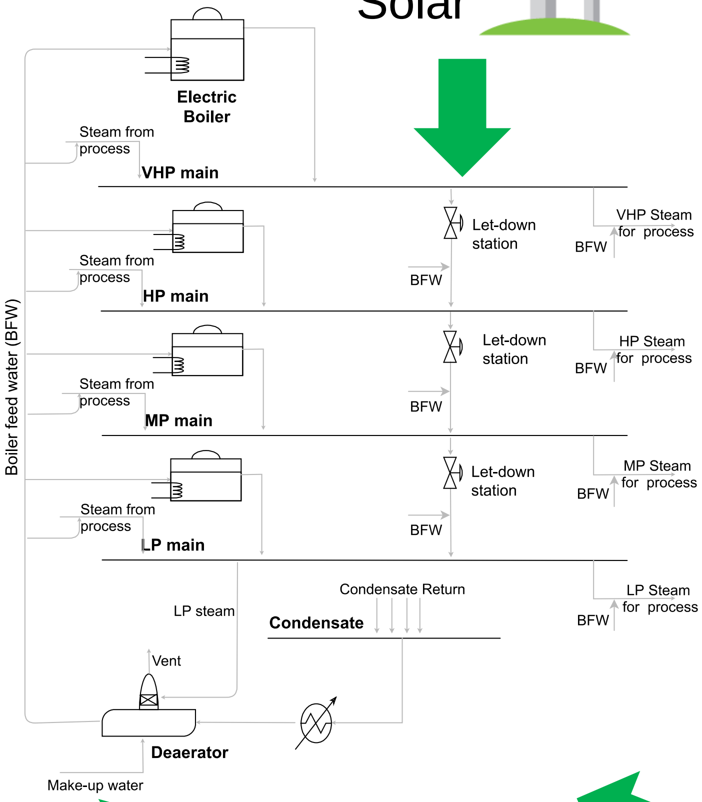
Introduction of Renewables



Integration of Renewables

Introduction of Renewables

Solar

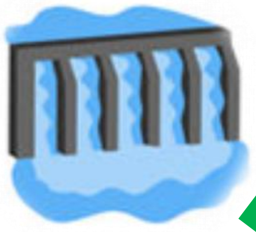


Wind

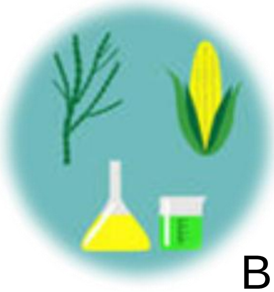
Hydro

- ➢ Switch to electric boilers?
- ➢ No need of steam turbines?
- ➢ Distributed electric boilers – greater options?

Introduction of Biomass and Waste

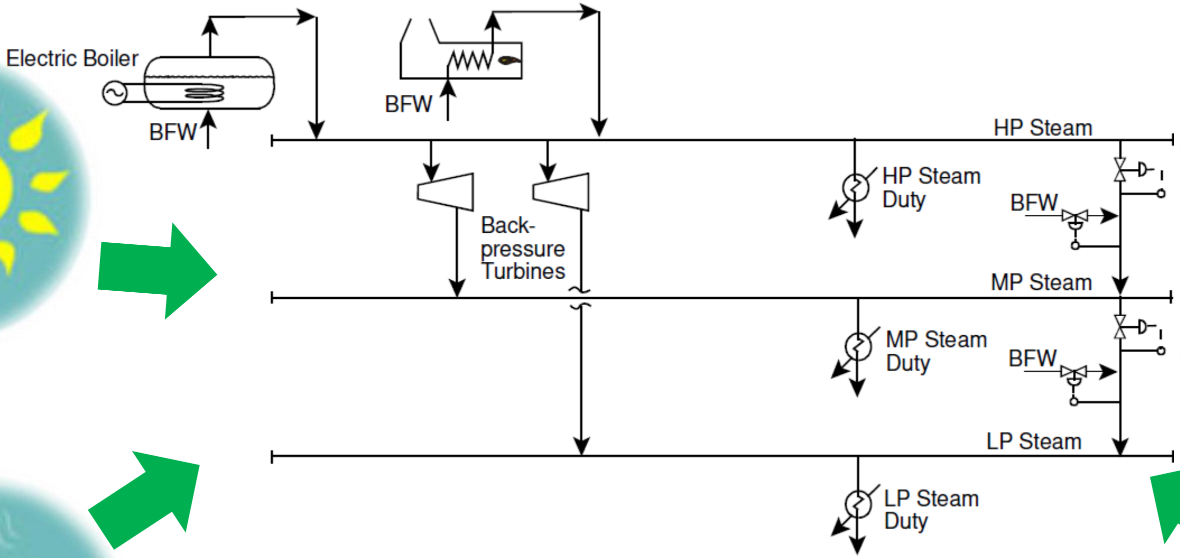


Hydro

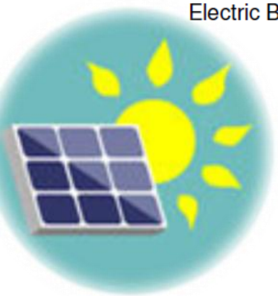


Biomass

Waste gases



Completely different system *configuration* and *operation*



Solar

Wind

Waste

Which is the appropriate mix of sources and technologies?

PART I

1. Background
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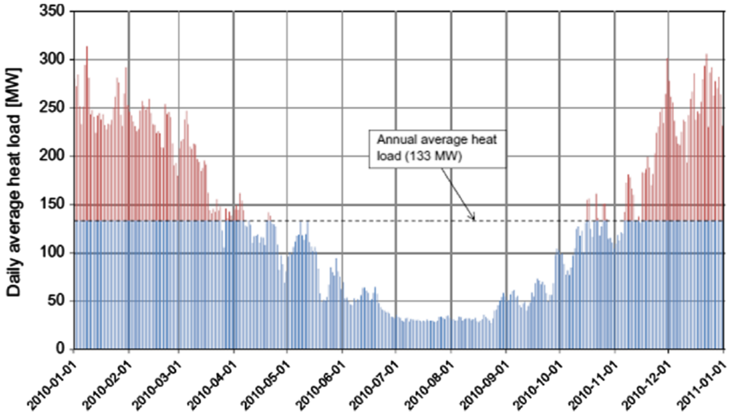
Features of Energy Demand and Supply

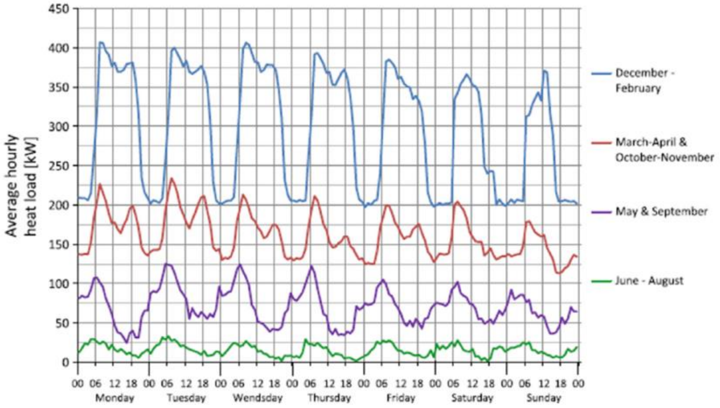
Both vary with **time** and **location**

Variability of demands

Energy demand can vary

- **hourly** during each day (start-ups, shutdowns, process disturbances)
- **seasonal** during the year (summer, winter, transition)





Uncertainty

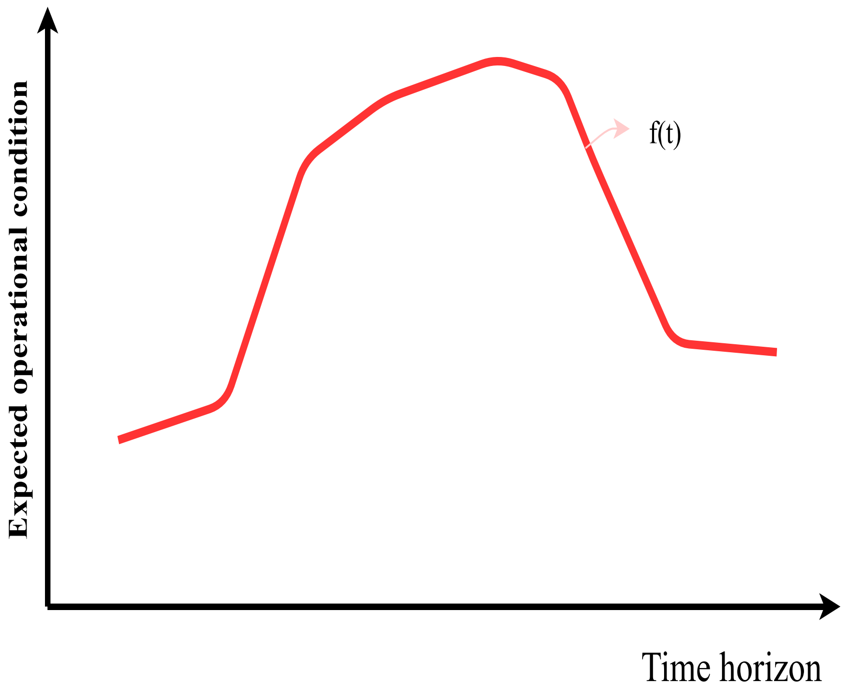
- system configuration
- equipment selection (number, size and type)
- equipment operation
- operation scheduling

Gadd H, Werner S. Heat load patterns in district heating substations. Appl Energy 2013;108:176–83.
Gadd H, Werner S. Daily heat load variations in Swedish district heating systems. Appl Energy 2013;106:47–55.

Features of Energy Demand and Supply

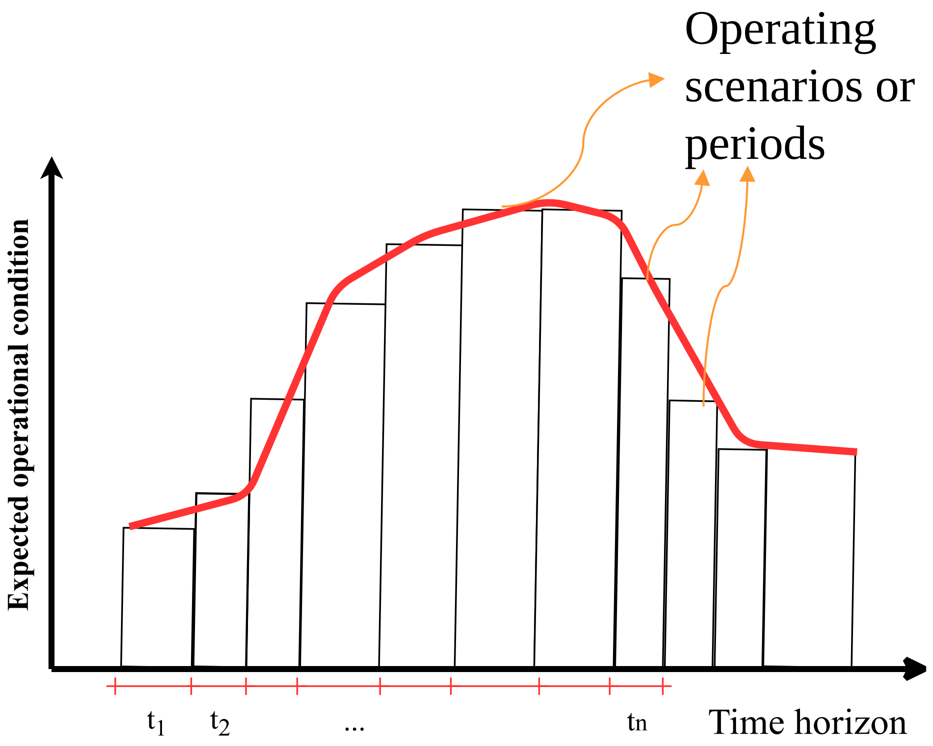
Variability with time

Dynamic approach



Conditions are functions of time

Multi-period approach



various scenarios to represent different operating scenarios

Features of Energy Demand and Supply

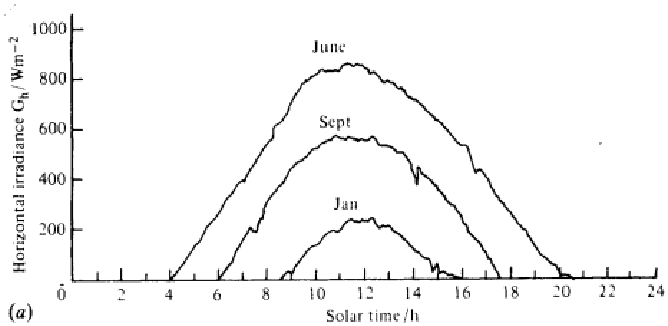
Variability of Renewable sources

For efficient exploitation – required overall ***availability*** and ***variability*** with ***time.***

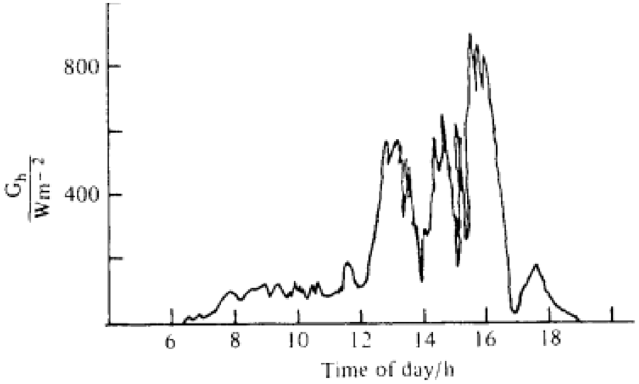
Biomass - supply varies by year seasons and by bio-waste availability (plus logistics problems).

Wind and Solar - varies more rapidly – in hours and even minutes.

Diverse time horizons of the changes



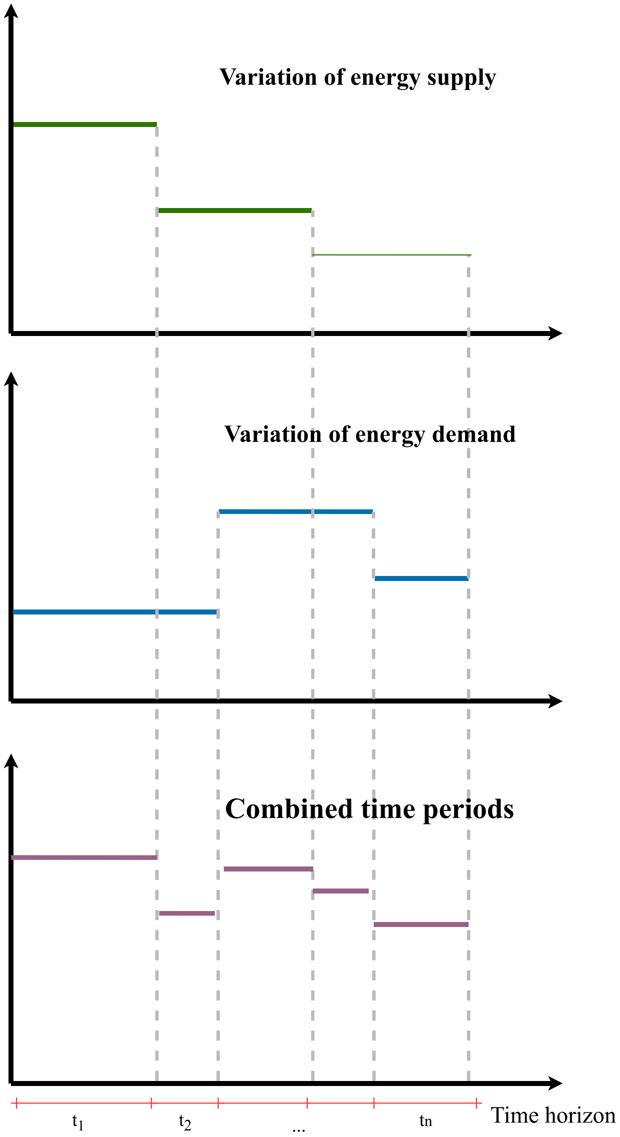
Clear Day



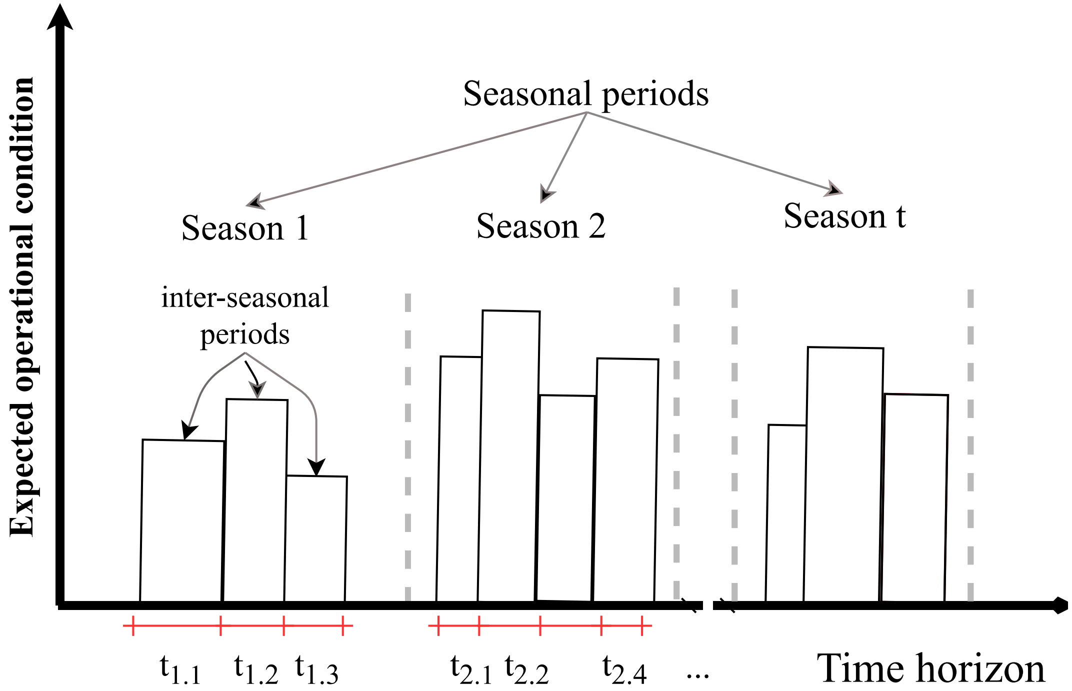
Cloudy Day

Features of Energy Demand and Supply

Multiple time frames

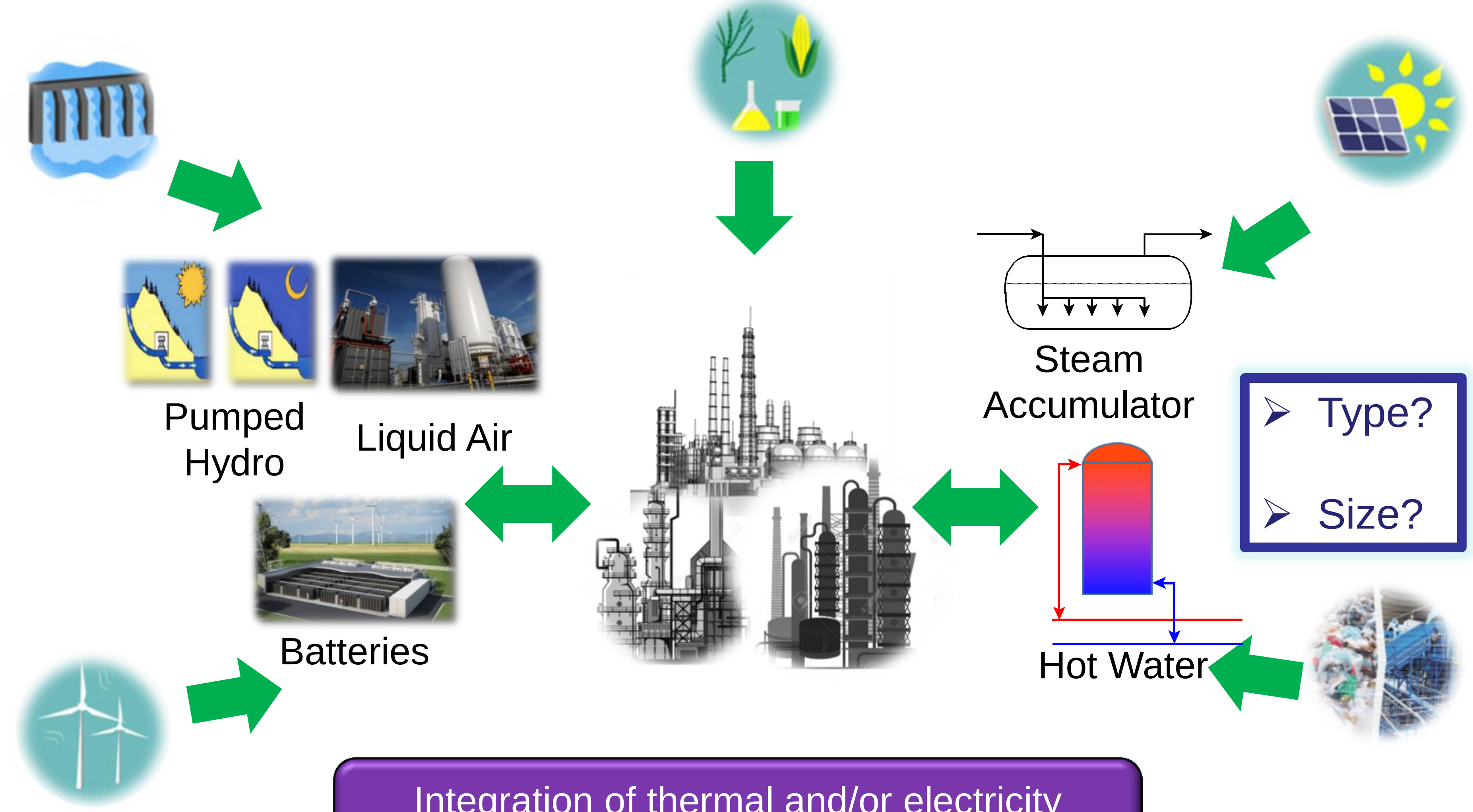


Diverse time horizons



but also…

Integration of energy storage



Pumped Hydro

Liquid Air

Batteries

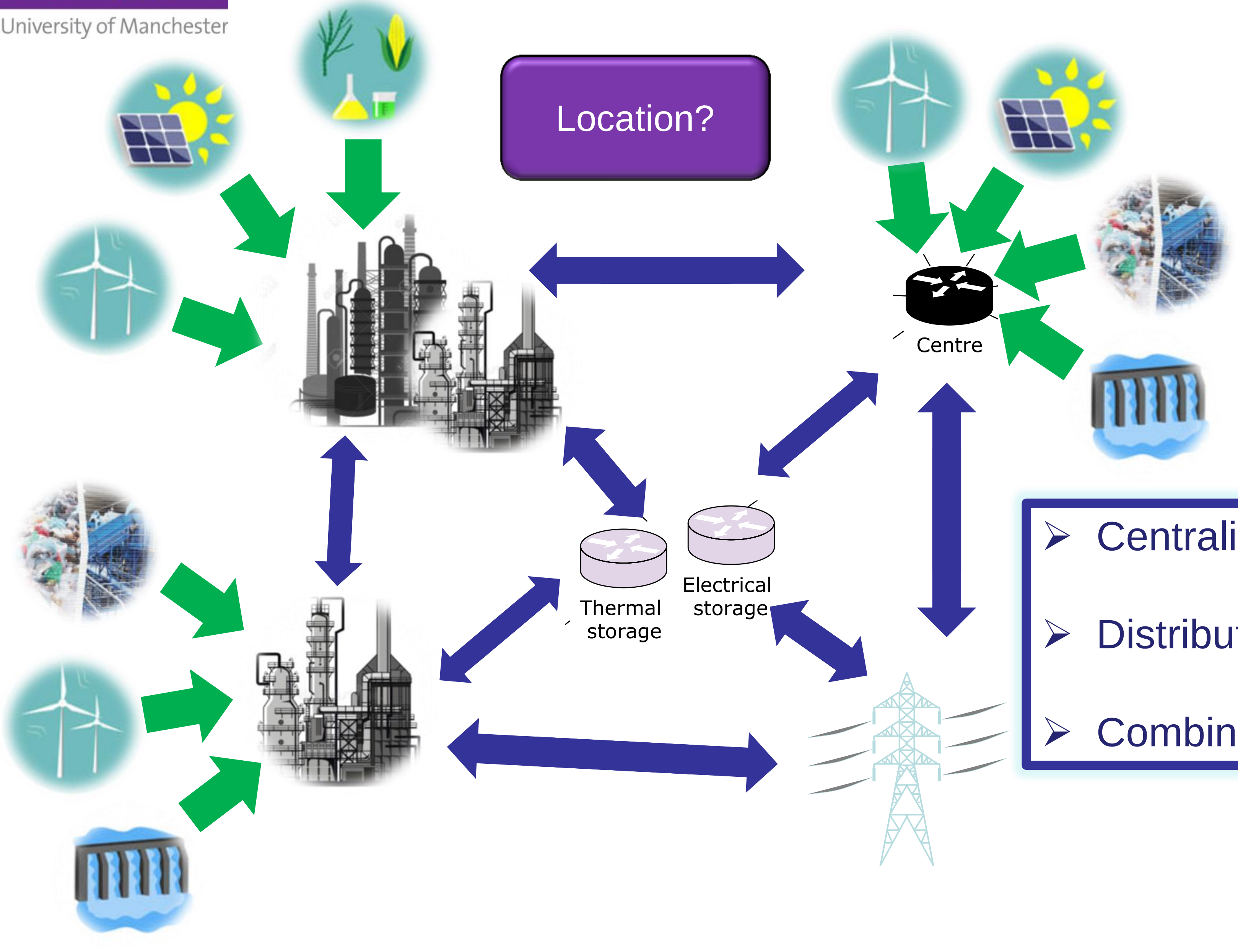
Steam Accumulator

Hot Water

- ➢ Type?
- ➢ Size?

Integration of thermal and/or electricity storage?

Integration of energy storage



- Centralised?
- Distributed?
- Combination?

Site Utility Systems

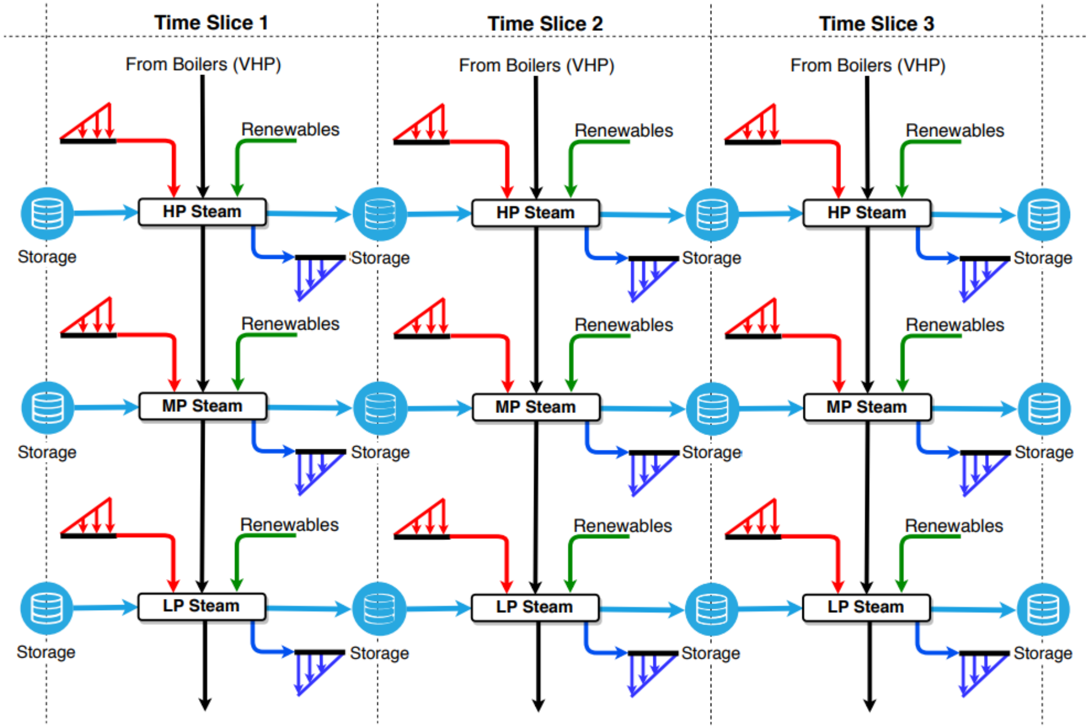
New Paradigm for Industrial Utility Systems

- ➢ **Multiple time frames**
- ➢ Integration of renewables
- ➢ Integration of energy storage

and…

- ➢ Maximize energy efficiency
- ➢ Based on ***full life cycle***

No '***one size fits all***' solution



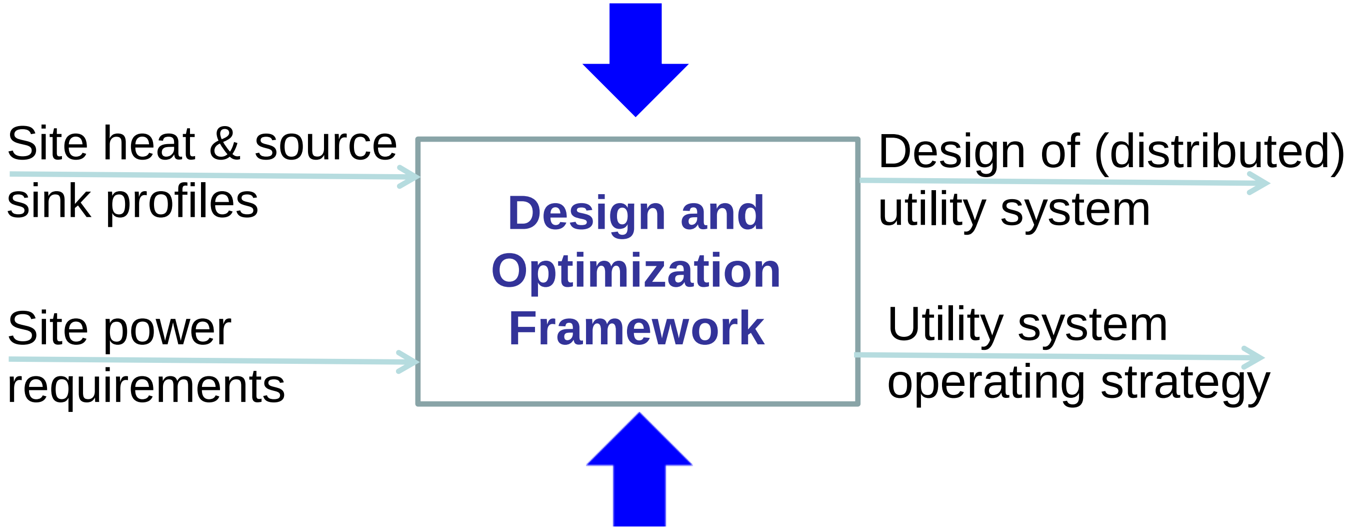
Integration Challenge

Necessity of…

- Extent the current Total Site methodology
- **Redesign** the utility systems

Design and Optimisation Framework

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



Site heat & source sink 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 in a **sustainable basis**

PART I

1. Background
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Summary

- Paradigm change required for the design and operation of industrial utility systems
  - Integration of renewable energy sources and technologies (including waste to energy)
  - Use of energy storage *where appropriate*
  - Distribution of utility systems *where appropriate*

- Tool requirement for the design and optimization of future industrial utility systems taking a wide range of options:
  - Accounting for time variability
  - Constrained by sustainability criteria
  - Based on life cycle costs

PART II

1. Project Objectives
2. Cogeneration targeting
3. Synthesis of utility system
4. Methodology
5. Case studies
6. Conclusions and future work

MANCHESTER
1824
The University of Manchester

Objectives

1. Site utility *targeting*

- More realistic and accurate utility targets
- Optimum steam level placement

2. Site utility system *synthesis* (with *redundancy*)

- System configuration and operation scheduling
- Equipment selection

To deal with variable demand and uncertainties

3. *Integration* of renewables, waste to energy systems and energy storage

- Analysis of different energy sources and technologies
- Development of simplified linear models

4. Implementation of the *life cycle assessment*

To develop an integrated decision-support methodology and tool capable of designing and optimising sustainable networks

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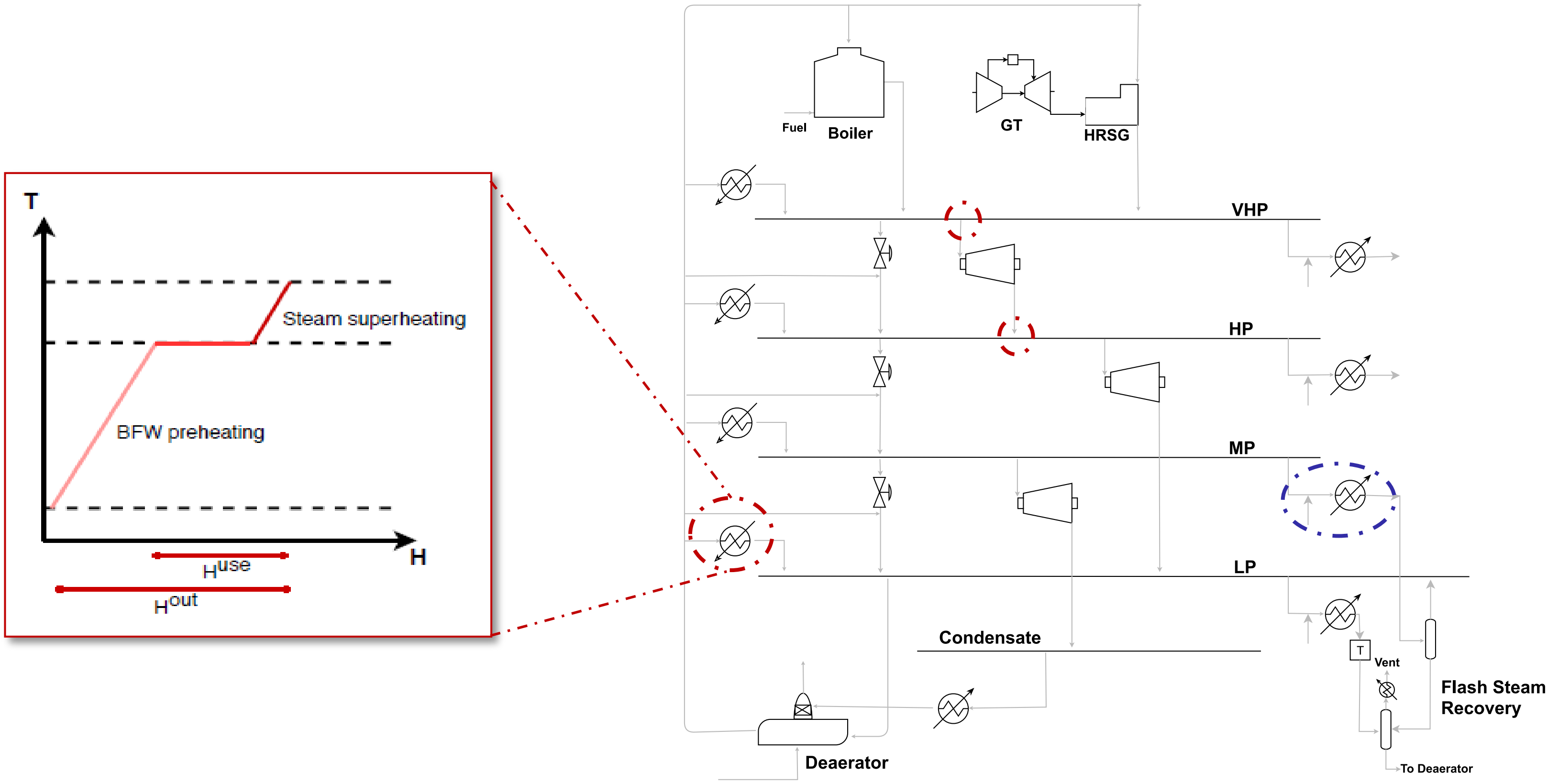
Process Integration in Utility Systems

Extensive literature for cogeneration targeting in utility systems

But..

- present a number of limitations and drawbacks
- restricted the scope of the options included



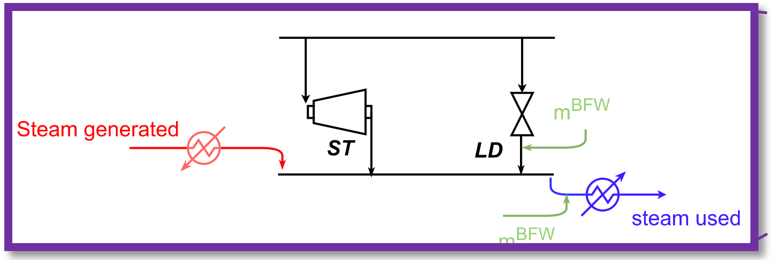
Process Integration in Utility Systems

Extensive literature for cogeneration targeting in utility systems

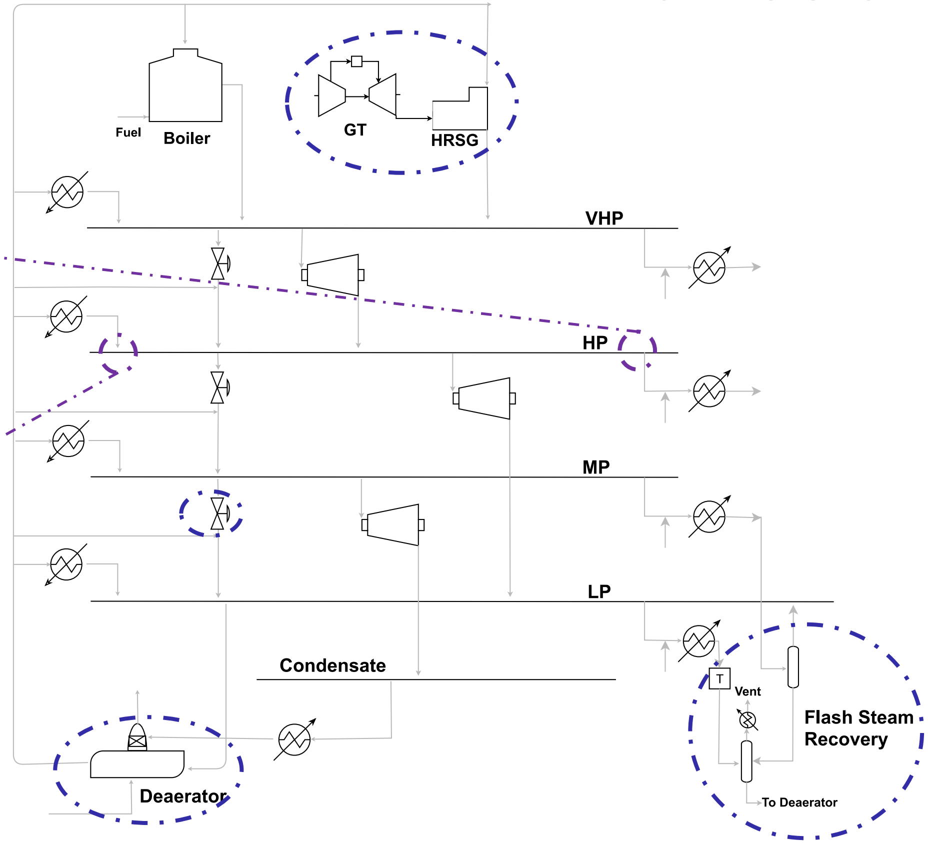
But..

- present a number of limitations and drawbacks
- restricted the scope of the options included

Unrealistic energy targets for the site



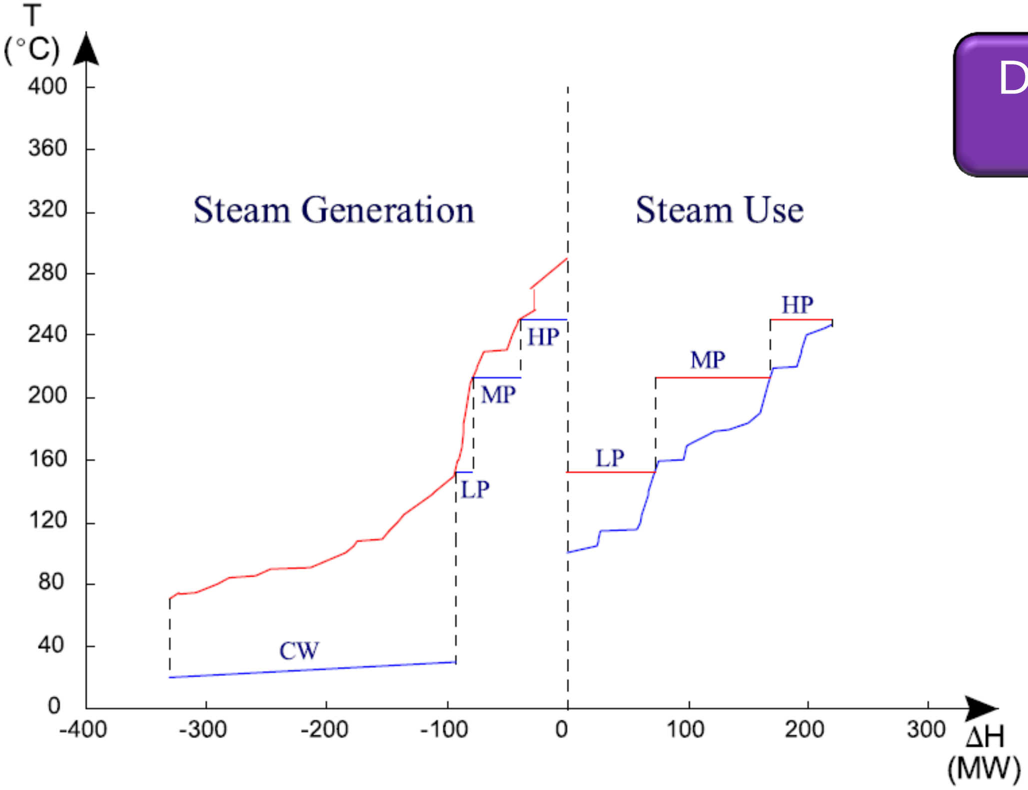
Not straightforward to calculate



Process Integration in Utility Systems

Steam mains conditions

Do we have our steam mains at the correct pressure?



Do we have the correct number of steam mains?

Trade-off

fuel use and cogeneration

PART II

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Reliability at design stage

Conventional optimization

Objective:

- Determine **type, number** and **size** of **new** units

  and *For variable demand*

- their **operational conditions**

BUT...

For **synthesis of utility systems** it is also required to consider...

Additional operating situations (*normal, maintenance and failure*) → Operational flexibility

- to reduce the overall cost of maintenance and losses due to failure
- to overcome utility demand and operational uncertainties

Process Integration in Utility Systems

Reliability and redundancy at the design stage

Number and size of units

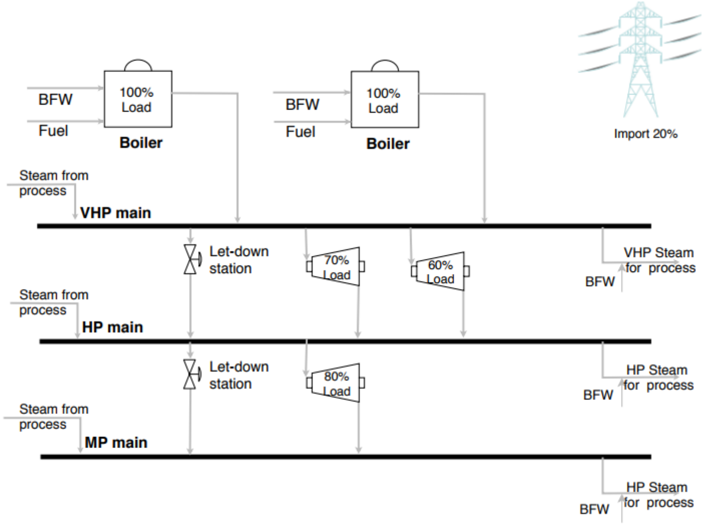
Large units at part-load operation during most of the time **(Active redundancy)**

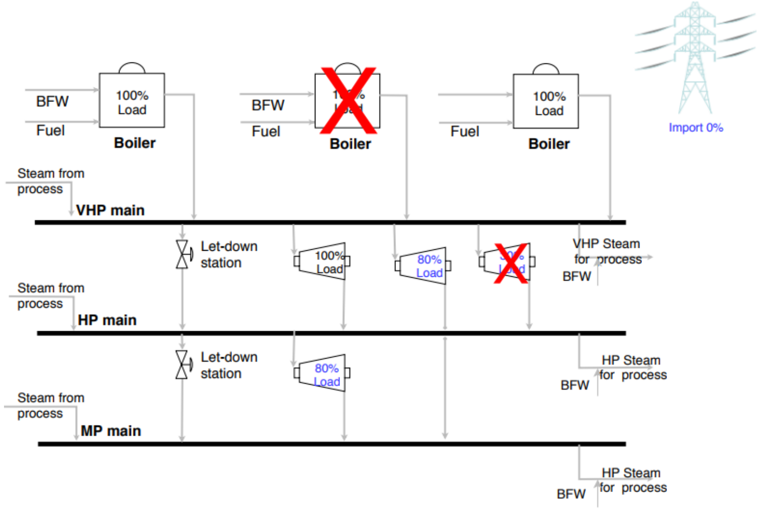
or…

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

?

- ➢ Bigger size → more efficient ***but…*** partial-load → less efficient
- ➢ Lower number of units → less expensive ***but…*** less number of units → less reliable





Process Integration in Utility Systems

Reliability and redundancy at design stage

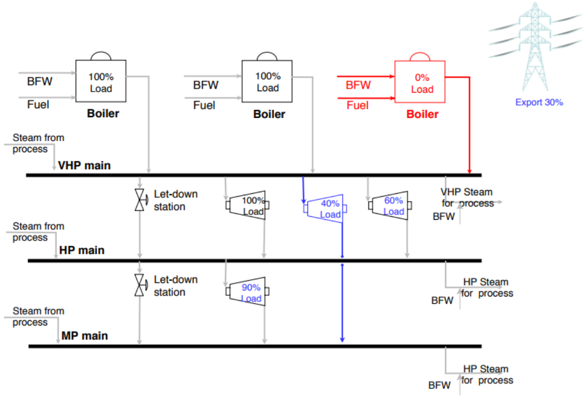
Type of units

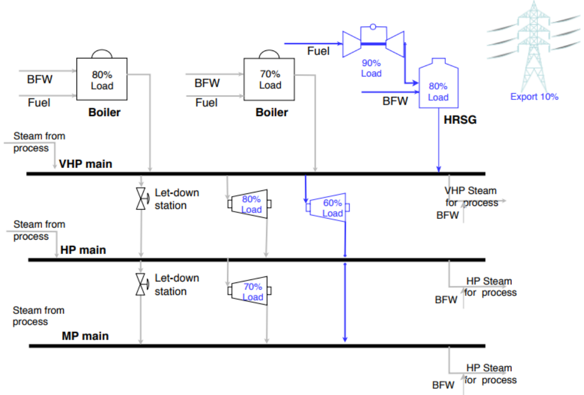
More units of the same type

or…

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

?





- Multiple design and operational degrees of freedom

- Variables highly interrelated

Complex optimization

PART II

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Methodology Aim

To provide a more realistic and accurate heat recovery and power targeting for synthesis of utility systems operating at optimum conditions for future utility systems.

- Able to determine:
  - ✓ Optimal steam main operating conditions
  - ✓ Utility system configuration

- Account for:
  - ✓ **Full** and **partial load** performance of equipment
  - ✓ Different type of equipment: Gas turbines/HRSG, Steam turbines
  - ✓ More realistic conditions (**steam superheating** and **de-superheating**)
  - ✓ **Process steam generation at different conditions** from the steam mains.

Minimum *Total **Utility** Cost **(TUC)***

Minimum *Total **Annualized** Cost **(TAC)***

MILP Optimisation

Model Formulation

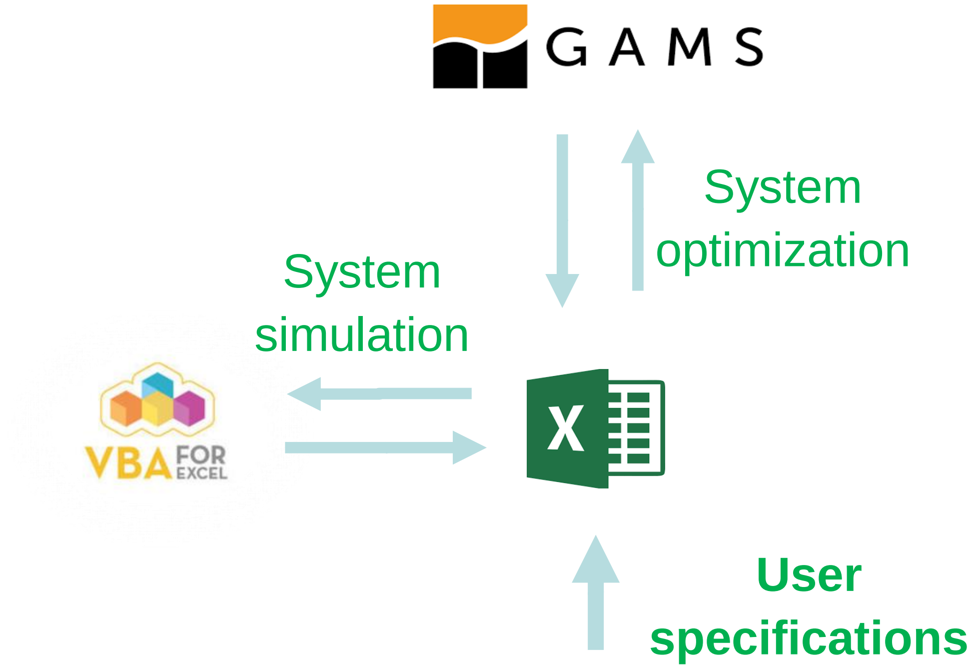
Objective Function:	***Minimise annualised cost*** **min TAC= CO+CC** **Operating costs:** Fuel, electricity, cooling water and treated water **Capital costs:** Boiler, HRSG, steam and gas turbines, deaerator, hot oil furnace
Continuous Variables:	Steam mass flow-rate Heat Loads
Integer Variables:	- **Potential steam levels for each steam main** - **Equipment selection** - **Equipment operation**
Constraints:	- Energy and Mass Balances in the **steam mains** - Energy and Mass Balances in the **deaerator** - Minimum **equipment load** - **Only one steam level can be selected for each steam main**
Solver:	CPLEX in GAMS

Methodology Approach

General Framework

How approach the problem?

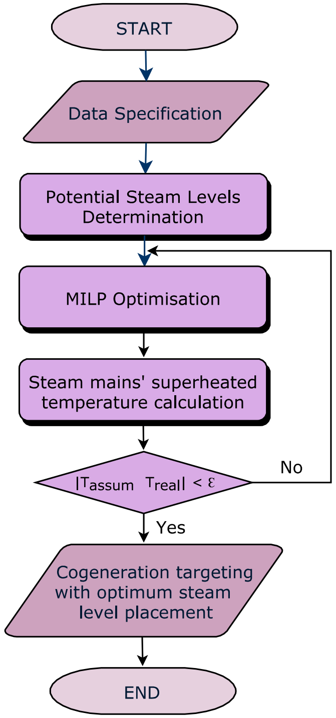
Successive MILP formulation



System optimization

System simulation

User specifications

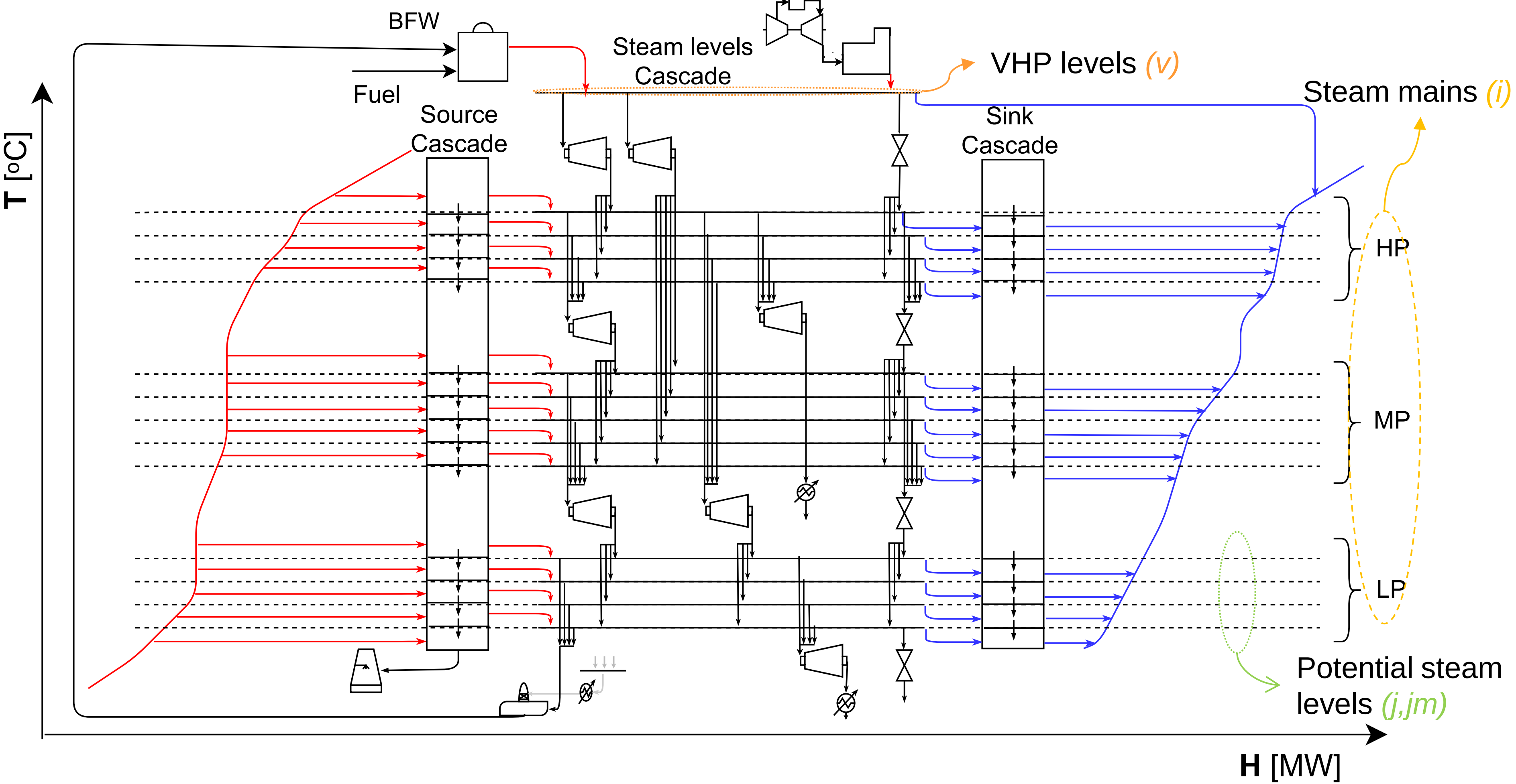


MILP Optimisation

Model Formulation

Cascading of Total Site Heat

Based on a **new transhipment method**

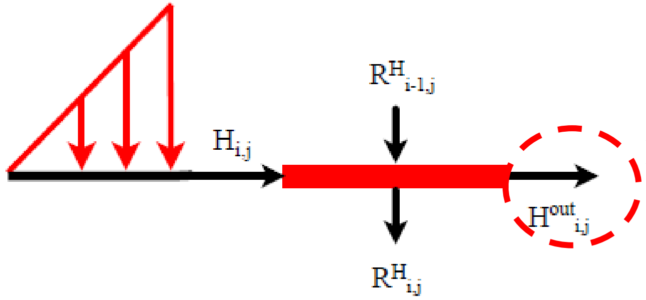


MILP Optimisation

Model Formulation

- **Main Constraints**

Heat Source Cascade



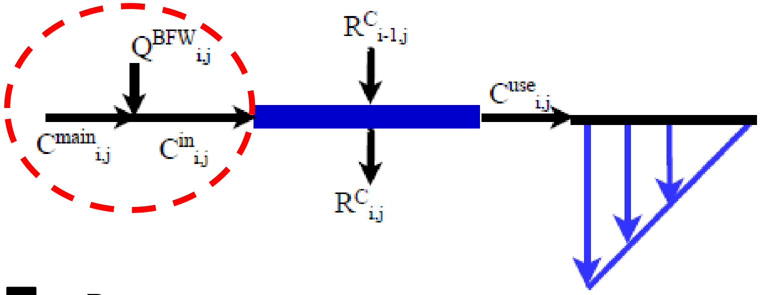
- **Steam generated** from BFW conditions to ***superheated conditions***

$$H^{in}_{i,j} + R^H_{j-1} = H^{out}_{i,j} + R^H_j$$

- Residual heat (R^H) is passed to the **next lower temperature interval** or the **cooling utility**

$$H^{out}_{i,j} = m^H_{i,j} \cdot \left(H_{sh}{}^H_j - H^{BFW}\right)$$

Heat Sink Cascade



- **Steam used** is ***desuperheated* (Injection of BFW)** (Q^{BFW})

$$m^C_{i,j} \cdot H_{sh}{}^{main}_j + m^{BFW_C}_{i,j} \cdot H^{BFW} = m^{C_{in}}_{i,j} \cdot \left(H_{sh}{}^C_j - H_l{}^C_j\right)$$

- **No residual heat** flowing **across steam mains**

$$R^C_{j-1} - U^C \cdot \left(1 - y^L_{i,j}\right) \le 0$$

⬛ Parameters

🟦 Continuous variables

🟩 Integer variables

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Case Study 1

Background

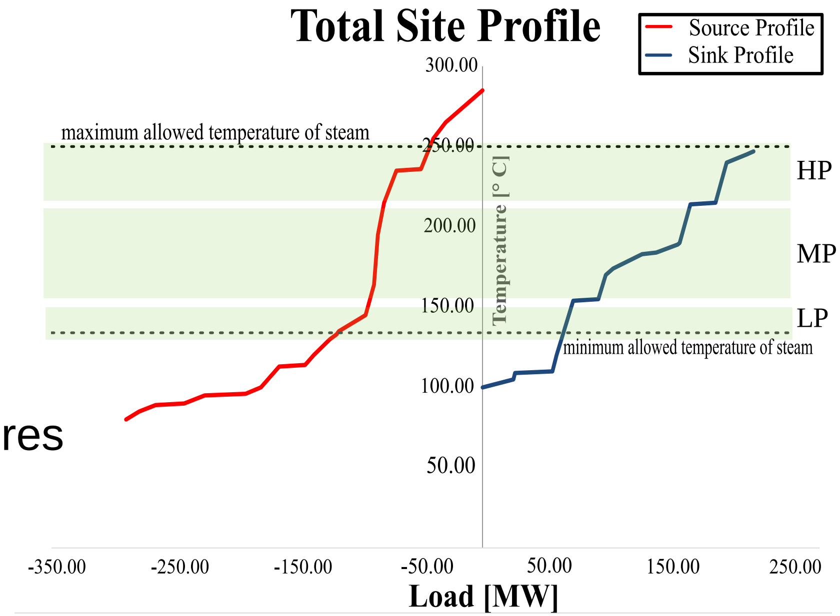
- A five-plant site
- Synthesis of a utility system to satisfy site thermal and electrical demand
- 3 distribution steam mains

Objective

- Minimum annualized cost

Constraints

- Max and min allowed utility temperatures
- Maximum electricity import 1 MW.
- Maximum electricity export 5 MW.
- Equipment load and size.
- No available steam imported or exported to or from the system.
- Steam generators spare capacity: 30%

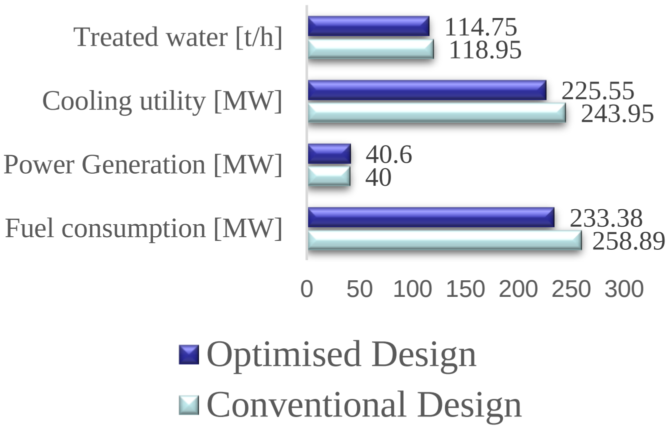


Case Study 1

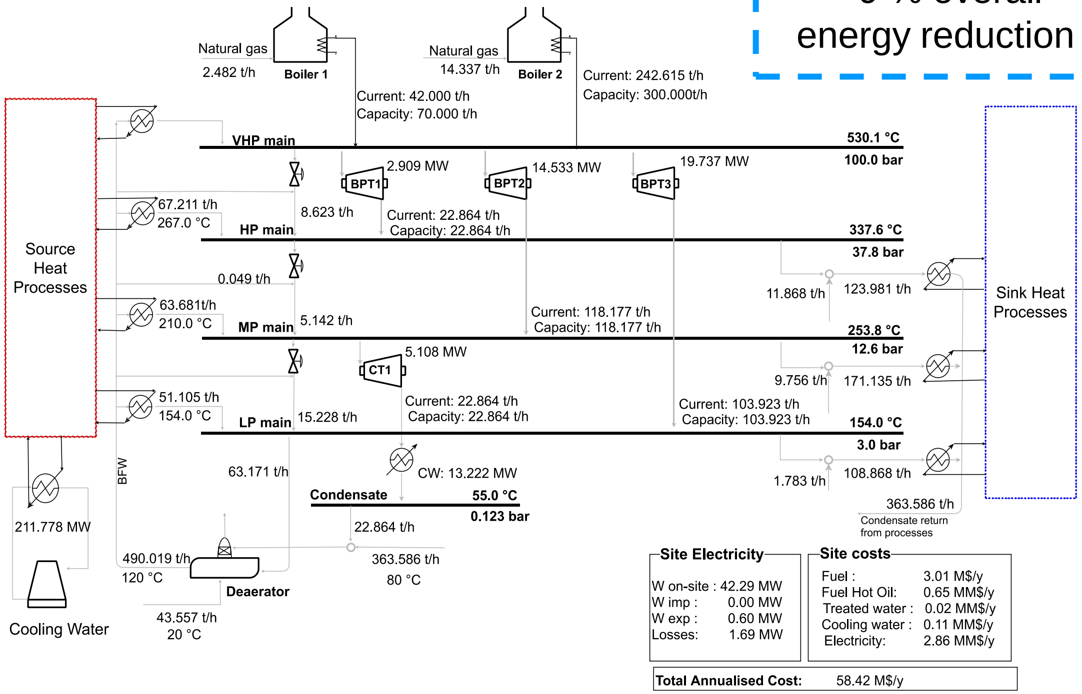
Steam main	‘Conventional’ design		Optimised design	
	Pressure [bar]	Temperature [°C]	Pressure [bar]	Temperature [°C]
VHP	**100**	501.4	**100**	530.1
HP	**40**	311.8	**37.8**	377.6
MP	**20**	282.8	**13.1**	253.8
LP	**5**	171.8	**3**	154.0

Natural gas price:	20.6 £/MWh
Electricity price:	
- Import	86.0 £/MWh
- Export	78.8 £/MWh

≈ 9 % overall energy reduction


Utilities consumption

Costs [M£/y]	Conventional	Optimised
Operating Costs	50.08	44.82
Capital Costs	15.20	13.50
TAC	**65.28**	**58.32**



Site Electricity

W on-site : 42.29 MW
W imp : 0.00 MW
W exp : 0.60 MW
Losses: 1.69 MW

Site costs

Fuel : 3.01 M$/y
Fuel Hot Oil: 0.65 MM$/y
Treated water : 0.02 MM$/y
Cooling water : 0.11 MM$/y
Electricity: 2.86 MM$/y

Total Annualised Cost: 58.42 M$/y

Optimal design

Case Study 1

Variation according to the location and type of industry

Utility	Country	Elegible	No- elegible
Natural gas [€/MWh]	UK	26	60
	Norway*	36	75
Electricity [€/MWh]	UK	130	160
	Norway	41	80

Source : Ecofys 2016 by order of: European Commission
Final Report "PRICES AND COSTS OF EU ENERGY"

Industries eligible for:

- Compensation
- Tariff reduction

Scenarios to analyse:

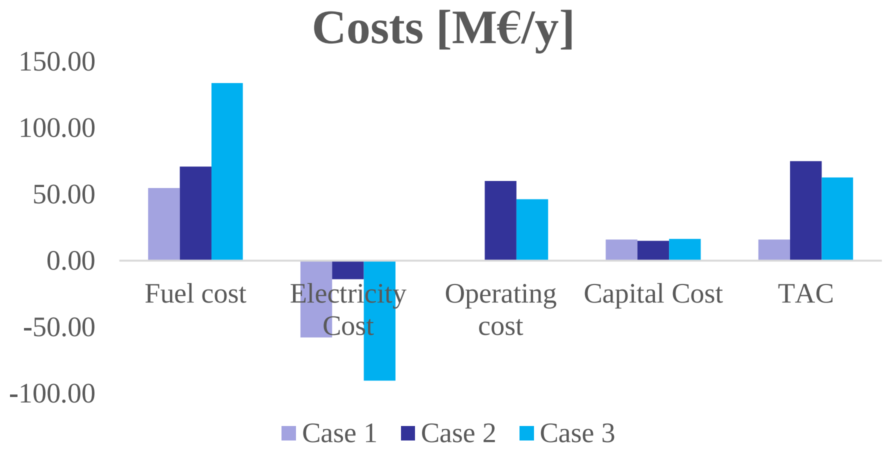
Case	Scenario	Natural gas [€/MWh]	Electricity [€/MWh]	Ratio price Natural gas /Electricity
1	Non-elegible UK	26	130	5.00
2	Non-elegible Norway	36	41	1.14
3	Elegible UK	60	160	2.67
4	Elegible Norway	75	80	1.07

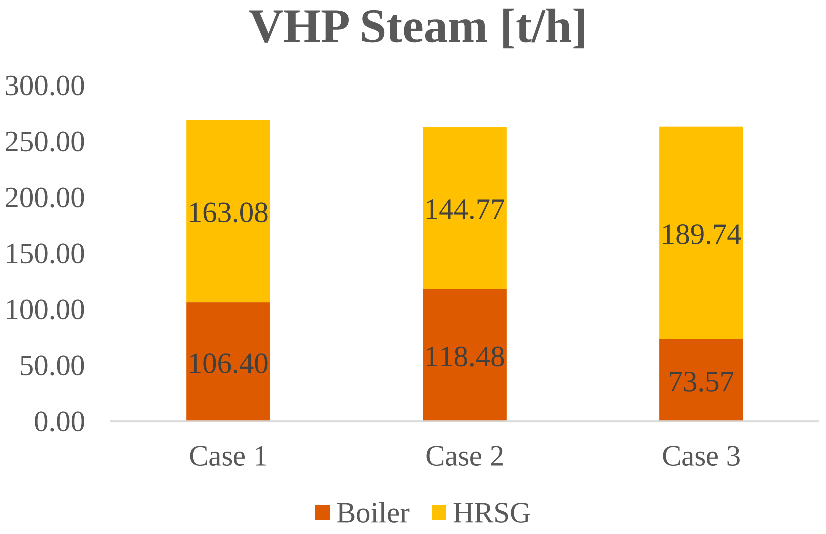
Similar ratio

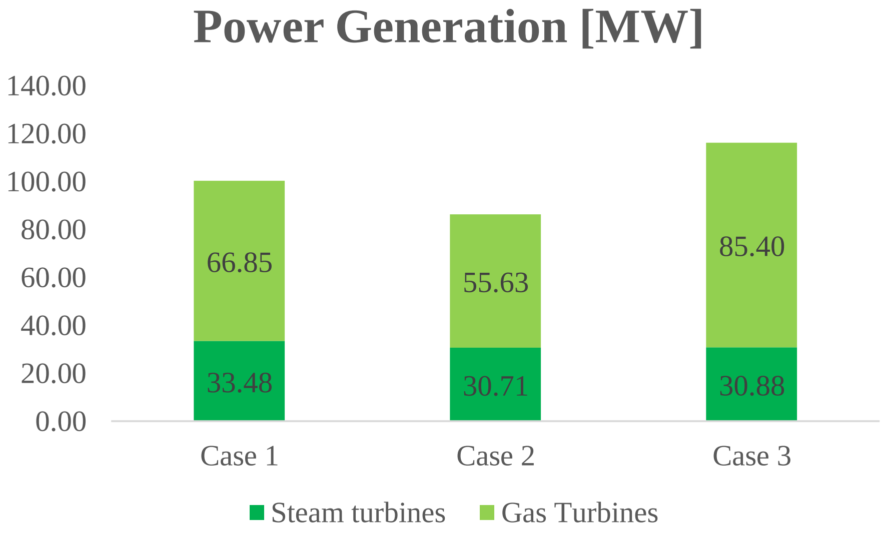
*The exact data for natural gas price is not available so an average of the Scandinavian countries values has been assumed for the analysis

Case Study 1

Sensitivity Analysis


Costs [M€/y]


VHP Steam [t/h]


Power Generation [MW]

Case Study 1

Conclusions

- The proposed methodology for site utility targeting with steam level placement is **efficient**.
  - ✓ Incorporate many ***realistic features*** not previously included.
  - ✓ Important ***reduction of the total energy requirement*** at the site compared to a conventional design.

- A sensitivity analysis has been performed to evaluate the utility system design towards the variation in key market parameters, such as the utility prices.

No ***'one size fits all'*** solution

Case Study 2

Background

- Total site energy demand
- Synthesis of a utility system that satisfy the thermal and electrical demand

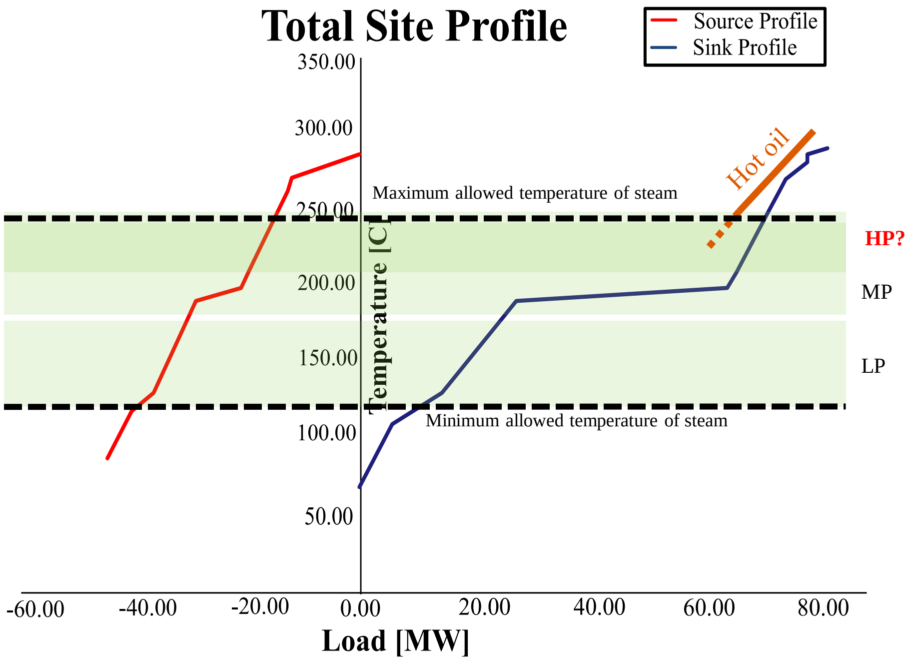
Objective

- Minimum total annualized cost

Constraints

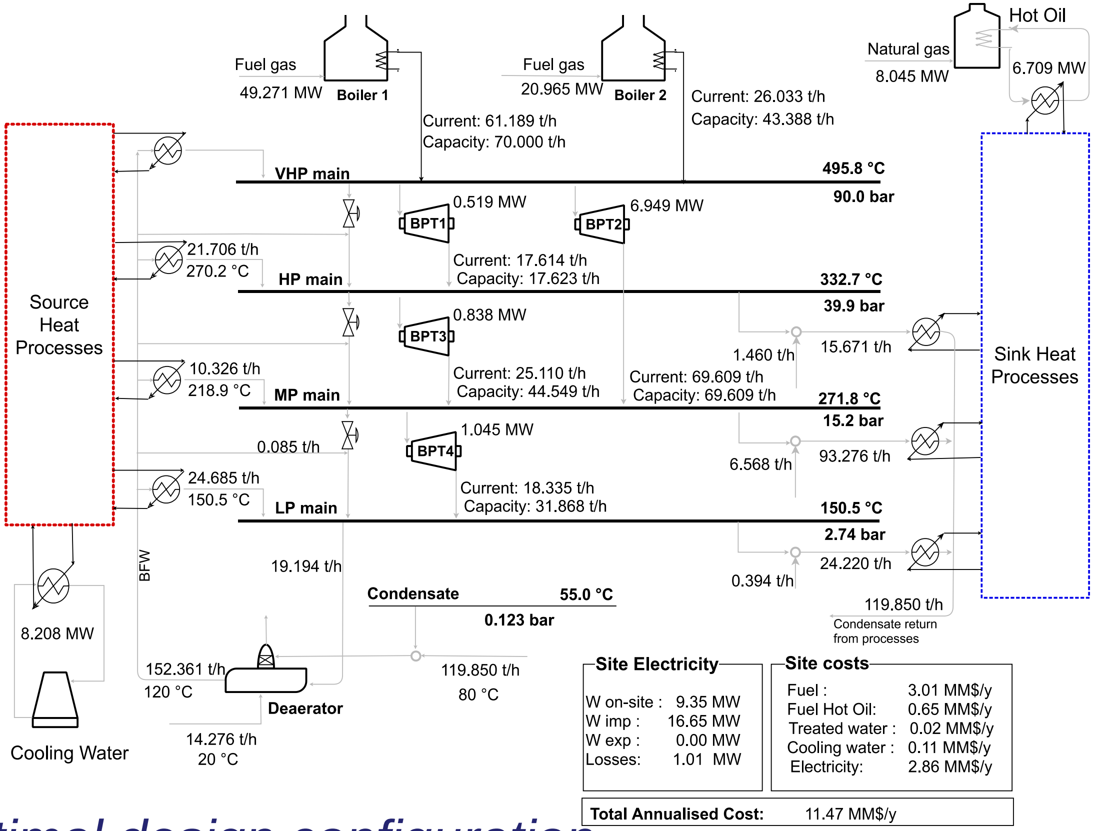
- Utility temperature constraints
- Which is the appropriate hot utility combination?
- How many steam mains?
- Maximum electricity export 5 MW.
- Equipment load and size.
- $T_{HO\ supply}$: 300 °C
- $\Delta T_{HO\ in\text{-}out}$: 90 °C

Fired heat required above 250 °C



Case Study 2

Options	MP pressure [bar]	Steam generation [t/h]	Power generation [MW]	Power generation per unit of boiler [MW h/t]
HO & 2 steam mains	**18.8**	75.90	7.38	**0.097**
HO & 3 steam mains	**15.2**	87.22	9.35	**0.107**



Site Electricity

W on-site : 9.35 MW
W imp : 16.65 MW
W exp : 0.00 MW
Losses: 1.01 MW

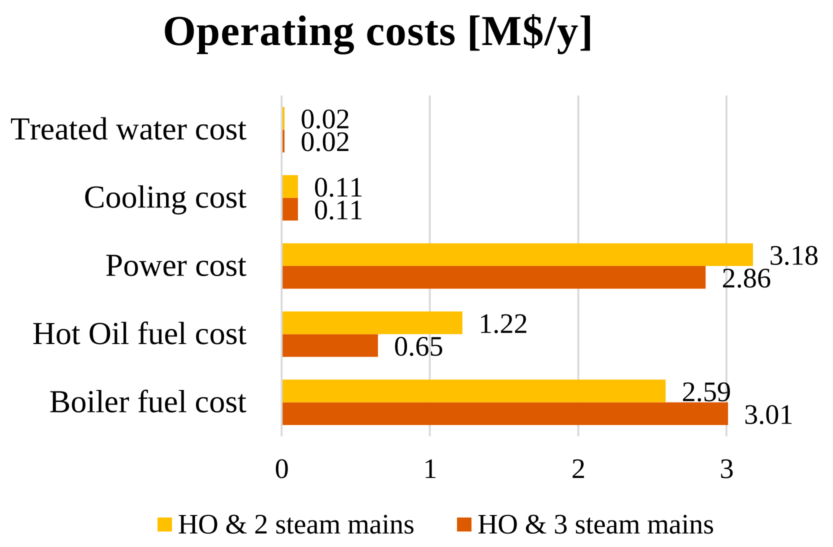
Site costs

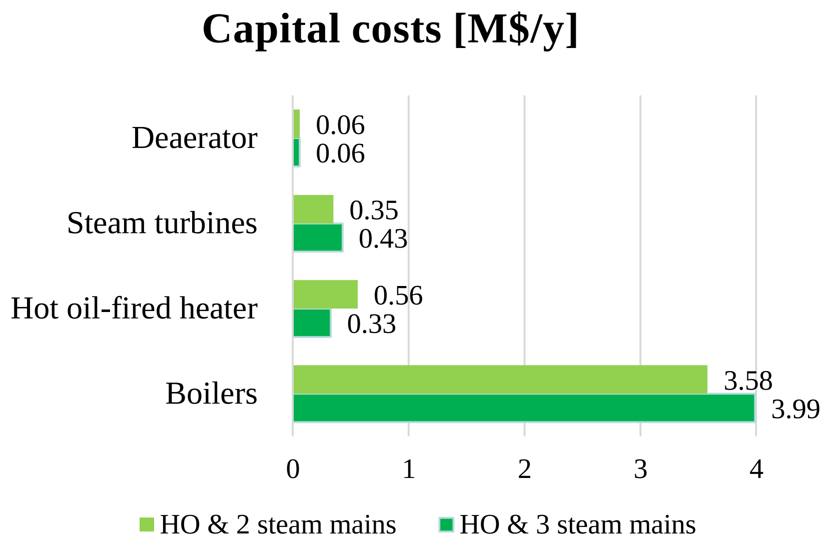
Fuel : 3.01 MM$/y
Fuel Hot Oil: 0.65 MM$/y
Treated water : 0.02 MM$/y
Cooling water : 0.11 MM$/y
Electricity: 2.86 MM$/y

Total Annualised Cost: 11.47 MM$/y

Optimal design configuration

Case Study 2





Options	Operating cost [M$/y]	Capital Cost [M$/y]	TAC [M$/y]
HO & 2 steam mains	7.12	4.55	**11.67**
HO & 3 steam mains	6.64	4.83	**11.47**

Case Study 2

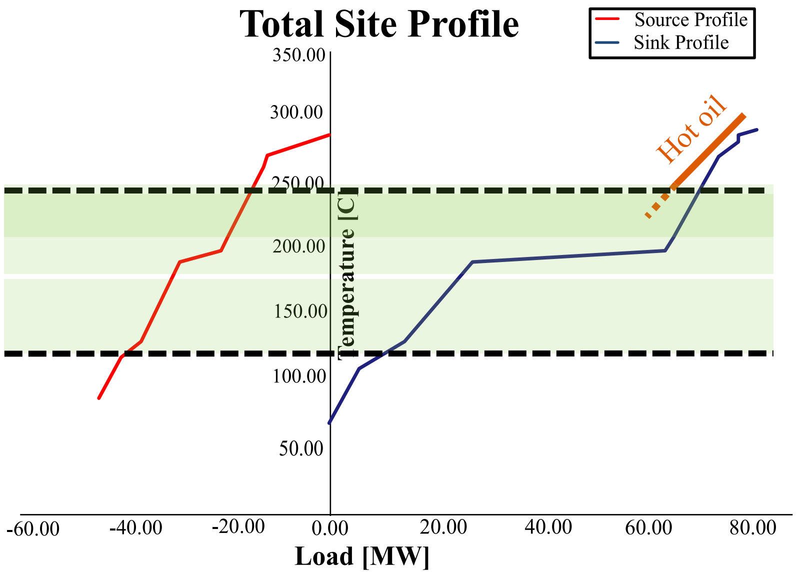
Conclusions

- There is a **trade-off** between the costs savings due to reduction of the boiler demand, and the power generation potential by steam expansion.
- **High complexity of the superstructure** gives rise different configurations with very close costs.
- Due to the close costs for the two configurations, further analysis of the implication costs of an additional steam main should be performed prior its implementation.

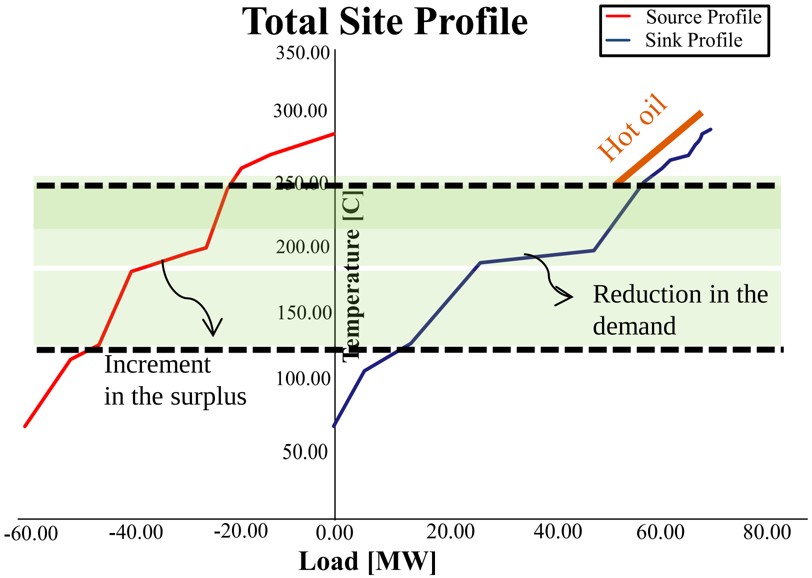
Case Study 3

Background

- The system's energy requirement changes seasonal and daytime
- In addition, the price of electricity change



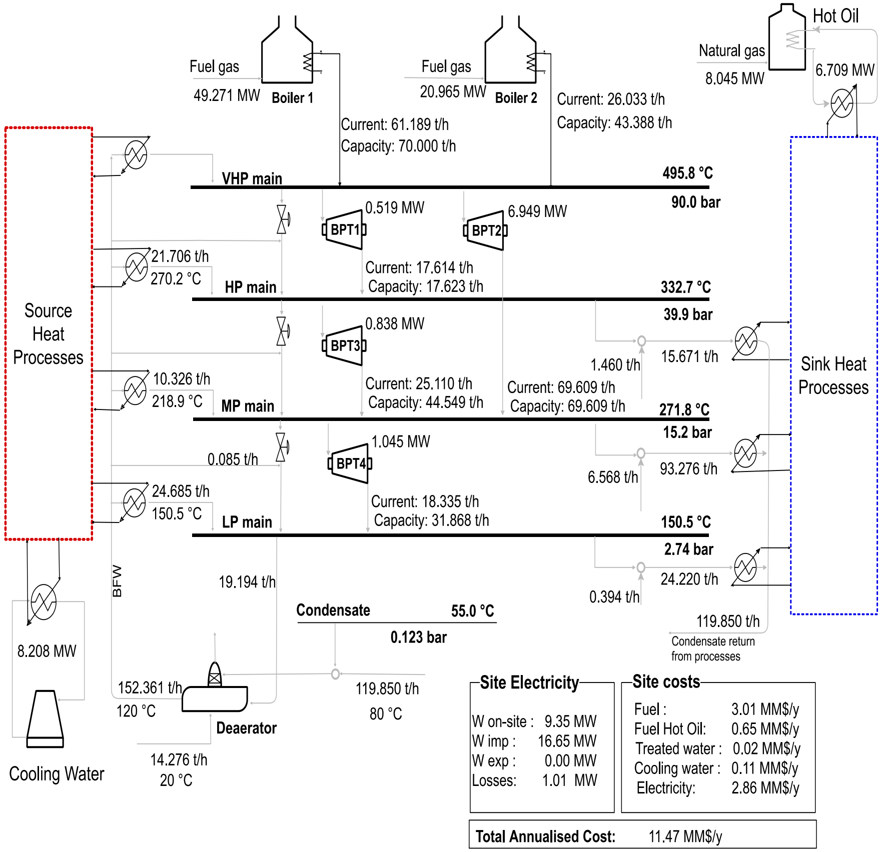
Winter period



Summer period

Parameters	Winter	Summer
Heating demand [MW]	83.024	68.215
Cooling demand [MW]	44.710	61.913
Power demand [MW]	25.000	30.000
Electricity Price [$/MWh]	30.00	20.00

Case Study 3



Site Electricity

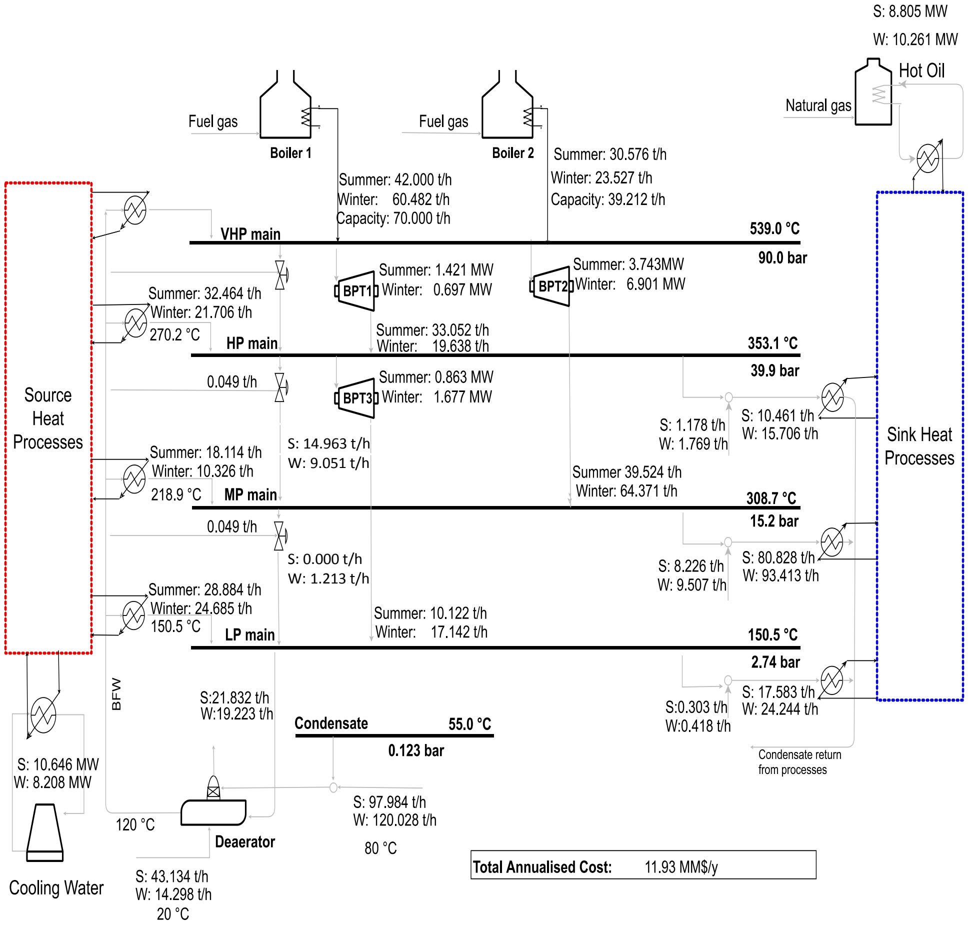
W on-site :	9.35 MW
W imp :	16.65 MW
W exp :	0.00 MW
Losses:	1.01 MW

Site costs

Fuel :	3.01 MM$/y
Fuel Hot Oil:	0.65 MM$/y
Treated water :	0.02 MM$/y
Cooling water :	0.11 MM$/y
Electricity:	2.86 MM$/y

Total Annualised Cost: 11.47 MM$/y

Optimal design configuration steady state



Total Annualised Cost: 11.93 MM$/y

Optimal design configuration multiperiod

PART II

1. Project Objectives
2. Cogeneration targeting
3. Design of utility system
4. Methodology
5. Case studies
6. Conclusions and future work

Conclusions so far

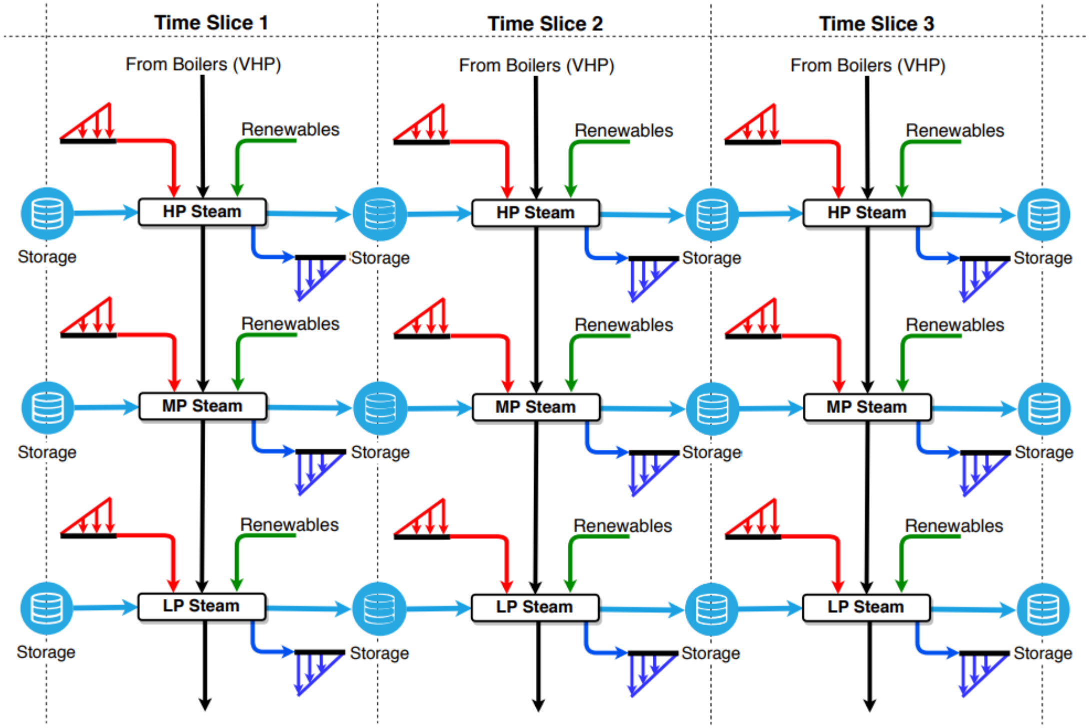
- Energy requirement can be further reduced by holistically optimising the steam mains operating conditions and the site heat recovery and cogeneration.

- Utility systems synthesis is sensitive to the variation of the utility price, restrictions of power import and export, and seasonal variations.

- Current methodology shows the necessity of integrate:
  - Low heat temperature technologies, for a better utilization of the heat
  - Energy storage to smooth the demand variation, and decrease the equipment size

- This work lays the **foundation for a systematic approach** to explore the next generation of **sustainable utility systems**.

Future work



- ➢ **Multi-period analysis**, considering *redundancy* and taking into account *uncertainties*.
- ➢ Integration of different energy sources and technologies, including energy storage.
- ➢ Implementation of life cycle assessment of each energy technology .

Thanks for your attention

Any question?