Sustainable Energy Technology Assessment using Multi-Objective Optimisation

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Introduction

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

Reduce well-to-wheel GHG gases emissions [Hugo et al., 2006]

Increase energy supply security [CONAMA 8, 2006]

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

1. Integrating efficient **fuel cells** into the vehicles
2. Improvement of **storage technologies**
3. Developing an **efficient infrastructure** for producing and delivering hydrogen

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

- Covering the **entire supply chain** (Life Cycle Assessment)
- Including several **environmental indicators and financial risk metrics** along with traditional economic performance criteria (Multi-Objective Optimisation)

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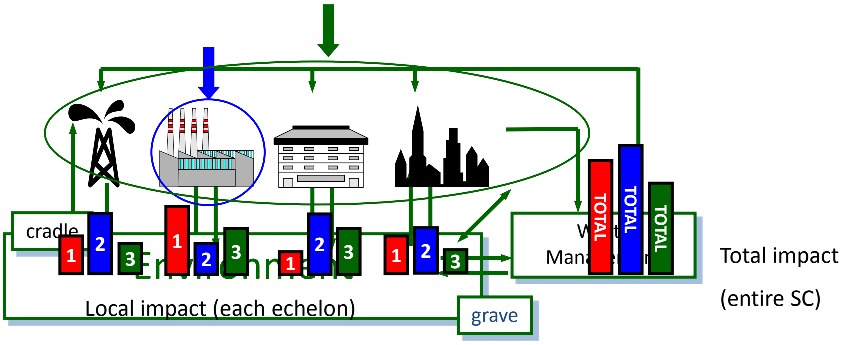
Life Cycle Assessment

Importance of covering the entire life cycle…

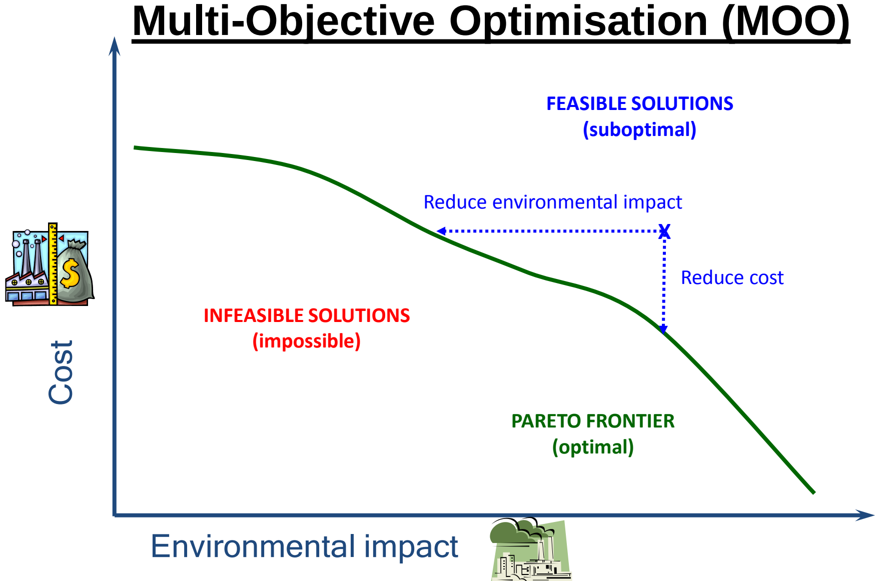


Objective

Develop a framework for the design and planning of sustainable processes:

- Cover the **entire hydrogen supply chain** (holistic view of the system)

Multi-Objective Optimisation (MOO)



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:

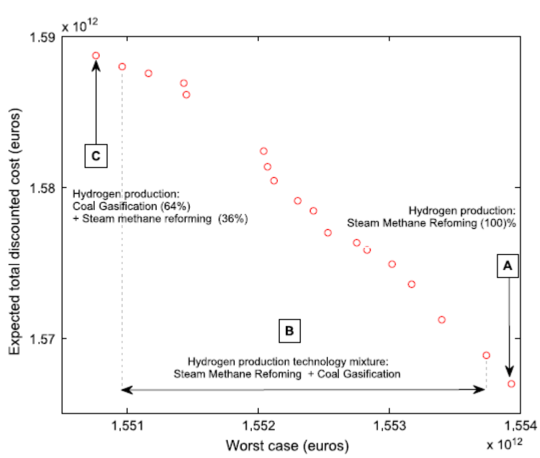
1) Minimize **Total discounted cost**

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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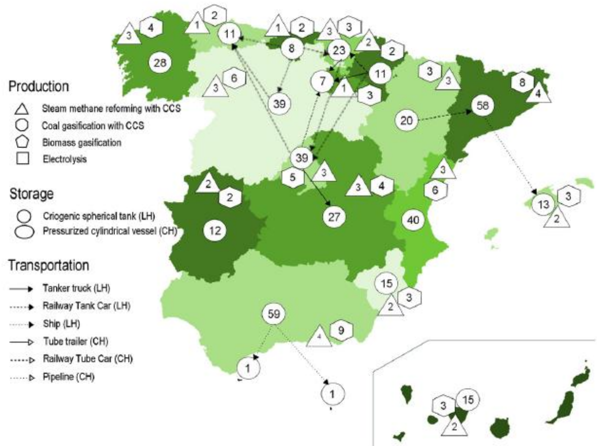
Results MOO Cost-Financial Risk metric (II)

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



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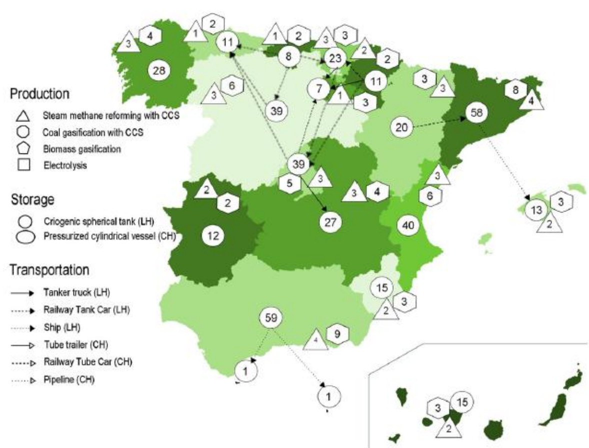
Results MOO Cost-Financial Risk metric (III)

Hydrogen supply chain design in Spain for Minimum Worst Case Solution

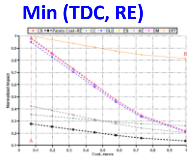


Results MOO Cost-Environmental Impacts (I)

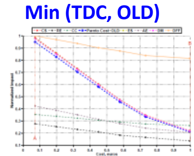
- We solved 8 sets of separate bicriterion optimization problems, run 7 iterations
- Two different solution patterns are identified within the results

Pattern 1: *collective impact indicators*

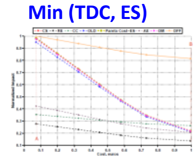
Min (TDC, RE)



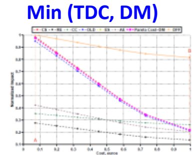
Min (TDC, OLD)



Min (TDC, ES)



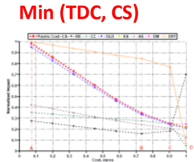
Min (TDC, DM)



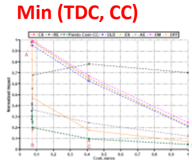
- While minimizing one metric all the rest are reduced

Pattern 2: *individual impact indicators*

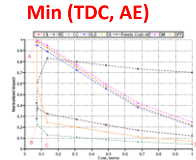
Min (TDC, CS)



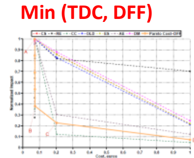
Min (TDC, CC)



Min (TDC, AE)



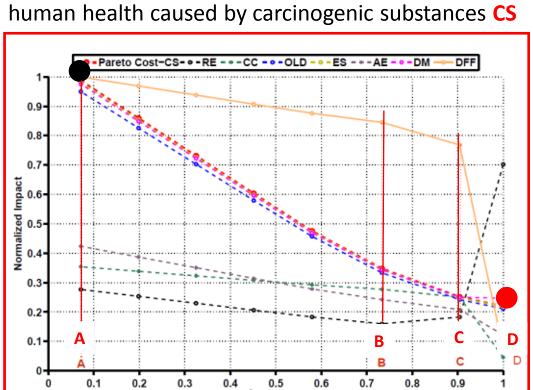
Min (TDC, DFF)



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

Results MOO Cost-Environmental Impacts (II)

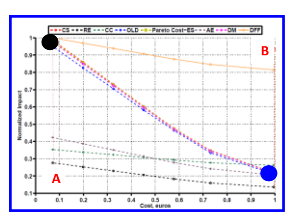
Minimizing total discounted cost and damage to human health caused by carcinogenic substances **CS**



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)

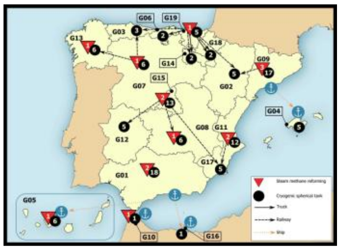
Minimizing total discounted cost and damage to ecosystem quality caused by ecotoxic substances **ES**



A→B Hydrogen produced via SMR goes from liquid to gaseous state

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

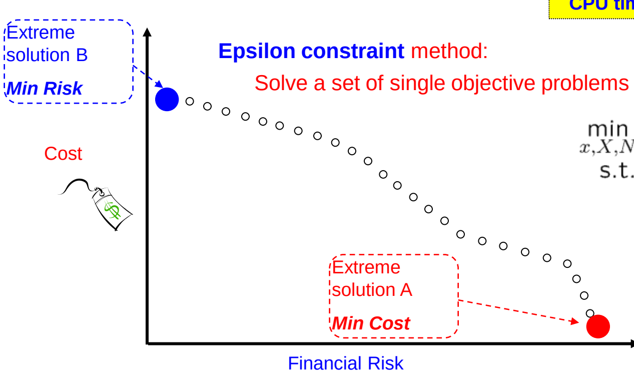
Bi-criterion MILP with risk concerns

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

Binary variables:	10580
Integer variables:	940
Continuous variables :	12701
Constraints:	35401
CPU time (s):	256

Epsilon constraint method:

Solve a set of single objective problems for different values of ε



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

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

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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

- Sabio, N., Gadalla, M., Guillén-Gosálbez, G., Jiménez, L. '***Strategic planning with risk control of hydrogen supply chains for vehicle use under uncertainty in operating costs: A case study of Spain***', International Journal of Hydrogen Energy, 35(13): 6836 - 6852 (2010)
- Sabio, N., Kostin, A., Guillén-Gosálbez, G., Jiménez, L.' ***Holistic minimization of the life cycle environmental impact of hydrogen infrastructures using multi-objective optimization and principal component analysis***', International Journal of Hydrogen Energy, 37(6): 5385-5405 (2012)

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Questions / Suggestions?

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