Doutoramento em Alterações Climáticas e Políticas de Desenvolvimento Sustentável

Class 4: 22nd March 2024 | Mitigation

Sofia G. Simoes

SEMINAR ENERGY & CLIMATE CHANGE

Climate Change and Sustainable Development Policies

LNEG
NOVA – NOVA SCHOOL OF SCIENCE & TECHNOLOGY
CENSE – center for environmental and sustainability research

#	DATE		TOPIC	PROF.
1	01/mar Fri	9h-11h	**ENERGY & CLIMATE CHANGE:** A COMPLEX RELATION, PERENE AND INTERDISCIPLINARY. Framework and purpose of the course in the PDACPDS. Practicalities and seminar program. Basic concepts of the energy systems.	J. Seixas, FCT NOVA
2	09/mar Sat	11h-13h	**Energy Concepts & Global energy system:** primary/final energy; energy efficiency; sankey diagrams; energy services; energy carriers; final energy supply cost curves; energy production and consumption regions; energy access; energy and carbon intensity. How GHG (greenhouse gases emissions) are estimated.	S. Simões
3	16/mar Sat	9h-11h	**Global balance of CO_2 emissions** associated with energy and industrial processes. The greenhouse effect. GHG emissions from fossil energy per sources and countries. Estimates of the Global Carbon Budget (http://www.globalcarbonproject.org/) and its relationship to the global energy system and changes in land use. Future scenarios for GHG emissions: SSPs and RCPs. Global emissions based on consumption vs. production.	S. Simões
4	22/mar Friday	16h-18h	**GHG Emission Mitigation options:** Mitigation vs adaptation. Fuel switch, renewable energy, energy efficiency, green hydrogen, nuclear power, carbon capture & storage/utilisation, carbon removal. Behavioural mitigation options. Introduction to assignment.	S. Simões
5	05/apr Friday	14h-16h	**Drawdown** - Multisector Climate Solutions	J.P. Gouveia
6	11/apr Thursday	14h-16h	**GHG Emission Mitigation options:** Hydrogen economy, check assignment status	S. Simões
6	12/apr Friday	14h-16h	**Renewables technologies:** Renewable energy technologies. Energy security of endogenous vs. imported resources. Learning curves of renewable energy technologies. Definition and usefulness of LCOE. System value of Renewables. Global renewables' market. Sustainability issues related with renewables. Land & water use, critical raw materials. Discussion: Where to place 7GW of solar PV in Portugal till 2030?	S. Simões

7	19/apr Friday	14h-16h	**Policy and economy of Climate Change:** Global framework to deal with climate change: UNFCCC, Paris Agreement. EU climate policy framework (FF55, REPowerEU, CBAM, etc.). Fundamentals of carbon and climate economics: risks and opportunities for organisations and businesses. State of the art on carbon pricing: emissions trading schemes, carbon taxes. Introduction to EN-Roads Simulation Game	S. Simões
8	03/may Friday	16h-18h	**30min Mini-quizz in class** (20% of final grade). **EN-Roads** simulation game: the transformation towards sustainability — interconnected challenges and solutions	students / S. Simões
9	10/may Friday	16h-18h	**Resources and datasets on energy and GHG emissions**: access to energy databases, Portuguese and European (PORDATA, DGEG, EUROSTAT). i) How to find and explore energy statistics and emissions of greenhouse gas (GHG) emissions for Europe and Portugal; ii) How to make energy conversions; iii) How to build indicators and charts with added value; iii) How to analyze economic sectors, and interpret their performance in terms of energy consumption and greenhouse gas emissions.	S. Simões
10	17/may Friday	16h-18h	**Energy systems modelling:** most well known models and exemplary applications at different scales & **Mentoring** with each students' group : discussion on the approach and methods adopted by the students, expected results to be obtained with the final work; assessing preliminary results, if any.	S. Simões
11	23/may Thursday	18h-20h	**Business strategy for climate change:** Climate change risks for companies. Mitigation, adaptation and risk management in companies. GHG emissions inventories. Carbon footprint of products. Rationale and examples of carbon voluntary markets.	S. Simões
12	24/may Friday	18h-20h	**Sustainable Cities and Buildings:** concept, components and implications for the energy systems. Energy poverty and the energy transitions.	J.P. Gouveia
13	07/jun Friday	18h-20h	**Evaluation**: assignment presentation by the students. Discussion in class (80% of final grade)	S. Simões / J. Seixas

If you need to discuss topics related to the course, including the assignment, I am available on Thursdays 10h-11h – send me an e-mail to book this slot at least 4 days before

Para discussão de assuntos relacionados com o seminário, incluindo o trabalho final, estou disponível às quintas 10h-11h – têm que enviar-me e-mail previamente (pelo menos 4 dias antes)

PROGRAM & RESOURCES @

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Climate Change and Sustainable Development Policies

Assignment

Challenge: Within the scope of your personal interests, select an economic activity: Fashion | Communication | Food and Beverage| Industry | Health services | Mobility | Other

Assuming your country will be in the midst of a pathway to achieve a carbon neutral economy by 2050 (as stated in the Paris Agreement) or earlier, how do you envisage the selected activity will picture by 2040?

Team work | Think out of the box | Innovate
What is the challenge for the activity? Who are the challenge owners?
What do you envisage the activity must/should deliver in the future?

Assignment | Suggestion of script for development:

- firstly, **formulate (and detail) the problem** as far as you are able;
- characterize the **activity at present** [for example, production / import technologies| type of markets and consumers | competition from other markets? | energy consumption profile | indicators of carbon intensity]
- **envisage the activity up to 2040** [technological options | product change - green| change of consumers | energy consumption profile | indicators of carbon intensity]
- systematize **opportunities for the mitigation** of the selected activities (identify needs of R & D, act on consumption preferences, the product value chain, among others)
- identify and anticipate **constraints and barriers to the desired mitigation**, and explain how to overcome them.

Tips: Start now; try to be objective and quantify what is possible; do not try to be exhaustive (you cannot do it within just one course); explore examples that already exist in other countries; be creative.

Assignment | **EVALUATION:**

Criteria [points/100], the goal of the exercise is to promote:

1. Your **ability to reason about the problem**, in a structured and integrated way (for example, within the value chain of the activity, including the international dimension if applicable); [25]
2. **Consistency and creativity in the scenario design** in 2040 taking into account the expectations of a 450ppm scenario (aggressive reduction of GHG emissions); [20]
3. Show **knowledge about technological mitigation options**, in particular regarding the energy component; [20]
4. Demonstrate **robustness of analysis and arguments**, focusing on aspects of cost effectiveness, carbon economics, competitiveness, among others. Demonstrate ability to synthesize information and data processing; [20]
5. **Quality of presentation document** & clear and concise **oral presentation** [15]

Assignment | How the work will be developed?

- **Groups of 3 students** (please send me an **email with the group members until end of march**)
- **Coaching session** to each group, on the work development (one class dedicated to this, 17th may)
- **Oral presentation**: 30 min/group [15 min for oral presentation + 10 min Q&A]
- **Deliverable**: at the day before the oral presentation at maximum (6th June 23h59), students will send to Julia Seixas & Sofia Simões the presentation by email.
  - Presentation in pdf format: maximum 10 slides + word document with 3 pages at maximum (only if needed for complementary information).

Oral presentation:
7 June 2023, Friday, 18:00h, ICS (tbc)

Climate Change and Sustainable Development Policies

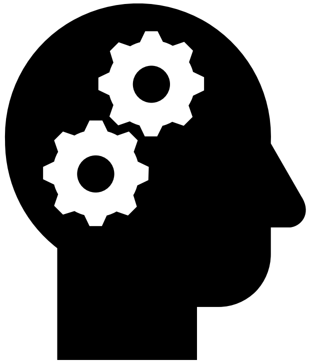
Assignment | GROUPS?

- **Any groups?**
  1. **Transport company in Africa**
  2. **Google/Azure**
  3. **EMAE – Electricity of São Tomé**
  4. **????**

- **Common suggestion – try to narrow down the topic**

Test your self: work in pairs | 10 min!!

1. What are the 6 GHG? And the 2 main ones where mitigation efforts are more focused?
2. Name 2 main carbon sources and 2 sinks
3. What is radiative forcing?
4. What are anthropogenic emissions?
5. What is CO_2e? And GWP?
6. What is IPCC? And UNFCCC?
7. What is the link between energy and climate change?
8. Why socio-economic trends are relevant for climate change?
9. What is the difference between direct (territorial GHG emissions) and indirect (consumption-based) GHG emissions?
10. Difference between primary, final and useful energy
11. What are energy services?
12. What is carbon intensity? And energy intensity?



Outline

- Mitigation vs adaptation
- Energy efficiency
- Behavioral mitigation options
- Fuel switch & electrification
- Renewable energy (includes bioenergy)
- Green hydrogen
- Carbon capture & storage/utilization (includes direct air capture)
- Synthetic Fuels and Power to X

Mitigation vs adaptation

What is climate change MITIGATION?

Climate change mitigation refers to **actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere and/or reduce their levels in the atmosphere.**

Mitigation includes **reducing the GHGs emitted from energy production and use** (e.g., that reduces use of fossil fuels), **and land use**, and methods to mitigate warming, for example, by **carbon sinks which remove emissions from the atmosphere through land-use or other (including artificial) mechanisms** (…).

https://www.ipcc.ch/report/ar6/wg3/downloads/faqs/IPCC_AR6_WGIII_FAQ_Chapter_01.pdf

What is climate change ADAPTATION?

In human systems, the **process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities**.

In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

https://www.ipcc.ch/sr15/chapter/glossary/

Decarbonize – how?

IEA identifies 7 pillars:

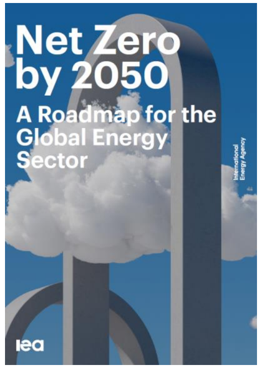
- Energy efficiency
- Behavioral changes

  “changes in ongoing or repeated behavior on the part of consumers which impact energy service demand or the energy intensity of an energy- related activity"
- Electrification

  "direct use of low-emissions electricity in place of fossil fuels”
- Renewables
- Hydrogen and hydrogen-based fuels
- Bioenergy
- Carbon capture and storage (CCS)

https://www.iea.org/reports/net-zero-by-2050

Which mitigation options to choose?



https://www.iea.org/reports/net-zero-by-2050

- **Costs (xyz € per kg or per MW)**
- **Mitigation potential (xyz /t of abated CO_2 or CO_2e)**
- **Effectiveness** [to which is degree it will be successful in delivering the desired mitigation?]

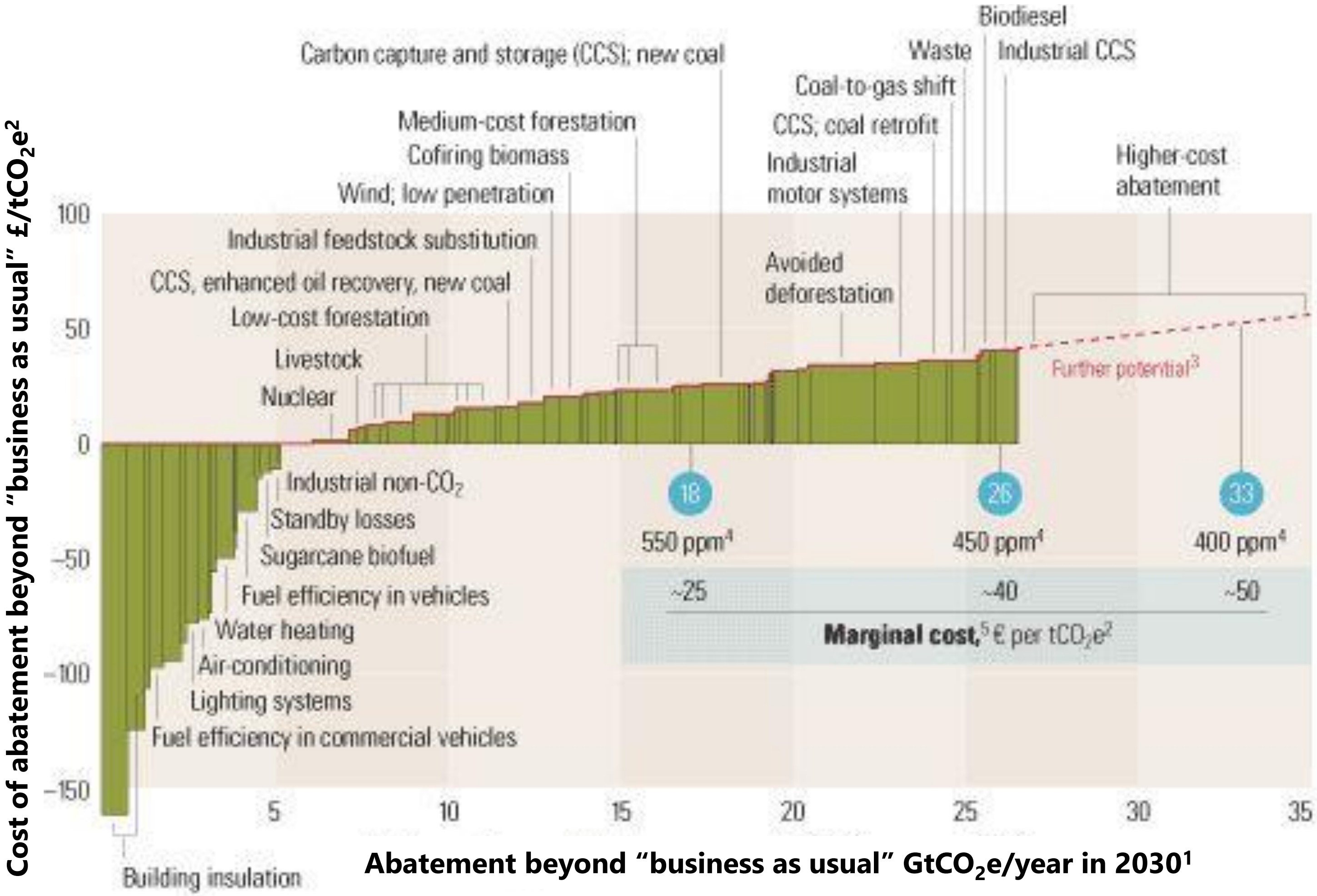
  Cost-effectiveness (xyz € per t of abated CO_2 or t of abated CO_2e)

- **Social acceptability**
- **Co-benefits: environmental, energy security, social gains (e.g. job creation)**
- **Technological maturity**
- **Time of implementation**
- **Technology ownership and know-how is available?**
- **…**

The McKinsey Abatement cost curve
(from 2007)

Approximate abatement required beyond "business as usual"

Global cost curve for greenhouse gas abatement measures beyond "business as usual"
GHG in $GtCO_2e$



[1] $GtCO_2e$ = gigaton of carbon dioxide equivalent; "business as usual" based on emissions growth driven mainly by increasing demand for energy and transport around the world and by tropical deforestation.
[2] tCO_2e = ton of carbon dioxide equivalent.
[3] Measures costing more than €40 a ton were not the focus of this study.
[4] Atmospheric concentration of all greenhouse gases recalculated into CO_2 equivalents; ppm = parts per million.
[5] Marginal cost of avoiding emissions of 1 ton of CO_2 equivalents in each abatement demand scenario.

McKinsey Sustainability

https://www.mckinsey.com/capabilities/sustainability/our-insights/a-cost-curve-for-greenhouse-gas-reduction

CO_2 savings in 2050 by technology maturity

https://www.iea.org/reports/net-zero-by-2050

Refrigerant-free advanced cooling

Advanced batteries

Next-generation biofuels

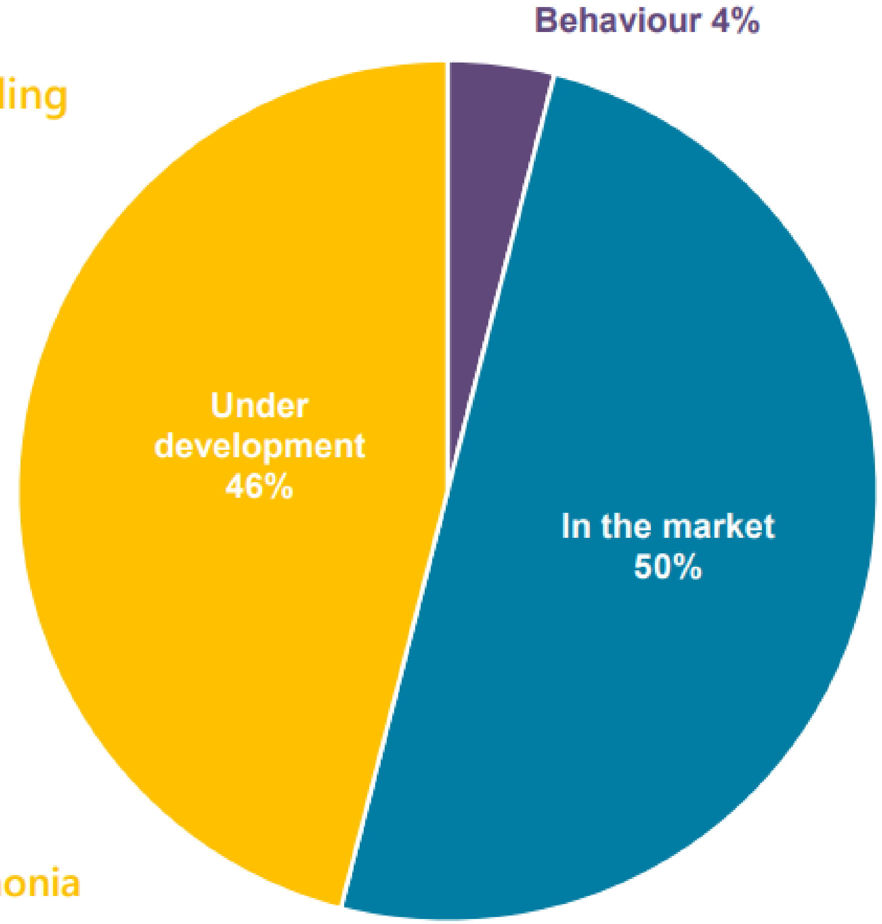
CO_2 capture from cement

Hydrogen-based steel

Small modular reactors

Synthetic liquid fuels

Electrolytic hydrogen for ammonia



Autonomous trucks

Optimised heat pump with storage

Direct air capture

Ammonia-powered ships

Electrolytic hydrogen for methanol

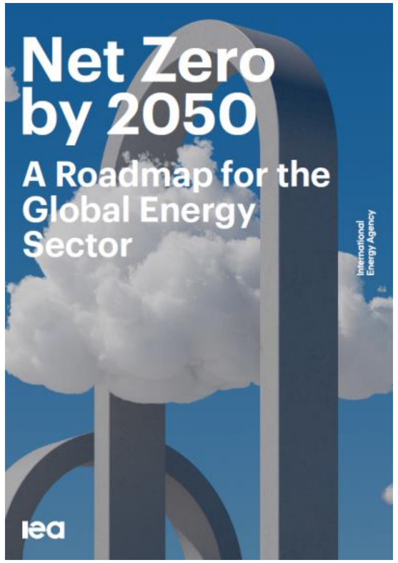
Building-integrated storage

Electric steam crackers

Unlocking the next generation of low-carbon technologies requires more clean energy R&D and $90 billion in demonstrations by 2030; without greater international co-operation, global CO_2 will not fall to net-zero by 2050.

Energy efficiency

Energy efficiency



https://www.iea.org/reports/net-zero-by-2050

Many efficiency measures in industry, buildings, appliances and transport can be put into effect and scaled up **very quickly**

Buildings: large scale retrofit (insulation!!!!), change heating and cooling systems with more efficient boilers and other equipment, change lighting and all household appliances with more efficient ones

Transport: more efficient cars, buses and trucks on the roads (i.e. same distance with lower fuel consumption)

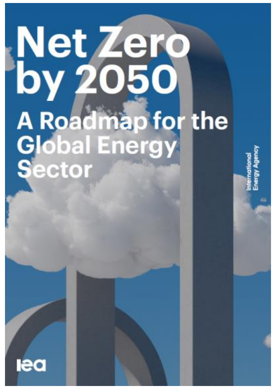
Industry:

- Energy management systems
- "best-in-class" industrial equipment as kilns, boilers, electric motors, variable speed drives, heaters and grinders
- process integration options such as waste heat recovery

Behavioral changes

Which behavior to change?

https://www.iea.org/reports/net-zero-by-2050



Reducing excessive or wasteful energy use

- reducing energy use in buildings and on roads, e.g. by reducing indoor temperature settings, adopting energy saving practices in homes and limiting driving speeds on motorways to 100 km/h

Transport mode switching

- shift to cycling, walking, ridesharing or taking buses for trips in cities that would otherwise be made by car
- replacing regional air travel by high-speed rail in regions where this is feasible.

(represent a break in familiar or habitual ways - public acceptance is key! Also require new infrastructure, as cycle lanes and high-speed rail networks, clear policy support and high-quality urban planning)

Materials efficiency gains

- reduced demand for materials, e.g. higher rates of recycling, and improved design and construction of buildings and vehicles

(the scope for gains to some extent reflects societal preferences, e.g. the shift away from the use of single-use plastics in recent years)

(Reduced demand for meat and dairy products) ***not mentioned by the IEA***

Change behaviour via “nudges”

NUDGE

Nudging consumers towards energy efficiency through behavioural science

Nudging is a soft push, that can make people act or react — and consume less energy — because they are told their neighbours or peers do so for instance or by changing the default settings of energy devices.

https://www.nudgeproject.eu/

Examples of “nudges” for energy efficiency: “facilitate” and “fear”

Nudging consumers towards energy efficiency through behavioural science

FACILITATING NUDGES – Nudges that facilitate desirable behaviours by diminishing the physical or mental effort of individuals

Nudge	Mechanism	Example
Default	Change the preset option	Temperature setting
Opt-Out	Consent is opt-in instead of opt-out	Consent to automated management or switch to manual
Suggesting	Suggest alternatives for decisions	Personalised push notifications

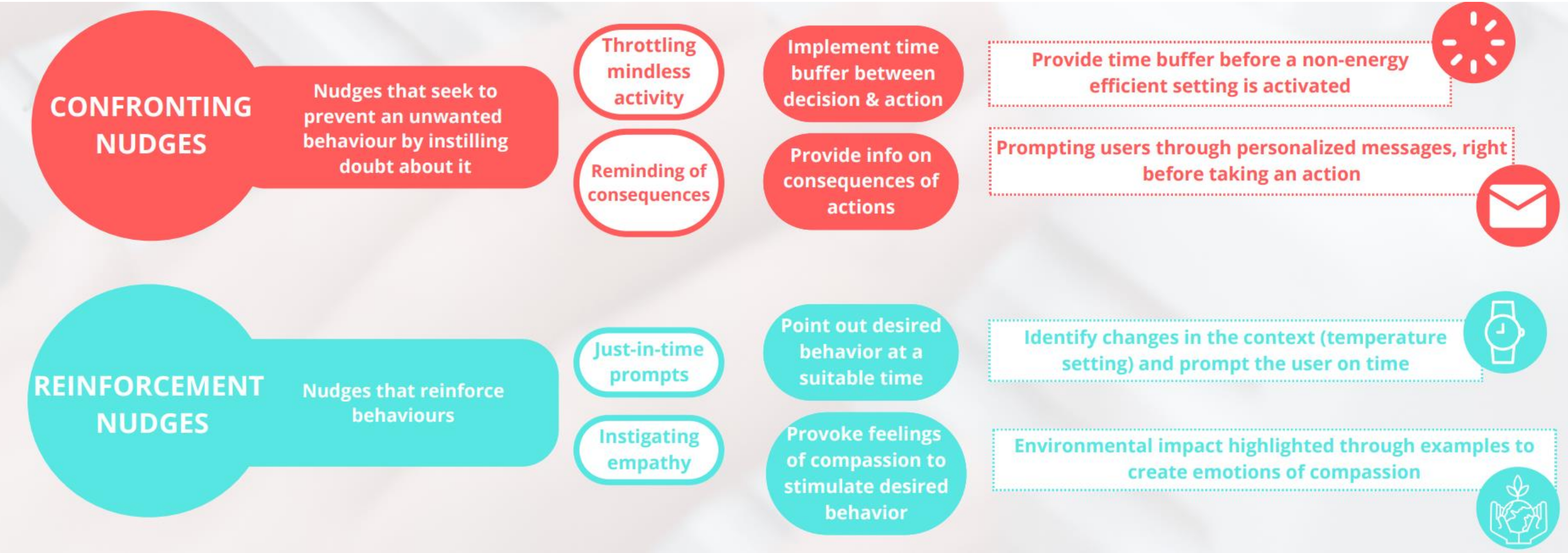
FEAR NUDGES – Nudges that attempt to generate fear and uncertainty

Nudge	Mechanism	Example
Resources scarcity	Create perception of scarcity	Inform that free PV energy is available for 2 more hours
Temporal discounting	Provide discount now instead of on the long run	Provide discount on installing monitoring equipment, so that they can save energy later

FREE

https://www.nudgeproject.eu/

Examples of “nudges” for energy efficiency: “confronting” & “reinforcing”

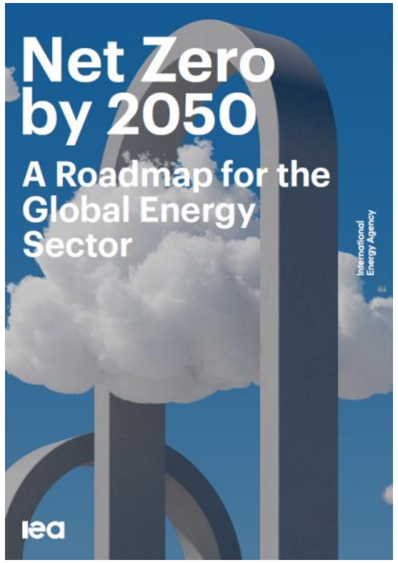


https://www.nudgeproject.eu/

Fuel switch and electrification

Electrification (and fuel switch)

The **direct use of low-emissions electricity in place of fossil fuels** is one of the most important drivers of emissions reductions

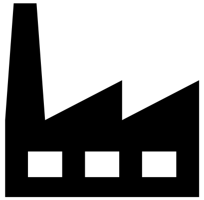


https://www.iea.org/reports/net-zero-by-2050

Buildings

- Electric-based low-medium temperature **heat** (instead of gas or LPG) – heat pumps! For space heating and water heating
- Electric **cooking** instead of natural gas or LPG cooking

Industry



- Electric secondary **scrap-based steel production** instead of coal based
- Electric (some) kilns and motors instead of gas or diesel based

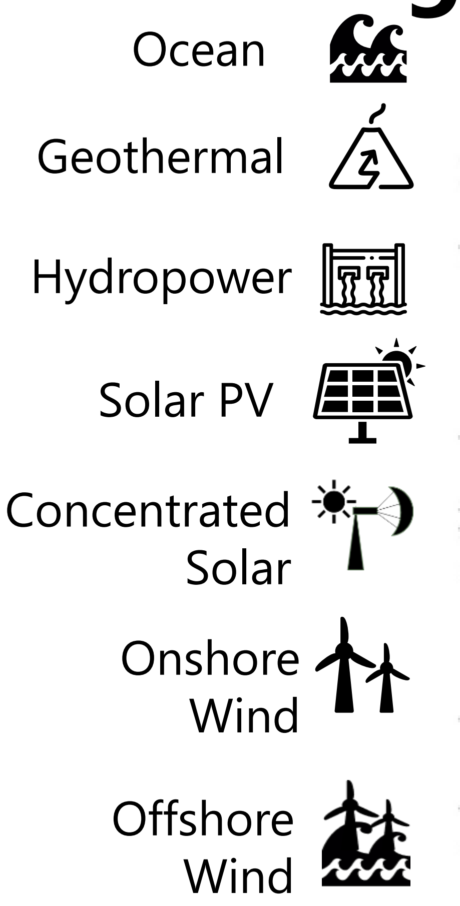
Transport

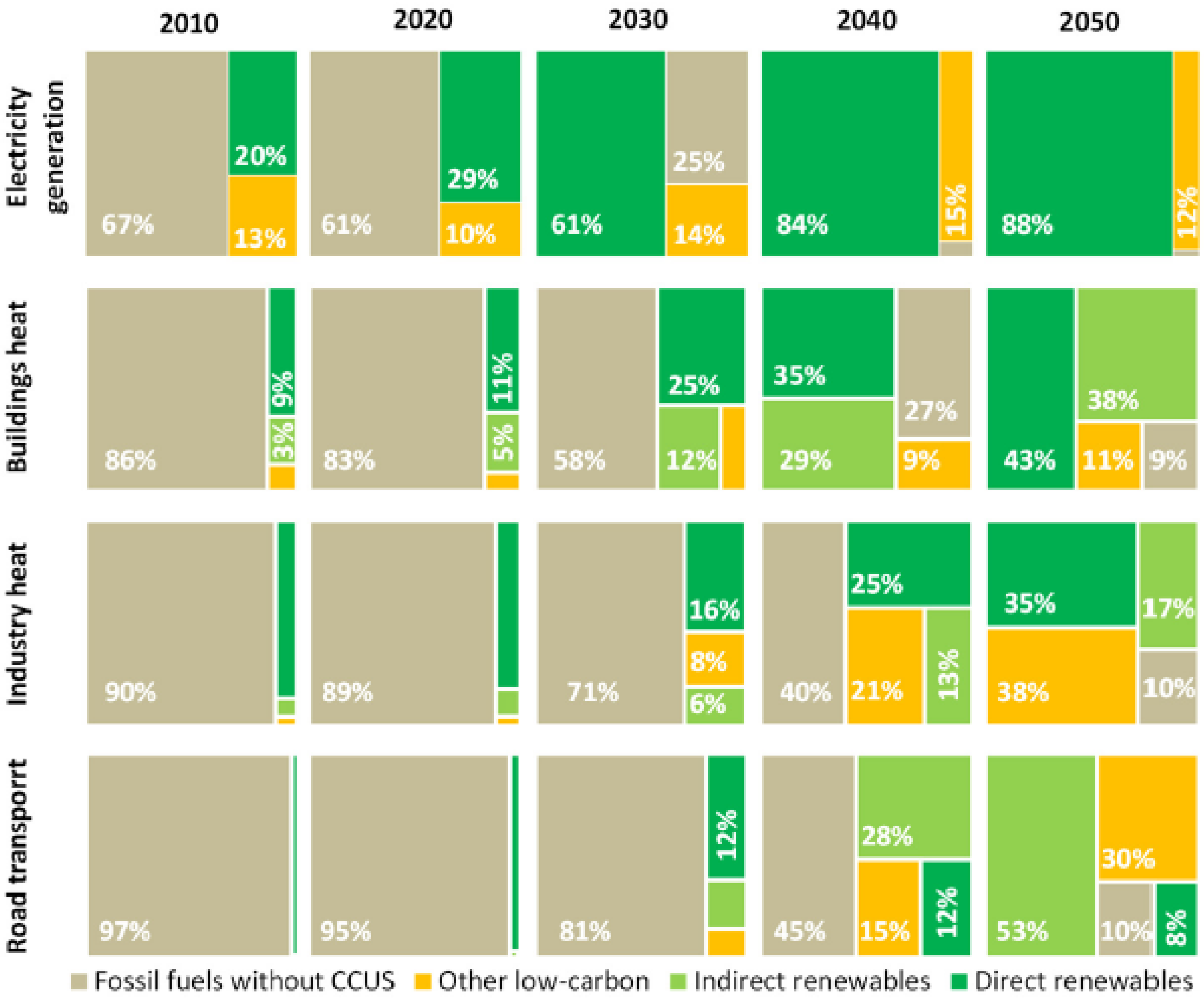
- Cars
- Trucks
- Buses
- Trains

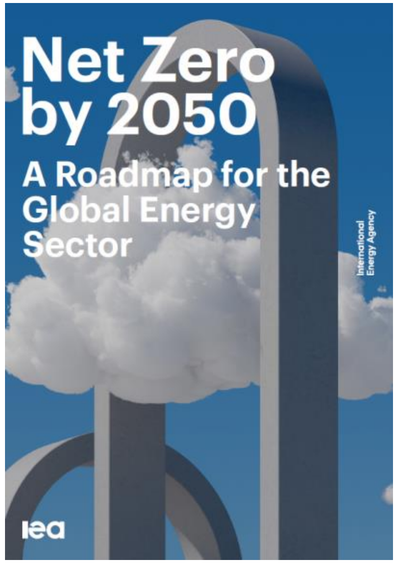
Replacing coal with natural gas is also a fuel switch that promotes decarbonization as gas has a lower C content

Renewable energy

Becoming renewable





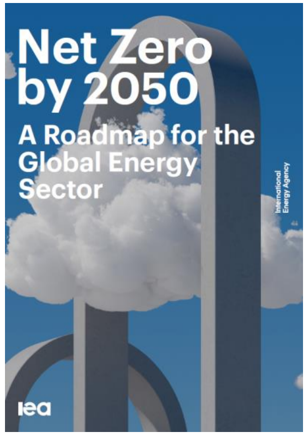


https://www.iea.org/reports/net-zero-by-2050

Renewables can be used either **indirectly**, via the consumption of electricity or district heating that was produced by renewables, or **directly**, mainly to produce heat

Renewables

https://www.iea.org/reports/net-zero-by-2050



Buildings

For space heating and water heating via **solar thermal** and **geothermal** technologies

Transport

Biofuels from **bioenergy**

Centralized heat/gas

Bioenergy for district heating systems
Biogas/biomethane from waste management and/or intensive livestock farming

Industry

bioenergy (wood chips, pellets, etc) is the most important direct renewable energy source for low- and medium-temperature heat
solar thermal, geothermal and biomethane produce low temperature heat for use in non-energy-intensive industries and ancillary or downstream processes in heavy industries

Power sector

solid **bioenergy** provides flexible low-emissions generation to complement generation from solar PV and wind – to be used as BECCS

The climate game

https://ig.ft.com/climate-game/

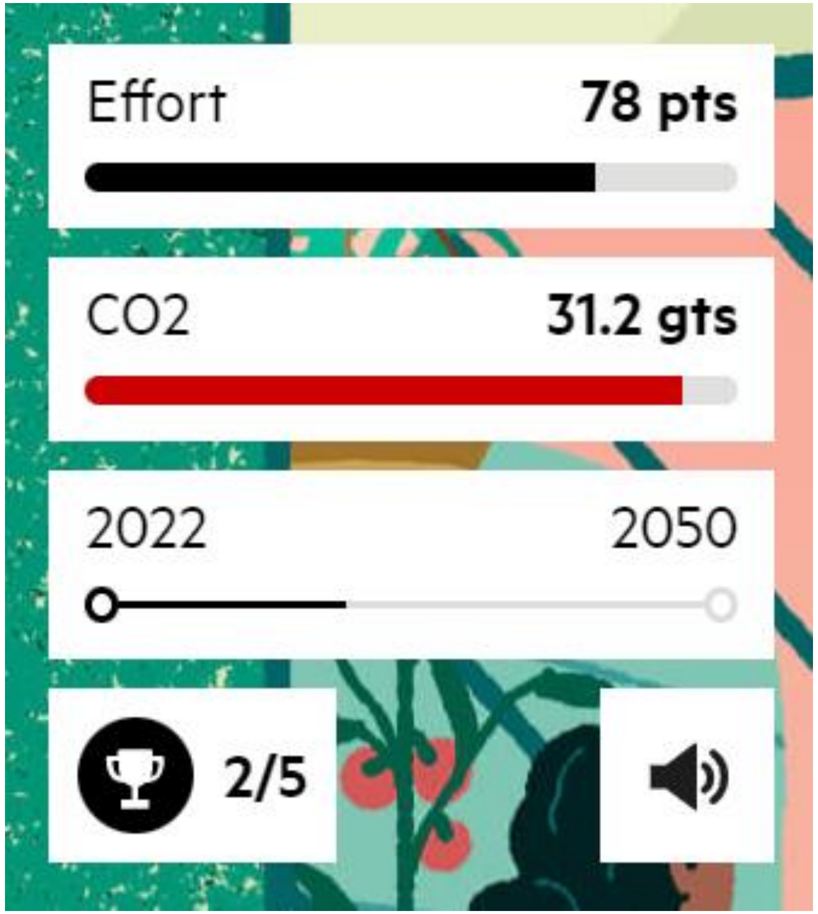
Other experts consulted: Tim Lenton, University of Exeter; Carlos Nobre, University of São Paulo; Scott Goetz, Northern Arizona University; David Armstrong McKay, Georesilience Analytics and University of Exeter; Ted Schuur, Northern Arizona University.

The climate game

https://ig.ft.com/climate-game/

Goal is to meet the 1.5°C target!

- **Divided in 3 periods:**
  - **now to 2025**
  - **2026-2030**
  - **2031-2050**
- **You will be asked to take decisions on mitigation options (mostly)**
- **You will have effort points that you will need to spend – not all options “cost” the same**
- **Climate will be changing as you go along**
- **Your measures will have sometimes unexpected impacts**

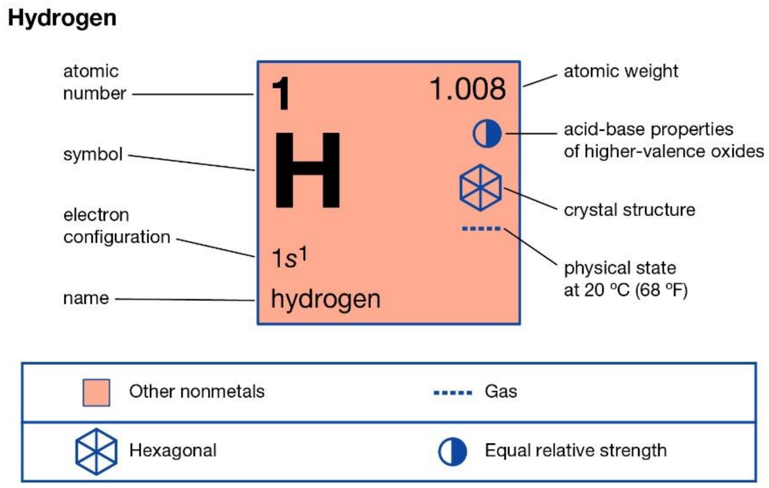


GO!!!!! 15 minutes!!!!!

Green Hydrogen and Hydrogen-based fuel (synthetic fuels)

What is H_2

- The most abundant chemical substance in the Universe.
- The lightest element in the periodic table.
- Contains more energy per unit of mass than natural gas or gasoline (3X) – lower energy per volume (1/10 of natural gas)



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larger volumes of hydrogen are needed to meet identical energy demands as compared with other fuels

Table 2. Physical properties of hydrogen

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Source: IEA, 2019a

Currently H_2 is used already

In pure H_2 form (~70 Mt/yr)

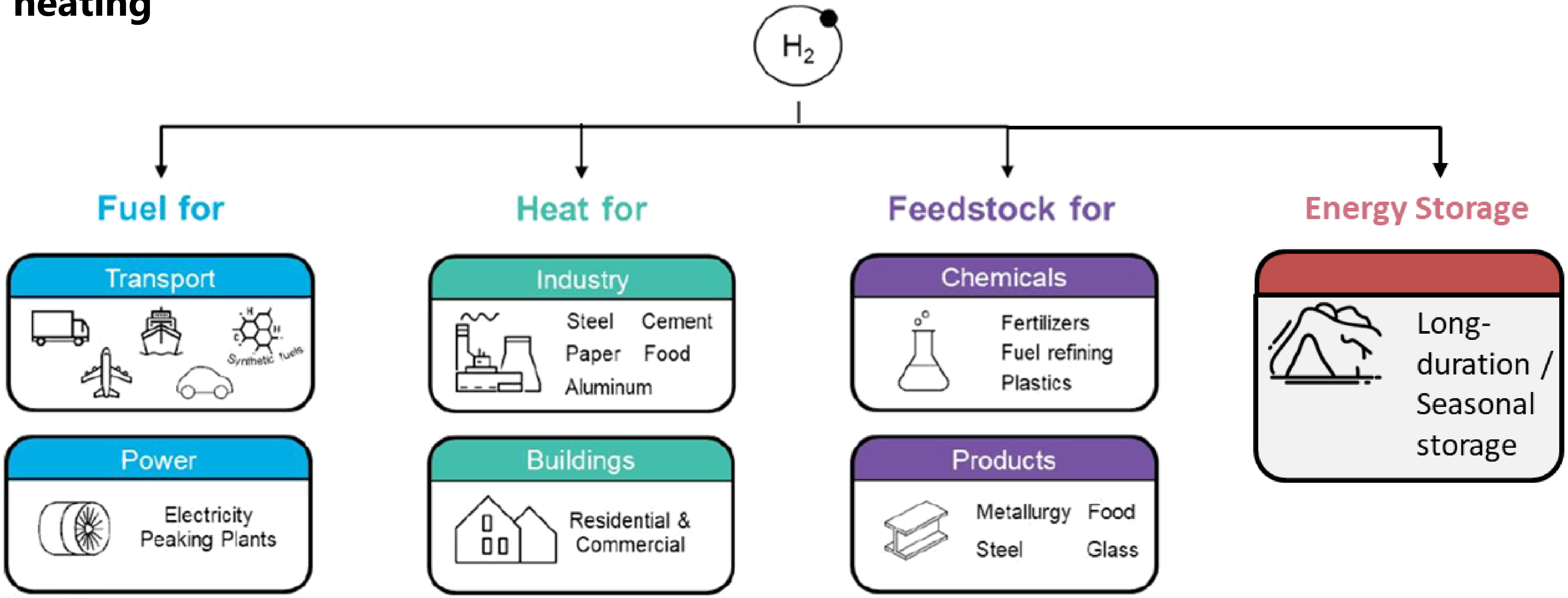
- refining petroleum (e.g., lower the sulphur content of diesel fuel),
- producing fertilizer (ammonia)
- other

Mixed with other gases as synthesis gas for fuel or feedstocks (~45 Mt/yr)

- DRI or directed reduced iron steel production
- Methanol production
- other

H_2 can play a key role in many economic sectors/uses

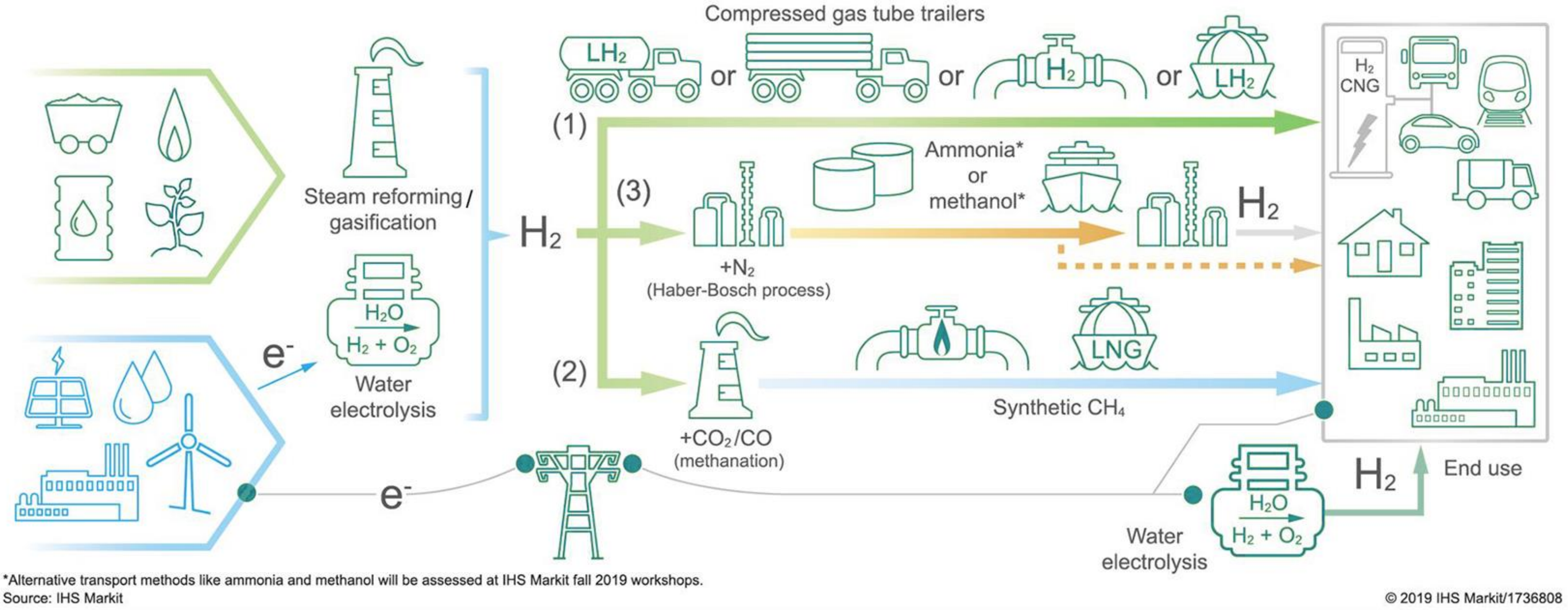
It can be a key mitigation option for decarbonization of transport, industry and heating



https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

 Adapted from Patrícia Fortes, 2021

What is the H_2 economy? | H_2 value chain



Barriers to the uptake of H_2 economy?

1. **High production costs**
2. **Lack of dedicated infrastructure for transport** (transmission and refueling)
3. **Energy Losses**

   30-35% losses energy used to produce H_2 via electrolysis + conversion of H_2 to other carriers (as ammonia) 13-25% energy loss + energy needed to transport H_2 (~10-12% of H_2 energy itself) + use H_2 in fuel cells 40–50% loss…
4. **Lack of value recognition**

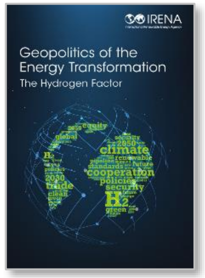
   “no green hydrogen market, no green steel, no green shipping fuel and basically no valuation of the lower GHG emissions that green hydrogen can deliver”
5. **Need to ensure that H_2 is green** (becomes more difficult with electricity from the grid for electrolysis)

IRENA
International Renewable Energy Agency

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

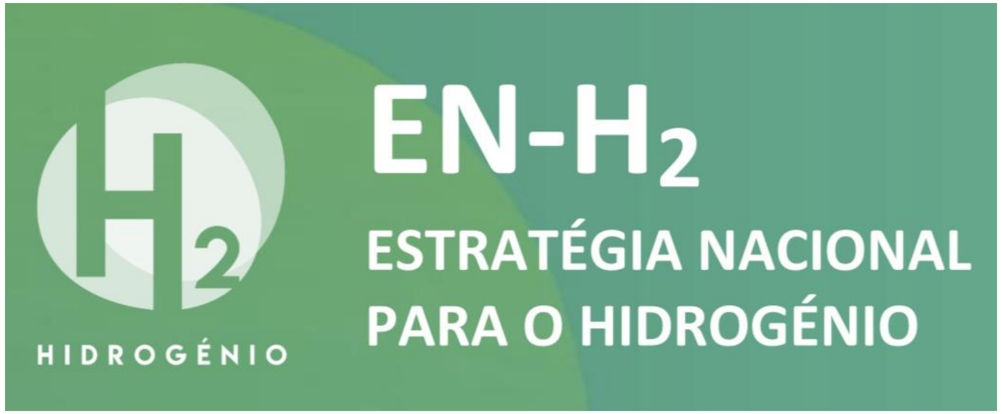
Even with the barriers there is world race to H_2

Countries with national H_2 Strategies in 2021



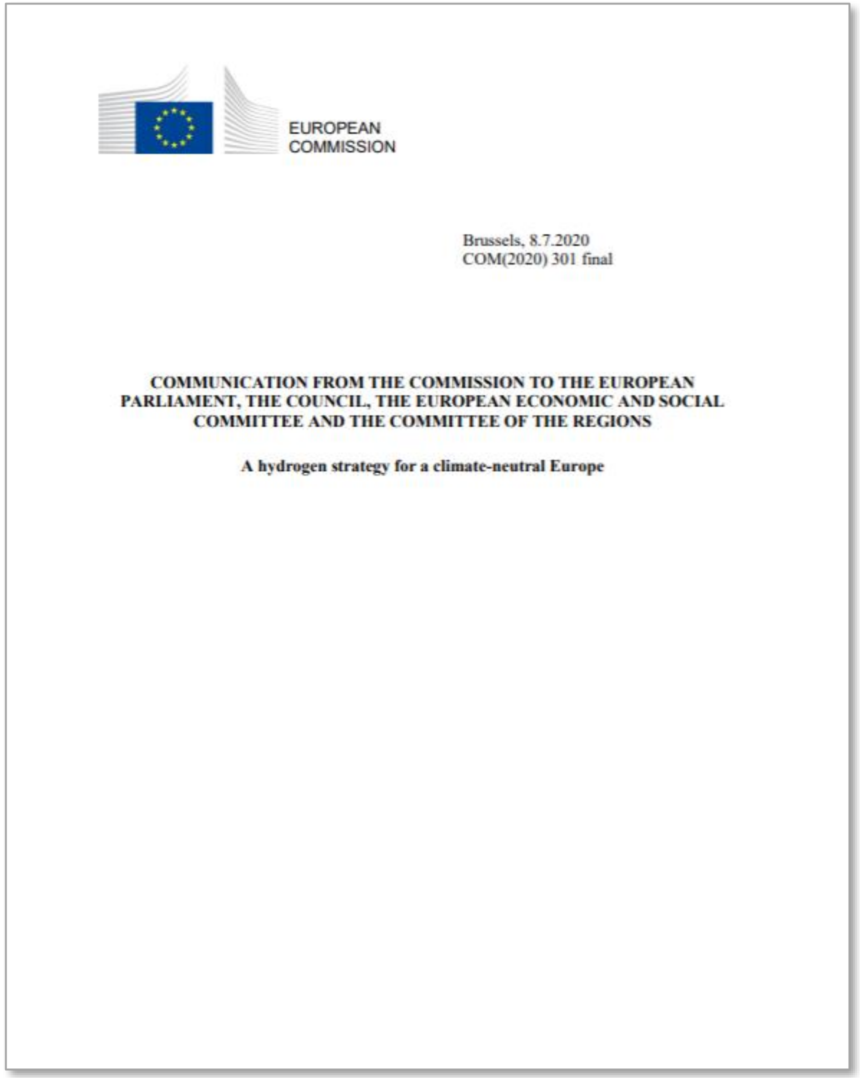
https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

In Portugal and in the EU



President of the European Commission Ursula von der Leyen announced on 14 September 2022 the intention of creating a new 'European Hydrogen Bank' to invest EUR 3 billion in the establishment of a future market for hydrogen

"Hydrogen can be a game changer for Europe. We need to move our hydrogen economy from niche to scale. With REPowerEU, we have doubled our 2030 target to produce 10 million tonnes of renewable hydrogen in the EU, each year. To achieve this, we must create a market for hydrogen, in order to bridge the investment gap and connect future supply and demand"


EUROPEAN COMMISSION

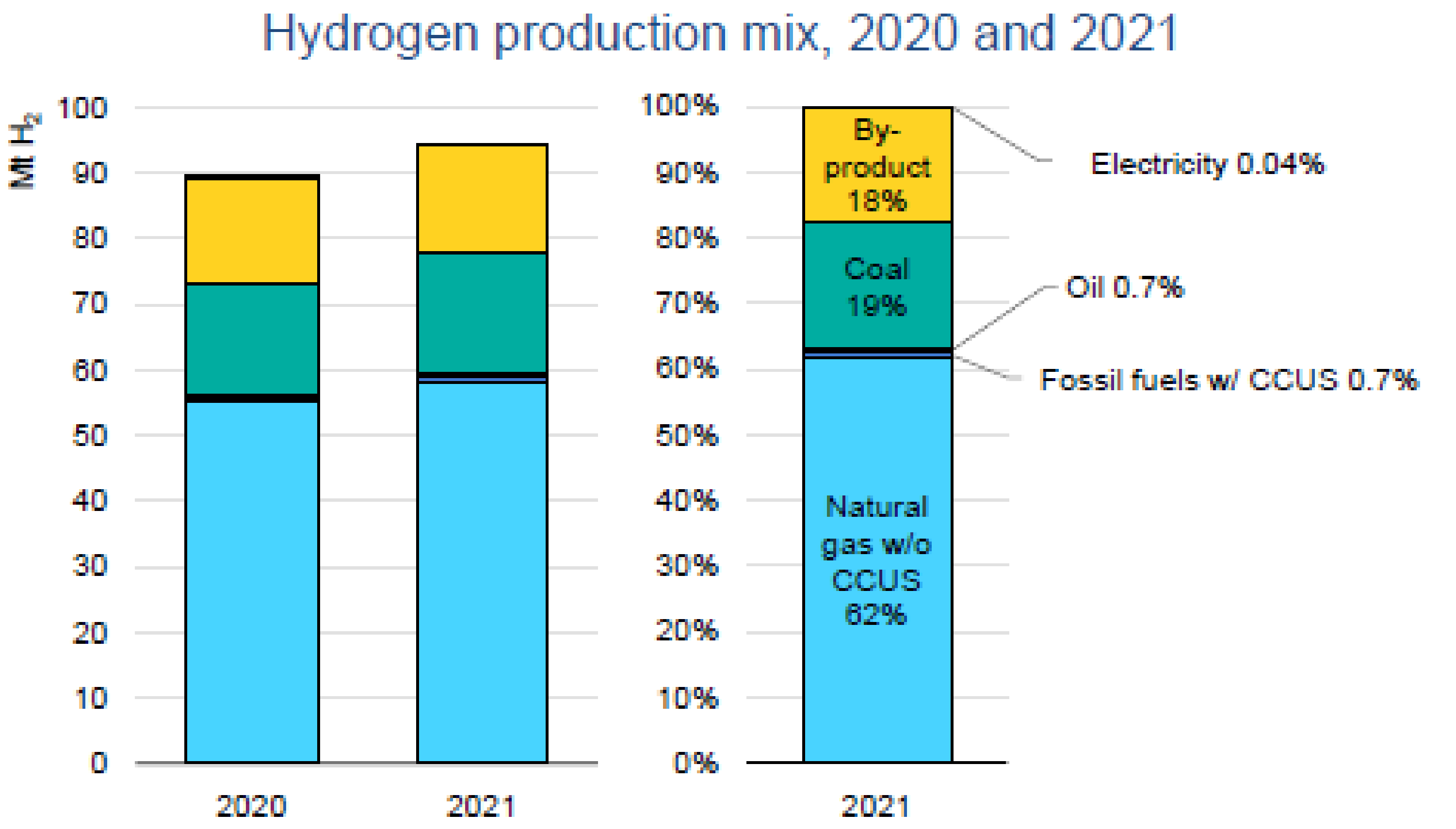
Brussels, 8.7.2020
COM(2020) 301 final

COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

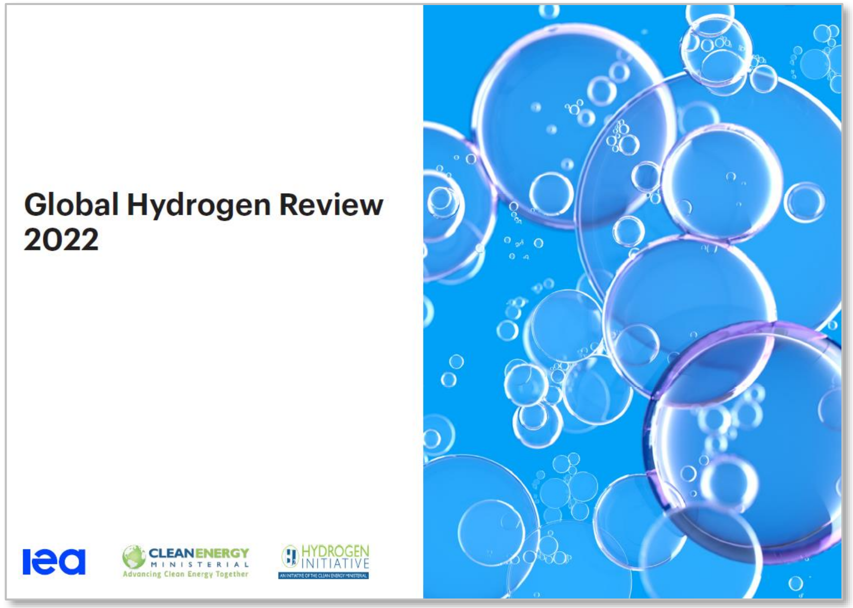
A hydrogen strategy for a climate-neutral Europe

https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

How is H_2 produced?



Note: CCUS = carbon capture, utilisation and storage.

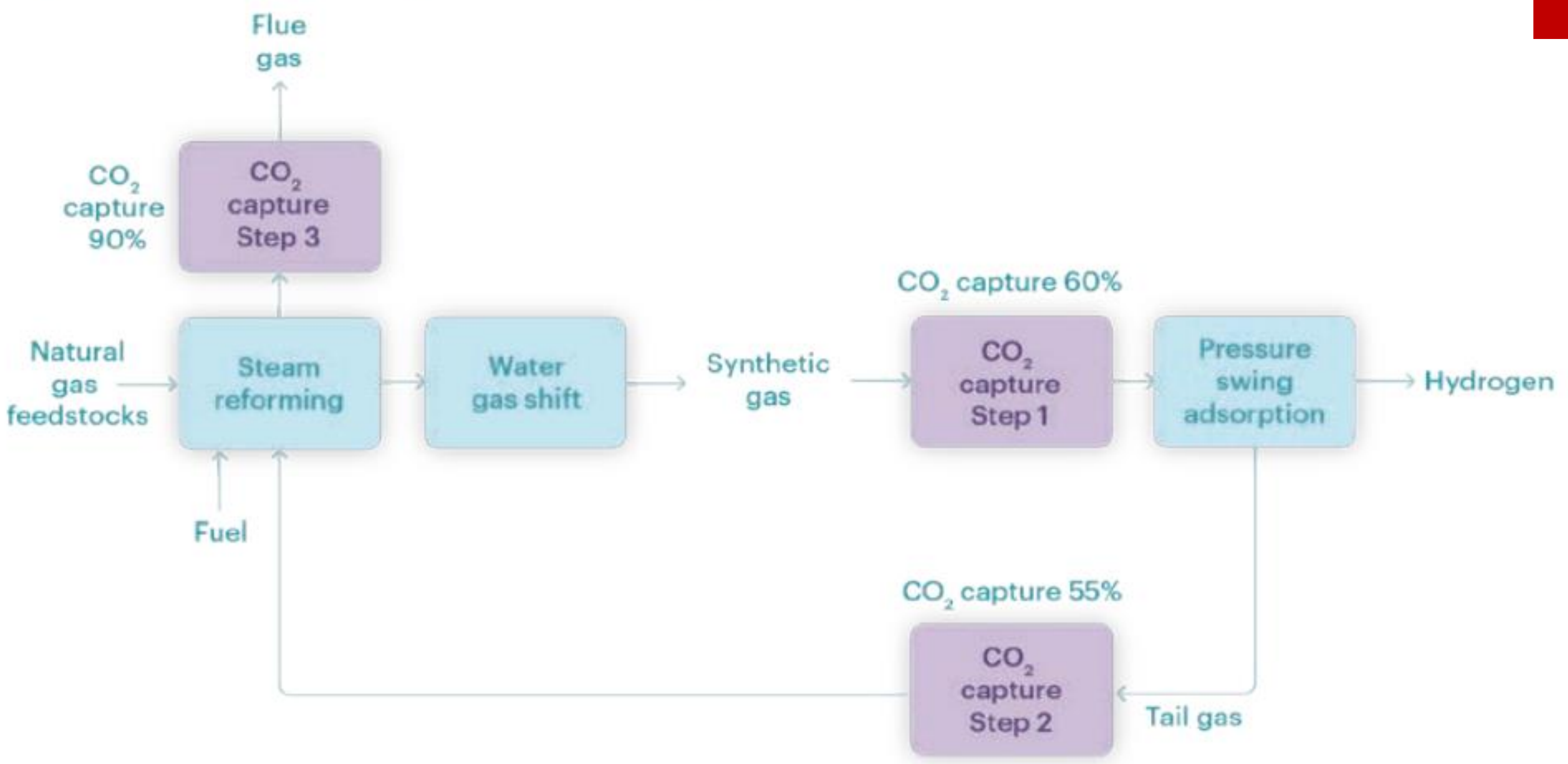


https://www.iea.org/reports/global-hydrogen-review-2022

H_2 production via SMR (steam methane reforming)

Natural gas to hydrogen (with CCUS)

Figure 8. Production process of hydrogen from gas with CCUS



Source: IEAGHG (2017a), "Reference data and supporting literature reviews for SMR based hydrogen production with CCS".

Most H_2 today is produced from fossil fuels – CCUS is not widely used for hydrogen production yet

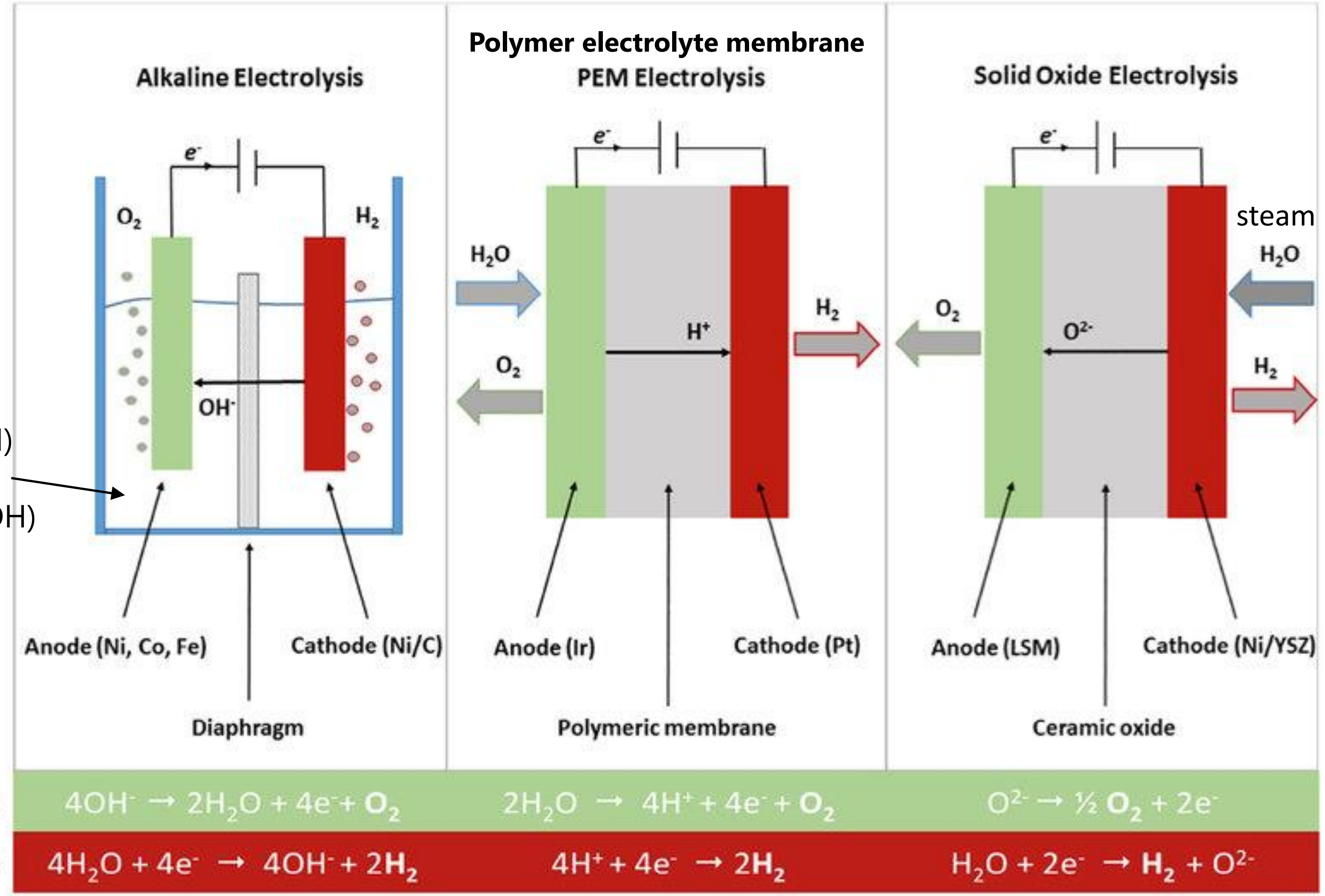
In SMR, **methane reacts with steam under pressure (3-25 bar) in the presence of a catalyst to produce H_2, CO, and small quantities of CO_2**.
Because this is and endothermic process, heat must be supplied.

H_2 production via electrolysis

This is the most mainstream solution to produce hydrogen for decarbonization

- **Electrochemical reaction that splits water into H_2 and Oxygen, using electricity.**
- **It is a 100% emission free and carbon-free process**

potassium hydroxide (KOH) or sodium hydroxide (NaOH) solution



<1 GW electrolyser capacity installed in the world in 2022

35 GW planned by 2030!!!!

Power: 1 MW electrolyser ↔ ± 18 kg/h H_2
Energy: +/- 55 kWh of electricity →1 kg H_2 ↔ ± 9 (12-14) liters demineralized water

The many colors of H_2

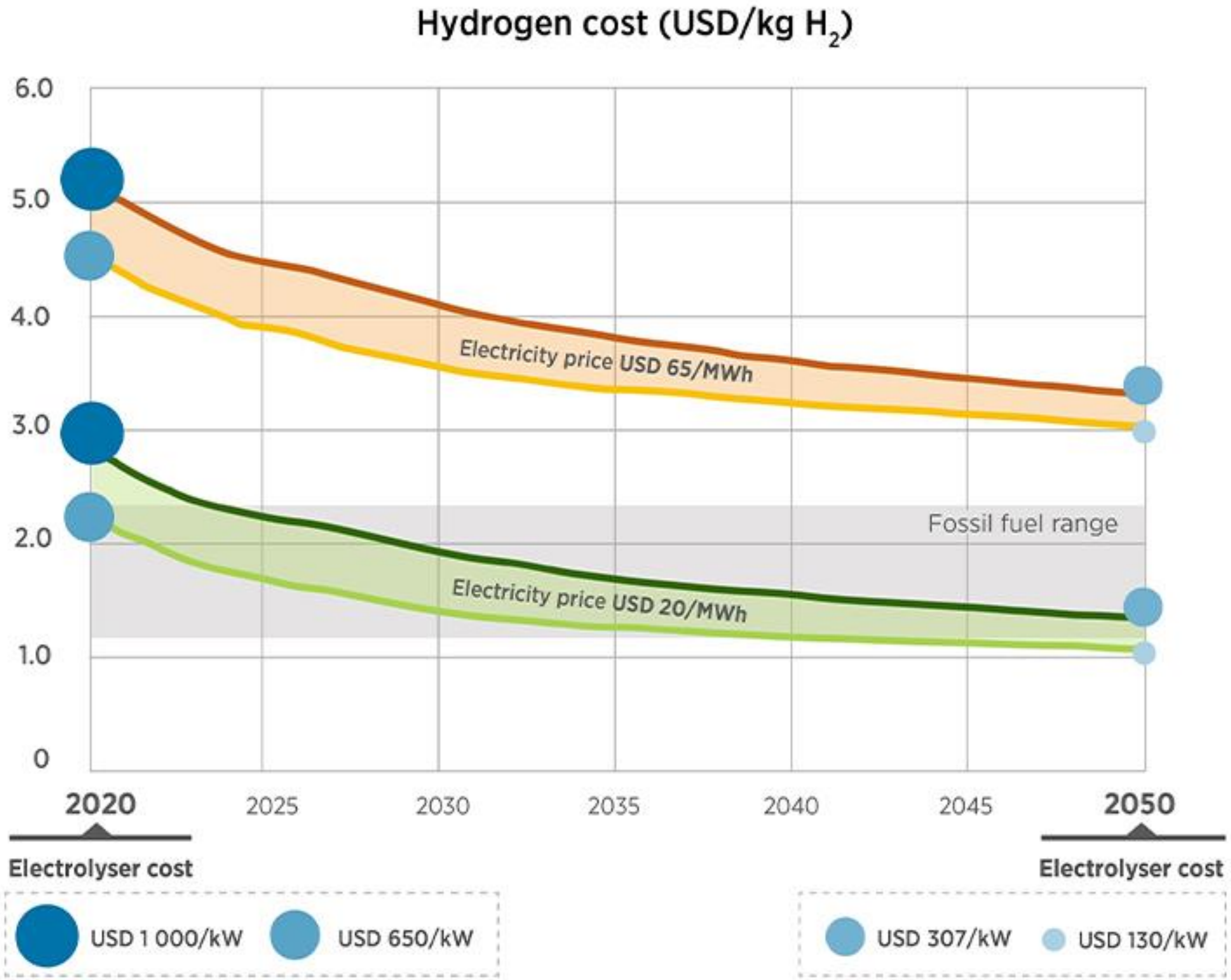
Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Note: SMR = steam methane reforming.
** Turquoise hydrogen is an emerging decarbonisation option.*

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

Note that there is also interesting developments along the production of hydrogen from biomass gasification

Electrolysers are expected to reduce their costs between 65-80% from 2020 to 2050



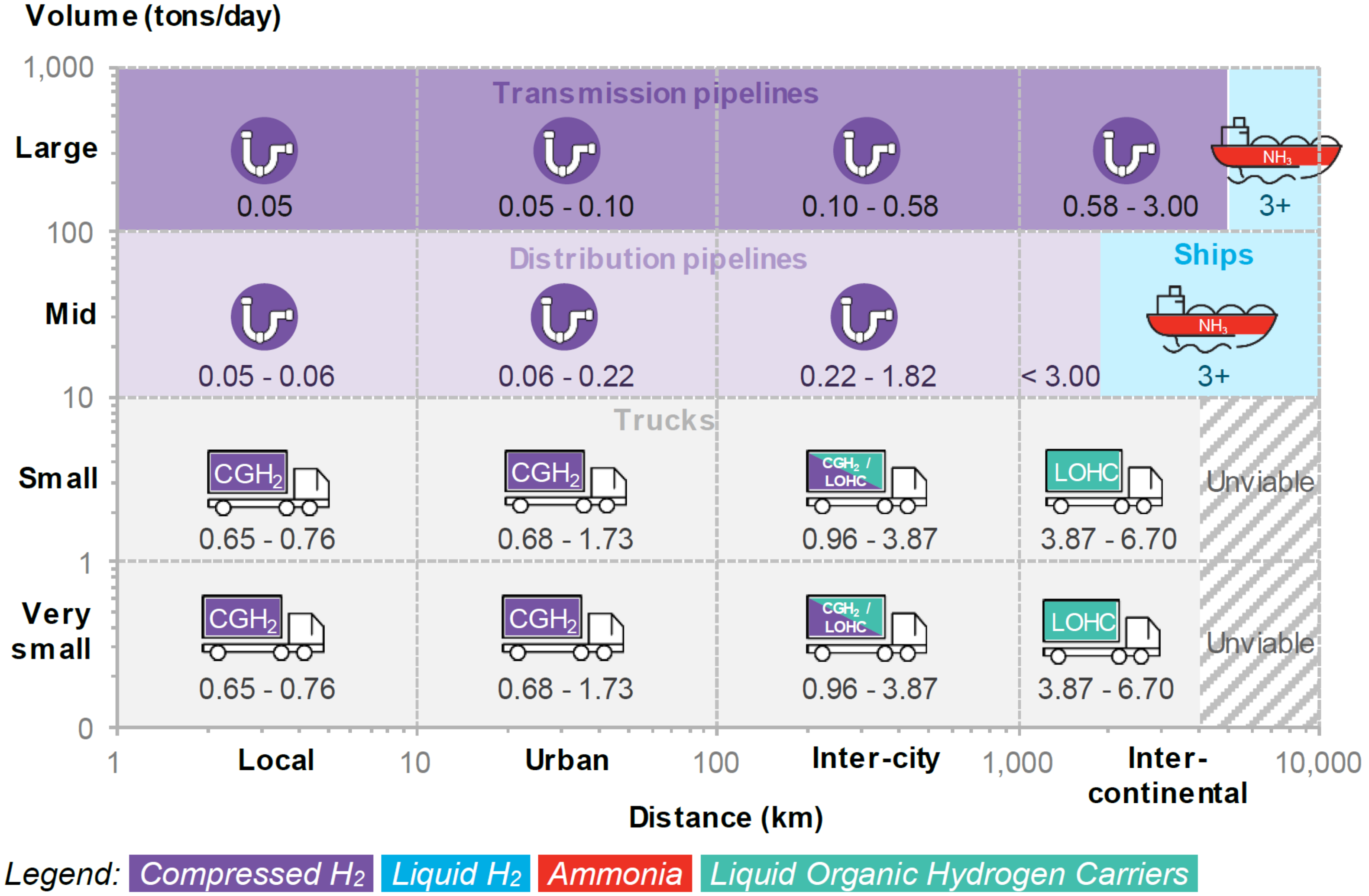
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf

Transport and distribution of H_2

- The low energy density of hydrogen means that it can be very expensive to transport over long distances

- The best options: **blending in the natural gas grid, dedicated grid, trucks or shipping** will vary according to geography, distance, amount of H_2 and the required end use of the hydrogen

Figure 4: H_2 transport costs based on distance and volume, $/kg, 2019



https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

 Adapted from Patrícia Fortes, 2021

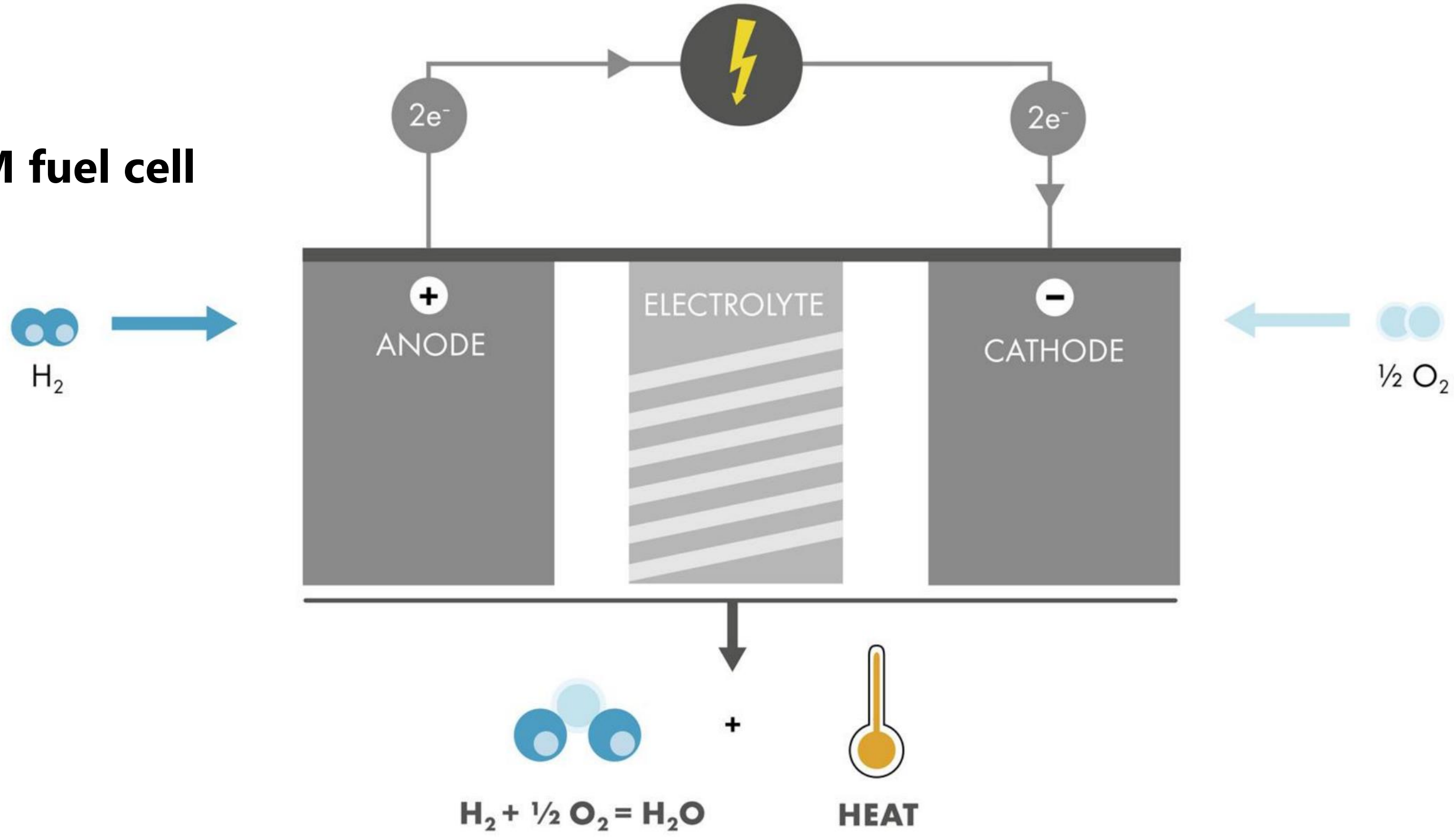
- **45 feet tube trailer model**
- **storage capacity of more than 1 ton of H_2 using the latest carbon fiber technology**
- **working pressure of 517 bar (7500 psi)**

https://www.calvera.es/calvera-hydrogen-develops-the-largest-ever-hydrogen-transport-tube-trailer-model-for-shell-hydrogen/

Final uses of H_2

FUEL CELLS (Pilha de combustível)

Using hydrogen to generate electricity:
Power production from a hydrogen PEM fuel cell from hydrogen (+/- 50% efficiency)
Energy: 1 kg H_2 → 16 kWh



https://www.youtube.com/watch?v=bXHwnKMchkk

H_2 fuel cell electric cars

Table 1. Fuel cell vehicles available on the automotive market

	Toyota Mirai	Hyundai ix35 Fuel Cell	Honda Clarity Fuel Cell
			
Acceleration 0-60 mph	9.6 s	12.5 s	11 s
Fuel Cell power	113 kW	100 kW	103 kW
Engine power	113 kW	100 kW	130 kW
Top speed	179 km/h	161 km/h	200 km/h
Range	ca. 550 km (NEDC test)	594 km	482 km
H_2 storage	70 MPa	70 MPa	70 MPa

http://www.combustion-engines.eu/The-use-of-electric-drive-in-urban-driving-conditions-using-a-hydrogen-powered-vehicle,116453,0,2.html

FCEV (fuel cell electric vehicle) are electric vehicles, but instead of storing electricity, store H_2
A fuel cell acts like a micro power plant to generate electricity on board based on H_2

H_2 fuel cell trucks

Volvo unveils hydrogen-powered truck with 1,000km range

Jun 21, 2022 — Swedish **truck** manufacturer Volvo **Trucks** has unveiled a **hydrogen** fuel cell **truck** which the company claims will have a range of up to 1,000 ...

https://thedriven.io/2022/06/21/volvo-unveils-hydrogen-powered-truck-with-1000km-range/

VOLVO

Volvo Trucks – the role of fuel cell electric trucks

https://youtu.be/bdaGMV6SWws

NIKOLA

DAF

H_2 based buses

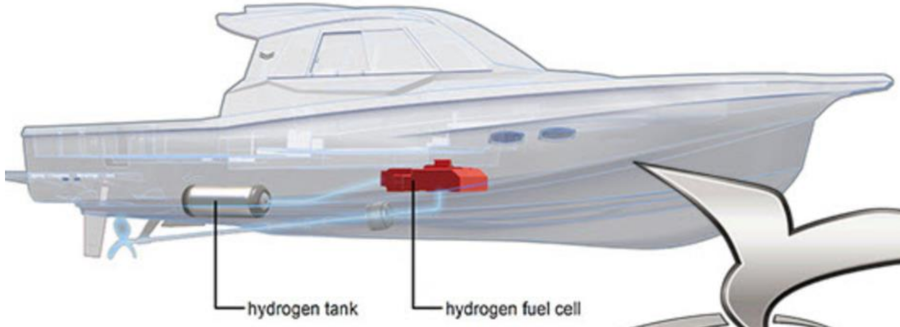
Caetano Bus (*fuel cell* Toyota) production of H2.City Gold

	CAETANO
Length	10 740 mm
Width	2 500 mm
Height	3 458 mm
Doors	2 or 3 doors
Capacity	Up to 64 passengers
Motor	Siemens (180 kW)
Fuel cell sistem	Hydrogen tanks- type 4: 5x 312l (max. 37.5kg: 350 bars) Fuelling time - <9 min (estimate) Nominal fuel cell power - 60kW (Toyota FC Stack)
Batteries	LTO
Charging	CCS Type 2 - AC/DC
Autonomy	Up tp 400 km
Consumption	from 6 kg/100 km

https://caetanobus.pt/pt/buses/h2-city-gold/

H_2 based Navigation

https://www.energy-reporters.com/



YANMAR

https://fuelcellsworks.com/

https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html

H_2 based trains

"The Coradia iLint™ is the world's first passenger train powered by a hydrogen fuel cell, which produces electrical power for traction. This zero-emission train emits low levels of noise, with exhaust being only steam and condensed water. The iLint™ is special for its combination of different innovative elements: clean energy conversion, flexible energy storage in batteries, and smart management of traction power and available energy. Specifically designed to non- or partially electrified lines, it enables clean, sustainable train operation while ensuring high levels of performance. "

https://www.alstom.com/solutions/rolling-stock/coradia-ilint-worlds-1st-hydrogen-powered-train

5 running in Lower Saxony in Germany since August 2022 with 9 more planned

https://www.smithsonianmag.com/smart-news/hydrogen-powered-passenger-trains-are-now-running-in-germany-180980706/

H_2 based trains

China's CRRC Datong and State Power Investment Corporation Hydrogen-Fuel Cell Hybrid Rail Locomotive completed 10 000 km operation assessment in April 2022

https://fuelcellsworks.com/subscribers/chinas-crrc-hydrogen-fuel-cell-hybrid-rail-locomotive-completes-10000-kilometer-operation-assessment/

Portugal's CP train company is looking into replacing diesel trains in the Vouga line with hydrogen-based ones

H_2 for heating in buildings and industry

H_2 can be used **in 3 forms**:

1. **Fuel-cell** (H_2 to produce electricity) – lower efficiency than direct use of electricity, higher control of power supply load curves
2. **Blended in natural gas** (% of blending depends on the equipment – due to *embrittlement factor*)
3. **100% H_2**

- **Lower flame brightness** affect some industrial sectors – e.g., glass, ceramic
- Higher production of **NO_X** (additional control measures) and H_2O steam
- H_2 higher volatility and requires **additional security measures to detect leakages**

with H_2 without H_2

Sources:
"Heat Transfer in Industrial Combustion" , Charles E. Baukal
"Computational modelling of turbulent flow, combustion and heat transfer in glass furnaces", Hoogendoorn et al (1994)
Stig Stenström (2019): Drying of paper: A review 2000–2018, Drying Technology

 Adapted from Patrícia Fortes, 2021

Key information you should have apprehended after the class

- Difference between mitigation and adaptation
- How to read the McKinsey Abatement Cost Curve
- 7 pillars of decarbonisation
- What mitigation options are cost-negative and why
- Criteria for assessing GHG mitigation options – especially cost-effectiveness
- What is green hydrogen and how it can be produced
- What is grey, blue and green H_2
- Varied roles that H_2 can play in the energy system (energy conversion and storage, end uses in transport, buildings and industry)
- Options to transport, store and distribute H_2
- Barriers to H_2 deployment