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WORKING PAPER

HYDROGEN ON THE HORIZON: READY, ALMOST SET, GO?

WORKING PAPER | HYDROGEN DEMAND AND COST DYNAMICS

World Energy Council, in collaboration with EPRI and PwC

ABOUT

WORLD ENERGY COUNCIL

The World Energy Council has been at the heart of global, regional and national energy debates for nearly a century, developing new thinking and driving effective action around the world to achieve the benefits of sustainable energy for all.

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The Council works dynamically across the whole energy sector as a global energy transitions platform, pulling together intelligent leadership to catalyse and inform the world's energy policy dialogue, create impact and drive practical action.

The Council does not advocate for any country, company, technology or source of energy. The World Energy Council remains thoroughly committed to the challenge of being both impartial and impactful.

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WORKING PAPER

This Working Paper on hydrogen is part of a series of publications by the World Energy Council focused on Innovation. It was developed in collaboration with the Electric Power Research Institute (EPRI) and PwC.

EPRI and Gas Technology Institute (GTI) have created the Low-Carbon Resources Initiative (LCRI) to address the challenges and gaps in achieving deep carbon reductions across the energy economy. LCRI is focused on the value chain of alternative energy carriers and low-carbon fuels—such as hydrogen, ammonia, biofuels (including renewable natural gas, and synthetic fuels—and research, development, and demonstration to enable their production, storage, delivery, and use across the energy economy. These energy carriers/fuels are needed to enable affordable pathways to economy-wide decarbonization by mid-century. This five-year, global collaborative will identify and accelerate fundamental development of promising technologies; demonstrate and assess the performance of key technologies and processes, identifying pathways to possible improvements; and inform key stakeholders and the public about technology options and potential pathways to a low-carbon future.

PwC is a network of firms in 155 countries with over 284,000 people committed to delivering quality in assurance, advisory and tax services, including more than 20,000 professionals engaged in the energy, utilities and resources sectors. With its global strategy, The New Equation, PwC is responding to the challenges shaping the world today, with a focus on building trust and delivering sustained outcomes that create value for organisations, their stakeholders and broader society. Climate change is one of the world's most pressing problems, and PwC has committed to reach net zero greenhouse gas emissions by 2030 and is working with organisations to accelerate their own climate-based transformation. PwC and the World Energy Council have a common goal of promoting energy transition and sustainability by engaging with policymakers and leading industry players. Our shared view is that energy transition and sustainability are achieved through the interaction of robust policy frameworks and a strong, competitive energy industry.
Learn more about PwC

In a fast-paced era of disruptive changes, this working paper aims at facilitating strategic sharing of knowledge between the Council's members and the other energy stakeholders and policy shapers and contribute to a global dialogue on hydrogen's role in energy transitions.

This working paper builds upon earlier work by the Council and involved extensive research on national strategy developments and interviews with 38 experts from 23 countries, reflecting 61 % of the global Total Primary Energy Supply – TPES (2018 data, OECD) and 70% of global GDP (2019 data, WB).

INTRODUCTION

The World Energy Council, in collaboration with EPRI and PwC, aims to provide a better understanding of hydrogen development worldwide for the energy community, building on the expertise and experience of its global network. In this context, we published a new Innovation Insights Briefing on Hydrogen in July 2021, seeking to start a multi-stakeholder, multi-level community dialogue on hydrogen's role in energy transitions.

Our work has identified the following 4 areas for further discussion:

1 **Significant divergences are emerging across countries and regions,** as national hydrogen strategies reveal varying attitudes towards hydrogen's role in energy transitions. This signals a need to embrace diversity – eliminating a one size fits all mindset – and enable differing technologies and use cases to be explored.

2 **Confusion over 'colours' is stifling innovation,** with over-simplification and colour prejudice risking the premature exclusion of some technological routes that could potentially be more cost- and carbon-effective. There is a need for further dialogue which looks beyond colour to also explore carbon equivalence.

3 **Demand-centric hydrogen perspectives are needed to advance the Humanising Energy agenda.** The current hydrogen conversation focuses heavily on supply, ignoring the role of hydrogen users. Discussions must explore what's needed to trigger demand, with a specific focus on the development of hydrogen infrastructure and a global supply chain.

4 **The hydrogen economy could stimulate job creation and economic growth,** potentially helping to fulfil 'build forward together' ambitions post-COVID-19. Several national hydrogen strategies highlight jobs as an important driver of hydrogen development, with opportunities to reskill the existing workforce and upskill a new workforce.

To help inform the dialogue on these 4 topics, we are releasing 3-part series working papers for the hydrogen road builders, providing additional insights on:

- National Hydrogen Strategies;
- Inputs From Senior Leaders On Hydrogen Developments;
- Hydrogen Demand And Cost Dynamics.

This Working Paper focuses on the dynamics of hydrogen demand and hydrogen cost development.

1. DYNAMICS OF HYDROGEN DEMAND

Hydrogen is being discussed as one important solution to meet the Paris climate goals, as it can be a clean fuel, feedstock, and reagent for many energy intensive processes and transport services. However, possible hydrogen demand trajectories up to 2050 can vary depending on the development of complementing technologies, such as energy efficiency, electrification, carbon capture, and hydrogen technologies themselves. This analysis aims to shed light on the different hydrogen demand and cost trajectories by analysing various reports and energy scenarios.

1.1 THE USE OF HYDROGEN

Most of the studies analysed focus on the use of hydrogen from low-carbon production sources, which partly aligns with their corresponding national strategies. Some countries or regions (e.g., the EU) favour hydrogen produced mainly using renewable energy sources as part of their plans to reduce CO_2 emissions (see Working Paper - National Hydrogen Strategies). Other nations, such as Gulf countries or energy importing countries, with different contexts (e.g., access to low-cost natural gas, openness to CCS-technology) and additional policy goals such as reducing air pollution in cities, consider more forms of low carbon hydrogen. Additionally, some studies and national strategies are intending to initially scale up the hydrogen market by combining hydrogen production pathways with CCS to first establish the infrastructure needed before or alongside exploring other avenues.

The hydrogen demand breakdown per sector can vary widely. This is reflected by the significant variation in numbers presented across different reports when analysing projections for clean hydrogen usage per sector. Currently, the focus appears to be on the industrial, transport, and energy sectors, while there are high uncertainties surrounding the use of hydrogen in buildings. Unfortunately, the 13 global scenarios analysed in this report do not contain consistent and comparable sector breakdowns.

1.2 HYDROGEN DEMAND PROJECTIONS

Hydrogen demand projections vary significantly due to differing underlying assumptions[1] regarding decarbonisation ambitions. We analysed estimates for global hydrogen demand from 8 different sources, with a total of 13 scenarios. While other hydrogen scenarios are available, they provide less detail or cover only specific sectors or countries and have therefore not been included.

METHODOLOGY

The report analyses and compares the hydrogen demand projections of 13 scenarios from 8 different reports (see details in Annex 1), clustering each scenario in one of the following three trajectories: low, medium, and high. The categories are defined along their ambition level to reduce the global temperature rise, which is suggested in each report. The following associations can be made:

- Low ambition trajectory with a >2.3°C global warming,
- Medium ambition trajectory with 1.8-2.3°C global warming, and
- High ambition trajectory with <1.8°C global warming.

Even though the specifics of each scenario vary to a certain extent, the analysis helps to show overall patterns of the demand development. However, it needs to be stated that this is only a clustering of the 16 scenarios analysed and that other energy scenarios might not fall into the three trajectories defined.

After grouping the scenarios, this report analyses the average growth trajectories of global hydrogen demand. Due to differences in the analysed scenario assumptions, the standard deviation was calculated for each trajectory. The standard deviation was chosen to show the upper and lower spread from the scenario average with the aim to help compare the scenarios and adjust for possible variances in the aforementioned assumptions. Hence, some upper and lower hydrogen quantities provided in the original reports do not appear in this comparison.

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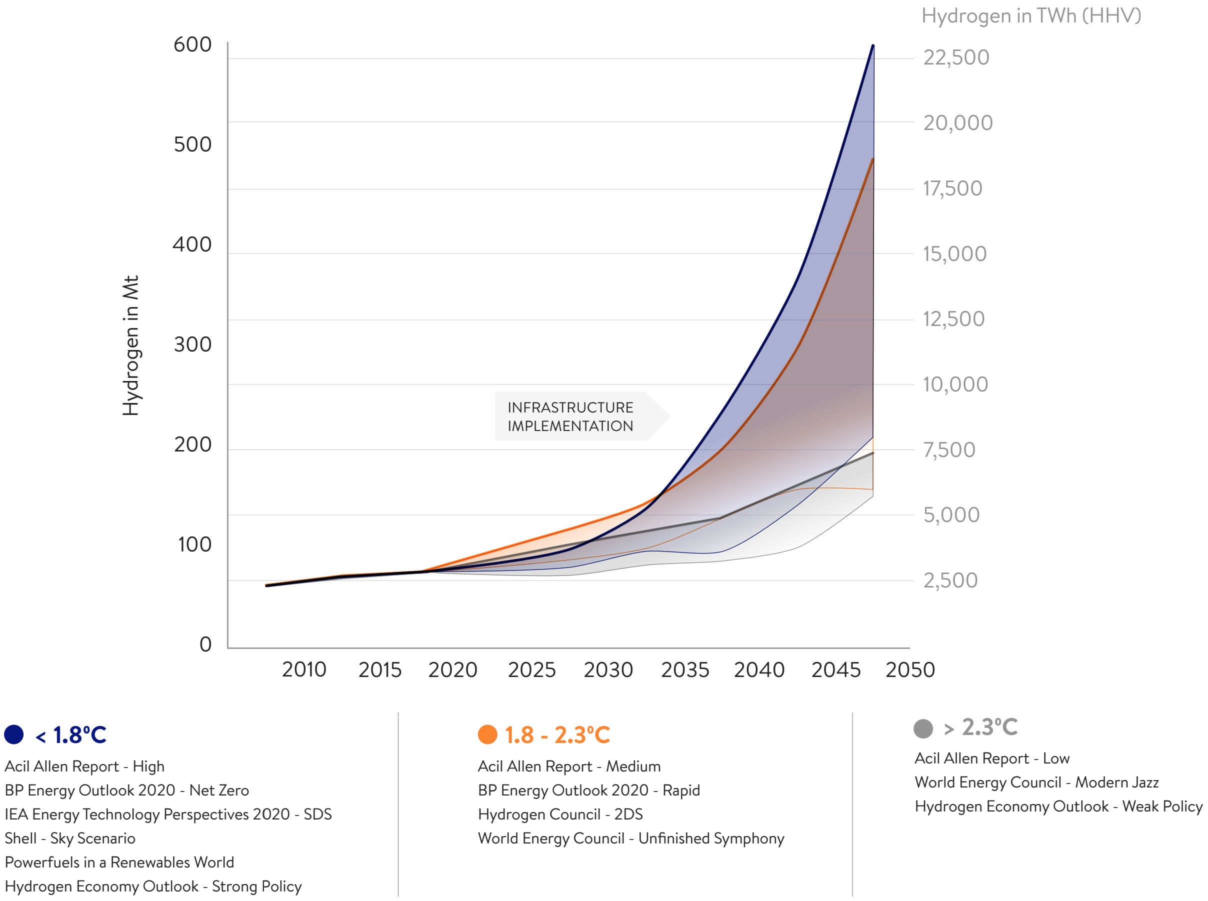
[1] *See details in annex 1.*

Figure 1. Range Of Hydrogen Demand Assessment By 2050



Source: World Energy Council*

The comparison was limited because the energy inputs, such as renewable electricity or gas, are not clearly defined and many underlying assumptions are not detailed.

1.3 LONG-TERM DEVELOPMENT OF HYDROGEN DEMAND

Clearly, depending on the assumptions (see Annex 1 for the different assumptions), the analysis revealed a broad range of possible future hydrogen demand. One common theme is that all estimates predict a limited but steady growth of hydrogen demand until 2030. There are several likely reasons for this. Firstly, current hydrogen projects under construction and in operation are, despite growing capacities, almost exclusively at pre-commercial phase and have limited electrolyser capacities, typically well below 50 MW. Proposed production plants have larger electrolyser capacities of 100 MW+, however this is still relatively small compared to production capacities of current fossil based, mainly grey, hydrogen plants. Secondly, putting in place the infrastructure for large scale hydrogen use, such as pipelines or export and import terminals, takes many years. For example, it can take up to 12 years to plan and build a natural gas pipeline and up to 10 years to build an LNG-terminal. The time to implement hydrogen infrastructure would be similar in length. In an ideal world, the required infrastructure would be built in parallel with growing hydrogen demand and falling costs to ensure that by 2030 hydrogen could be traded and transported in the necessary quantities.

Post-2030, the higher ambition scenarios see stronger hydrogen demand with another strong increase from 2035 onwards. This is in line with the time required to develop the infrastructure, whose planning begins now to achieve the hydrogen targets and demand growth envisioned after 2030.

> ***"Hydrogen as large scale energy storage can enable higher penetration of intermittent renewables, and hydrogen made from fossil fuels where the carbon is sequestered at the point of extraction can enable us to leverage those energy resources even while aggressively focusing on decarbonising the overall energy system."***
>
> ***SABINA RUSSEL, ZEN CLEAN ENERGY SOLUTIONS, CANADA***

1.4 HYDROGEN DEMAND IS RELATABLE TO UNDERLYING TEMPERATURE GOALS

The estimated hydrogen demand figures for 2050 vary significantly, ranging from 150 to 600 Mt. The higher volumes of hydrogen are needed to achieve more ambitious climate targets, even though the demand differences between the indicated temperature categories may not be as significant as expected. The wide range of hydrogen demand estimates results from the differing underlying assumptions about the technologies used, e.g., continued use of natural gas, efficiency improvements, direct electrification, or CCS. The scenarios for higher ambition climate goals require higher hydrogen demand by 2050, estimating demand to range between 200 to 600 Mt. The highest climate ambition seems to have higher hydrogen demand in the hard to abate sectors, such as steel or chemicals, substituting current grey hydrogen and creating new demand in further applications/products. The scenarios with medium climate ambitions identify a range between 160 to 490 Mt by 2050, with an average growth of around 330 Mt. The less ambitious scenarios only see a small and almost linear growth in hydrogen demand with the continued use of natural gas, and estimate that it will vary between 150 to 200 Mt in 2050.

2. HYDROGEN COST DEVELOPMENT

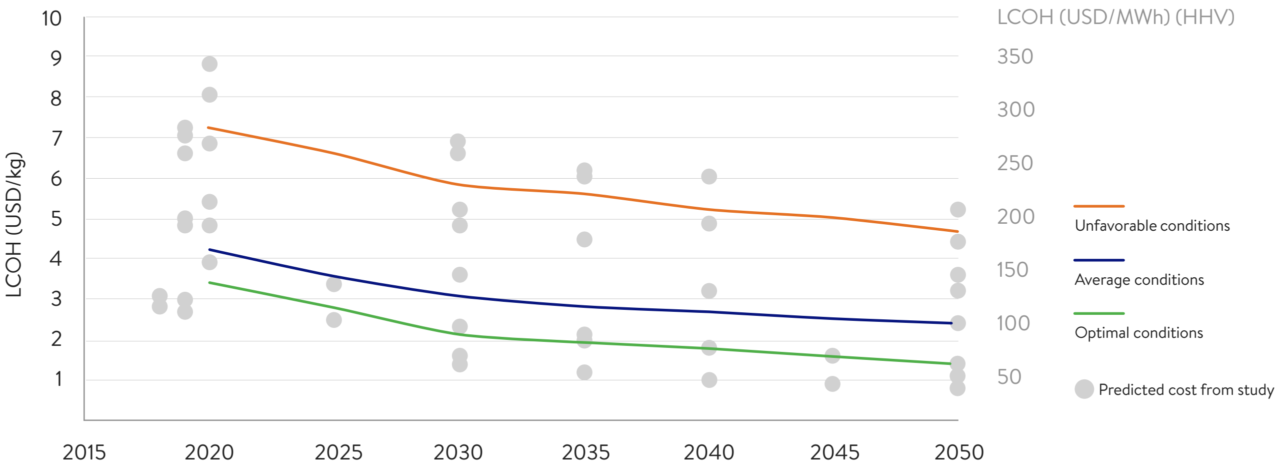
The future cost of hydrogen will be critical to its uptake across the various end sectors where we see significant energy cost differences between but also within the sectors. The hydrogen cost for the end-user will be a function of production and distribution costs. Many of the production technologies are still new so learning curves and scale effects can help drive down future costs. At the same time, many commentators believe that a significant expansion of renewables such as solar and wind could bring down the cost of renewable electricity, which is considered a significant driver for hydrogen's expansion in the energy system. On the other hand, countries with surplus renewable capacities will consider clean hydrogen as a way to avoid curtailment. This depends very much on country context. Carbon pricing is predicted to be a fundamental 'enabler' to hydrogen uptake by bridging the cost gap with higher CO2 alternative fuels. It is also likely that the combination of carbon pricing and an abundance of renewable electricity can promote hydrogen production via electrolysis.

Distribution costs for hydrogen covering storage and transportation are likely to be substantial and could limit growth. Distributing hydrogen as a liquid in the form of ammonia could enable the repurposing of some existing oil infrastructure to reduce costs, while natural gas pipelines could be repurposed to distribute hydrogen in gaseous form.

2.1 METHOD OF THE COST CALCULATION FIGURE

In order to identify the future production costs of renewable hydrogen, another set of 6 additional reports with a total of 16 different scenarios of forecasted hydrogen production prices were analysed.[2] Most of the reports included different price development scenarios regarding the production conditions, with the electricity price and full load hours of the electrolyser having the highest influence. Based on this, 3 different price corridors were developed, indicating the range in which the future price of renewable hydrogen is likely to fall.

Figure 2. Renewable Hydrogen Cost Dynamics By 2050



Source: World Energy Council*

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[2] *Agora (2020). Klimaneutrales Deutschland. | Greenpeace Energy (2020). Blauer Wasserstoff. | Deutscher Bundestag (2020). Kosten der Produktion von grünem Wasserstoff. | Hydrogen Council x McKinsey & Company (2021). Hydrogen Insights. | Strategy& (2020). The dawn of green hydrogen. | DOE Hydrogen (2020). Hydrogen Production Cost From PEM Electrolysis.*

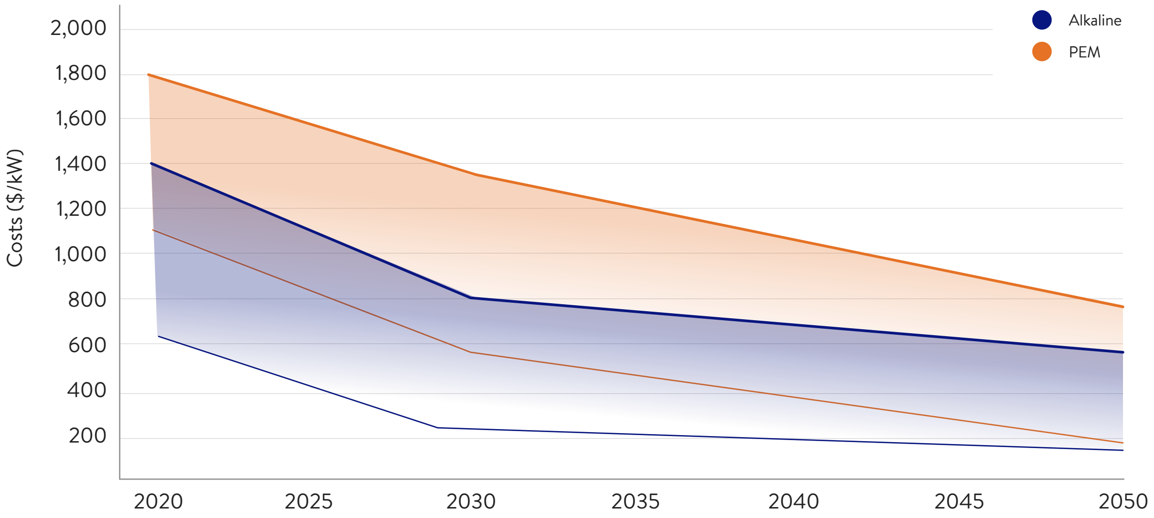
2.2 GLOBAL PRODUCTION COST DYNAMICS: A STRONG PRICE DECREASE EXPECTED

Currently, the production price for the so called “green hydrogen” ranges globally between US$2.7-8.8/kg, with all studies anticipating a significant price decrease by 2030 to a range of US$2-6/kg due to falling renewable electricity costs and hydrogen technologies following a learning curve with technology improvements and economies of scale. For green hydrogen, the Operating Expenses (OPEX) are directly linked to renewable electricity costs, and thus are the main drivers for lowering the production costs. These are anticipated to decrease further with solar electricity already achieving levelised costs below US$17.5/MWh. As for the Capital Expenses (CAPEX), the cost of electrolysers are expected to decrease significantly with time as economies of scale and their production are streamlined in the future. With further technology improvements and project implementation, the cost of blue hydrogen production will also decrease.

By 2050, the studies estimate a price range between US$1.5-5/kg, with some expecting cost of US$1/kg or lower for green hydrogen in countries with excellent renewable resources. However, there will be significant differences between countries and production sites dependent on the price of renewable electricity, with production being cheaper in countries like Australia or Chile which have lower renewable electricity costs and, by association, higher capacity factors for the electrolyser.

Further work is needed to understand the differing costs for producing hydrogen, how much different stakeholders could or would be willing to pay for hydrogen, as well as the CO_2 emissions from different production sources and the CO_2 price needed to make low carbon hydrogen production more economically attractive.

Figure 3. Electrolyser Costs Dynamics By 2050



Source: World Energy Council*

Hardware cost reductions are important as well. Standardisation and mass production as well as project learnings will lower the cost of electrolysers, carbon capture systems, balance of plant equipment, as well as overall construction costs. Figure 3 shows potential electrolyser capital cost trajectories for the current two main technologies, which are alkaline and PEM electrolysers. Additionally, increases in the capacity of low-carbon hydrogen projects will lead to further declines in production costs. With significant research underway, technology improvements are expected to further reduce production costs while growing project numbers will also decrease finance costs.

> ***“To bring down the cost of hydrogen technologies, we don’t need to have new innovations, we need mass-production.”*** *A.J.M. VAN WIJK, TU DELFT, THE NETHERLANDS*

ANNEX 1

HYDROGEN DEMAND SCENARIOS

	Acil Allen Report	BP Energy Outlook 2020	Hydrogen Economy Outlook	Hydrogen Council – 2DS	IEA	Powerfuels in a Renewables World	Shell – Sky scenario	World Energy Council
Total hydrogen demand estimates (Mt)	**High:** - 2030: 93 - 2040: 161 - 2050: 401 **Medium:** - 2030: 84 - 2040: 113 - 2050: 213 **Low:** - 2030: 77 - 2040: 94 - 2050: 148	**Net Zero:** - 2030: 104 - 2040: 282 - 2050: 560 **Rapid:** - 2030: 102 - 2040: 173 - 2050: 284	**Strong policy:** - 2030: N/A - 2040: N/A - 2050: 696 **Weak policy:** - 2030: N/A - 2040: N/A - 2050: 187	- 2030: 111 - 2040: 201 - 2050: 567	**Energy Technology Perspectives (ETP) 2020 - SDS:** - 2030: 90 - 2040: 135 - 2050: 290 **Net Zero Scenario:** - 2030: 212 - 2040: 391 - 2050: 528	- 2030: 86 - 2040: 164 - 2050: 346	- 2030: 80 - 2040: 94 - 2050: 149	**Unfinished symphony:** - 2030: 117 - 2040: 164 - 2050: 228 **Modern Jazz:** - 2030: 99 - 2040: 125 - 2050: 185
Hydrogen production route		Green, Blue, Grey hydrogen			**ETP 2020:** Electricity, Fossil w CCUS, Refining CNR, Fossil w/o CCUS **Net Zero Scenario:** Fossil fuels, Refining CNR, With CCUS, Electricity, Biomass	Green hydrogen		
Projected demand by application	Transport, Space heating and cooling, Power sector	Power, Buildings, Transport, Industry	Buildings, Power, Industry, Transport	Buildings, Power, Industry, Transport, Energy system	Net Zero Scenario: Transport (shipping, road, aviation), Iron and steel, Chemicals		Industry (heavy, light), Transport (road, air, ship)	
Ambition to limit global warming	**High:** a 50% chance of limiting the peak in global temperature (temp.) to between 1.5-2°C **Medium:** a 50% chance of limiting the peak in global temp. to 2°C **Low:** 50% chance of limiting the peak in global temp. between 2-4°C	**Net Zero:** limiting temp. rise to 1.5°C above pre-industrial levels **Rapid:** limiting temp. rise to well below 2°C above pre-industrial levels	**Strong policy:** H2 supply 27EJ of energy in global economy, meeting 4% of projected final energy needs in 2050 or 7% in 1.5°C scenario **Weak policy:** H2 supply 99EJ of energy in global economy, meeting 15% of projected final energy needs in 2050 or 24% in 1.5°C scenario	Limit global warming to 2°C	**ETP 2020:** hold the temp. rise to below 1.8°C with a 66% probability without reliance on global net-negative CO2 emissions **Net Zero Scenario:** a 50% chance of limiting the temp. rise to 1.5°C	Achieve the goals of the Paris Agreement of achieving zero GHG emissions from the energy sector by 2050	Limiting the global average temp. rise to well below 2°C from pre-industrial levels	**Unfinished symphony:** <2.3°C confirmed with study authors **Modern Jazz:** >2.3°C confirmed with study authors

Source: World Energy Council*

ANNEX 2

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