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
Outline

1. Industrial Energy Consumption and Emissions

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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

Industrial Clusters mission (UK)

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

Energy Demand

Industry is the largest consumer of energy worldwide

Share and breakdown of energy demand, 2016 [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
**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

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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**
**Current Situation**

**Renewable Energy Growth**

Based on current plans and policies

**2015**
- 19% of global energy demand
- 23% of power generation
- Only 9% in industrial sector

**By 2030**
- 21*- 37%** of global energy demand
- 13*- 23%** in Industry

**By 2050**
- 23*- 61%** of global energy demand
- 37*- 82%** of power generation
- 16*- 39%** in Industry

**Gives effective de-carbonisation**

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

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

But..

Flexible CHP systems can provide these grid services

but little attention paid so far

Integration of Renewables and Waste in Industrial Systems

Which is the appropriate mix of sources and technologies?

- Biomass
- Hydro
- Solar
- Wind
- Waste gases
- Waste

Possibly completely different system configuration and operation
Integration of Energy Storage in Industrial Systems

Integration of electricity and/or thermal storage storage?

- Type?
- Size?
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 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**?

- **Steam system**

- **Fired heating**
  - Furnace?
  - Hot oil circuit?

- **Steam mains**
  - Number?
  - Operating conditions?

**“Waste heat”**
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**

Steam Boiler performance as function of load

Efficiency may decrease up to 20% $\eta_{\text{max}}$
Steam Turbines
- Type
  (Condensing turbine, BP turbine, extracting turbine)
- Size, load
- Inlet and outlet conditions (T and P)

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

Stein turbine performance as function of load:

\[
\frac{\eta}{\eta_{\text{max}}} [-] \quad \frac{W}{W_{\text{max}} [-]}
\]

Gas turbine performance as function of load:

\[
\frac{\eta}{\eta_{\text{max}}} [-] \quad \frac{W}{W_{\text{max}} [-]}
\]

Efficiency decrease drastically with part-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
Steam mains

Do we have our steam mains at the correct pressure?

At saturated conditions?

Do we have the correct number of steam mains?
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
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:

- Equipment selection
- Equipment operating status
- Steam main selection (P)
- Energy balances
- Equipment performance models
- Steam thermodynamic properties

Complex and time consuming
Previously, the designs were based on **nominal operating conditions** of each process

**BUT...**

In the reality, operating conditions and the environmental conditions will vary significantly through time

- 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
Multi-period approach

Operating scenarios or periods

Various scenarios to represent different operating scenarios
Synthesis of utility systems accounting for energy demand variation

Variation with time
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)
## Decomposition

Two different approaches to the optimisation

<table>
<thead>
<tr>
<th>Description</th>
<th>sMILP</th>
<th>Two-stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence of MILP optimisation and simulation stages.</td>
<td>Master problem (rMINLP) followed by a non-linear sub problem</td>
<td></td>
</tr>
<tr>
<td>CPU time</td>
<td>Fastest (&lt; 500 s)</td>
<td>Faster than commercial global solvers (&lt; 1000 s)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- BARON 10 times slower</td>
</tr>
<tr>
<td>Global optimality</td>
<td>Cannot be guaranteed</td>
<td>Guaranteed</td>
</tr>
</tbody>
</table>
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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)

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

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

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

<table>
<thead>
<tr>
<th>Case</th>
<th>Considerations</th>
<th>Objective Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>Variable energy demand</td>
<td>TAC</td>
</tr>
<tr>
<td>Case B</td>
<td>Variable energy demand</td>
<td>CO₂ emissions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electricity prices*</th>
<th>Off-Peak</th>
<th>Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>purchase (£/MWhel)</td>
<td>111.4</td>
<td>127.2</td>
</tr>
<tr>
<td>sale (£/MWhel)</td>
<td>81.7</td>
<td>96.4</td>
</tr>
<tr>
<td><strong>Mid-season</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>purchase (£/MWhel)</td>
<td>111.4</td>
<td>127.2</td>
</tr>
<tr>
<td>sale (£/MWhel)</td>
<td>81.7</td>
<td>96.4</td>
</tr>
<tr>
<td><strong>Winter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>purchase (£/MWhel)</td>
<td>111.4</td>
<td>127.2</td>
</tr>
<tr>
<td>sale (£/MWhel)</td>
<td>81.7</td>
<td>96.4</td>
</tr>
</tbody>
</table>

*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).

<table>
<thead>
<tr>
<th>Emissions factors [t CO₂/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
</tr>
<tr>
<td>Fuel gas</td>
</tr>
<tr>
<td>Natural gas</td>
</tr>
</tbody>
</table>
Case A: Variable Energy Demand

Comparison of the designs

Optimal design configuration
– nominal

Optimal design configuration
– variable demand

Different configuration and sizes

Different temperature conditions

Comparison of the designs
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

<table>
<thead>
<tr>
<th>Difference Between Peak and Off-peak Electricity</th>
<th>40%</th>
<th>60%</th>
<th>80%</th>
<th>100%</th>
<th>230%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost (mm£/y)</td>
<td>7.99</td>
<td>7.29</td>
<td>7.35</td>
<td>7.45</td>
<td>7.64</td>
</tr>
<tr>
<td>Capital cost (mm£/y)</td>
<td>6.81</td>
<td>6.63</td>
<td>6.69</td>
<td>6.58</td>
<td>6.60</td>
</tr>
<tr>
<td>Battery Capacity (MWh)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4.00</td>
</tr>
</tbody>
</table>

- 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 CO₂ Emissions

- Electricity import is favoured due to lower CO₂ 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
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.

### Case Study Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>Base Case</th>
<th>Case A</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective function</td>
<td>min TAC</td>
<td>min TAC</td>
<td>min CO₂ emissions</td>
</tr>
<tr>
<td>Electricity price variation</td>
<td>N/A</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Operating costs [m£/y]</td>
<td>6.64</td>
<td>6.80</td>
<td>9.65</td>
</tr>
<tr>
<td>Capital costs [m£/y]</td>
<td>4.83</td>
<td>5.13</td>
<td>8.70</td>
</tr>
<tr>
<td>CO₂ emissions [t/y]</td>
<td>153,866</td>
<td>138,855</td>
<td><strong>108,247</strong></td>
</tr>
<tr>
<td>TAC [m£/y]</td>
<td>11.47</td>
<td>11.93</td>
<td><strong>18.35</strong></td>
</tr>
</tbody>
</table>
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Society needs energy in the form of electricity, heat and transportation energy.
Supply of these needs has traditionally not been integrated.
Energy and Society

Electricity
Energy
Heat
Water
Food

Transportation Energy

BUT, this needs to be considered in the context of the Energy-Food-Water 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

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**

- **Power Plants** (50-5000 MW<sub>elec</sub>):
  - Efficiency 35-45% (up to 60% for combined cycle)

- **Central Grid**:
  - Distribution losses (5-7% of electricity)

- **Home and Building Heating** (stand-alone boilers):
  - Heat loss ~20% of fuel energy content

- **Large Scale Industry** (combined heat & power):
  - Waste heat ~40% of energy input

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**Distributed Systems**

- **Power storage**
- **Energy sources**
- **Waste Heat**
- **Distributed energy centre**
- **District heating**
- **Heat storage**
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
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...
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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
# Case Study II - Input

Energy supply units (including CHPs and heat only units)

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

[CHP units](#)

[Heat only units](#)
Case Study II - Input

Present and future energy prices

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Natural gas price (p/kWh)</td>
<td>2.93</td>
<td>3.97</td>
<td>4.05</td>
<td></td>
<td></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>3. Electricity price (p/kWh)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off peak</td>
<td>4.80</td>
<td>5.58</td>
<td>9.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average price</td>
<td>6.80</td>
<td>7.91</td>
<td>12.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak</td>
<td>7.00</td>
<td>8.14</td>
<td>13.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source:
Department of Energy and Climate Change, Interdepartmental Analysts’ Group, Valuation of energy use and greenhouse gas (GHG) emissions, tool kit, 2012
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
• CO₂ emissions can be taxed if appropriate
• Formulate as MILP

Constraints
• Maximum/minimum load on units
• Maximum CO₂ 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

Conclusions
• 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.
Acknowledgement

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Thanks for your attention

Any question?