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Ramp-up and role of hydrogen-based power generation

Working Group-3 focus paper

ETIP SNET

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Smart Networks for Energy Transition

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WG3 focus paper

ETIP SNET

CONTENTS

INDEX OF FIGURES

1. Motivation of this paper

Give a guideline and provide recommendations about provision of H2 for electric power generation.
Maintaining a stable and steady electric energy supply that is mainly based on variable RES (Renewable Energy Sources) requires a flexible and dispatchable balancing solution for electric power generation. Balancing electric power generating solutions based on chemical energy carriers (i.e. fuels like H_2, methanol, ammonia, synthetic hydrocarbons which can be stored easily) can provide large amounts of energy (MWh to TWh) and it can dispatch it quickly at a large variety of power scales (< 1MW up to the GW scale). Both of these features can be maintained for longer periods of time (days/weeks/months). Other grid balancing solutions such as battery based energy storage systems can unfortunately only provide moderate power capacities and only for a few hours (typically less than a day). Hydro plants with week-to-months storage capacity are the traditional long-term balancing means, but they are only suited for certain geographies and cannot satisfy all the needs in future power systems.
H_2 based power electric generation will not be a low cost solution as it is dependent on the price of renewable H_2 which will be a scarce and high cost energy carrier for about another decade. Nevertheless H_2 solutions will be mandatory to keep the balance of electricity supply and demand at all circumstances.

2. Dispatchable electric power generation technologies

Future chemical energy carriers (in this paper we focus on H_2) will become 100% renewable based over time and can be used in all kinds of established and mature technologies for centralised and distributed power generation, including flexible and highly efficient combined heat and power (CHP) units based on fuel cell, gas turbine and gas engine designs. Using existing infrastructure and technology, and serving only the end-use sectors electricity and heat, allows for simplified demonstration and fast implementation at reasonable cost, thus allowing a predictable realistic transformation roadmap to be planned.
The main advantage of using rotating machines (turbines and engines) for CO_2-free generation in the power system is to continue exploiting their intrinsic mechanical characteristics: inertia, short circuit power, regulating speed, frequency support, reactive power provision, voltage support; this would imply a correspondingly lower need of other flexibility means, which shall indeed compete on the basis of offered cost and type of performances.
Currently (green) hydrogen is the most prominent solution for large (TWh capacity) electric power generation combined with inter-seasonal renewable energy storage of H_2 (liquid/gas) and its derivatives (methanol, ammonia, methane, synfuels, …). Biofuels are a complementary option, but cannot cover the same (large) scale. Biofuels might be more suitable for use in the mobility sector (land, sea & air).

While most fuel cells are originally designed for operating on hydrogen, developments are ongoing to extend operation to other H_2 derivatives. Hydrogen fuel cells have started to be used as both stationary and portable energy converters in a range of applications such as transportation – including electric cars, trucks, buses and trains – but also in the building and industry sector generating power & heat for homes as well as for industrial processes[1]. Transportation, heating and electricity generation are foreseen as potential applications of fuel cells closest to commercialisation[2].
Gas engines and gas turbines can be converted from natural gas to hydrogen operation. Blending hydrogen to natural gas and conversion of such units from natural gas to hydrogen operation has been investigated and already demonstrated up to 100% H_2[3]. The competitiveness of actual hydrogen-fuelled gas turbines is driven by emissions restrictions when using different mixtures of hydrogen, natural gas and biomethane. The highest competitiveness of hydrogen-fuelled gas turbines (together with hydrogen storage) is found in electricity systems with high shares of wind power[4]. When 100% hydrogen is being used as fuel, the thermal efficiency of gas engines and gas turbines is similar to that observed by using carbon-containing fuels; this effect arises thanks to the outstanding properties of hydrogen as a fuel.
Heat only solutions based on H_2 are prohibitive due to the high cost of hydrogen and its limited availability for the mid-term future.

3. Current situation and expected developments

Hydrogen based power generation plays only a negligible role in the power sector today. It accounts for less than 0.2% of global electricity generation[5].
However, electricity generation technologies that can use hydrogen are already commercially available today. Some current designs of gas engines, fuel cells and gas turbines are technically capable of operating on hydrogen-rich gas mixtures or even pure hydrogen[6].
Despite the low deployment levels of hydrogen in the power sector so far, interest in the use of hydrogen is increasing.
There are three criteria which will impact the penetration of hydrogen in the power sector:
First, the availability of the infrastructure to transport and store hydrogen, as well as the production of sufficient green hydrogen (to run power generation units with hydrogen for the required time periods),
Second, the price for hydrogen production.
Third, the regulatory framework that will push hydrogen re-electrification into the market.
Existing ramp-up scenarios in hydrogen generation, transport and storage promise a strong increase of hydrogen availability and related cost reductions up to 2030 and beyond.

Co-firing with hydrogen can already reduce CO2 emissions in existing gas-fired power plants in the near term. H_2 co-firing will already be

[1] DOI: 10.1007/978-981-10-7326-7_17
[2] DOI: 10.1016/j.seta.2022.102739
[3] New plants | EUGINE, H2-Ready | EUTurbines
[4] DOI: 10.1016/j.ijhydene.2022.07.075
[5] Global Hydrogen Review 2022, International Energy Agency, https://www.iea.org/reports/global-hydrogen-review-2022
[6] U.S. EPA, Doc. ID No. EPA-HQ-OAR-2023-0072, https://www.iea.org/reports/global-hydrogen-review-2022

necessary in order to comply with the emission thresholds set by the EU taxonomy[7] (access criteria for participation in capacity market: long-term reduction down to <100 g CO2/ kWh).

In the longer term, 100% hydrogen-fired power plants can support the integration of variable renewables by providing flexibility or large scale, seasonal storage to electricity systems.
Before 2030, gas-fired power plants will dominate thermal capacity additions compensating coal (and nuclear) retirements. Beyond 2030, it is expected that there will be significant additions of hydrogen-based (CHP) units, and a switch from natural gas to hydrogen.

4. The proposed transition pathway(s)

(for the EU-27)		2030	2040	2050
Electric power generation capacity (in operation, fueled by H_2)	[GW]	2.4 → 4.9	8.7 → 24.4	27.6 → 97
Electricity produced (operation of 1000 hours/year, fueled by H_2)	[TWh/y]	2.4 → 4.9	8.7 → 24.4	27.6 → 97
H_2 (required)	[1'000t H_2/y]	134 → 281	491 → 1'375	1'540 → 5'390
Electrolyzer capacity needed (in operation)	[GW]	1.9 → 4.0	6.9 → 19.3	21.6 → 75.6
Electricity consumed by electrolysis (operation of 4000 hours/year)	[TWh/y]	7.5 → 15.8	27.6 → 77.3	86.5 → 303
Round trip efficiency (power-H_2-power)	[%]	32	(33)	(35)

Figure 1: (low/high) scenarios for ramp-up of H2-based power generation

In order to secure residual load requirements for future RES dominated electricity systems, it is important to have sufficient dispatchable power generation capacity installed which can support the adequacy of the electricity supply in certain deficit (I.e. high demand / low RES supply) situations. Besides demand-response management, traditional & new (pumped) hydropower, biomass-based power generation systems and – with growing importance – electric energy storage technologies (e.g. batteries), also other low-carbon power generation technologies at significant scale will be required to cope with this task.
The dispatchable electric power generation technologies (gas turbines, gas engines, fuel cells) would need to be operated with low/zero carbon fuels (like H_2) or in combination with carbon capture & storage (CCS) technologies in order to meet strict CO_2 emission limits. To keep pace with the rapidly growing base of variable RES and be prepared for the resulting future residual load scenarios, it is opportune to start with the ramp-up of the installation of such dispatchable power generation systems run on H_2 as fuel already in the short- to mid-term.

Several projects have been announced or are under development that could represent around 3500 MW of hydrogen-fired power plant capacity worldwide by 2030[8], e.g. the EU funded projects HYFLEXPOWER and FLEX4H2, as well as the initiative for the 1.4 GW Magnum power plant (30% co-firing) in the Netherlands. Around 85% of these projects focus on the use of hydrogen in combined-cycle or open-cycle gas turbines. The use of hydrogen in fuel cells and for co-firing in thermal power plants each accounts for around 10% and 6%, respectively, of the project pipeline capacity until 2030. Most of the gas turbine projects initially start with a hydrogen co-firing share in the range of 5-10% in energy terms (15-30% volumetric), but plan to move to higher shares and in some cases even 100% hydrogen firing in the longer term. These projects are mainly located in the Asia Pacific region (40%), Europe (33%) and North America (26%)[9].
Gas engine power plants have been demonstrated to run on 100% H2 with several 100 kW and up to 1 MW electric output already (SW Hassfurt and HanseWerk Natur for example). Larger multi MW dedicated H2-engines will come on the market around 2025. The technology roadmap[10] shows that the power density of dedicated H_2-engines will be soon similar to gas engines running on natural gas today. Almost all gas engines installed to run on natural gas can be converted to hydrogen.

[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852
[8] Global Hydrogen Review 2022, International Energy Agency (p. 67)
[9] Global Hydrogen Review 2022, International Energy Agency (p. 67)
[10] https://www.eugine.eu/brochures/the-need-for-clean-flexibility-in-europes-electricity-system

Given current trends, the demand for hydrogen in electricity generation is expected to remain quite low, around 0.3 Mt, in the period up to 2030. The outlook in the Announced Pledges Scenario pushes demand for hydrogen in the power sector up to 5 Mt by 2050.

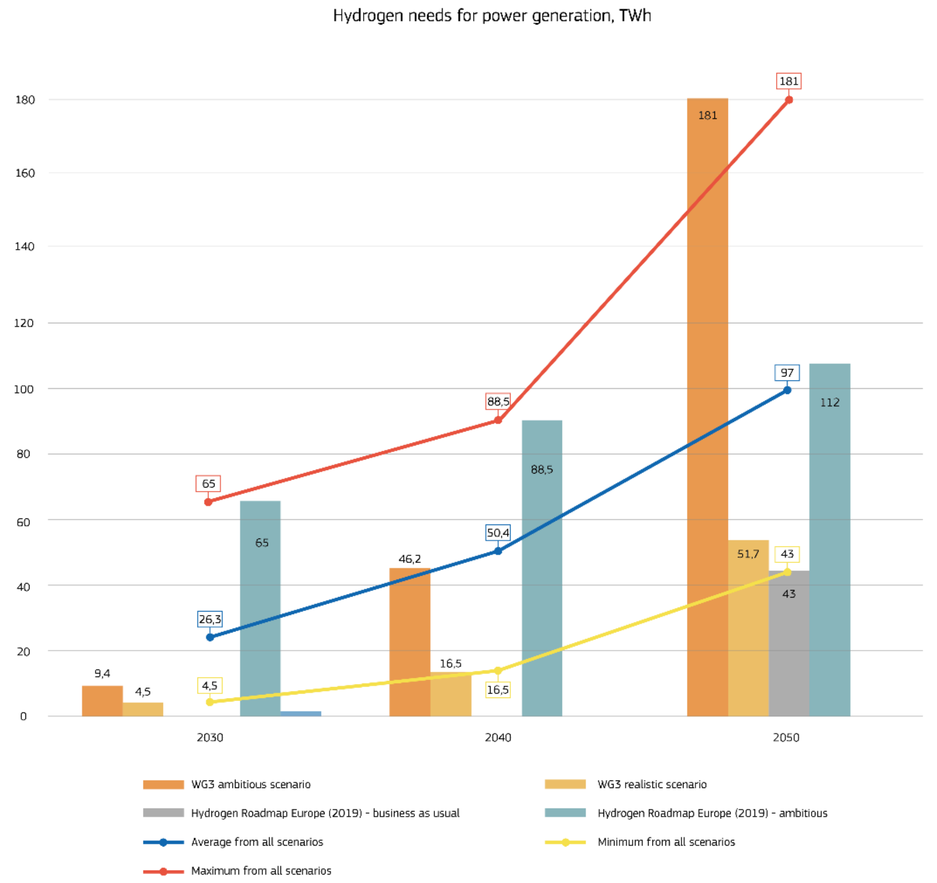

Figure 2: Proposed (low/high) scenarios for ramp-up of H_2-based power generation[11]

Scenarios for hydrogen power generation	2030	2040	2050
WG3 ambitious scenario	4.9	24.4	97
WG3 realistic scenario	2.4	8.7	27.6
Hydrogen Roadmap Europe (2019) - business as usual	N/A	N/A	43
Hydrogen Roadmap Europe (2019) - ambitious	65	88.5*	112
Average from all scenarios	24.1	40.5	69.9
Minimum from all scenarios	2.4	8.7	27.6
Maximum from all scenarios	65	88.5	112

Renewable-based hydrogen can be used for various applications besides green electricity production, including transportation and industrial processes such as heavy industry, chemical and pharmaceutical[12]. Thus a fair share of the limited CO_2- free H_2 resources has to be assigned to the different H_2 end-use sectors. More specifically, H_2 is suitable for distribution and use in (almost) all industrial applications where natural gas is currently used. A partial replacement (~20%) of natural gas with hydrogen is viable without significant modifications to infrastructure and utilities, while higher shares of H2 will require an increasingly demanding replacement of the currently used hardware. In transportation H_2 could be used directly where infrastructure would be reasonable (long-haul traffic, private and public urban fleets), or combined into constituents of liquid fuels (e.g. methanol and hydrocarbons) that can be used with existing infrastructure and motors. As for the heavy industry, increasing quantities of H2 will be needed in reduction processes (e.g. to produce iron and alloys), and for the chemical and pharmaceutical industry hydrogen is essential to synthesise e.g. ammonia, a base chemical of many other compounds.
The proposed build-up of the power generation assets needs to go hand-in-hand with the development of a H_2 supply infrastructure (H_2 production/distribution/storage) based to a growing extend on water electrolysis driven by renewable electricity in times of low demand / high RES production. The need for such synchronised build-up of respective technologies is widely accepted, and reflected in corresponding European (European Hydrogen Strategy) and national development programmes (e.g. Germany, EEG2023 – calls for 4.4 GW of electric power generation capacity from green hydrogen in 2023-2028 and additional 4.4 GW of electric power generation capacity linked with H_2-based

[11] https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf
[12] DOI 10.1016/j.renene.2022.09.057

electricity storage).
Required residual power capacity (to be operated on renewable fuels like H_2) is forecast to be 175 GW by 2030, growing to 345 GW by 2050 (ENTSO-E/ENTSO-G – TYNDP2022; Fig. 26).
Water electrolysis capacity is supposed to be manufactured and installed at GW scale (global manufacturing capacity of 380 GW by 2030; EU – 6GW in 2024, corresponding to an annual production of up to 1 Mt H_2, and 40 GW until 2030 resp. 10 Mt H_2; Germany – National H_2 strategy calls for 10 GW installed by 2030).
H_2 networks are under consideration in Europe (European Hydrogen Backbone EHB – H2 network to support a 10/20.6 Mt H_2 market in 2030/2040) and in national strategies (e.g. Germany – National H_2 strategy calls for a H_2 network capable of receiving/delivering up to 100 GW of H_2 per year by 2030).

5. Provision of residual power and other services to the electric grid

As outlined above, it is important to have sufficient dispatchable power generation capacity installed which can support the stability of the electric grid in prolonged periods of high demand/low RES supply situations. Such periods would deplete other flexibility means (like direct electricity storage in batteries, flywheels, compressed air energy storage systems (CAES)) and therefore dispatchable power generation at a significant scale will be required to cope with this task. In addition to (pumped) hydropower and biomass, other low-carbon power generation technologies must be considered for this.
In this respect, the combination of (water) electrolysis and electric power generation based on H_2 (Power-to-H_2-to-Power) can provide valuable support services to the electricity grid.

Electrolysers are able to provide short term flexibility (via load management), i.e. services for the safe operation of the interconnected power grids. Such services[13] include:

- Grid balancing and frequency control
- Congestion management
- Improvement of system stability
- Peak shaving and energy shifting
- Reactive power support and voltage control
- Power oscillation damping
- Distribution grid services

Involvement of hydrogen in various grid services gives additional income, improves its profitability and makes the system more economically attractive. Power to Power with hydrogen energy storage is a strong option in small isolated power systems, where several system challenges appear together. Such challenges include limitation of renewables integration, lack of system inertia, unequal geographical distribution of load centres, etc. Business cases are only possible by using all system services markets, and all market regimes need to be adapted. For grid-connected applications, a significant price spread (difference in buy vs. sell price) is required for PtH2tP to be economically viable.

Flexibility from electric power generation units based on hydrogen (PtH2tP) transforms surplus energy – delivered by renewable sources and stored in form of H2 produced by electrolysis – back to electricity (e.g. via fuel cell converters; see Figure 3) during high electricity demand periods. In both legs of the roundtrip cycle (for electrolysis, as well as for power generation), the intermittent nature of renewable power can be balanced to match the demand profile of power grids. Interest in hydrogen-based energy storage systems is growing due to their potential for high storage capacities (as compared to other storage technologies like flywheels, capacitors, batteries and CAES systems and the full set of services they can potentially offer to power systems.

The proposed dispatchable electric power generation units (gas turbines, piston engines, fuel cells) operated on H_2 as a fuel can provide residual power as well as balancing power very efficiently at different power scales (capacity) adapted to the specific conditions (e.g. capacity of cables, electric demand) given at their individual connection point to the electricity grid. Some of these technologies can also provide much needed grid ancillary services such as system inertia, reactive power control, voltage control, short circuit power, among others. Dispatchable H_2-based power generation can serve distributed networks down to microgrid scale (MW to kW scale) as well as large urban and industrial zones (50 to 500+ MW). Due to their favourable operation characteristics (quick response times – seconds/minutes - as well as sustained power output over longer time frames – hour/days/weeks) they can nicely complement other power provision technologies (like flywheels, batteries). Placement of H_2-based power generation units will need to be accounted for in respective network development plans considering additional boundary conditions such as the proximity to gas networks and storage sites for the appropriate supply of H_2.
The amount of residual power that can be supplied by H_2-based power generation – in case the proposed ramp-up scenarios are being realized – would be significant (5 GW in 2030, growing to 100 GW in 2050) but still cannot meet (by far) all the demand forecast for 2030 / 2050 (175 GW in 2030, growing to 345 GW in 2050 (ENTSO-E/ENTSO-G – TYNDP2022; Fig. 26). This emphasizes the urgent need to take the paths outlined, as otherwise important overarching goals (secure electricity supply with a low carbon footprint) will be missed by a large margin.
More details about the hydrogen impact on grids are described in the ETIP SNET whitepaper from 2023 "Impact of hydrogen integration on power grids and energy systems (link)" and thus not repeated here in more detail.

[13] https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-hydrogen/13-Electrolysers-as-grid-service-providers

6. Technology developments required to support the transition pathways

It is obvious that certain developments are paramount to enable the transition pathways with the schedules outlined above. Developments will be needed for both infrastructure and final end-use equipment (the focus here in this paper is on fuel cells, gas turbines and gas engines). Existing industrial hydrogen networks will need to be expanded, while existing natural gas (NG) networks will require (partial) conversion to hydrogen with some network parts needing upgrades to accept shares of H_2 higher than ~20%. Due to low volumetric energy density, power demand for pipeline transportation is likely to be increased by a certain factor. Compressor stations have to be upgraded or even replaced to deal with the different thermodynamic properties of hydrogen[14]. Developments towards a more decentralised system will be needed in terms of the management of a much larger number of nodes, comprising numerous points of supply for locally produced hydrogen. Safety will need to be reassessed due to the higher risks (explosion limits) with H_2 than NG.

Fuel cells will need to improve their impact on resources (use of rare materials) and increase fabrication capacity to serve more and larger projects. Fuel cells will also need to become more robust against poisoning impurities in the gas which may stem from production, transport or underground storage processes. Such developments will be also needed for applications where H_2 is made available via a carrier (e.g. methane, ammonia, methanol). As an example, solid sxide fuel cells (SOFC) are currently produced (with no need for either nickel or platinum) up to single MW scale, and developments are ongoing to improve their size, fabricability, robustness to pollutants, and with the capability to operate on various H_2 carriers. Additionally, development is ongoing to improve the reversibility of such fuel cells, allowing operation to be shifted from fuel cell operation (using hydrogen for electricity production) to electrolysis mode (SOEC) using electricity to produce H_2.

The development of H_2-based gas turbines and gas engines is already well on its way, but it still needs dedicated effort until commercial solutions are available in the required power range (presumably 30 to 300 MWe). This applies to both new-built units as well as to retrofit solutions for existing assets. Maintaining full power capacity (no down-grading because of H_2), highest efficiencies (same as for today's NG fleet) and lowest emissions (below 25ppm NOx) are the targets to be achieved. As the equipment will be used to meet residual load requirements, a high operational flexibility will be mandatory without compromises on reliability and durability of the equipment. Steep load ramps and frequent start/stop cycles will need to be covered by respective H_2-fired gas turbine and gas engines.

From the various hydrogen production technologies, all require certain improvements[15]. Industrial by-product hydrogen has abundant sources and the developments should focus on gas separation and purification technology. For water electrolysis coupled with renewable energy power generation it is necessary to reduce the price of renewable energy power generation and improve the efficiency of the water electrolysis process in order to produce H_2 at competitive cost. Photocatalytic and photo-electrochemical hydrogen production processes are still not mature enough to satisfy the demands of large-scale industrial applications, and more basic research and demonstration applications are needed.

Concerning the (chemical, physical) storage of hydrogen and its distribution, all technical solutions involve the development of stations (compressors, pumps) and pipelines capable of handling high-pressure gas and/or low-temperature liquids. Liquified hydrogen (LH_2) is an option to transport and store hydrogen, which competes with hydrogen-derived ammonia for the same purpose. Synthesis and decomposition of chemical H_2 carrier species is a matter of current research and needs further improvement. Chemo-physical adsorption and desorption of hydrogen into and from (solid, liquid) H_2 carrier media requires significant progress in order to play a role in future H_2 based energy systems.

Last but not least, standardisation around hydrogen production, transport and storage as well as hydrogen power plants is essential. Therefore, it is important that required norms and standards as identified by the EU Clean Hydrogen Alliance are developed and implemented in a timely fashion to ensure alignment of the legal/regulatory framework with the technology development pathways.

7. Conclusions and Recommendations

Driven by the persistent need for dispatchable electric power generation CO_2-free hydrogen will become in due time an important component of future integrated energy systems, comprising production units, logistics (transportation and storage) and final end-use applications. Its long-term, massive and cheap storage capabilities make it well suited to exploit long-term (i.e. months) shift-in-time of surplus vRES electricity (during summer) into periods of high residual load (during the winter season). Stored H_2 can be utilised in various end-use sectors (mobility, industry) or for re-conversion to electricity, much the same service as pumped hydro storage and batteries can deliver on different storage time scales. Even though this service can be provided only with limited energy efficiency (35-50% round-trip efficiency), it is highly valuable and indispensable for system reliability. The economy of related business cases will decide at which cost and for which power capacity the respective technologies will contribute their corresponding shares to the given electric power generation needs.

Dispatchable reconversion to electricity of H_2 can take place through gas turbines, gas engines or fuel cells. These technologies are characterised by flexible operation (steep load ramps, dynamic duty cycles) and present added advantages in terms of grid operation, providing services such as inertia, reactive power management, voltage and frequency support. They are also able to be converted from one fuel to another, in order to provide a favourable transition framework for upgrading existing assets while the required hydrogen ecosystem is being developed and deployed.

It is opportune to start now with all innovation developments mentioned (technological, standardisation, qualification to grid services, business models for proper remuneration), in order to prepare the thermo-electric power generation park to become H_2-ready within the given time frame for the transition of the whole energy system.

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[14] ACER Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure

[15] https://doi.org/10.1016/j.ngib.2022.04.006

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