Optimisation of integrated energy conversion systems

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Example: Thermo-economic modeling of power plants

Thermodynamic models
\[ \dot{m}_i, \dot{W}_i, P_i, T_i \Rightarrow \text{Size}_i \]
Cost \( i \) = \( f(\text{Size}_i, P_i) \)

Thermo-economic models
\[ \dot{m}_{NG}, \dot{m}_{CO_2}, \sum \dot{W}_i \]
\[ \text{OC} = \dot{m}_{NG} * C_{GN} + \dot{m}_{CO_2} * T_{CO_2} - C_{el} * \sum \dot{W}_i \]

System Performances

System investment
\[ IC = \sum Cost_i \]
**Superstructures**

Equipments options
Low Nox burner, O2 burning

Equipments selection
1 / 2 gas turbines, CO2 separation

Equipments interconnection
draw-off, heat exchangers

System integration
heat exchange system

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**Optimisation**

Decision variables
Continuous Variables $\dot{m}_i, T_i, P_i$
Integer Variables $\text{Option}_i, \text{equipment}_i$

Objective functions
Op. cost, Total cost, Investment, Emissions, Efficiency

Solving methods
Multi-objective optimisation

Decision variables
Continuous Variables
\( m_i, T_i, P_i \)
Integer Variables
\( \text{Option}_i, \text{equipment}_i \)

Objective functions
Op. cost
Total cost
Investment
Emissions
Efficiency

Multi-objective optimisation (MOO)
- Evolutionary algorithm
- Mixed Integer Non Linear Prog.
- Clusters of solutions

Pareto Curves

Emissions (kg CO2/kWh)
Investment Cost ($/kW)
Infeasible
Min Emissions for a max Investment
Min Investment for a max emission
Performances
System configuration
Equipment design specifications
For each configuration:
- Selected equipments
- Operating conditions: \( T, P, m \)
- Interconnections
- Sizes

Technically inaccessible region

Calculations for 1 plant size

Typification Map

GT & NGCCs based on ALSTOM Catalogue

Based on public data from ALSTOM Website
Definition of technology port-folio

- Competing options
  - Different markets
  - Different objectives
- Market identification
  - For a given technology
  - For a given goal
    - E.g. CO2 emissions
- CDM Potential
  - Effect of CO2 value wrt to baseline

Typification Through Thermoeconomic Modelling and Multi-Objective Optimization

Natural Gas Price Sensitivity Analysis(1)

Natural gas price: 1 UScents/kwh, Annual operating hours: 7500, Depreciation period: 15 years
Typification Through Thermoeconomic Modelling and Multi-Objective Optimization

Natural Gas Price Sensitivity Analysis (2)

Natural gas price: 2 US cents/kwh, Annual operating hours: 7500, Depreciation period: 15 years

Typification Through Thermoeconomic Modelling and Multi-Objective Optimization

Natural Gas Price Sensitivity Analysis (3)

Natural gas price: 3 US cents/kwh, Annual operating hours: 7500, Depreciation period: 15 years
**Cost of Electricity vs CO2 Emission Rate**

NGCCs based on ALSTOM Catalogue

1 GT26
2 GT26
1 GT1
2 GT1
3 GT1
1 GT13
3 GT13

**Sensitivity analysis: CO2 impact**

From technology data base

\[
\frac{\dot{m}_{NG}^i\dot{E} + \dot{O}^i + \frac{1}{T^i} I^i}{\dot{m}_{CO2}^i - \dot{m}_{CO2}^\text{ref, i}} - \text{LEC}^\text{ref, i}\dot{E}
\]

\[
\frac{\dot{m}_{NOx}^i - \dot{m}_{NOx}^\text{ref, i}}{\dot{m}_{CO2}^i - \dot{m}_{CO2}^\text{ref, i}}
\]

Country i

Country 1

Country 2
The same system in different context

Configuration with 2 GT 26

Annual operating hours: 8000, Depreciation period: 15 years

Optimal Configuration 57.6% 845 MW
Optimal Configuration 58.2% 826 MW
USA NG Price: 0.9 UScents/kWh
Germany NG Price: 1.0 UScents/kWh
China NG Price: 1.45 UScents/kWh

Advanced power plants

CO₂ Sequestration Subsystem
GAS TURBINE SUBSYSTEMS
GAS SUPPLY SUBSYSTEM
STEAM CYCLE SUBSYSTEMS
Transportation and Storage
CO₂ separation
CO₂ to atmosphere
Project: Supply 400 MW to a community

\[ \text{Min (COE}_{av}, \ RCO2_{av}) = f(\vec{x}, \vec{y}) \]

subject to

\[ \begin{align*}
  & h_j(\vec{x}, \vec{y}) = 0 \quad j = 1, \ldots, J \quad \text{(equality constraint s)} \\
  & g_k(\vec{x}, \vec{y}) \geq 0 \quad k = 1, \ldots, K \quad \text{(inequality constraint s)}
\end{align*} \]

Average Cost of Electricity \( \text{COE}_{av} \) [US$/kWh] =

\[ \frac{\text{Annual Capital Cost} + \text{Annual O&M Cost} + \text{Annual Fuel Cost} + \text{Power Importation Cost}}{\text{Total Annual Power Demand}} \]

Average \( \text{CO2} \) Emission Rate \( \text{RCO2}_{av} \) [gCO2/kWh] =

\[ \frac{\text{Annual CO2 Emission from NGCC combustion} + \text{Annual CO2 Emission Due to Natural Gas Leakage} + \text{Annual CO2 Emission due to Power Importation}}{\text{Total Annual Power Demand}} \]

Pareto Optimization Frontier (POF) of a 400 MW Power Supply Project in Germany

Natural gas price is of 1 UScents/kWh; Electricity importation price is of 3.8 UScents/kWh
Sensitivity Analysis (I)                                       
Different CO2 Tax Levels
 0 US$/tonCO2
Baseline:       ... Importation
C1
30 US$/tonCO2
A1
B2 C1
D2
CO2 emission 
limitation
D1
COEav (UScents/kWh)
RCO2av (gCO2/kWh)

Alternative Presentation: Relative CO2 Abatement Cost

For a given baseline (Reference Case)

\[
\text{CO}_2 \text{ abatement cost (ABC)} \ [\text{US$/tonCO2}] = \frac{(\text{COE}_{\text{av}} - \text{COE}_{\text{baseline}})}{(\text{RCO2}_{\text{av}} - \text{RCO2}_{\text{baseline}})} \ [\text{US$/kWh}] \div \text{tonCO2/kWh}
\]

\[
\text{CO}_2 \text{ abatement percentage (AP)} \ [%] = \frac{(\text{RCO2}_{\text{av}} - \text{RCO2}_{\text{baseline}})}{\text{RCO2}_{\text{baseline}}} \ [\text{gCO2/kWh}] \div \text{gCO2/kWh}
\]
CO2 Abatement Percentage vs CO2 Abatement Cost

BASELINE: Full Electricity Importation from Power Grid

Further financial aid is needed

CO2 Abatement Percentage - AP (%)