CHALMERS
UNIVERSITY OF TECHNOLOGY

TRA275 - Fuel Cell Systems 2025

Linear Optimization Modelling for Cost-Effective Hydrogen Integration in Energy Systems and Transport

Creators:
Jaakko Kivekäs
Punit Chandrappa

Supervisor:
Maria Grahn
Department of Mechanics and Maritime Sciences

Introduction

As the entire world is confronting climate change, the Paris Agreement has set key climate goals to limit global temperature rise in accordance with IPCC reports. Hydrogen (particularly green hydrogen) plays a vital role in achieving these goals. As a clean and versatile energy carrier, hydrogen can help reduce emissions in sectors such as heavy industry and transport, which are difficult to decarbonise. Green hydrogen, produced using renewable electricity from sources like wind and solar, can significantly lower CO_2 emissions, supporting the Paris Agreement's goal of limiting global warming to well below 2 °C. By increasing the adoption of hydrogen, we can build a sustainable, low-carbon economy and drive emission reductions.

Global Energy Transition model (GET)

The model used in this study is a linearly programmed, cost-optimizing GET model. It is provided with global energy system data together with numerous parameters and constraints, such as cumulative global CO_2 emissions and CO_2 storage capacity for carbon capture and storage. Based on the input and considering the given constraints, the model calculates the cost-minimized solution through linear optimization and presents the corresponding fuel and technology mix. The model can also be used to estimate the percentage of energy conversion technologies that can be used over the century to minimize CO_2 emissions. The model presents the results from 2030 to 2100 at 10-year intervals.

Relevant fixed parameters and constraints

Electrolyser (electricity to H_2)
- Present CAPEX: 1,300 USD/kWH_2
- Load factor: 80%
- Efficiency: 80%

Conversion H_2 to MeOH
- Efficiency: 89%
- Present CAPEX: 625 USD/kWMeOH
- 2050 CAPEX: 375 USD/kWMeOH

Carbon capture and storage (CCS)
- CO_2 storage capacity: 1,000 GtCO_2 [1]
- Fixed CAPEX: 60 USD/tCO_2

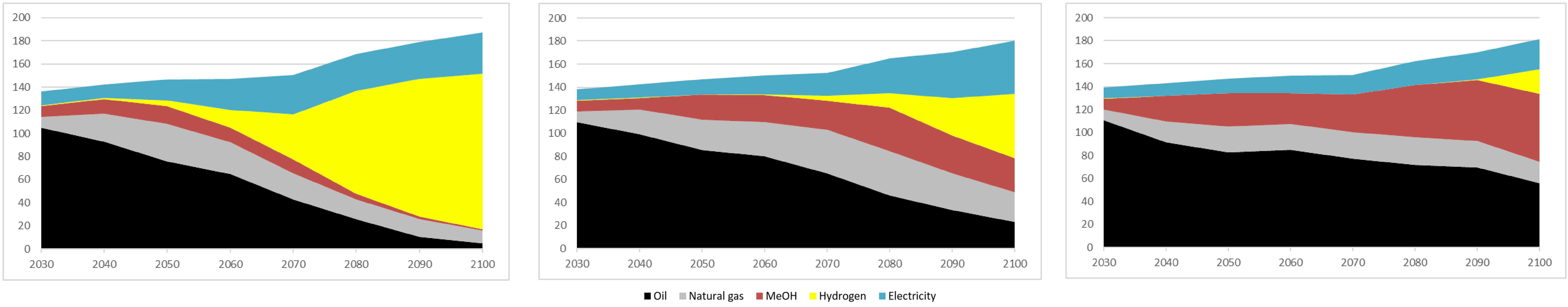
Direct solar to H_2 (photoelectrochemical and photocatalytic)
- Fixed CAPEX: 2,500 USD/kWH_2

Climate action scenarios for energy carriers in the transport sector

In these graphs, the cost-optimal distribution of energy carriers for the entire transport sector – including road transport, shipping and aviation – is presented. The GET model is constrained by different limits on global cumulative CO_2 emissions (i.e. carbon budget). The strictest limit is 905 billion tonnes of CO_2, leading to an estimated global temperature rise of 2 °C and narrowly achieving the Paris Agreement's goal. The second scenario, with a carbon budget of 1,705 billion tonnes, would result in an estimated temperature rise of 3 °C, failing to meet climate goals. The third scenario represents a purely market-based situation with a practically unlimited carbon budget. The electrolyser baseline CAPEX of 750 USD/kWH_2 for 2050 is used in all these scenarios.

Variable: cumulative CO_2 emissions 2010-2100
- 905 GtCO_2; estimated 2 °C global warming
- 1,705 GtCO_2; estimated 3 °C global warming
- No CO_2 emission constraint; no climate action

Fixed: electrolyser CAPEX 2050
- 750 USD/kWH_2

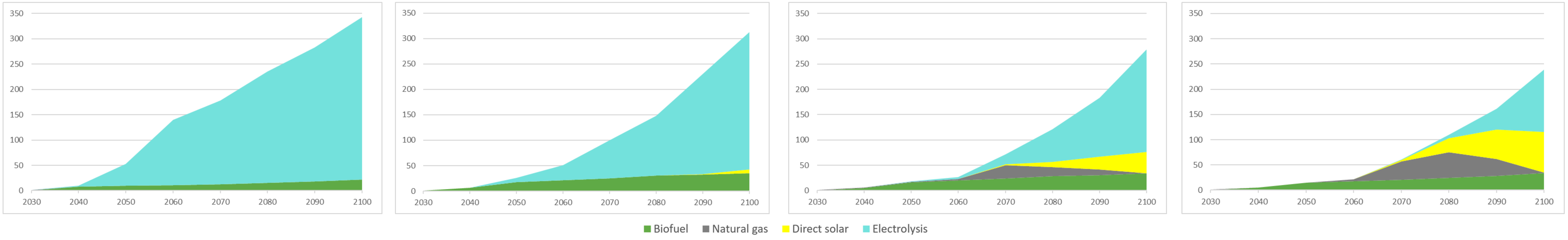

2 °C global temperature increase (EJ) **3 °C global temperature increase (EJ)** **No climate action (EJ)**

Hydrogen production by source with varying electrolyser cost

In these scenarios, the GET model is adjusted based on different electrolyser investment costs in 2050. The constraint for cumulative CO_2 emissions is fixed at 1,255 GtCO_2, which is projected to result in a global temperature rise of approximately 2.5 °C. By varying the electrolyser CAPEX from 300 USD/kWH_2 to 1,200 USD/kWH_2, the model calculates the most cost-effective hydrogen production distribution and volume. The biofuel source represents extracting hydrogen from biofuels, possibly with CCS, while the direct solar method refers to emerging technologies that convert solar irradiation directly into hydrogen without an electrolyser. However, its large share in scenarios with high electrolyser costs should be interpreted with caution, as it is an immature technology.

Variable: electrolyser CAPEX 2050
- 300 USD/kWH_2
- 600 USD/kWH_2
- 900 USD/kWH_2
- 1,200 USD/kWH_2

Fixed: cumulative CO_2 emissions 2010-2100
- 1,255 GtCO_2; estimated 2.5 °C global warming


300 USD/kWH_2 (EJ) **600 USD/kWH_2 (EJ)** **900 USD/kWH_2 (EJ)** **1200 USD/kWH_2 (EJ)**

Results & discussion

It is notable that batteries remain competitive regardless of climate goals in the first modellings, suggesting that hydrogen is mainly needed for hard-to-abate sectors. Interestingly, with less stringent climate goals, electrofuels (represented as MeOH) thrive and compete with fossil fuels instead of pure hydrogen. In such cases, hydrogen is not needed to use directly to maximize CCS and prevent rapid combustion of captured carbon. However, the efficiency (89%) and/or CAPEX values for electrofuel production may be overly optimistic.

CO_2 storage capacity has little impact on the total hydrogen volume, but it influences how it is produced. When testing a CO_2 storage capacity of 2,000 GtCO_2, the model indicated increased hydrogen production from natural gas with CCS, highlighting the role of economic CO_2 storage capacity.

The electrolyser load factor affects competitiveness, but its impact is smaller than that of CAPEX due to the wide projected cost range for 2050. Testing load factors of 0.7 and 0.9 showed limited influence compared to cost variations.

The electrolyser CAPEX range for 2050 was selected based on a minor price drop from the present cost to the lower estimates found in the literature [2]. The upper limit exceeds typical projections, but the assumed electrolyser efficiency (80%) is also higher than many estimates [2]. By considering a scenario with only a minor price drop, we can see that a significant reduction in CAPEX is necessary for electrolysers to become competitive.

Conclusions

- The more ambitious climate target, the more hydrogen should be used as an energy carrier in the transport sector to achieve it.
- To reach climate targets, the majority of the hydrogen produced should be green hydrogen (hydrogen produced through electrolysis).
- The cost of electrolysers is a crucial factor in determining their use in hydrogen production.

Abbreviations

H_2: Hydrogen
CO_2: Carbon dioxide
MeOH: Methanol, used as a proxy for all biofuels and electrofuels
Oil: Fossil oil-based petroleum fuels
CAPEX: Capital expenditure (i.e. investment cost)
CCS: Carbon capture and storage

References

[1] IPCC (2023). Climate Change 2023: Synthesis Report. P. 86-87.
[2] Broghan Helgeson & Jakob Peter (2020). The role of electricity in decarbonizing European road transport – Development and assessment of an integrated multi-sectoral model. P. 19.