PAUL SCHERRER INSTITUT
PSI

Evangelos Panos :: Energy Economics Group :: Paul Scherrer Institute

Hydrogen as an energy carrier: modelling challenges and its role in decarbonisation and system flexibility

TU Berlin, Operations Research - Methods for Energy and Resource Markets (OR-RES) 3.11.2022

PAUL SCHERRER INSTITUT

Outline

- The model orbit of Energy Economics Group of PSI
- Some challenges in hydrogen representation in large scale energy systems models
- Deep dive into the specific challenge of modelling hydrogen infrastructure
- The role of hydrogen in decarbonisation and system flexibility provision
  – insights from Switzerland

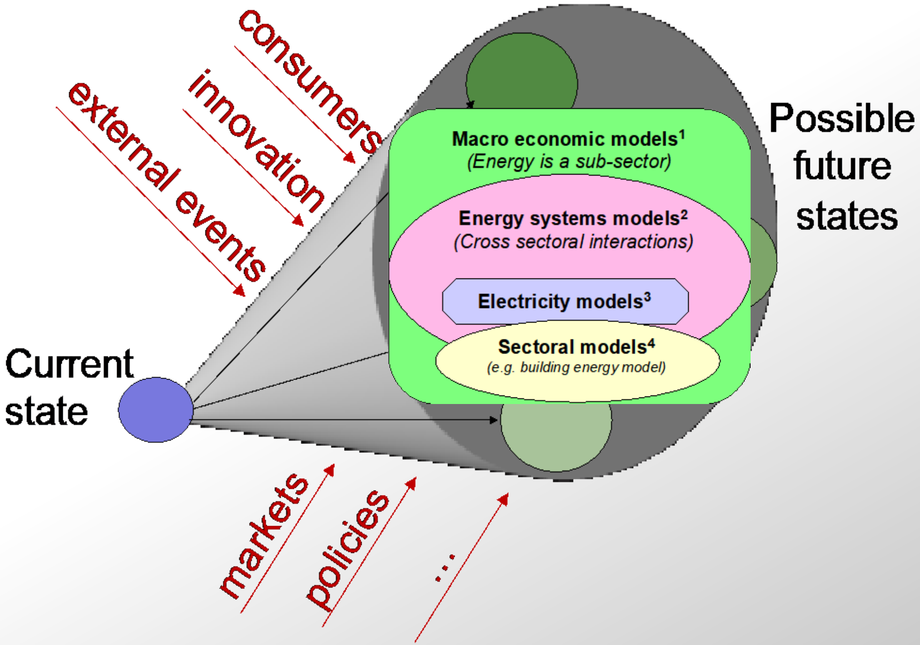
A couple of words about
Energy Economics Group of PSI

https://www.psi.ch/en/eem

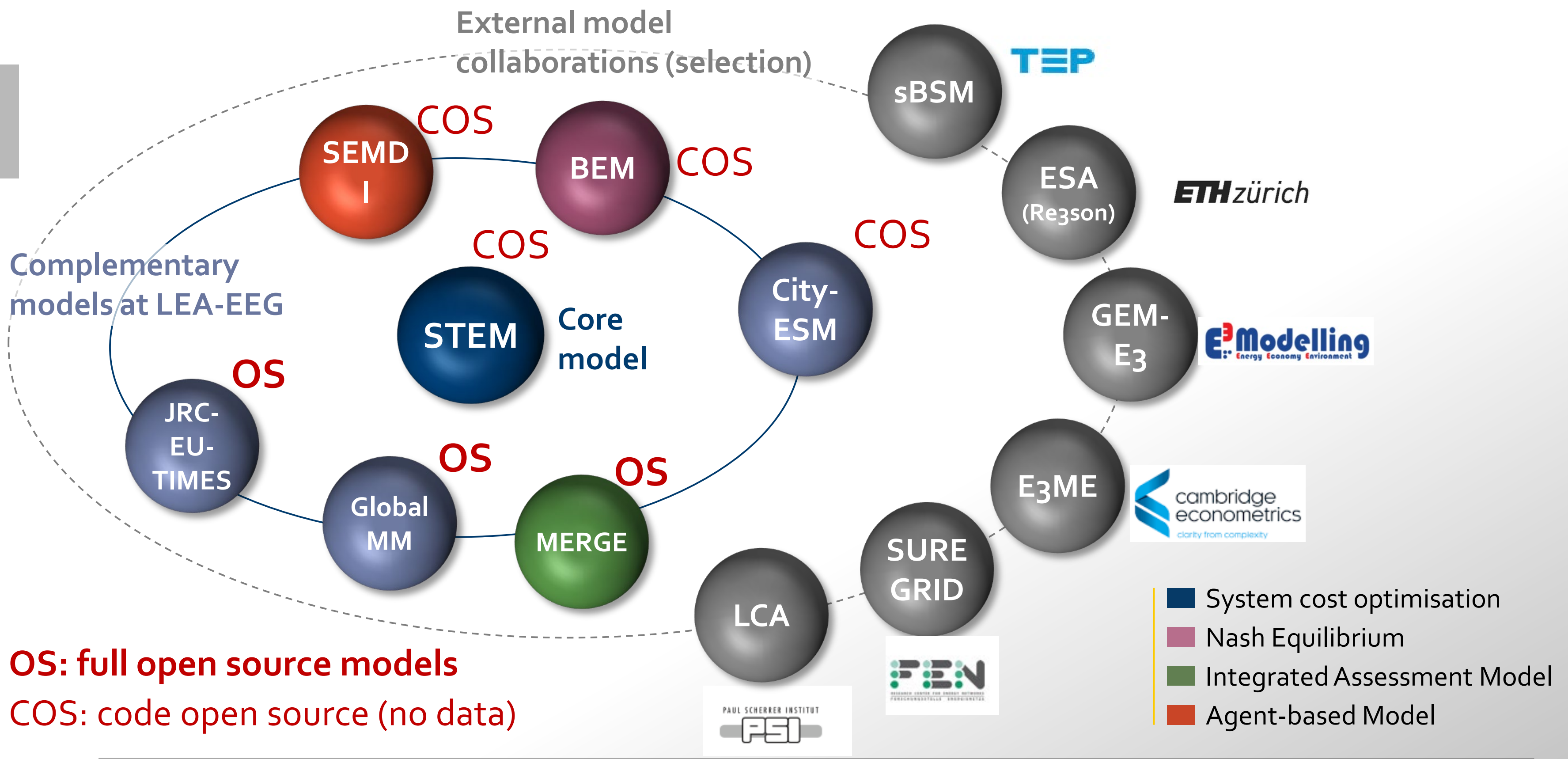
The Energy Economics Group (EEG) at PSI

Scope: Improve understanding of energy transition pathways and policy strategies for realising sustainable long term energy systems at the Swiss, European and global levels

Method: energy-economic models and scenario technique to explore the transformation of the energy system



The model orbit at EEG



OS: full open source models

COS: code open source (no data)

PAUL SCHERRER INSTITUT

Glance at selected running research projects

sweet swiss energy research for the energy transition

SURE

https://sweet-sure.ch

Sustainable and Resilient energy for Switzerland

- Novel interdisciplinary analysis framework
- Stakeholder engagement

PoliZero

Swiss decarbonisation pathways towards zero CO_2 emissions

https://polizero.ch

Efficient policies for Swiss pathways towards net-zero

- Efficient policies, their timing and critical contextual influences
- Stakeholder engagement and Dynamic Adaptive Policy Pathways

WORLD ENERGY COUNCIL

26th CONGRESS ROTTERDAM 4 - 7 December, 2023

https://www.worldenergy.org

World Energy Scenarios

- Stakeholder-driven explorative scenarios
- Announced at the World Energy Congress (>4000 delegates, 90 countries)

Glance at selected running research projects

SCENE

Swiss Centre of Excellence on Net-Zero Emissions

- High resolution time-dynamic energy systems modelling
- Holistic GHG emissions mitigation

PROBOUND

Bounded rationality in the Swiss energy transition

- Co-simulation of consumer behaviour and social planner perspective
- Clean mobility diffusion and supportive policy designs

ESI

SHELTERED

Synfuel-ETH

Power-to-X and hydrogen economy projects

- Close cooperation with PtX pilot projects at PSI
- Synfuels pathways and perspectives for Switzerland and the EU

https://www.psi.ch/en/media/overview-esi-platform

PAUL SCHERRER INSTITUT

The Energy Economics Team

11 members with highly interdisciplinary skills and thinking

- 5 senior staff
- 6 PhD students

https://www.psi.ch/en/eem/people

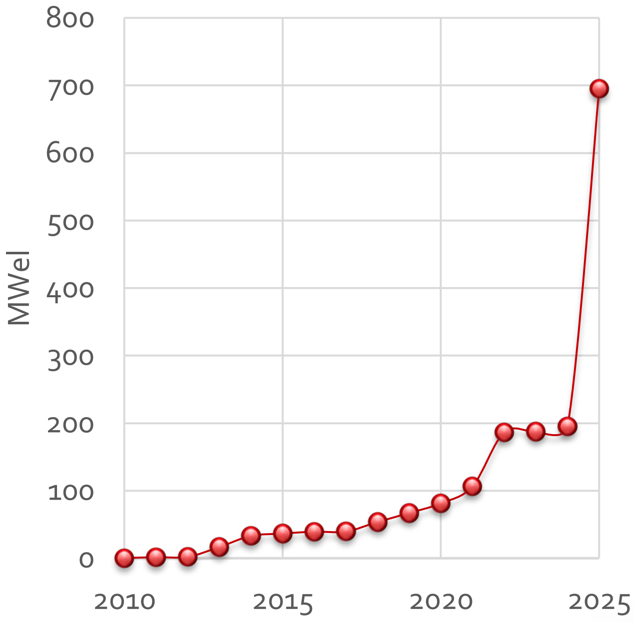
Hydrogen

It enjoys an unprecedented political and business momentum

It imposes formidable challenges in energy systems modelling community

EU27 in 2030: 550x more electrolysis than 2022

Operational and under construction electrolysis capacity in the EU27



Source: IEA, 2022

EU Hydrogen Strategy / RePowerEU plan:

- 2020-2024: 1 Mt H_2 from electrolysis ~ 9 – 10 GW^*_{el}
- 2025-2030: 10 Mt H_2 from electrolysis ~90 – 100 GW^*_{el}

If electrolysis capacity grows like solar PV of today, we can achieve max 70 GW_{el} by 2030

* Calculated based on 58-64% utlisation rate, 50 KWh/kgH_2 efficiency

Integration is key for hydrogen acceleration

Integrated cross-sectoral policy approaches

Access to multiple markets:

- Electricity
- Gas
- Heat
- CO_2

Market integration

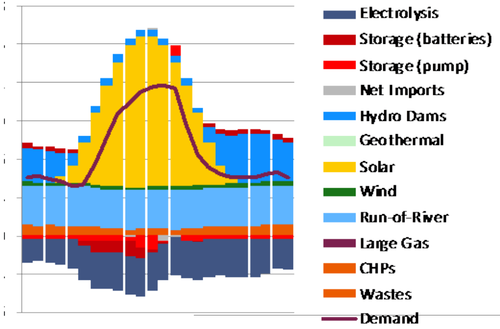
Hydrogen economy

Technical integration

Supply push effect
(integration variable renewables)

Demand pull effect
(decarbonisation of energy demand services)

- -Industrial process heat
- -Space and water heat
- -H_2 and e-fuels for mobility



e^-

Low cost electricity:

- Generation source
- Grid fees
- Annual utilisation

Heat integration: fuel cells and electrolyser

C-sources in case of synfuel production

- Bioenergy
- Industrial point sources

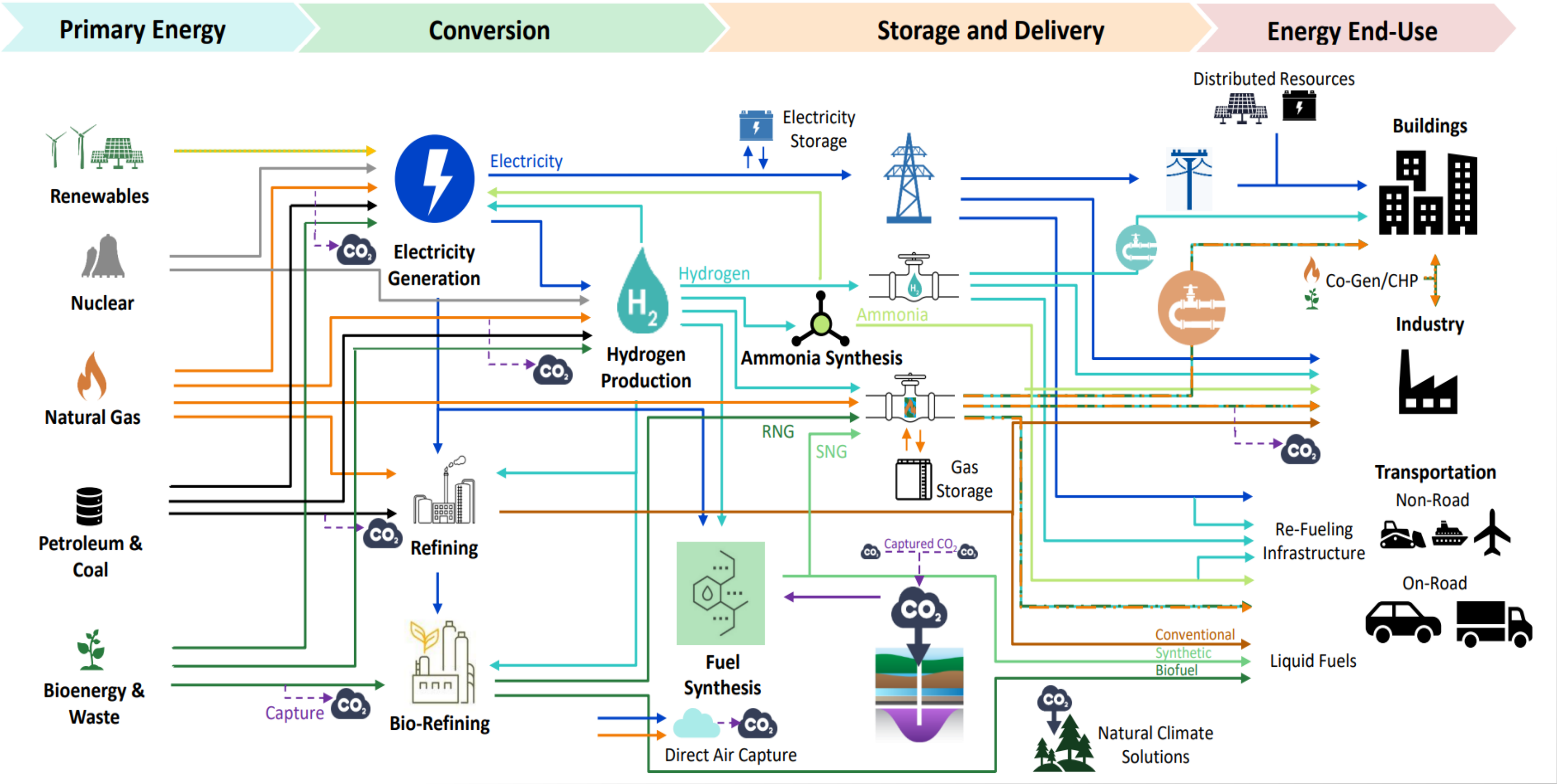
Revenues from by-products:

- Oxygen

Modelling a H_2-economy is a challenging task

- H2-technology flexibility imposes challenges in energy systems modelling community :
  - we need to incorporate a complete economy – production, transportation, storage, utilization, environmental and social impacts and costs…
  - … for an energy system **that does not currently exist**

A hydrogen reference energy system



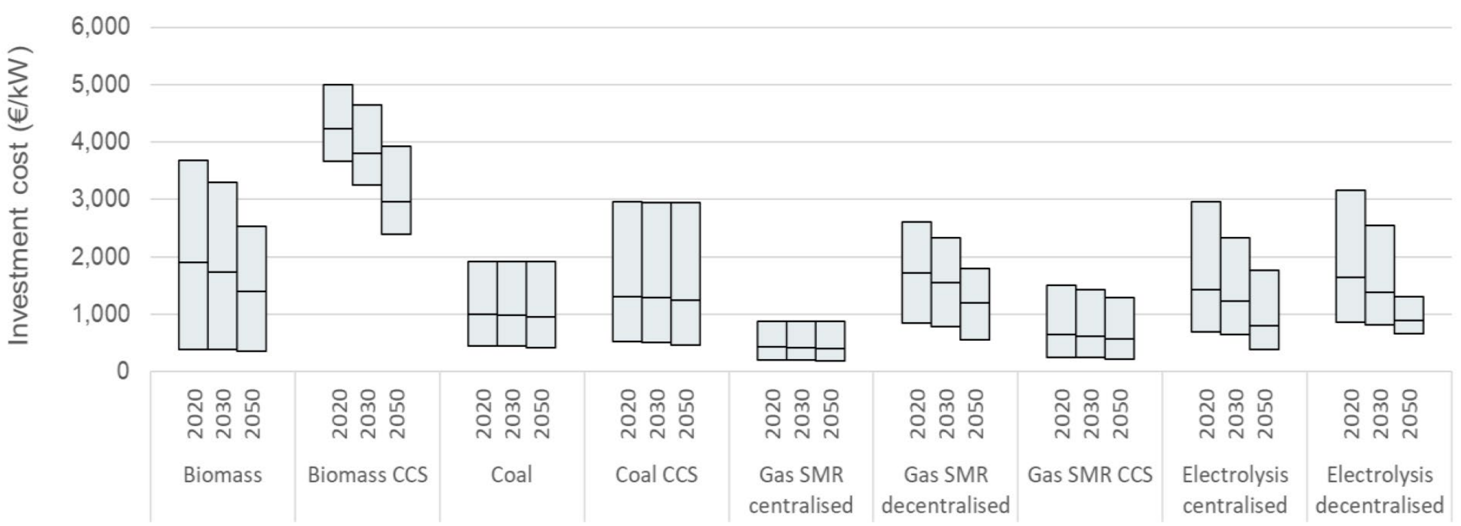
Source: Blandford et al, 2022

Cost and performance fundamentals

UNCERTAINTY ANALYSIS

- Except SMR all other technologies are essentially pre-commercial
- PEM and SMR need high temporal resolution and dispatch constraints in modelling
- H2 applications are in sectors with low data availability: trucks, aviation, shipping, etc.
- Literature on technology costs and prospects is often «confusing»

Comparison of hydrogen production cost assumptions across 10 TIMES models



Source: Dodds et al., 2022

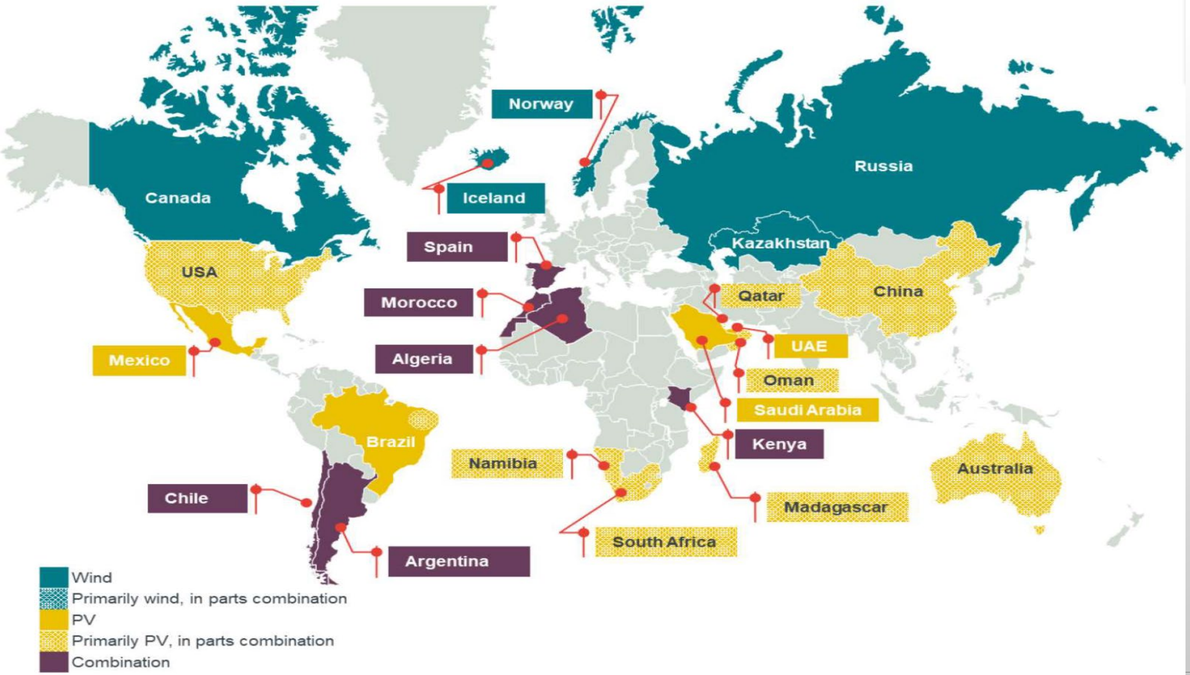
PAUL SCHERRER INSTITUT

Unknown market structure and trade options

NEW & UNIQUE SCENARIOS

- Unclear which market incentives produce the best outcomes
- Hydrogen can be an international commodity,
- Regulatory policy is in its infancy

Strongest potential synfuel producers worldwide



Sources: Perner & Bothe, 2018 ; WEC 2021

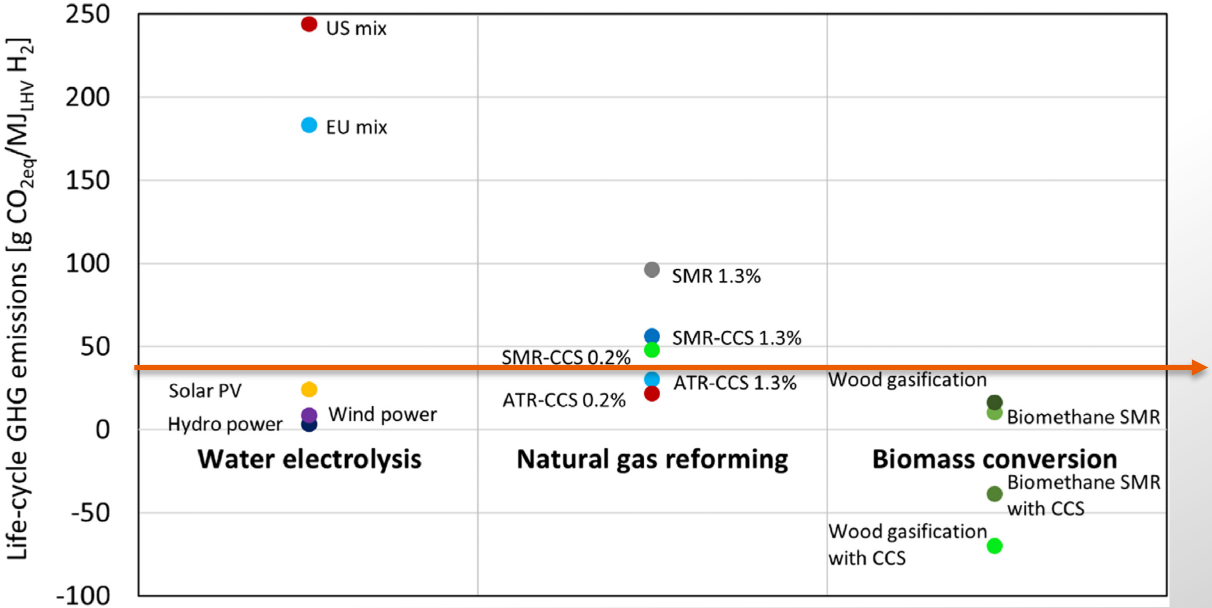
PAUL SCHERRER INSTITUT

Unknown broader environmental impacts

INTEGRATED MODELLING

- Hydrogen leakage can create air pollution and GHG emissions
- Water scarcity impacts are largely unclear at the moment

Life-cycle GHG emissions of hydrogen production GWP100



European CertifHy initiative low carbon threshold 36.4 $gCO_2/MJ\ H_2$

Source: Reigstad et al. 2022

PAUL SCHERRER INSTITUT PSI

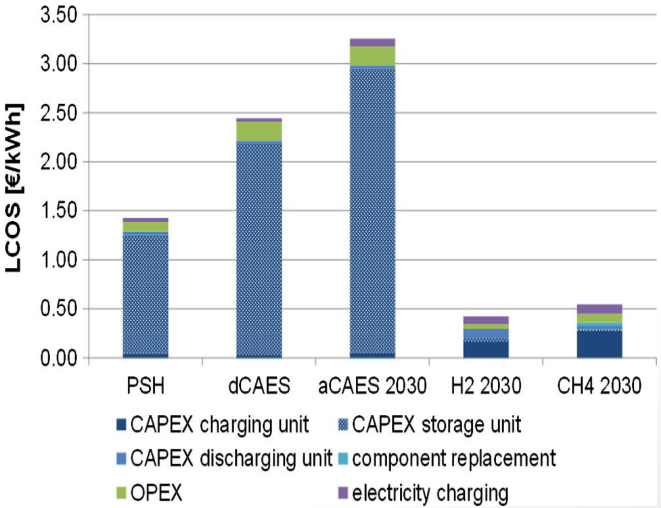
Interactions with electricity and storage value

HIGH RESOLUTION MODELLING

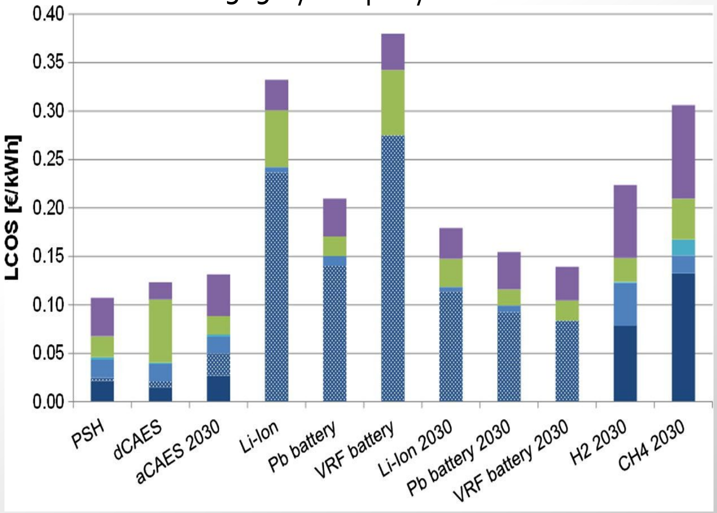
- Power sector can be producer and end-user of hydrogen
- Hydrogen provides a different value proposition than battery storage
- Complex interactions requiring high temporal resolutions and technical details

LCOS for long-term storage (left) and short-term storage (right)

1-cycle per year



365-cycles per year



Source: Jülch et. al. 2016

PAUL SCHERRER INSTITUT

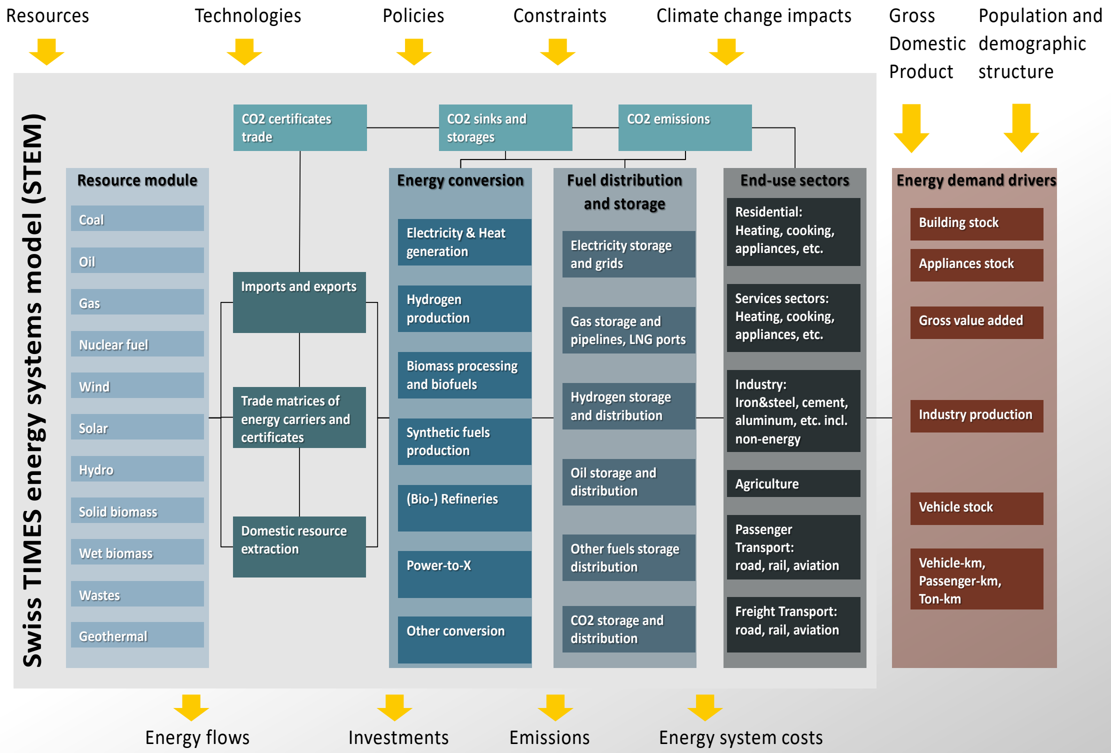
Deep dive into a specific modelling challenge:

Domestic hydrogen T&D infrastructure

The approach used in the Swiss TIMES energy systems model (STEM)

The Swiss TIMES Energy systems Model (STEM)

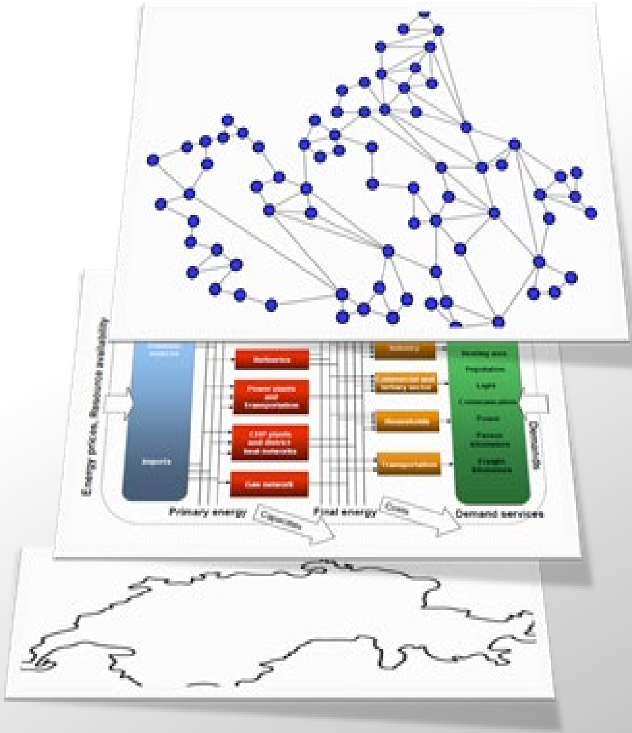
- Entire energy system
- Long term horizon
- 288 hourly time steps
  - 4 seasons
  - 3 days per season
- Age structure of assets
- Full unit commitment
- Infrastructure modelling:
  - electricity grids
  - gas and H2 grids
- Ancillary markets
- Endogenous RES variability
- Endogenous hourly load profiles
- DSR options
- Agent-based demand modelling
- High Performance Computing



Source: Kannan et al. 2014, Panos et al. 2019, Panos et al. 2021, Kannan et al. 2022

T&D infrastructure modelling in STEM: main principles

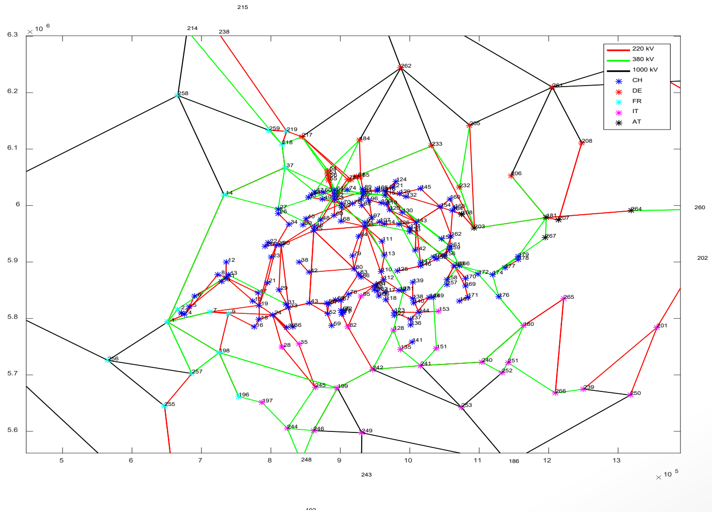
- Pseudo-spatial modelling to avoid increasing complexity
- Infrastructure constraints are an add-on to the model without changing its original structure or design
- Exogenous allocation of demand and supply to the infrastructure add-on nodes
- Decisions made by the model need to respect the infrastructure constraints
- Exploration of the constraints duals to decide their inclusion into the model and further reduce complexity

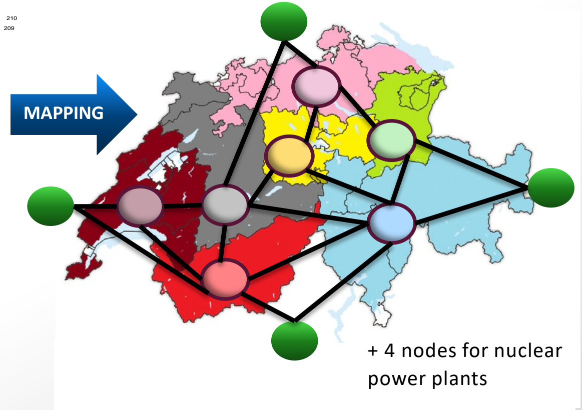


Source: Panos et al., 2019

Example: electricity transmission grid in STEM

- The detailed transmission grid is reduced to *N*=15 nodes and *E*=319 bi-directional lines
- Fixed dissagregation of the reduced network injections to the detailed network injections





$$-\mathbf{b} \leq \mathbf{H} \times \mathbf{D} \times (\mathbf{g} - \mathbf{l}) \leq \mathbf{b}$$

Where $\mathbf{H}$ is the PTDF matrix of the detailed network, $\mathbf{D}$ is the fixed dissagregation matrix, $\mathbf{g}$ is the vector with injections, $\mathbf{l}$ is the vector of withdrawals, and $\mathbf{b}$ is the vector of line capacities. The matrix $\mathbf{D}$ is not unique

Source: Panos et al., 2019

T&D H2-infrastructure modelling follows similar principles

- **Challenge**: no previous paradigm, near- and long-term T&D options may differ
- **Approach**: model a «hydrogen regional cluster» at an initial stage of a take-off of the H2-economy

Main elements of the H2-regional cluster

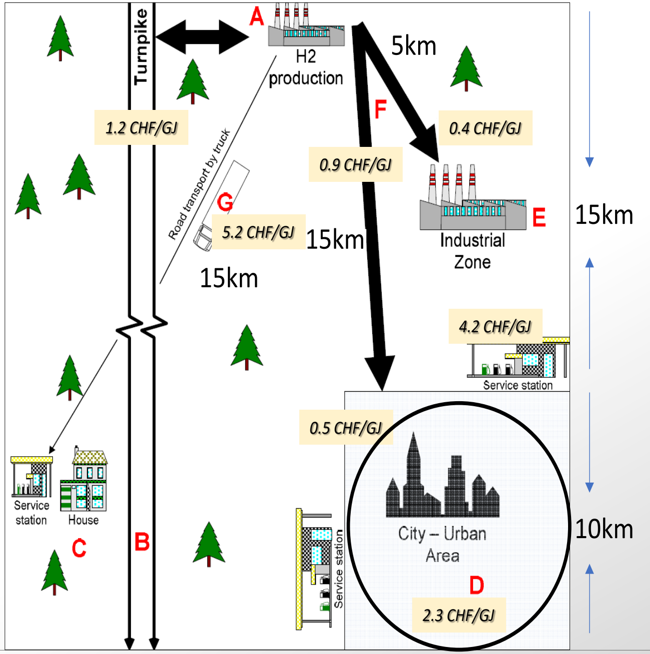
(A): H_2 production or storage facility

(B) "turnpike" pipeline connecting "reference" areas together

(C) rural area served via trucks

(D) urban area pipelines and backbone ring

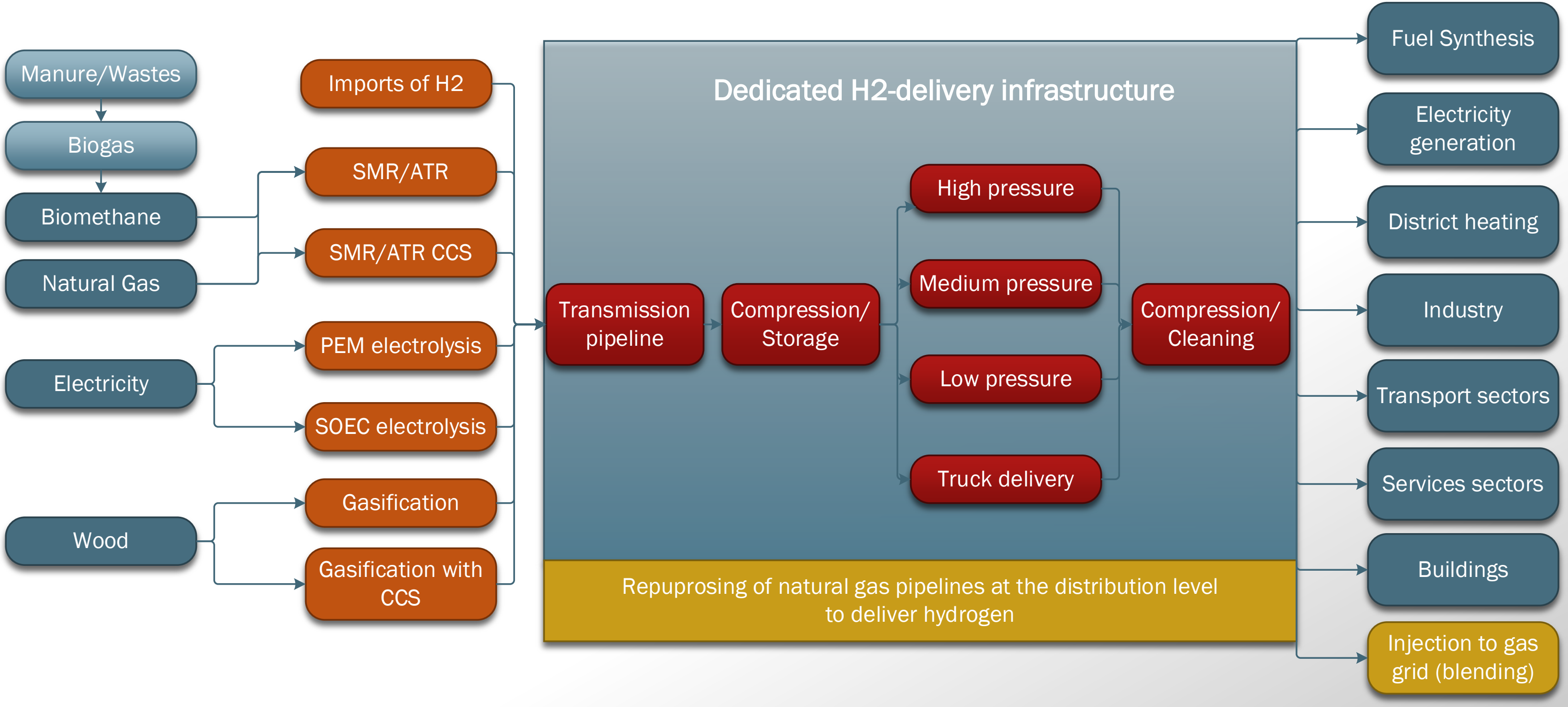
(E) Pipeline to an industrial zone



Reference Area Characteristics	
Switzerland density /km2	218
Swiss Plateau density /km2	450
Total Area km2	625
Urban Area km2	100
Urban Area Density /km2	2000
Total Population	281250
Urban Population	200000
Rural Population	81250
Number of cars	149063
Number of households	127841
Urbanisation rate	71%
Reference Area Hydrogen Consumption	
H2 consumption in industry (TJ)	285
H2 consumption in buildings (TJ)	1'273
of which urban	905
of which rural	368
H2 consumption in cars (TJ)	738
of which urban	*525*
of which rural	*213*
Total H2 needs (TJ)	3'569
Size of H2 production facility (MW)	340
H2 Production facility output (TJ)	3'569
Operating hours of the H2 production facility (h)	3000

Source: Panos and Kober, 2020

Simplified view of the hydrogen RES in STEM



Source: Panos and Kober, 2020

PAUL SCHERRER INSTITUT

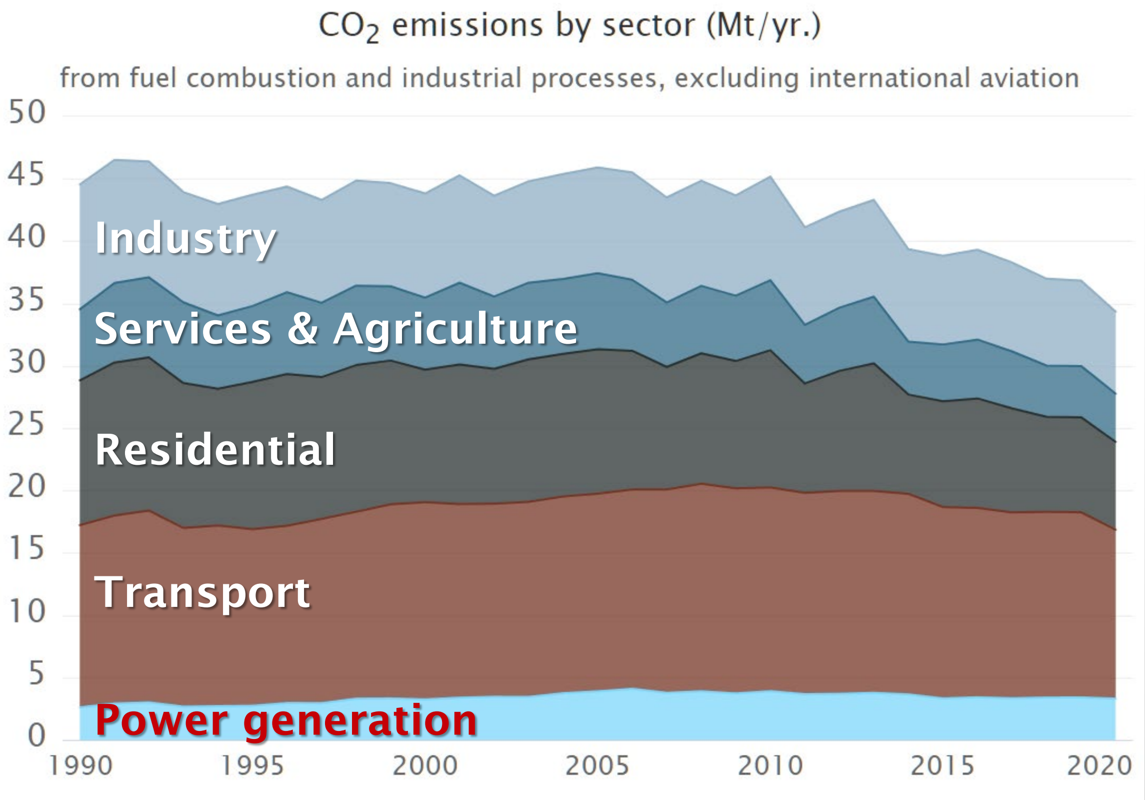
Hydrogen integration
and its role in the Swiss energy system

Insights from several relevant studies with STEM

CO_2 emissions in Switzerland: -23% in 2020 from 1990

Challenges in the Swiss transition to net-zero CO2 emissions in 2050:

- Limited renewable sources
- Seasonal and daily balancing
- CO2 storage
- Population growth
- Energy security



SCCER JASM to assess the Swiss energy transition

- The Swiss Competence Centres for Energy Research (SCCERs) program:
  - 250 MCHF for 2013-2020 to 8 challenges of energy transition (biomass, storage, industry, buildings, transport, electricity, grids, society)
- SCCER JASM (5.6 MCHF) is a cross-SCCER activity assessing net-zero pathways

JASM

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

Scenarios*	**Energy trade availability**	**Renewables and CCS deployment**	**Society and lifestyles**	**Policies**
CLI: core scenario	good	cost optimal	cost optimal	technology and building standards
ANTI: fragmented solutions	moderate	moderate	fragmentation	local markets
SECUR: energy security	low	cost optimal	pay for security	zero net imports

*a subset of the STEM JASM scenarios is shown here, focusing on those discussed in this presentation

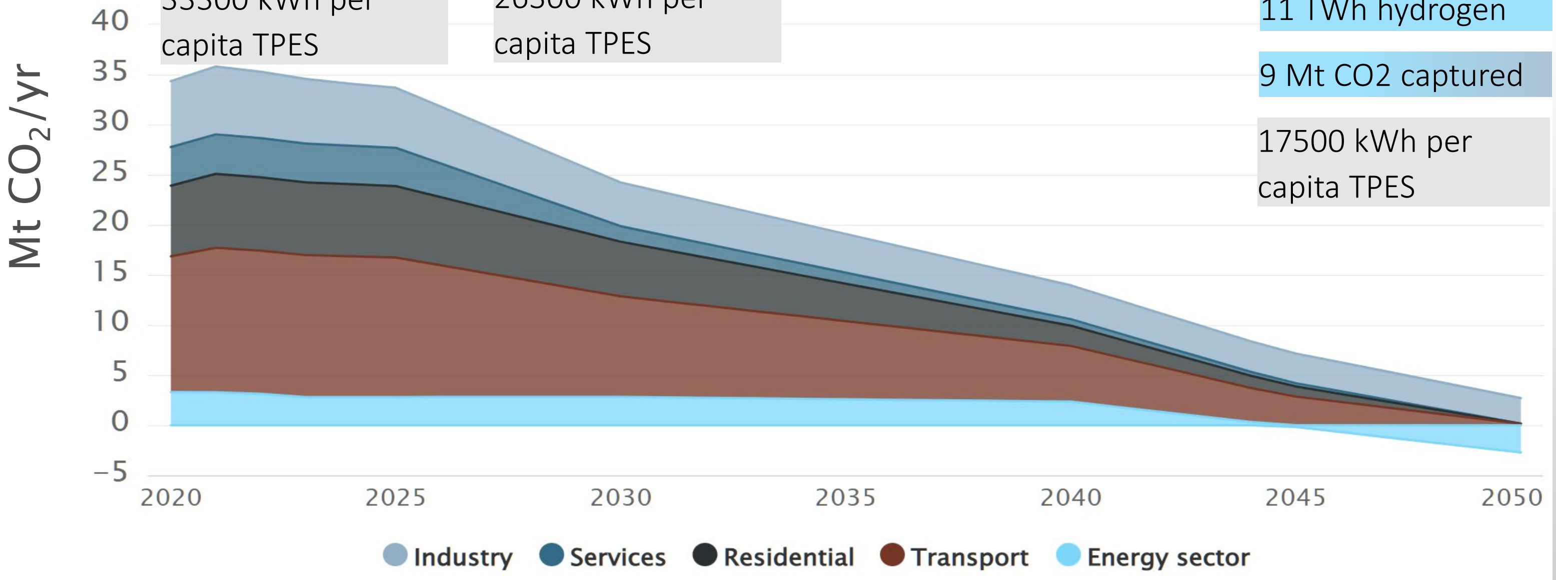
Source: Panos et al. 2021

SCCER JASM website https://sccer-jasm.ch

Milestones to net-zero CO_2 emissions in 2050

CLI SCENARIO

2020	2030	2050
12% Heat Pumps	35% Heat Pumps	75% Heat Pumps
15% EVs in car sales	38% EVs in car sales	83% EVs in car stock
3 GW solar PV	8 GW solar PV	27 GW solar PV
33300 kWh per capita TPES	26300 kWh per capita TPES	11 TWh hydrogen
		9 Mt CO2 captured
		17500 kWh per capita TPES

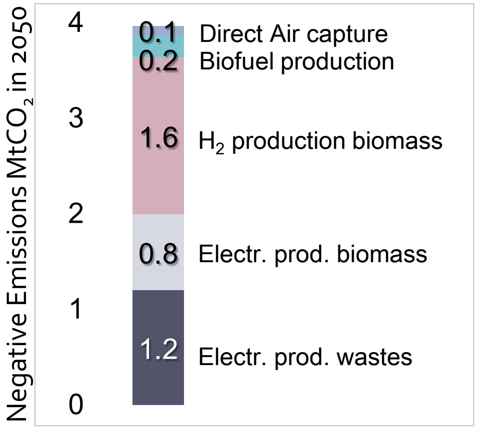


Source: Panos et al. 2021

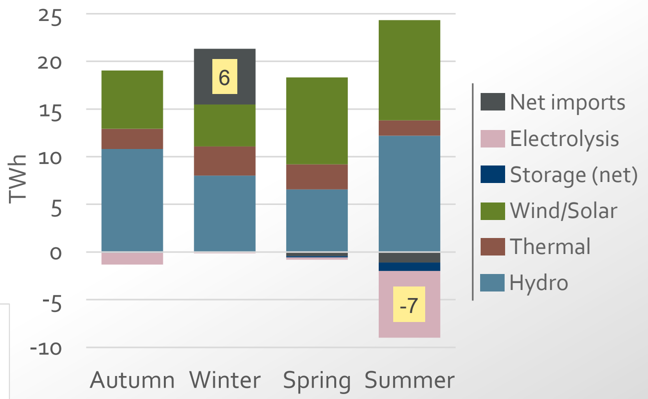
Net-Zero is impossible for Switzerland without H_2

CLI SCENARIO

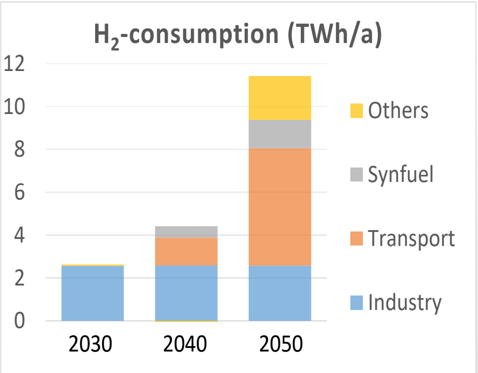
1 Delivers 40% of the negative emissions in 2050



3 Provides seasonal flexibility to integrate more than 25 GW solar/wind



2 Decarbonises all end-uses, first industry and then scales up in mobility

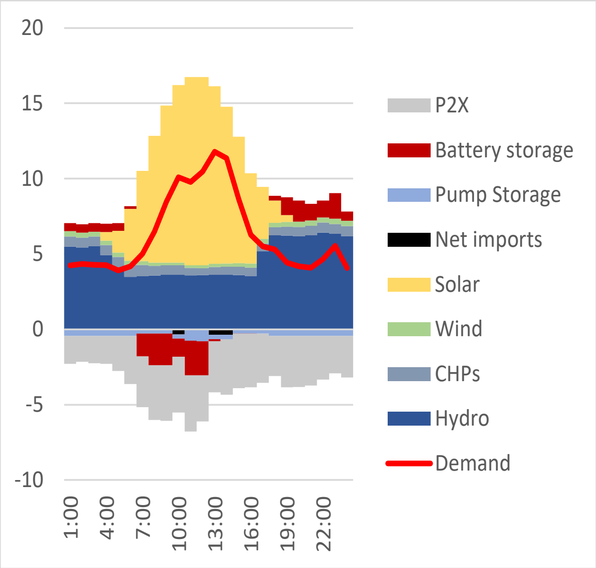


Source: Panos et al. 2021

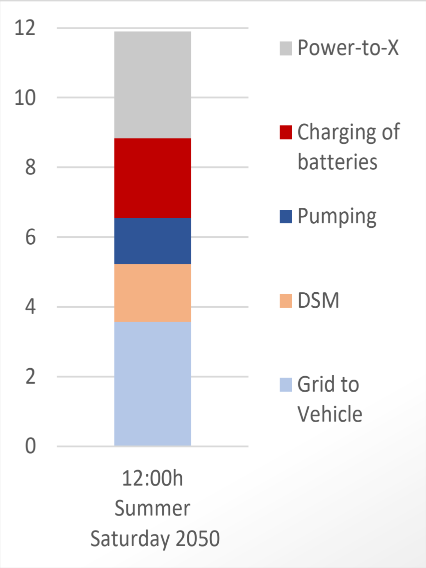
Hydrogen complements other storages in flexibility provision also at the daynite levels

CLI SCENARIO

Electricity Supply and demand in Summer Saturday 2050 in GW



Coordinated flexibility deployment at 12:00 in Summer Saturday 2050 GW



Total deployment of flexibility options in 2050

Flexibility option	Deployment (capacity)
Pump storage	4.5 GW , 520 GWh
Stationary batteries	2.1 GW , 11.5 GWh
Thermal storage	5.8 GW , 35 GWh
Thermal storage (seasonal)	1.4 TWh
H2 storage (seasonal)	1.6 TWh
Vehicle-to-Grid (V2G)	output 0.5 TWh (from 13% of the electric cars)
FCR+ reserve demand	+ 45% from 2020 (624 MW)
Electricity shifts (DSM) in industry, services, residential	10% of demand (5.5 TWh)

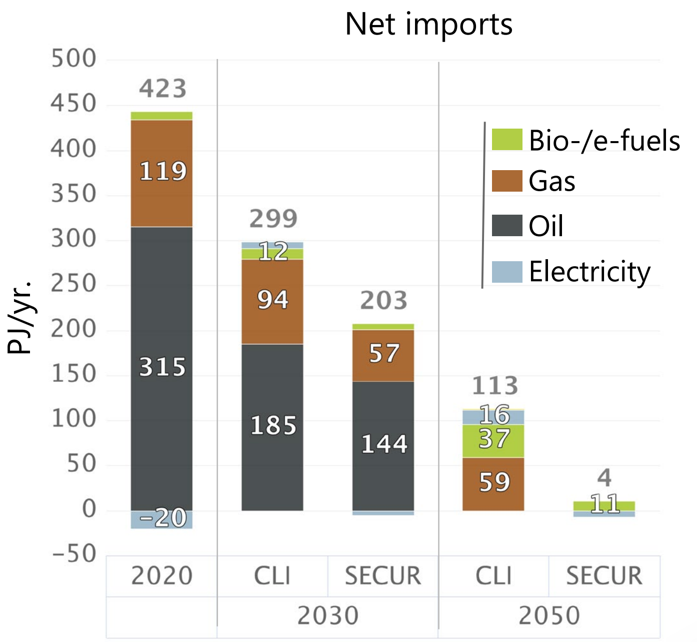
Source: Panos et al. 2021

«Zero» import dependency and zero CO_2 ?

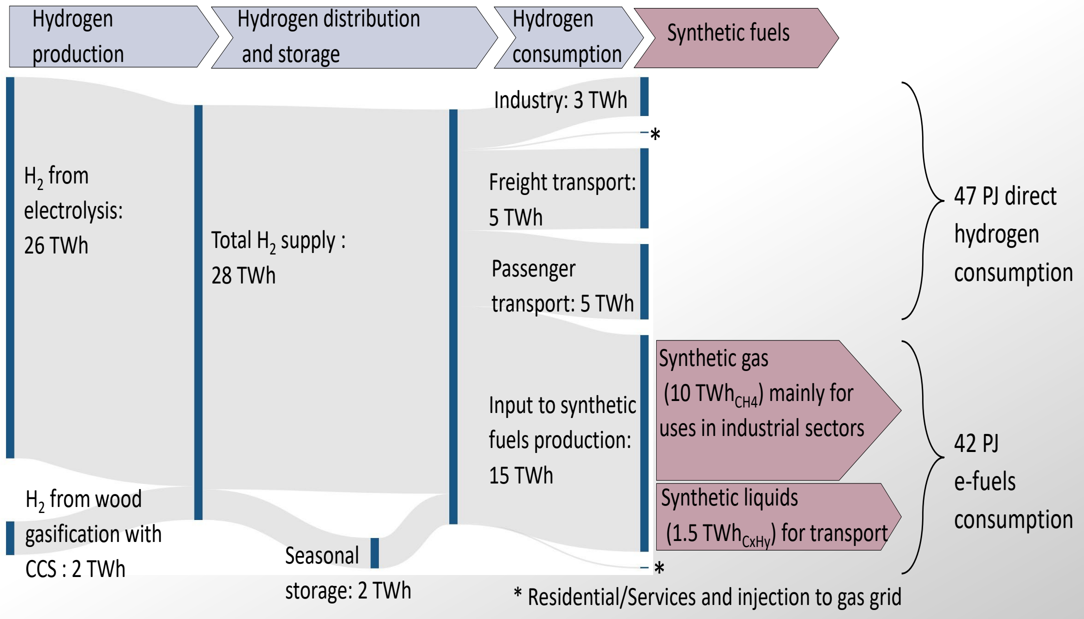
SECUR SCENARIO

PAUL SCHERRER INSTITUT PSI

Import independence of fossil fuels is possible but bio/e-fuels imports are needed



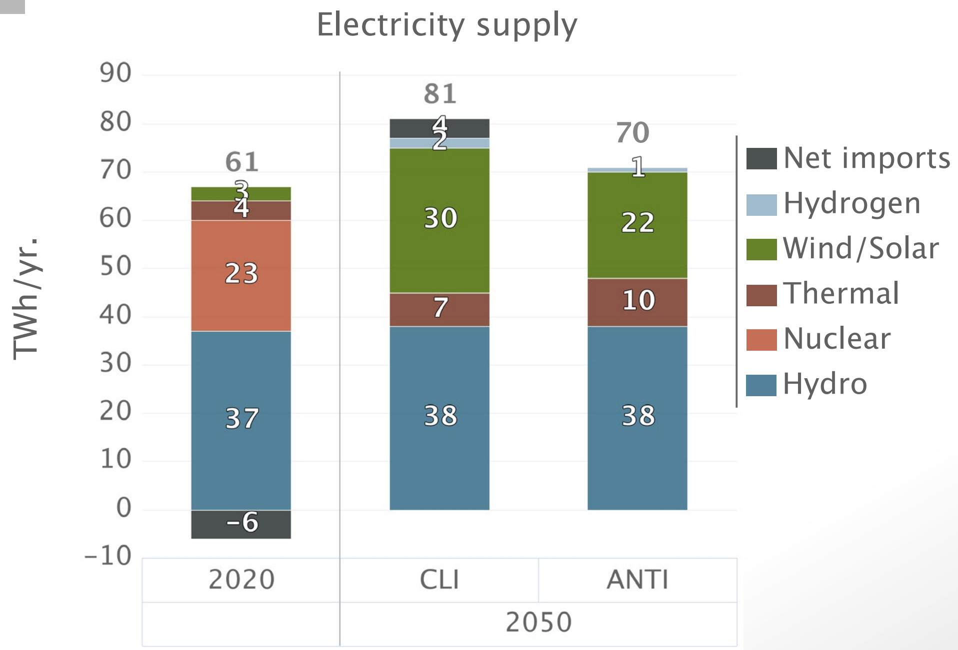
In 2050, hydrogen-based synfuels substitute in SECUR more than 90% of the gas imports occurring in CLI



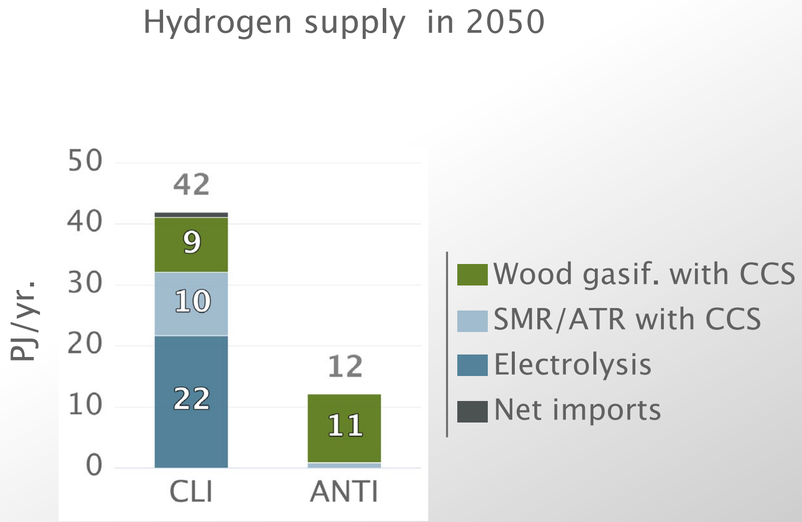
Hydrogen needs climate and renewable policy

ANTI SCENARIO

Slower renewable energy uptake creates a supply gap of 11 TWh under net-zero



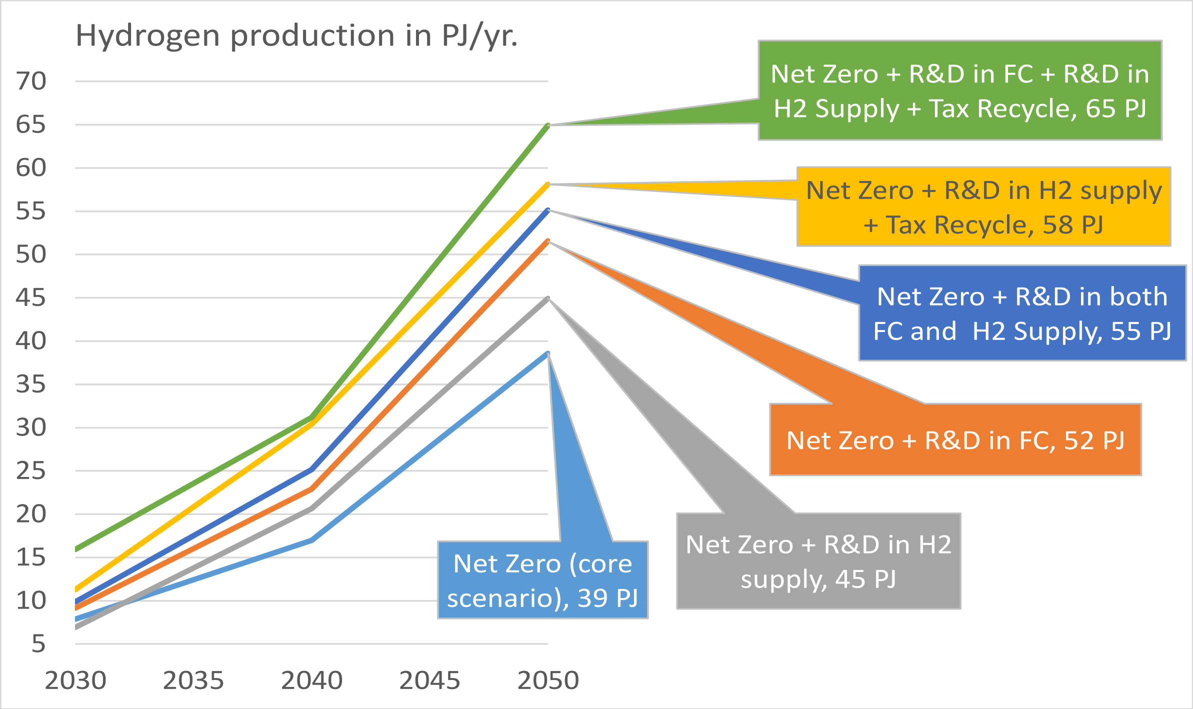
Domestic H2 production is limited and H2 use is prioritised to industry and transport



Source: Panos et al. 2021

Demand pull more critical than supply push for large-scale hydrogen uptake

- Fuel Cell stack cost is a decisive factor for accelerating hydrogen uptake
- Cost reductions in hydrogen supply and infrastructure benefit more the stationary than the mobile applications of hydrogen



Source: Panos and Kober 2020

PAUL SCHERRER INSTITUT

Conclusions

- Modelling the hydrogen system:
  - Increases model complexities
  - Needs to account for uncertainty, integrated and high resolution modelling
- H2-infrastructure modelling is computetional demanding and extremely complex
  - approximations adopted and derived from the oil and gas paradigms
- Due to H2-regulations infancy modelling has the opportunity to contribute to policy development, but faces the challenge of creating and analysing new and unique scenarios
- Many studies confirm that net-zero emissions without hydrogen is not possible for many geographies in the world, while H2 could also contributes to system flexibility and energy security
- It is unlikely to have a full hydrogen economy by 2050, and to scale-up its penetration:
  - we need renewables development and clear climate change mitigation targets
  - accelerate fuel cell innovation to create demand pull effects – infrastructure will follow

Thank you very much for the attention

Dr. Evangelos Panos
Paul Scherrer Institute
Energy Economics Group
Laboratory for Energy Systems Analysis
e-mail: evangelos.panos@psi.ch

References

- (Blandford et al., 2022) Blandford G et al, 2022: Modeling hydrogen in US Energy Systems. US Hydrogen Workshop 2022, https://355898.fs1.hubspotusercontent-na1.net/hubfs/355898/Hydrogen%20Forum_Exec%20Summ%20and%20Presentations/Blanford_OnLocation_H2modelForum[2].pdf
- (IEA, 2022) International Energy Agency, Hydrogen Projects Database, 2022 https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database
- (Dodds et al., 2022) Dodds P et al., 2022. Modelling of Hydrogen. Report to IEA-ETSAP https://iea-etsap.org/projects/Hydrogen_RES_Analysis.zip
- (Perner & Bothe 2018) Perner J and Bothe D, 2018. International aspects of a PtX Roadmap. A report prepared for the World Energy Council Germany https://www.weltenergierat.de/wp-content/uploads/2018/10/20181018_WEC_Germany_PTXroadmap_Full-study-englisch.pdf
- (WEC 2021) World Energy Council 2021. Decarbonised hydrogen imports into the European Union, https://www.weltenergierat.de/wp-content/uploads/2021/10/WEC-Europe_Hydrogen-Import-Study.pdf
- (Reigstad et al., 2022) Reigstad G. et al. 2022. Moving toward the low-carbon hydrogen economy: Experiences and key learnings from national case studies https://doi.org/10.1016/j.adapen.2022.100108

References

- (Jülch et. al. 2016), Jülch V. 2016. Comparison of electricity storage options using levelized cost of storage (LCOS) method. Applied Energy https://doi.org/10.1016/j.apenergy.2016.08.165

- (Kannan et al. 2014). R. Kannan and H. Turton (2014). Switzerland energy transition scenarios – Development and application of the Swiss TIMES Energy system Model (STEM), Final Report to Swiss Federal Office of Energy, Bern http://www.bfe.admin.ch/forschungewg/index.html?lang=de&dossier_id=02886

- (Panos et al. 2019) Panos, E., Kober, T., Wokaun, A. (2019). Long term evaluation of electric storage technologies vs alternative flexibility options for the Swiss energy system, Applied Energy, 252, https://doi.org/10.1016/j.apenergy.2019.113470

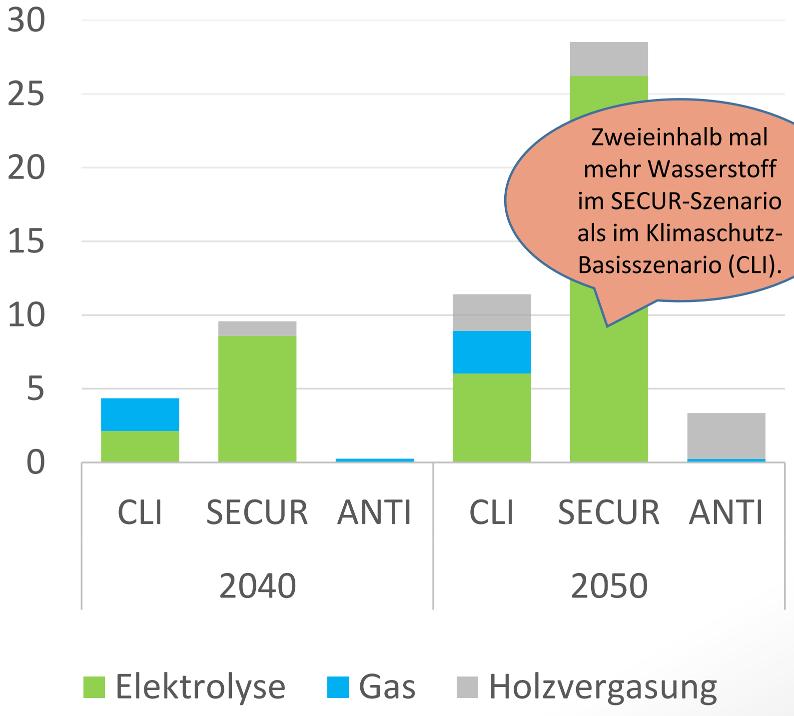
- (Panos et al. 2021) Panos E., T. Kober, R. Kannan and S. Hirschberg (2021). Long-term energy transformation pathways - Integrated scenario analysis with the Swiss TIMES energy systems model. SCCER JASM final report, Villigen PSI https://doi.org/10.3929/ethz-b-000509023

- (Panos and Kober, 2020) Panos, E. and Kober, T. (2020). Report on energy model analysis of the role of H2-CCS systems in Swiss energy supply and mobility with quantification of economic and environmental trade-offs, including market assessment and business case drafts. EU H2020 https://www.psi.ch/en/media/63140/download

Comparison of H2-pathways in the three scenarios

PAUL SCHERRER INSTITUT PSI

H_2-Produktion (TWh/a)



H_2-Verbrauch (TWh/a)