Hydrogen era: yes, but when and at what cost of delivered energy?

Presenter:

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A green hydrogen that by burning produces water and its multiple possible uses (buildings, mobility, industry) makes it fascinating to contribute to the energy transition –

The hydrogen economy that has been talked about for decades is now in a different situation than in the past given the strong development and collapse of the costs of the kWh produced by wind and photovoltaic, and RES can be seen in 2 roles:

--«active» party in P2G as «energy suppliers» to produce green H2

- "interested" party in a H2 Gas to Power (G2P) for long-term storage and auxiliary services for a better integration of the RES themselves in the electrical system to compensate for their variability and non-programmability

FOR A BETTER ANALYSIS OF H2 SITUATION IN THE ENERGY ARENA LET US LOOK AT

GLOBAL PRIMAY ENERGY RESOURCES AND CO2 EMISSIONS

GLOBAL PRYMARY ENERGIES CONSUMPTION

PRIMARY ENERGY DEMAND (WORLD 2019 - 14100 MTEP)				
	% OF WORLD	AAG 2008-2018	Growth % 2019 over 2018	H2 %
WORLD	100%	1,6%	1,3	2,1
NON - OECD	60%	3,0%	2,8	NA
OECD	40%	0,0%	-0,8	NA
EU	11,80%	-0,8%	-1,4	1,8
ITALY	1,10%	-1,5%	-2,4	1,2

PRIMARY ENERGY CONSUMPTION IN 2019
83,4% FROM FOSSIL FUELS

PRIMARY ENERGY: SHARE OF DIFFERENT SOURCES 2019						
	Oli	Gas	Coal	Nuclear	Hydro	RES
WORLD	33	24,3	27	4,3	6,4	5
NON - OECD	29,6	21,8	35,9	2	7,2	3,5
OECD	38,4	27,8	13,7	7,6	5,3	7,2
EU	38,3	24,5	11,2	10,7	4,3	11
ITALY	39	40	4,7	0	6,3	10

CO2 EMISSIONS FROM FOSSIL FUEL COMBUSTION (WORLD 2019 - 34170 Mt)			
	% OF WORLD	AAG 2008-2018 %	Growth % 2019 over 2018
WORLD	100%	1,1%	0,5%
NON - OECD	65%	2,5%	2,4%
OECD	35%	-0,8%	-2,9%
EU	9,70%	-1,8%	-3,9%
ITALY	1,00%	-2,8%	-2,0%

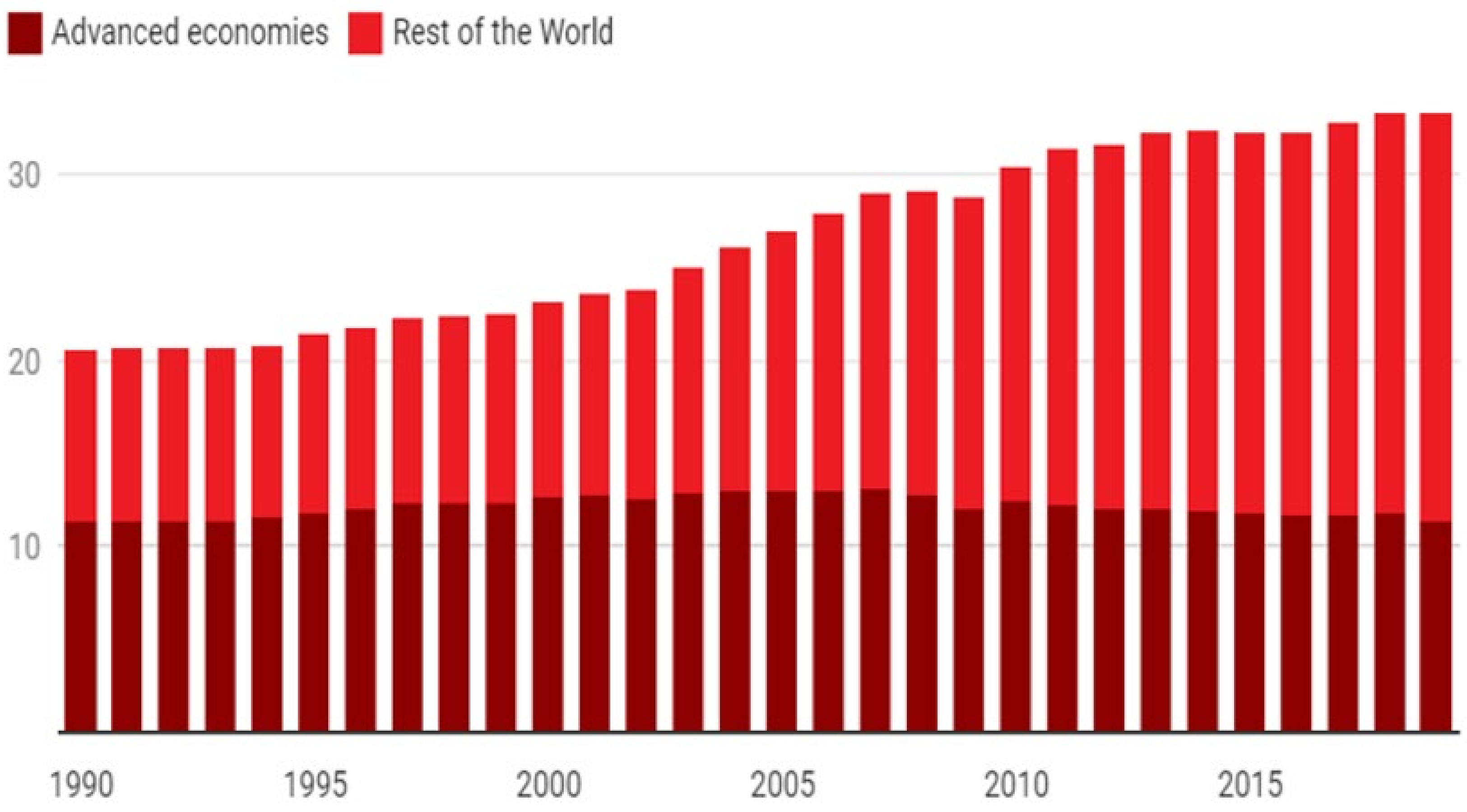
Emissions from H2 production in 2019:

Wolrd nearly 1000 Mt (3%)

EU nearly 100 Mt (3%)

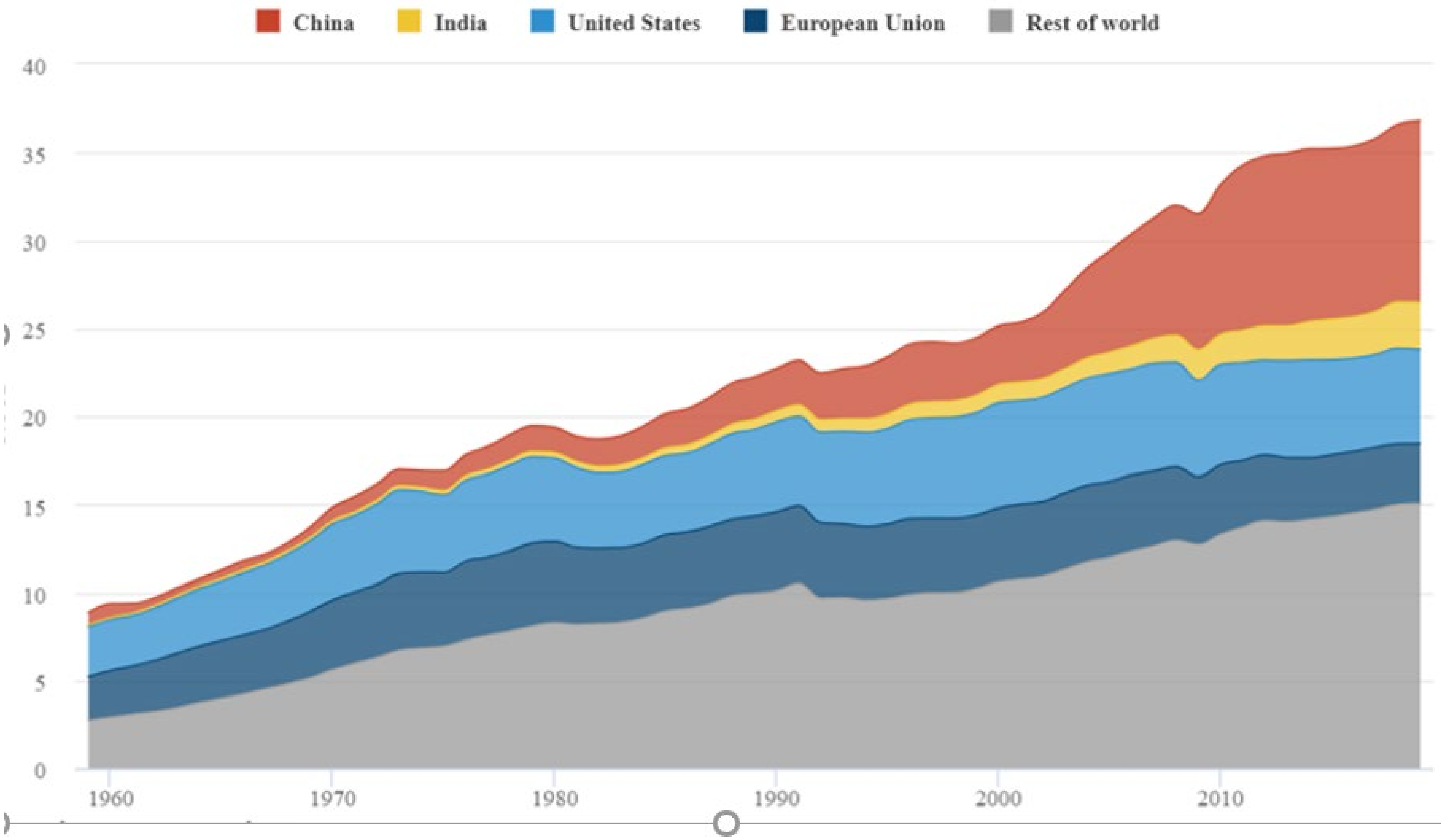
Italia nearly 5 Mt (1,5%)

CO2 FROM IEA



Advanced economies
Rest of the World
30
20
10
1990
1995
2000
2005
2010
2015

CO2:MAJOR CONTRIBUTORS



In 2030, EU will have around 6% of global CO2 emissions ;the green deal will have little effect on the global solution; an EU-centric vision is not enough.

ENERGY A PRIVILEGE FOR SOMEONE OR A RIGHT FOR ALL?

For a global perspective necessary for sustainable decarbonisation :

-**Sub Saharan Africa with 1 billion inhabitants consumes energy** (and emits CO2) for **1/20 per capita compared to the EU** (and such values to divide by 10 in some countries) over **600 million people without electricity** and the maximum population expansion;

-**India** with its 1 billion and 350 million inhabitants, **considered a major emitter of CO2** after China and the United States, **emits about 1/5 per capita of CO2 with respect to EU**

GLOBAL PRIMARY FOSSIL RESOURCES (from WEC)

"2018 proven resources (R) and actual production (P), have R/P ratios:

oil ~ 50 years **gas ~ 55 years** **coal ~ 155 years**

Proven resources for oil and gas are now 50% larger than 20 years ago even with the substantial consumptions in the last 2 decades. **Predictable resources for unconventional oil and gas are very large**

Real problem is not the lack of possible fossil fuel resources (peak oil production is out of fashion with respect to a peak oil demand) **but now**:

- their uneven distribution between production and consumption areas (mainly oil and gas) and the geopolitical effects
- and now **mainly how to burn them without impact on the environment**."

THE NEW EXPLOSION OF INTEREST ON HYDROGEN

-**During the full day on hydrogen at the World Energy Congress of September 2019 in AbuDhabi**,we discussed a **lot in particular of H2 from electrolysis of water with the main stakeholders** interested in its development; (Hydrogen Council, H2 Europe, IRENA, ENGIE, Siemens, Saudi Aramco and WEC).

-**In July 2020 the European Commission** came out with the document "**A Hydrogen strategy for a climate-neutral Europe"** with H2 key element for zero emissions by 2050.A new document on December 11,2020

-There **is increasing talks on green hydrogen in all the world**, from Australia to Chile passing through China, the Middle East, Europe and North America and **especially with proposals for mega electrolysis plants powered by RES**

extensive applications of hydrogen with safe and economically sustainable production, compression, storage, transport and use, great challenges are still open for the world of research and academia, for industry, for standards and regulatory bodies, for the political and financial world

We are witnessing a considerable media "resonance" on the future of H2 and many numbers (on the increase in efficiency and power of electrolysers , reduction of its cost per kg, **jobs created, etc.); but few numbers on the characteristics of H2 and on the cost not per kg of H2 but on the hydrogen energy cost for end users –I will cocentrate my presentation on green H2 production costs with some comments on challanges to use existing methane transport**

THE "COLORS" OF H2

For the "colors" to be attributed to hydrogen according to its production, there is no agreed declaration :on the basis of the talks in Abu Dhabi, I will consider :

-"black" hydrogen, from fossil fuels, without any capture of CO2 emissions; (99% of current production)

-“gray” hydrogen, produced with partial sequestration of CO2 emissions;

-»blue» hydrogen, from non-renewable energies but without CO2 emissions (for example from fossil fuels with total CO2 capture or electrolysis from nuclear electricity);

“green” hydrogen, produced entirely from renewable energies.

CHARACTERISTICS OF HYDROGEN

Hydrogen is found in water and organic compounds but is practically not present in the free state on earth and can be produced with various processes that require energy; it is not a primary energy resource but an energy "vector".

Apart from flammability field, activation energy and diffusion coefficient of $H2$, the energy per volume unit both in the gaseous and liquid state (-253 ° C) is about 1/3 of that of methane while by weight 1 kg of $H2$ has 2.5 times the energy of 1 kg of $CH4$ - **1 kgH2 = 33.2 kWh of energy content**

The volume for gaseous H_2 tanks with the same energy content as methane is significant at same pressure and a reduction in H_2 volumes at high pressures around 700 bar and beyond involves costs and weights for fixed and mobile tanks.

Liquefaction of H_2 consumes 1/3 of its energy content and transport has additional consumption to maintain a temperature at - 253 ° C and evaporation rates of a fraction of % per day

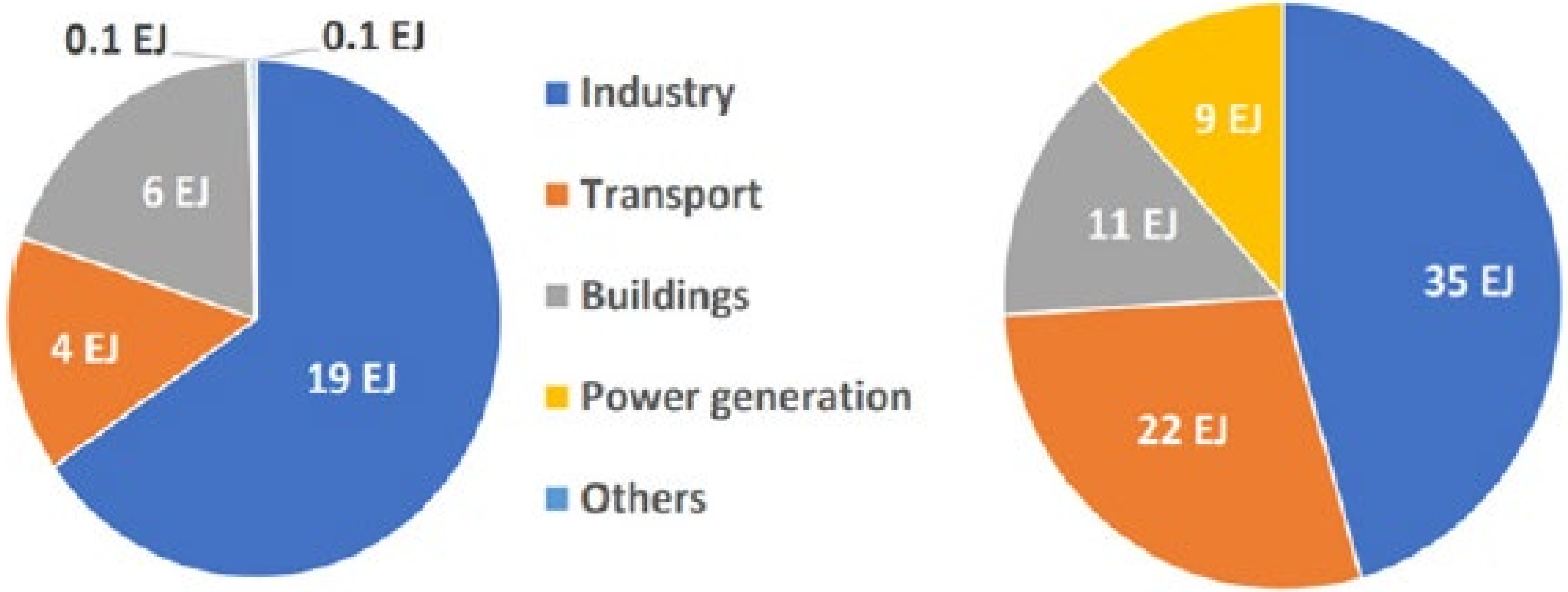
FUTURE SCENARIOS ON H2 GLOBAL CONSUMPTION IN 2050

For global hydrogen consumption in the future scenarios to **2050, there is a noticeable difference between the sources and a gap in the utilization shares** of the various sectors - and these future scenarios vary rapidly for each source.

IRENA at ABU DHABI: 29 Exa Joule equal to **8060 TWh** (just over double the current consumption of 14 EJ) **Bloomberg:** 97 Exa Joule equal to **27000 TWh**

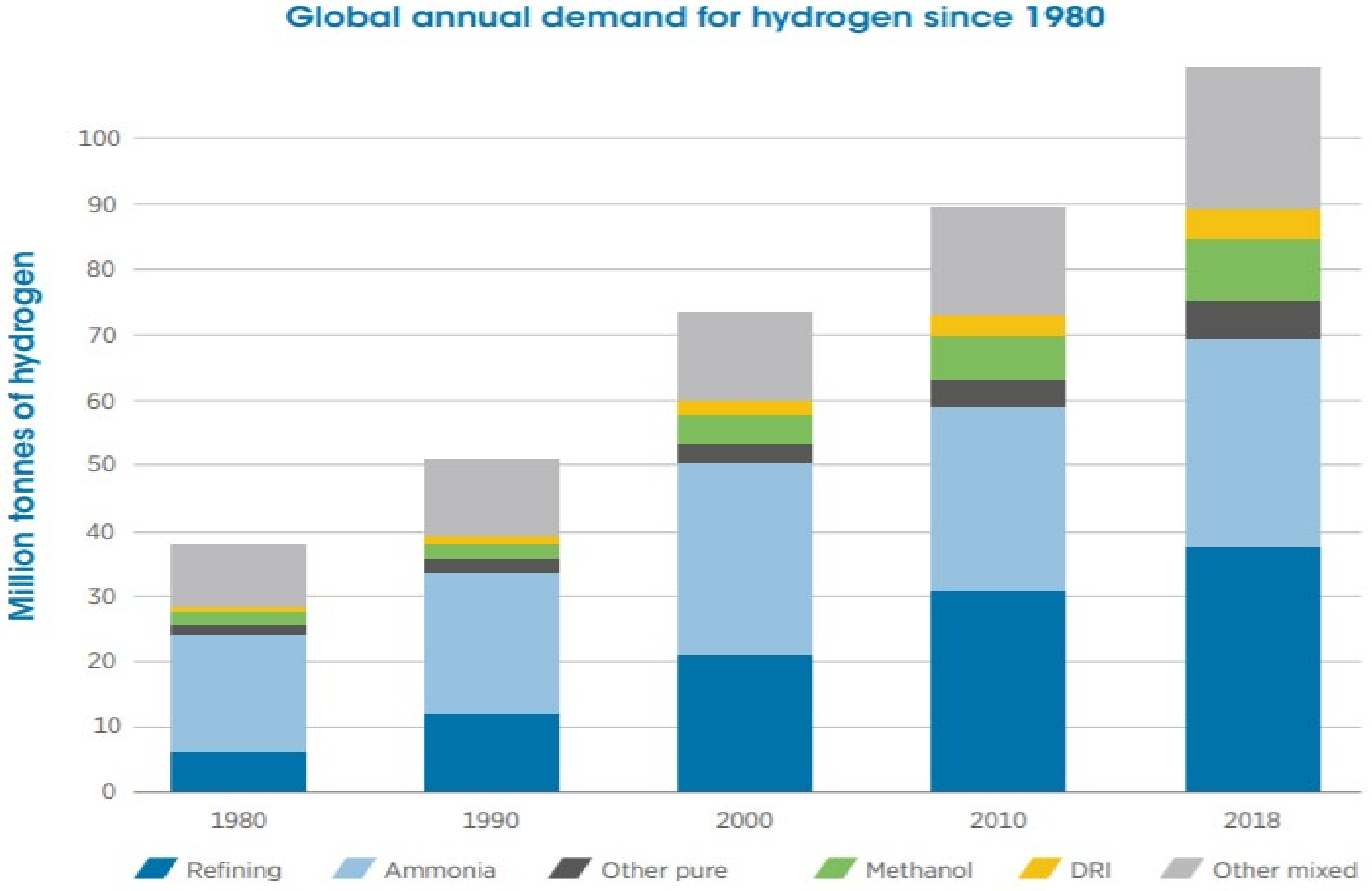
Hydrogen Council: 79 Exa Joule equal to **21900 TWh** (5.5 times the current)

SIGNIFICANT DIFFERENCE BETWEEN IRENA AND HYDOGEN COUNCIL ALSO IN THE QU



GLOBAL CONSUMPTION OF H2 AND ITS USES

The consumption of hydrogen globally **in 2018 estimated by IEA is 110 Mt (3656 TWh**) compared to 50 Mt in 1990. There are also numbers 20 -35% lower.

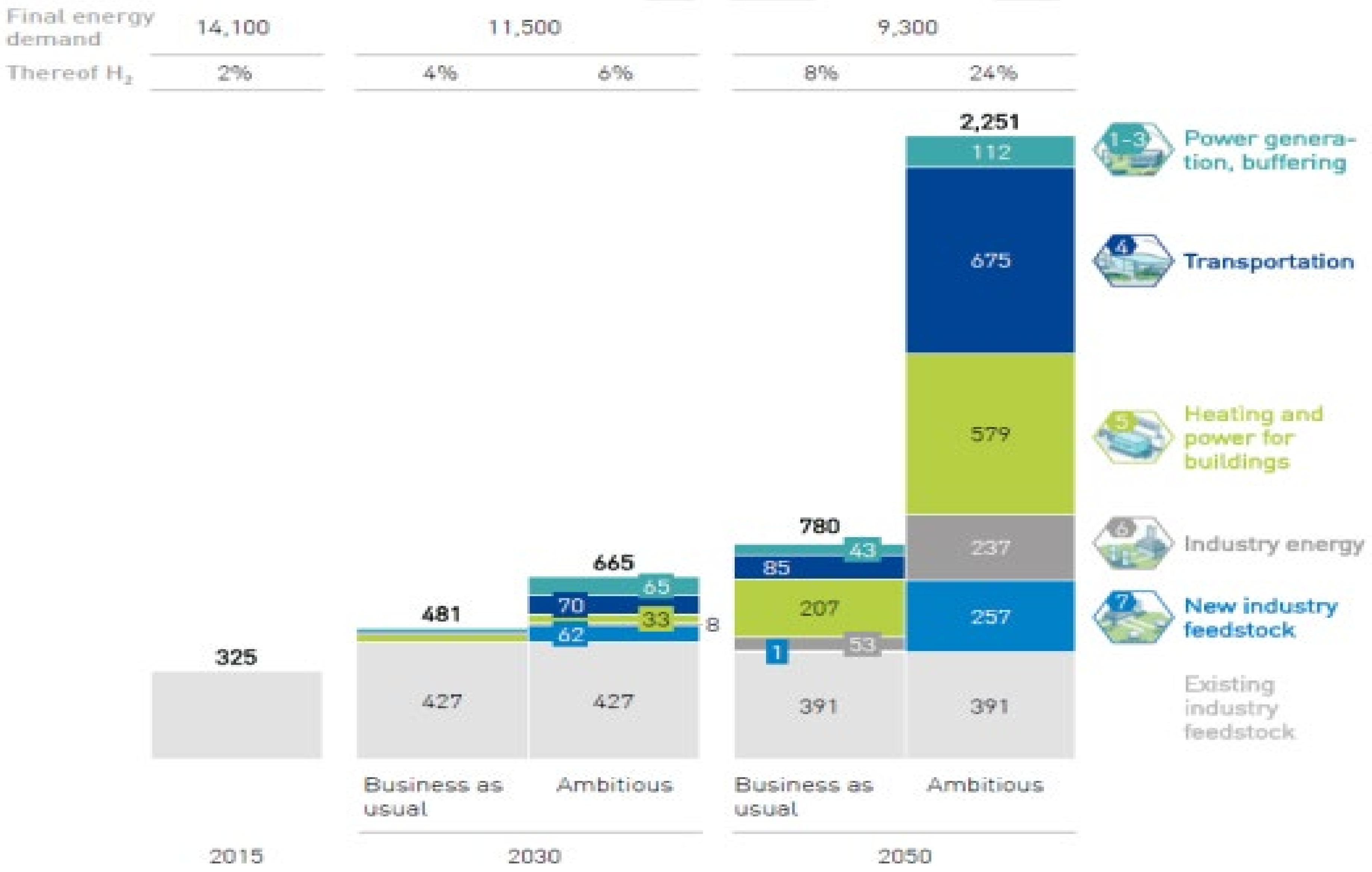


Source: IEA, 2019

H2 consumption in the EU in TWh up to 2050 (Hydrogen Europe event 2019)

From EC in 2050
1850 TWh

Figure 2: Hydrogen demand in 2050 in Europe, under various scenarios



H2 consumption in Italy in TWh up to 2050 (The European House Amrosetti study commissioned by SNAM)

218 TWh for various uses + electricity production (G2P) of about **100 TWh**

Italian RSE in 2050 around 8%

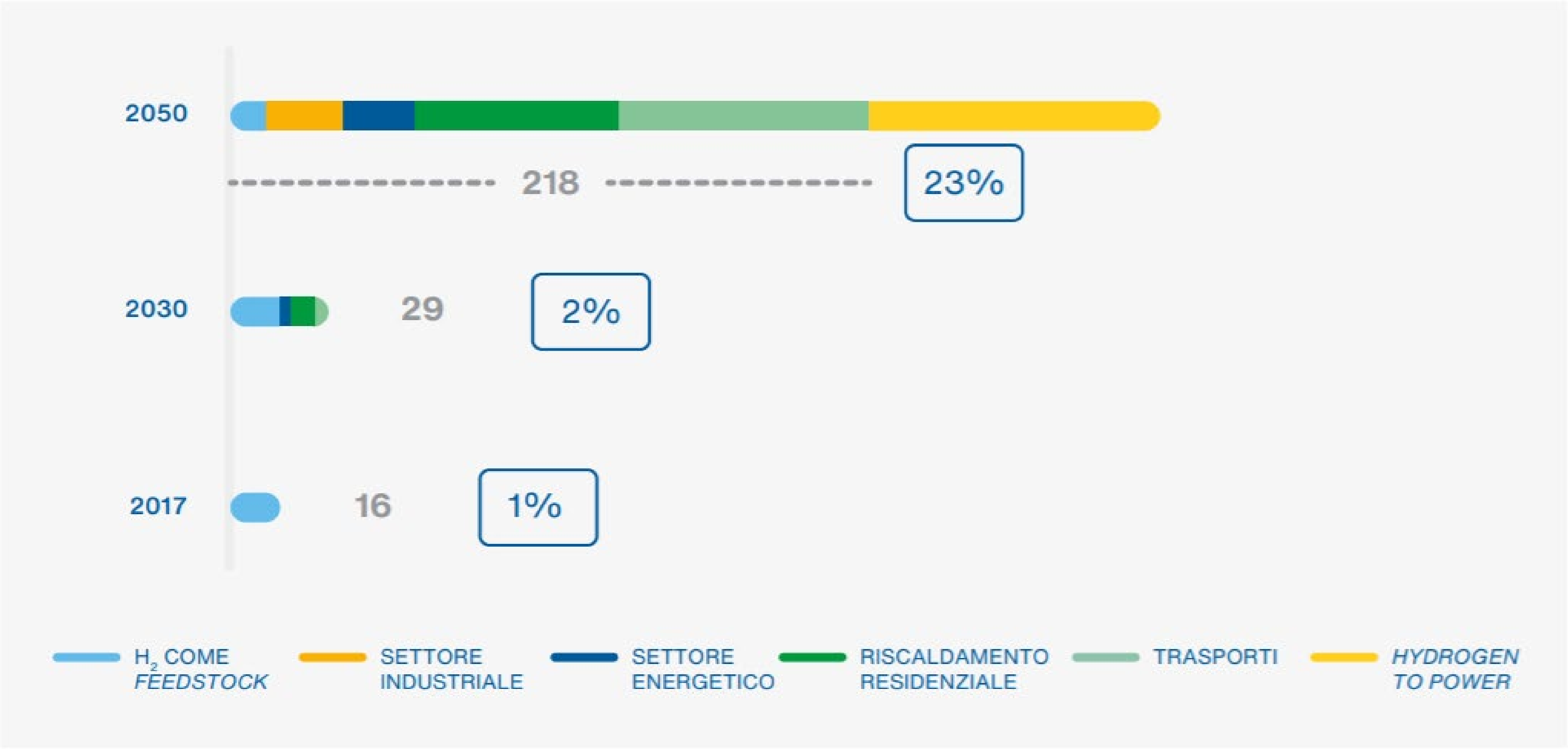


Figura 37 – Idrogeno nella domanda energetica finale in Italia (TWh e valori percentuali su totale consumi), 2017, 2030 e 2050.

Fonte: elaborazione di The European House – Ambrosetti su dati "The Hydrogen Challenge", 2020.

ludwig bölkow systemtechnik

Overview H_2-strategies and activities (Status: August 2020)

WORLD ENERGY COUNCIL | WELTENERGIERAT DEUTSCHLAND

31	Europe
11	Asia & the Pacific
6	South America & the Caribbean
5	Middle East & Africa
3	North America

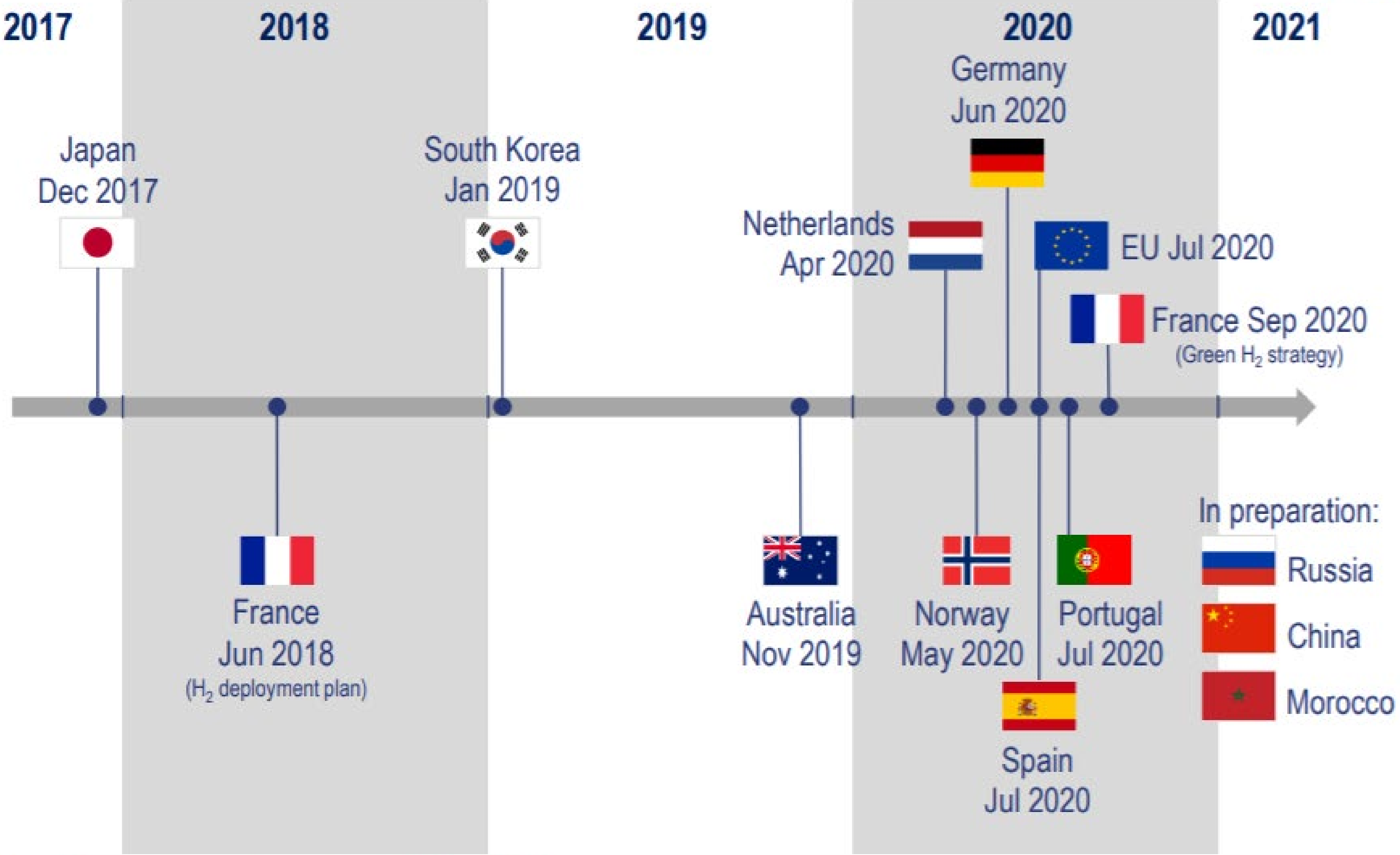
56

No. of countries analyzed

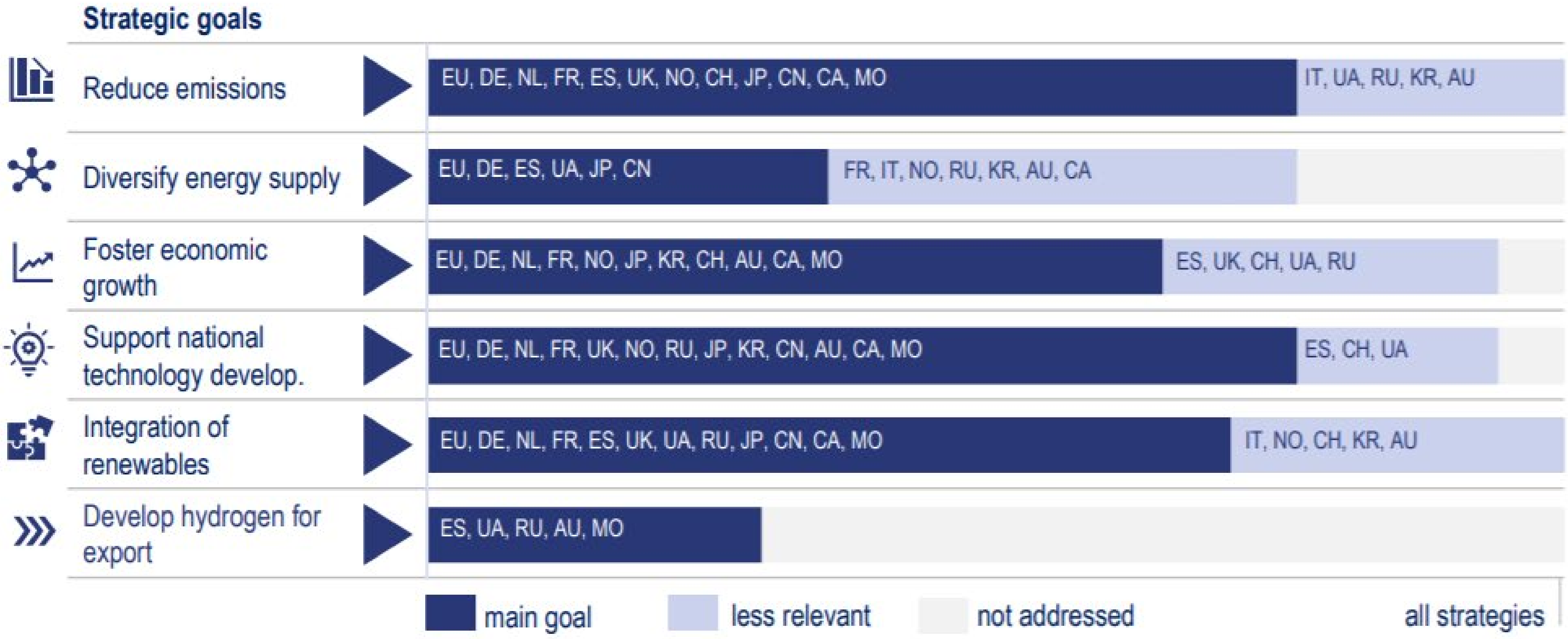
9	National hydrogen strategy available
11	National hydrogen strategy in preparation
14	Support for pilot and demonstration projects
17	Initial policy discussions
5	No relevant activities

August 2020, World Energy Council, LBST

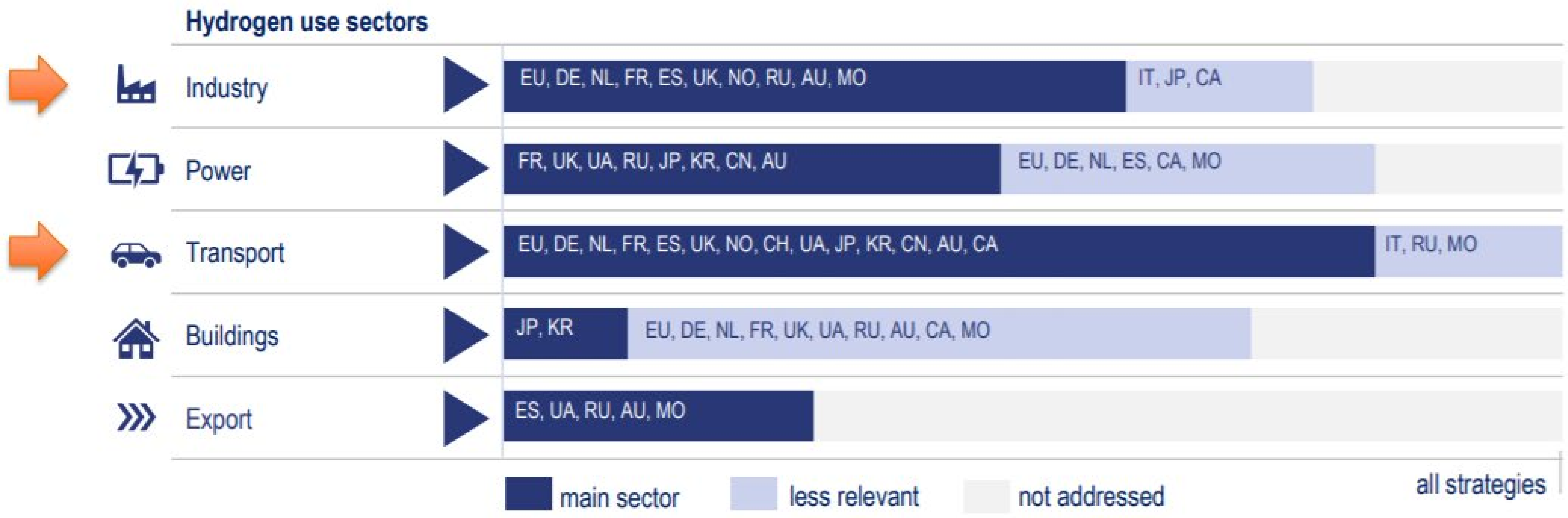
“Hot” strategic hydrogen summer 2020



Main goals of current H_2 strategies per country



Main target sectors of current H_2 strategies per country



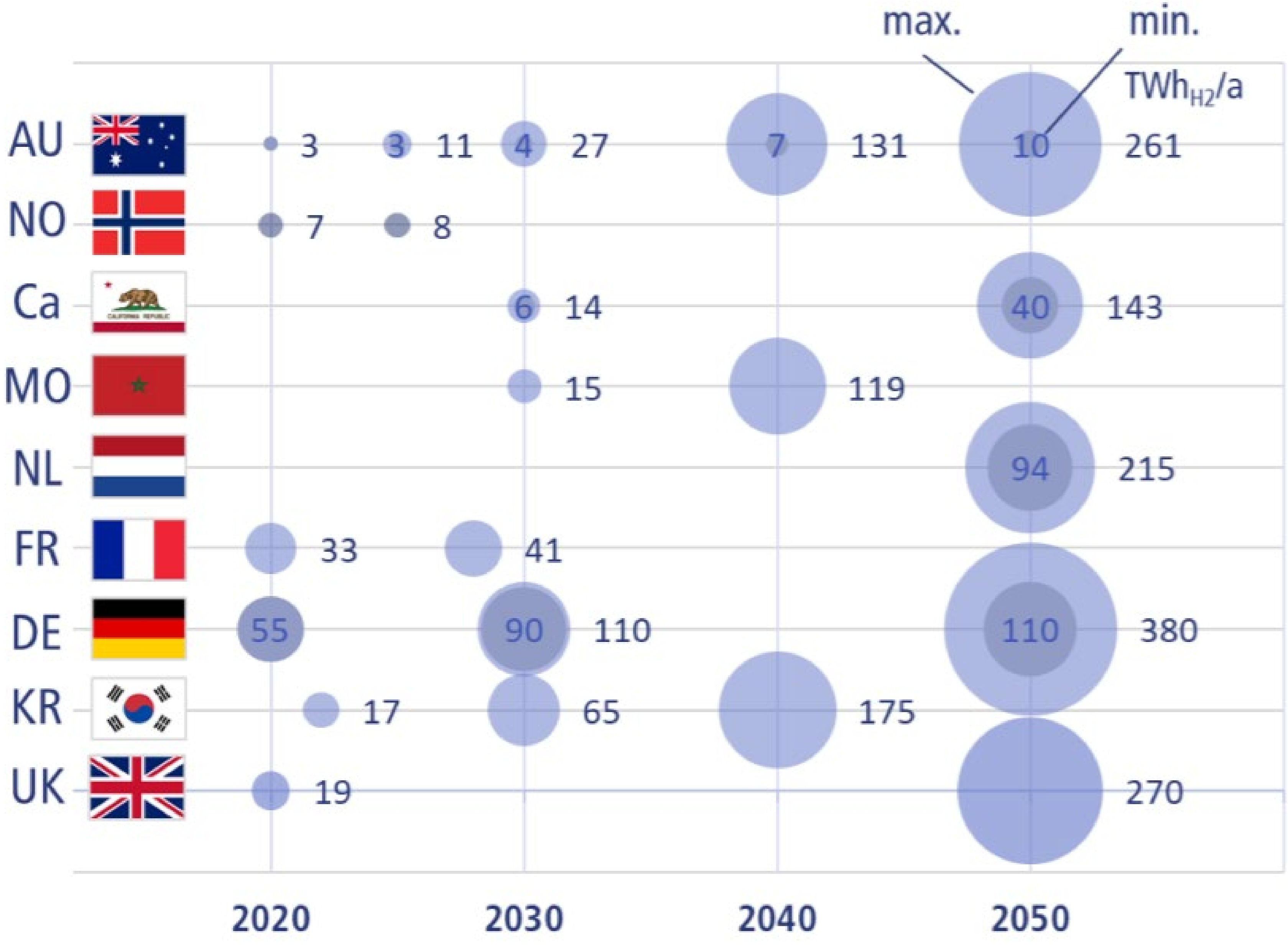


Figure 11: Expected annual hydrogen consumption inTWh$_{H2}$ per year

PRODUCTION COSTS IN 2019 AND 2030

99% of hydrogen produced today is "black". The production has significant greenhouse gas emissions and **with the high temperature Steam Methane Reforming (SMR) process, approximately 9 kg of CO_2 are emitted for 1 kg of H_2**

The production cost of "black" H_2 estimated **for the 2019-2024 period in the range of 1,25-2,5 $ / kg (from 32 to 64 € / MWh) according to local gas costs and neglecting or not a CO_2 penalty or CCS –With CCS in 2018 from IEA *1.5-2.7 $/kg***

Green H_2 cost at exit of electrolyser in 2019 was evaluated by Hydrogen Europe at the Abu Dhabi session in € 7.8 / kg (€ 235 / MWh) with reference to on shore wind in Northern Germany

The main factors of the cost of 1 kg H_2 from electrolysis are:

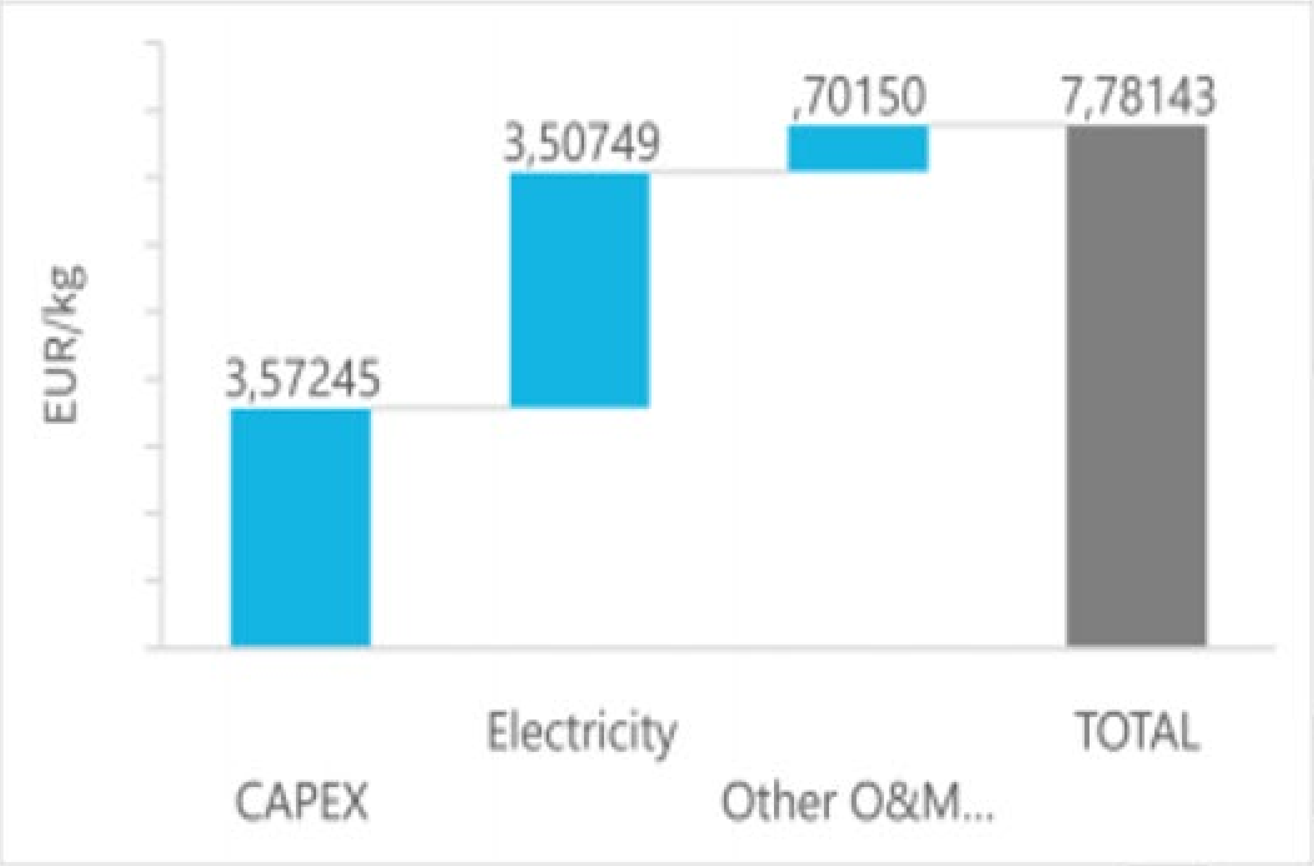
-CAPEX and ELECTROLYZER EFFICIENCY AND ITS LIFE AND HOURS OF USE (sharp decline with developments) –

-RENEWABLE ENERGY COST AND ITS LOAD FACTOR (fundamental with low electrolyser costs) –

2019 COST OF GREEN H2 AT THE ELECTROLYZER without considering electrical storage to optimize the power and hours of use of the electrolyser powered by variable RES -

Source: Hydrogen Europe.

Note: costs calculated with the following assumptions: capital costs – 8%, CAPEX – 1,200 EUR/kW, O&M costs – 2% of CAPEX, electr consumption – 58 kWh per kg of H2, renewable electricity price of 60 EUR per MWh, capacity factor of 2,000 h pa.



greatly affect the cost of hydrogen production, especially with low future costs of the CAPEX of the electrolyzers expected with large increases in size and efficiency

3 main alternatives to feed the electolysers with RES energy having an interesting load factor for the economy of the produced H2

- **electrolyser at the RES plant** (does not pay transport / system charges) having a combination of electricity price and relative load factor «interesting»

- **power supply through a dedicated line from a RES plant** (does not pay transport / system charges) pays interconnector investment (different rules in different countries)

- **power supply from a substation of the transmission grid :**pays transport / system charges, (in Germany some tens of € / MWh excluding incentives to RES) resulting in higher cost of energy at the electrolizer and therefore higher cost of H2

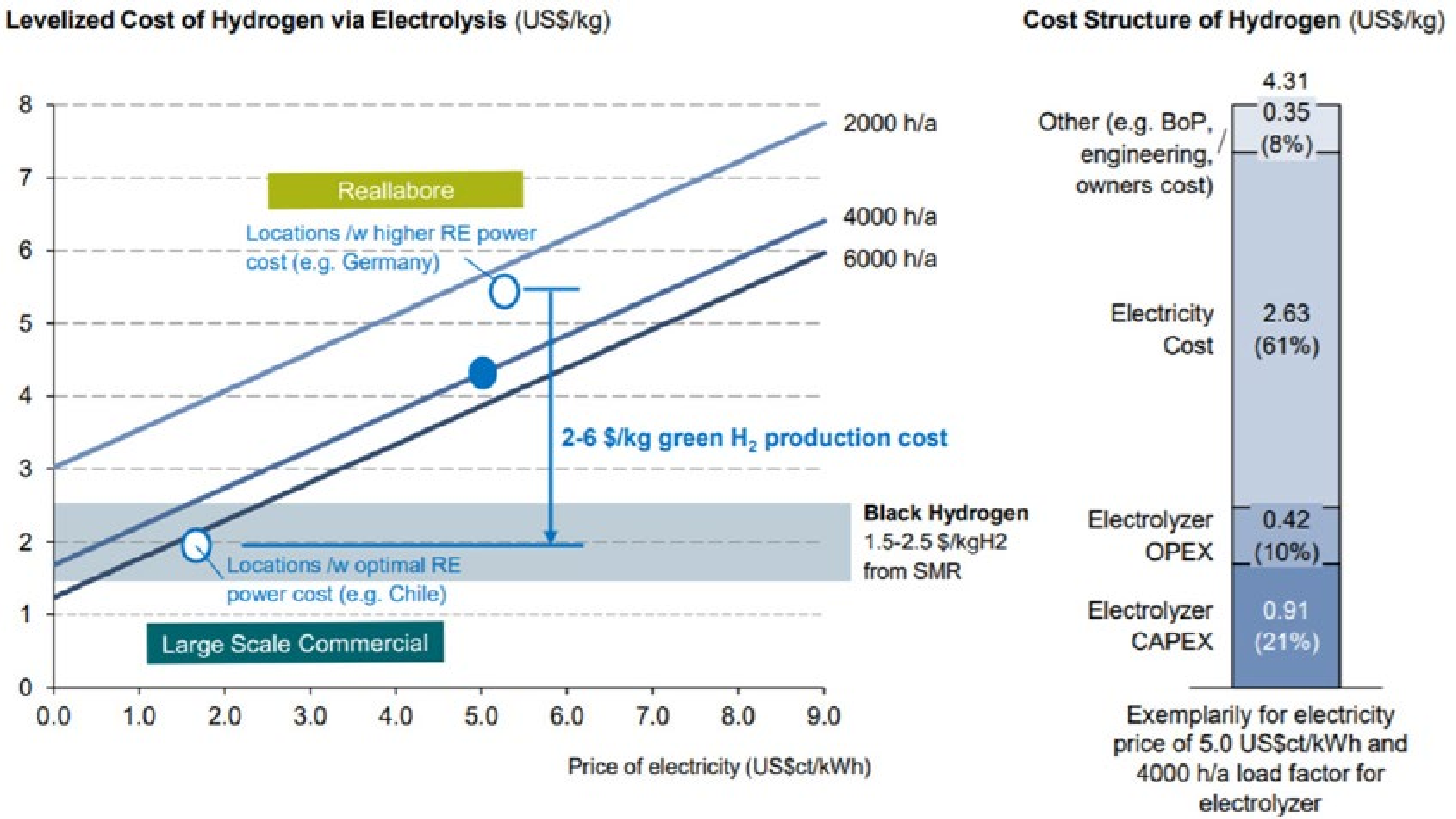
Around 2030 ,Hydrogen Europe predicts in Germany a cost of green H2 at the electrolyser of 3 € / kg (90 € / MWh), with a CAPEX of electrolysers more than halved to 500 € / kW compared to 2019 values, efficiency at 66% with electrolysers of 100 MW and 50 € / MWh for RES from offshore wind with a load factor of 4,500 hours / year.

The values in Qatar and the Arab Emirates of $ 13.5-20 / MWh from photovoltaic plants of about 1000 MW each, albeit with a reduced load factor compared to the aforementioned wind, are interesting for the cost of hydrogen. These values characterized by considerable insolation and virtually zero costs of the areas and very low for the local labor **are certainly not exportable to new photovoltaic plants of Western Europe.**

Siemens for the expected H2 cost in 2030 at the electrolizer reported at the 2019 Conference in Abu Dhabi with RES cost of 43 € / MWh

- **4.9 € / kg H2(147 € / MWh) with a load factor of 2,000 hours / year**
- **and approximately 3.7 € / kg (113 € / MWh) with a load factor of 4,000 hours / year**

LCOH 2030 for green H2: Siemens evaluations in different hypotheses



Underlying assumptions: WACC 8.9%, Capex electrolyzer 640 US$/kW; electrolyzer efficiency 75%, 20 year lifetime, OPEX 5% of CAPEX (incl. exchange of electrolyzer module)

PRODUCTION COST

IRENA assumes possible at global level that with

-a cost of $ 200 / kW of large electrolysers of several hundred MW
-RES cost of 20 $/MWh and load facctor of 4,200 hours / year

The green hydrogen at the electrolyzer exit would cost in 2050 **1.4 $ / kg H2 equal to 1.2 / € kgH2………..**
which corresponds to 36 € / MWh
and this is about 3 times the 13 € / MWh of CH4 in EU gas market , CLEARLY WITHOUT A PENALTY FOR CO2

G2P- SYNTHETIC METHANE FROM H2 AND CO2

Downstream of a Power to Gas (P2G) for H2 production it has been proposed:

-**a subsequent transformation of H2 into electricity** (Gas to Power-G2P)

-or **the production from H2 combined with CO2 of a synthetic methane** that could use all the structures ,power plants,machinery and equipment and user facilities developed and in operation since decades –

Even with a strong reduction in the cost and increased efficiency of methanizsers, **the price of the energy content of synthetic methane produced in 2050 in the EU (Horizon 2020 Store & Go project) would be between 50 and 120 € / MWh**

Some comments on green H2 in Italy

Italy has an extensive methane gas transport network for 33,000 km (with 20 billion cubic meters of storage) and distribution networks for approximately 250,000 km; the development of hydrogen and syngas therefore assumes strategic importance.

However, **both a green hydrogen cost of 90 € / MWh at the electrolyser and a synthetic methane of 140 € / MWh based on a green H2 at 3 € / kg ,are levels that require challenging efforts with difficulty to be reached by 2030.**

Assuming the 2150 equivalent hours / year of the PNIEC (Integrated National Energy and Climate Plan) in the production of electricity from new wind plants with a cost of about € 50 / MWh, even with large electrolyzers (but how many feasible in our country?) ,**the cost of 1 kg of green H2 at the electrolyser located at a wind** plant **would now**

By 2050, halving the cost of electrolysers and electricity (assumed for instance from amortized wind farms) we would reach 3 € / kg H2 (90 € / MWh) .

With a **G2P from H2, the kWh of electricity would cost around 5 times the present production cost of CCGT plants with CH4 (not considering a CO2 penalty) and of the direct production from utility scale RES plants.**

- Clearly, hydrogen from Italian PV plants with 1500 equivalent hours / year would require challenges and detailed studies for the storage of electricity and perhaps of H2 to have a non-exorbitant cost of 1 kg H2.

If we want to decarbonise in Italy by 2030 with green H2 **the production of H2** (expected in 2021 in 600,000 tons), apart from economic and legislative assessments, even with efficiencies of 75% for electrolyzers, **about 26 TWh of "green" electricity would be needed** ; and **this would correspond** for Italian load factors of wind and solar **as a minimum to an additional 12,000 MW of wind power or 18,500 MW of photovoltaics to the already ambitious PNIEC programs** of around 10 GW of wind and 32 GW of photovoltaics to be installed from 2020 to 2030.
And **with the very recent EC increase of DEC 11 of the CO2 reduction for 2030** of 55% with respect to the previous 40% objecve considered in PNIEC, **additional FER will be required.**
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H2 IN EXISTING PIPELINES - THE CASE OF ITALY

Experiments with hydrogen mixed with methane (BLENDING) in gas pipeline sections are underway at an international level and Italy is also in the front row with **2 series of tests in 2019 by SNAM, the first with a percentage of H2 by volume of 5% and the second 10% in December**.

With the regulations that today see hydrogen with caution and due to the various technological problems, **as per SNAM reports on their interesting blending experiments, they had to take into account practical limits.**

The section of pipeline concerned of about 1 km to feed 2 industrial end users (with consumption of gas not sensitive to H2 in methane) had

-**no connections to compressed gas distributors** (maximum 2% of H2 for existing regulations) **and to storage systems**

-**did not contain compression stations or feeding to distribution systems**

MORE COMPLEX EXPERIMENTS PLANNED BY SNAM AS NECESSARY FOR FUTURE EXTENDED APPLICATIONS

Apart from a blending in some local applications or on specific backbones, *in the hypothetical use on the whole Italian network of a blending at 10% by volume of H_2, we would have on 70 billion cubic meters / year of methane (612.5 TWh)* a hydrogen contribution of 7 *billion cubic meters / year (19.3 TWh) which would, however, cause the loss of 7% in calorific value of the entire mixture (43 TWh / year)-*
This with various impacts to be verified including legislations, interoperability between different networks and billing to users for a lower calorific value.

The advantages of a reduction of 13.5 Mt of CO_2 / year must be compared with the necessary investment costs to be defined in detail

From D. Muthman of OGE Germany at the IAEE Hydrogen Europe Webinar of 02/11/2020, it clearly emerged that for any blending of H2 or with 100% of H2, confining oneself to the transport system only, in addition to storage problems, it will be necessary to carefully check all components and modification / upgrading costs

An advantage of blending, as mentioned by somone ,is the "support of an initial national production of green hydrogen with developments in the entire Italian supply chain"; but our H2 production is more expensive than in favored nations for wind or sun and / or local costs.

For the use of existing methane pipelines, as ventilated by some, **with 100% hydrogen,** apart from serious checks for upgrading / replacement of subsystems / components and necessity of new standards, **at the same presuure it will be lost approximately 2/3 of the the present actual energy transport capacity with CH4** (with a 48-inches diameter , corresponds to around 24 GW)

EUROPEAN COMMUNITY AND H2

EU now has 300 small / medium electrolysers in operation which produce about 7 TWh of H2 equal to about 4% of the total hydrogen production.

The document "A Hydrogen strategy for a climate-neutral Europe" sets the EU strategic goal of installing **at least 6 GW of electrolysers by 2024 and to have "40 GW of electrolysers to produce 10 million tons of green hydrogen" (333 TWh) by 2030.** An **additional 40 GW "imported" is expected.** Mentioned «investments of € 25-40 billion for electrolysers alone + hundreds of billions for dedicated RES plants».

Some doubts about the GW of electrolyzers needed to have 333 TWh of green H2

-A) <u>40 GW of electrolyzers</u> with an efficiency of 75% powered by off shore wind farms having a super load factor of 5,000 hours / year would produce <u>150 TWh of green hydrogen (4.4 Mt) per year</u>

-B) <u>for 333 TWh of green H2 (10 Mt) , 89 GW of electrolizers would be needed ,having an efficiency of 75% and fed by electricity with a load factor of 5000 hours / year.</u>

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-**C) 40 GW with a mega load factor of 8,300 hours / year,** conceivable **with a power supply from the grid** (with high spot prices for electricity supplies for over 8000 hours except from nuclear power), **would give 333 TWh of H2 but at what costs?** - **In 2030 EU production will not be 100% from RES and H2 would be partly blue from nuclear** (very cheap with amortized plants with extended life) **or black/gray** ;**in any case with high transport / system costs compared to those of today for a greater share of non programmable RES which requires seasonal storage,fast storage devices for inertia,ramp rsponse etc.This would increase the costs of H2 compared to direct supply from large RES plants, even if this direct supply needs deeper analyses on the actual performance of electrolizers fed by variable sources**.

In 2050 with 100% RES, H2 costs would have an additional increase due the rise of system costs for quality and security of supply-

CONCLUSIONS

In the consumption of primary energies, fossil sources contribute today 83.4% ;substantial continuous increase in non-OECD countries of CO_2 emissions not compensated by the continuous decrease in OECD countries led by EU.

Fossil fuels now contribute 63.5% to electricity production compared to 64.7% in 2001-

With an EU 27 contribution of around 6% to global emissions expected by 2030, the "green deal" does not produce a substantial contribution to the solution of the global environmental problems that requires a new approach not only Eurocentric -

A possible era of green hydrogen is fascinating for the intersectorial connections of electrons and molecules.

Investments on H2 specifically in R&D, prototypes and experimental plants and strong participation in the development of new internationally agreed standards / legislation/regulations(including adequate penalties to CO2 emossions) are welcome in Italy to contribute to a possible extensive application of H2.

Industrial policy choices and strong initial subsidies are needed to achieve challenging goals by optimizing Italian presence along the global chain to get grants/ subsidies in a strategic way for a local long lasting industrial development, both as users of H2 and as suppliers of equipment, machinery and plants also for exports.

For Italy it is a very difficult challenge to approach now, and perhaps in the future, the values for production costs per kg of green H2 as in some countries favored with local conditions and possibility of large electrolyzers (eg PV in the Middle East, wind plants with 4500 equivalent hours the North Sea compared to our 2200 hour "breezes", ... or blue H2 from nuclear power in France with load factor of 8000 hours / year).

In about a decade ,with important MW from RES plants amortized and at the end of the incentives it will be worth checking the situation of the real RES prices offered for kWh in Italy, taking in due account the local load factors of wind and solar

The results of studies and actions undertaken and the reactions of the markets and customers and of the financial world and the fiscal / incentive policies of the sector will be able to outline effective quotas for green hydrogen and real times and costs for a green hydrogen era also in Italy, perhaps not too close but it is worth checking it with a realistic approach.

It will be necessary to compare with the results of parallel studies and actions for blue hydrogen for the spread of H2 in the most convenient way for the country, especially to facilitate an initial phase of «CO2 free »H2 diffusion.

The current amount of H2 consumption(concentrated in industrial uses), the current cost of green H2 production, the already difficult task /need to an always increasing use of electricity from RES in its "own market" require the use of all the technologies at our disposal, starting from those ones capable of providing an effective and rapid decarbonization response and which can act as a bridge for future solutions that are not yet mature today.

It is necessary a balanced parallel development of the supply and multisectorial demand of H2; and this is a strong challenge that requires not negligible interactions and times. And **a holistic approach to optimize the Italian presence along the complete H2 chain to exploit the available grants/subsidies in a strategic way** for our industrial development.

Given the challenges still open, it is necessary to proceed with caution in proposing now too optimistic times and low energy costs especially for green hydrogen. Once longer times and real costs became evident, strong reactions would emerge that would have a serious impact not only on the development of hydrogen but also on a stable and lasting transition.

to involve and raise awareness of all citizens, reminding them that the transition will not be an easy walk and it will be necessary to be willing to spend more for a green energy in order to create a possible better future for world environment.

A GREAT WORK FOR EVERYONE IN THIS PHASE OF THE TRANSITION AND FOR THE POSSIBLE DEVELOPMENT OF H2 THAT STILL REQUIRES STRICT ANALYSES AND EXPERIMENTATIONS WITH P2G and G2P , WITH AN APPROACH NOT ONLY TECHNOLOGICAL BUT ALSO SOCIO ECONOMICAL- AN EFFECTIVE TEAM WORKING FOR REAL LASTING IMPACTS IS ESSENTIAL.

FROM ASPERA AD ASTRA

THANKS FOR YOUR LISTENING

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