Sustainable Energy Technology Assessment using Multi-Objective Optimisation

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IEA-ETSAP meeting, Lisbon, Portugal, 10-12 December 2012

Introduction

Main motivation for the adoption of hydrogen as an alternative energy career:

\begin{itemize}
  \item Reduce well-to-wheel GHG gases emissions [Hugo et al., 2006]
  \item Increase energy supply security [CONAMA 8, 2006]
\end{itemize}

Main obstacles to achieve the hydrogen transition [Jensen and Ross, 2000]:

\begin{itemize}
  \item Integrating efficient fuel cells into the vehicles
  \item Improvement of storage technologies
  \item Developing an efficient infrastructure for producing and delivering hydrogen
\end{itemize}

Objective: develop frameworks for the strategic planning of infrastructures for producing and delivering hydrogen that provide a holistic view of the system

\begin{itemize}
  \item Covering the entire supply chain (Life Cycle Assessment)
  \item Including several environmental indicators and financial risk metrics along with traditional economic performance criteria (Multi-Objective Optimisation)
\end{itemize}

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Importance of covering the entire life cycle...

Objective
Develop a framework for the design and planning of sustainable processes:
• Cover the entire hydrogen supply chain (holistic view of the system)

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Multi-Objective Optimisation (MOO)

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Problem Statement
Hydrogen supply chain in Spain

In each region...

Production
- p=1 → Steam methane reforming
- p=2 → Coal gasification
- p=3 → Electrolysis

Storage
- s=1 → Liquid hydrogen (LH) storage
- s=2 → Compressed gas (CH) storage

Transportation
- l=1 → Liquid hydrogen (LH) tanker truck
- l=2 → Compressed-gasous hydrogen (CH) tube trailer
- l=3 → Liquid hydrogen (LH) railway tank car
- l=4 → Compressed-gaseous hydrogen (CH) railway tube car
- l=5 → Liquid hydrogen (LH) ships
- l=6 → Compressed-gaseous hydrogen (CH) pipelines

Model objectives are:

1) Minimize Total discounted cost
2a) Minimize Financial Risk
2b) Minimize Environmental Impacts CS, RE, CC, OLD, ES, AE, DM and DFF

Results MOO Cost-Financial Risk metric (I)
Pareto optimal solution curve for a 6 time period problem

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Results MOO Cost-Financial Risk metric (II)

Hydrogen supply chain design in Spain for Minimum Expected Total Discounted Cost Solution

Results MOO Cost-Financial Risk metric (III)

Hydrogen supply chain design in Spain for Minimum Worst Case Solution
Results MOO Cost-Environmental Impacts (I)

- We solved 8 sets of separate bicriterion optimization problems, run 7 iterations
- Two different solution patterns are identified within the results

Pattern 1: collective impact indicators

Min (TDC, RE)  Min (TDC, OLD)  Min (TDC, ES)  Min (TDC, DM)

- While minimizing one metric all the rest are reduced

Pattern 2: individual impact indicators

Min (TDC, CS)  Min (TDC, CC)  Min (TDC, AE)  Min (TDC, DFF)

- While minimizing one metric, other metrics are incremented and trends change

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Results MOO Cost-Environmental Impacts (II)

Minimizing total discounted cost and damage to human health caused by carcinogenic substances CS

Minimizing total discounted cost and damage to ecosystem quality caused by ecotoxic substances ES

A→B Liquid hydrogen to compressed hydrogen produced via steam methane reforming (SMR)

B→D Compressed hydrogen produced via water electrolysis (WE) (in some cases liquid hydrogen is produced in B)

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Results MOO Cost-Environmental Impacts (III)

Minimum Total Discounted Cost

• Liquefied H2 produced via steam methane reforming
• 10 H2 plants fulfill the total demand
• Quite centralized design
• Short distance road transport is done by trucks, middle distance by railroad
• Melilla, Balearic and Canary islands import H2 via freighted ships

Minimum Collective Environmental Impacts

• Compressed H2 steam methane reforming
• No H2 transport: pure decentralized design

Minimum Individual Environmental Impacts

• Compressed H2 via water electrolysis
• No H2 transport: pure decentralized design

Solution procedure and example

Bi-criterion MILP with risk concerns

\[
\min_{x,X,N} \quad (TDC(x, X, N), \Omega(x, X, N))
\]
\[
\text{s.t.} \quad g(x, X, N) \leq 0
\]
\[
\quad h(x, X, N) = 0
\]
\[
\quad x \in \mathbb{R}, X \in \{0, 1\}, N \in \mathbb{N}
\]

Epsilon constraint method:

Solve a set of single objective problems for different values of \( \varepsilon \)

\[
\min_{x,X,N} \quad (TDC(x, X, N))
\]
\[
\text{s.t.} \quad g(x, X, N) \leq 0
\]
\[
\quad h(x, X, N) = 0
\]
\[
\quad \Omega(x, X, N) \leq \varepsilon
\]
\[
\quad x \leq \varepsilon \leq \bar{\varepsilon}
\]
\[
\quad x \in \mathbb{R}, X \in \{0, 1\}, N \in \mathbb{N}
\]

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Conclusions

- **MOO** can unveil the extent to which the different objectives considered by a decision maker are compromised, therefore providing as a sensitivity analysis for the objectives considered.

- **Implementation** in MARKAL/TIMES:
  - constraints already account for different metrics (e.g. GHG emissions)
  - Objective functions need to be implemented
  - The solution algorithm can be customized to obtain a certain number of points of the Pareto Front
  - Computational limitations? Hypothesis: can be overcomed by parallelization (running on multiple clusters)

- **Value added?** Flexibility to implement different objective functions, and therefore contributing to the current sustainable multi-goal energy problem

Current work

- Revamping and disaggregating the industrial sector for UK MARKAL/TIMES
- Energy efficiency and emission reduction in the shipping sector

Publications on hydrogen supply chain


Questions / Suggestions?

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