DELPHI STUDY

THE FUTURE OF HYDROGEN

Future Watch study on Power-to-X and hydrogen economy

COPENHAGEN INSTITUTE FOR FUTURES STUDIES

BUSINESS FINLAND

Summary

On behalf of Business Finland, the Copenhagen Institute for Futures Studies (CIFS) has conducted a Delphi study to gather experts' views to understand the key change drivers and potential developments in green hydrogen over the next 20 years. "In total, 58 different experts from varying backgrounds provided responses and input to this study.

The answers of the hydrogen panel can be divided into three categories: a small group of pessimists, a larger group of optimists and an even larger group that can be described as conservative optimists. This pattern means that there are few topics where consensus is reached. The difference in opinions cannot be explained by areas of profession, nor expertise, but points to a deep disagreement about the future of hydrogen. This reflects the immaturity of the field and the large uncertainties related to the size of the future green hydrogen market. A main explanatory factor of the differences in responses can probably be found in different underlying assumptions in the groups and rests on expectations for the price of carbon in 2040. With optimists expecting a price of carbon above USD $100 implemented in key regions and pessimist assuming no significant change. Given that the majority expects carbon prices above USD $50 in 2040 this study clearly supports the notion that green hydrogen will play an important part in the energy transition.

Content

Prepared for:
BUSINESS FINLAND

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Introduction

Introduction

The transition away from fossil fuels in line with recommendations from the International Panel of Climate Change and the objectives set out in the Paris Agreement is forcing industries to explore how decarbonization can be achieved within the intended timeframes. The EU aims to be carbon neutral by 2050. Energy efficiency, renewables and direct electrification will constitute the bulk of solutions. Even so, approximately 20% of emissions are hard to decarbonize using direct electrification. This is where green hydrogen comes into the picture. Green hydrogen is produced by splitting hydrogen from water through electrolysis, using electricity from renewable sources such as wind turbines or solar panels.

Green hydrogen is incredibly versatile and can be used in a wide variety of settings; hence the concept Power-to-X (PtX). Depending on usage, green hydrogen can be converted into ammonia, methanol, etc. which can be used in shipping. It is technically feasible to use green hydrogen for storage and grid buffering, or for decarbonized high-heat in industrial processes where electrification is ill-suited or as feed stock in industrial processes or the fertilizer industry. It can also be applied in heavy transport, e.g. trucks and airplanes. The array of usage means it can create synergies and couple different sectors like industry, energy and transport.

The challenge is that the economics of PtX are not yet secured, and technical feasibility does not necessarily translate into economic reality. However, the European Commission's 2050 climate plan enumerates several technology scenarios where PtX is a prerequisite for the 2050 goals. Green hydrogen promises to unite the sectors in ways that would be hard to achieve with other technologies. Thus, the future of the hydrogen economy has a strong bearing on the future of the energy transition. Green hydrogen is however also criticized for resulting in conversion losses that are too high to be economical and exhibiting some of the characteristics of hyped technologies. For this reason, Business Finland has sought to gain a deeper understanding of the different perspectives on green hydrogen to better assess the opportunities that lie ahead.

Business Finland

ABOUT

Business Finland is the Finnish innovation funding, trade, investment and travel promotion organization, headquartered in Helsinki. Business Finland is fully owned by the Finnish Government. Business Finland employs 700 experts in 40 offices globally and in 15 regional offices around Finland.

The goal of Business Finland is to offer a smooth, joint service path for customers in Finland and abroad when they need innovation funding, advice in growing internationally, investing in Finland or bringing visitors to the country.

Business Finland is part of the Team Finland network. The Team Finland network promotes Finland and boosts the success of Finnish companies abroad. The Team Finland network brings together all state-funded actors and the services they offer to promote the internationalization of Finnish companies and to attract foreign investments to Finland.

CIFS

ABOUT

The Copenhagen Institute for Futures Studies is an independent think tank and non-profit research & innovation centre based in Copenhagen with more than 50 years of experience in supporting companies, public organizations and intergovernmental bodies in their strategic planning and innovation needs.

The Copenhagen Institute for Futures Studies was founded in 1969 by Professor Thorkil Kristensen, former Secretary-General of the OECD. It was set up in collaboration with a number of visionary organizations that wanted to qualify their basis for making strategic decisions through futures studies and foresight. Through research, analysis, seminars, lectures and reports CIFS identifies and assesses trends that affect the future nationally and internationally.

With more than five decades years of doing foresight, CIFS is an internationally recognized competence centre and one of the first of its kind specialized in foresight. CIFS' work is interdisciplinary. The staff represents different areas of academic and professional backgrounds such as economics, political science, ethnography, psychology, technology, etc.

The Delphi Study

METHODOLOGY

A Delphi study is a collaborative futures studies method designed to elicit consensus building among a panel of experts on a series of propositions and questions. The method is based on the principle that collective forecasts from a structured group of experts provide superior insights and orientation around potential future developments, particularly when dealing with complex areas with a high degree of uncertainty – such as the development of green hydrogen.

At the Copenhagen Institute for Futures Studies we work with the online real-time Delphi method, which is an advanced form of the Delphi approach. The real-time fashion of the Delphi allows participants to monitor the Delphi panel's overall opinions and shifting consensus, as well as any comments and arguments made by other participants in real time.

The Hydrogen Delphi Study

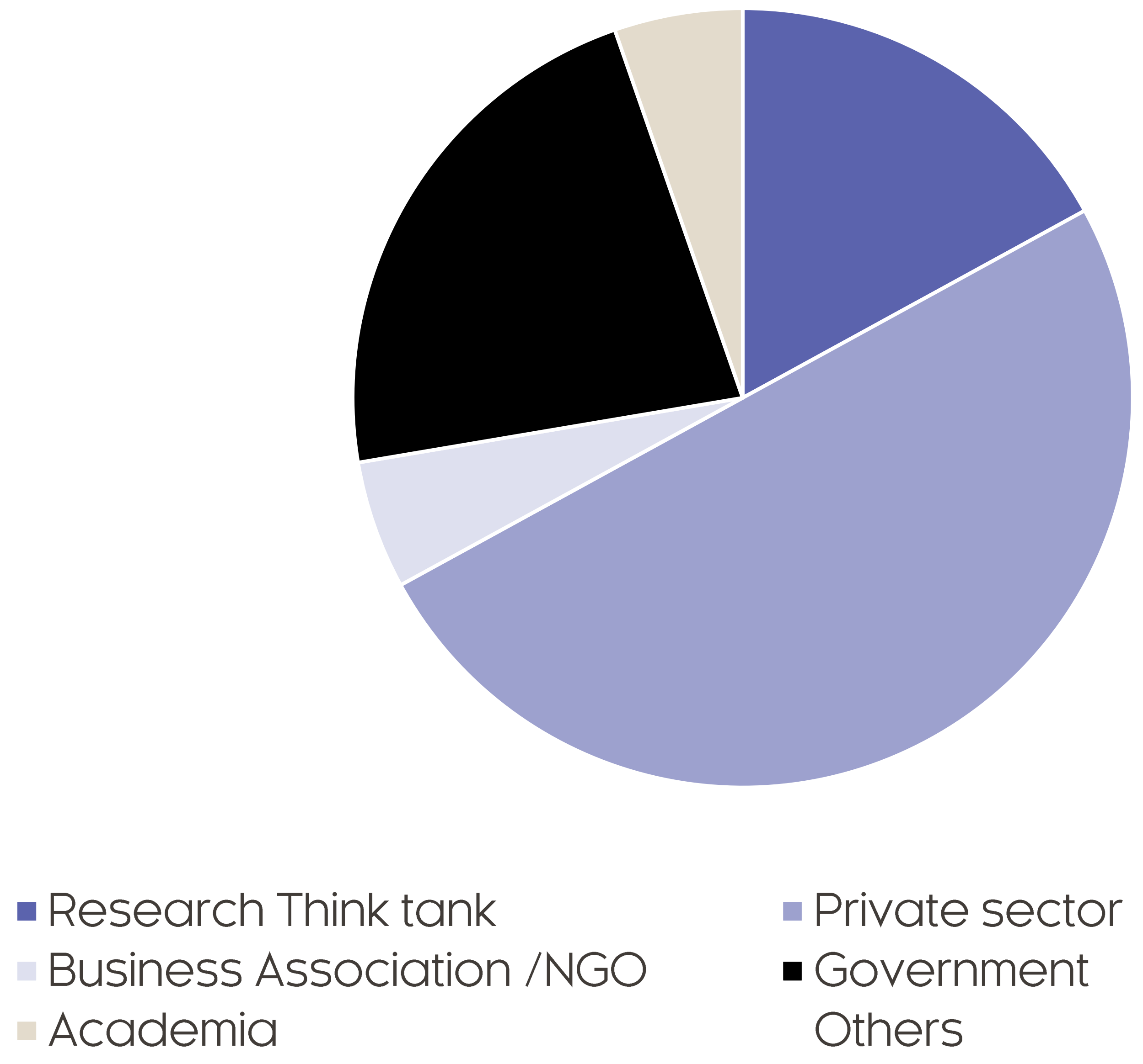
METHODOLOGY

The present Delphi study was designed with the primary objective of understanding the ongoing energy transformation at a global level, its speed and cross-sectoral implications, and the sectors impacted. The report was commissioned by Business Finland. A set of questions was developed, and an online real-time Delphi study was conducted.

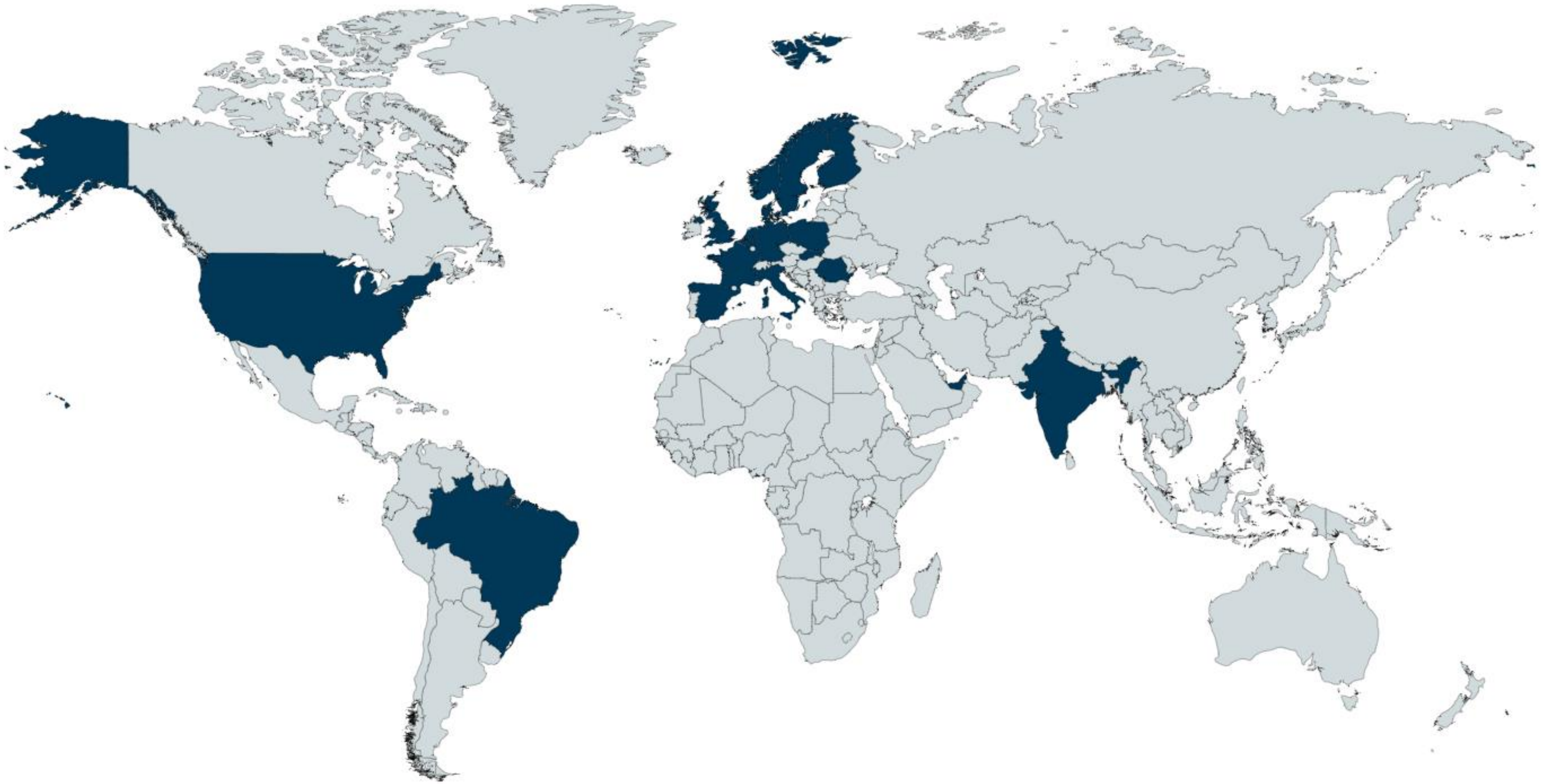
A large and diverse group of more than 300 experts selected by CIFS was invited to join the Delphi campaign. 58 experts actively engaged in the campaign by answering the questions as well as entering free-text comments to support the reasoning behind their answers. Comparing the obtained Delphi results (quantitative response statistics and free-text comments) revealed alignments, as well as contrasts, and differences regarding views on the position of green hydrogen technologies in 2040. The present Delphi report summarizes alignments as well as contrasts and discusses possible implications, to serve as input to Business Finland's further work.

Distribution of participants

From a sector-representation perspective, a large proportion of the respondents came from the private sector, whereas the remainder consisted of persons working for – or associated with – governmental agencies/authorities, think tanks and research institutes and other types of organisations. The representatives from the private sector included major global stakeholders in the hydrogen value chain.

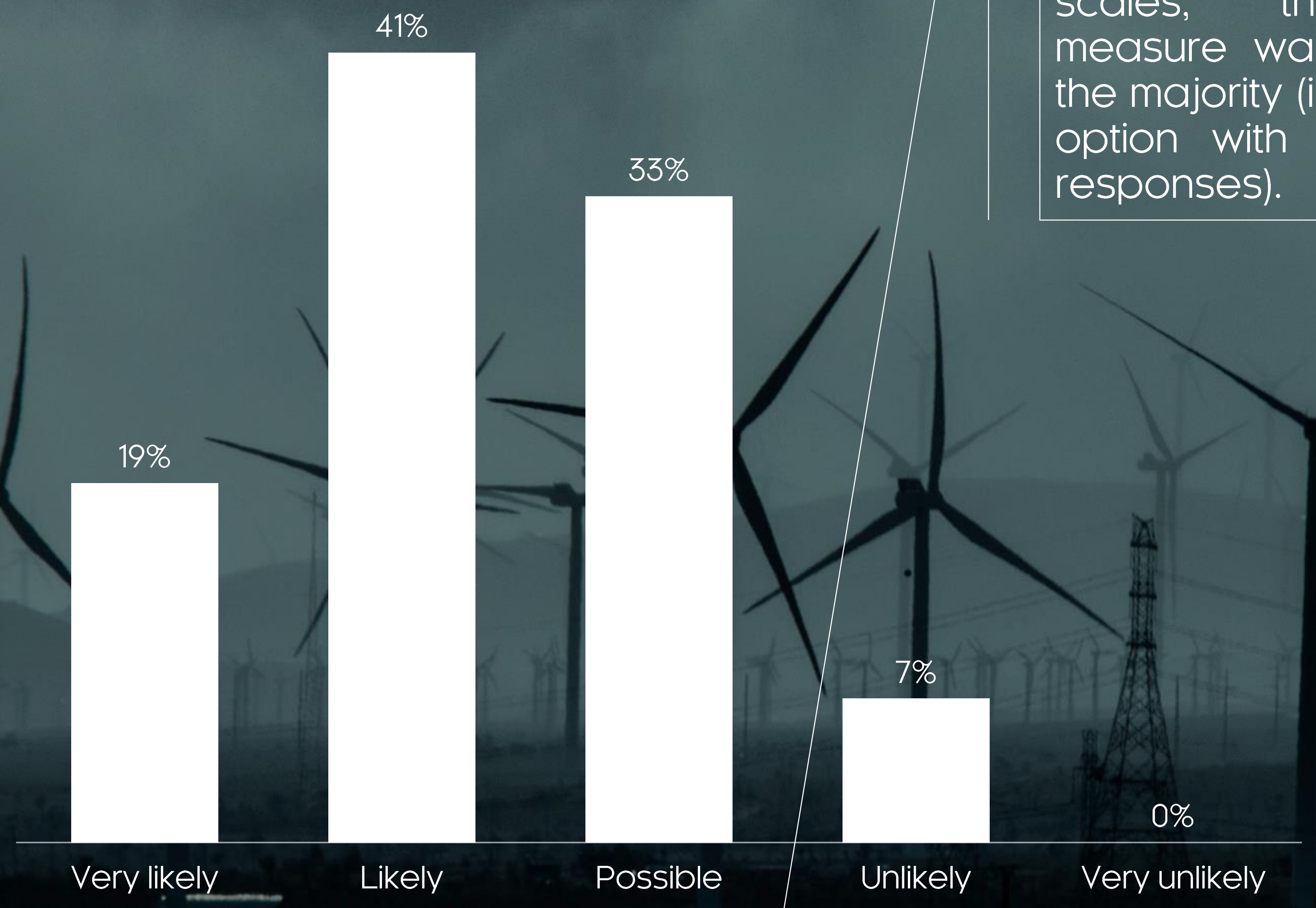


Geographical Coverage



How to read the Delphi data

The **CONSENSUS STATUS** indicates if the panel reached consensus or not on a given question. The consensus threshold was set as a group stability above 50% for all questions. No consensus is shown when there are multiple answer options .



PANEL CONSENSUS PICK was measured in different ways, depending on the question type. If the question response categories followed a 4-point or 5-point Likert scale, the consensus measure was calculated as the arithmetic mean. In case of non-Likert scales, the consensus measure was calculated as the majority (i.e., the response option with the majority of responses).

GROUP STABILITY (i.e. the strength of the consensus) was calculated in different ways, depending on the question type. For 4-point and 5-point Likert scale questions, group stability was measured as the coefficient of variation, while for non-Likert scale, group stability was measured as the percentage function.

Consensus	**Likely**	**62%**
CONSENSUS STATUS	PANEL CONSENSUS PICK	GROUP STABILITY

Future Global Hydrogen Market

Question 1: Which scenario best describes your expectations for the global green hydrogen economy in 2040?

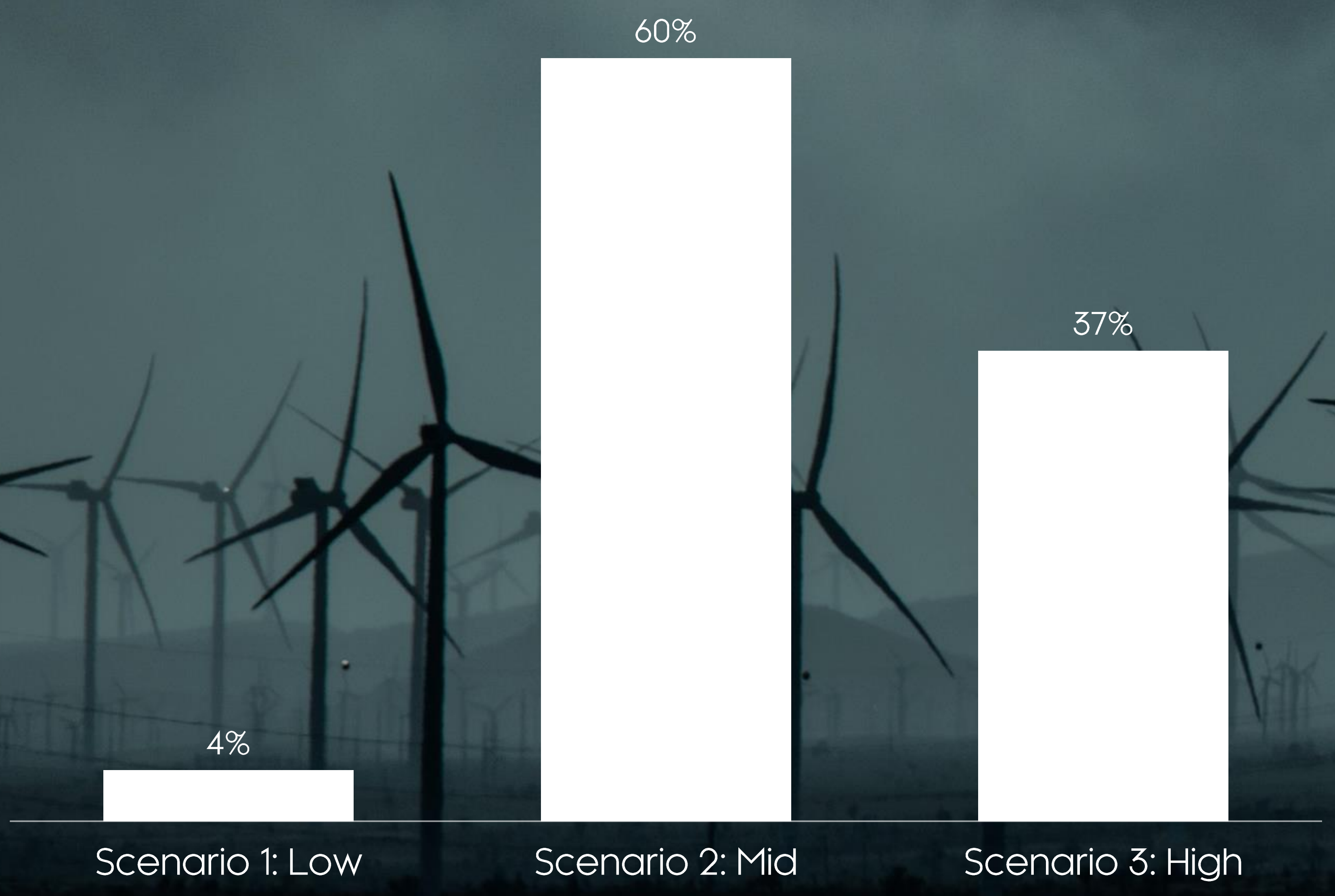
The debate about the role of green hydrogen has been going on for years. There are claims that hydrogen will play a minimal in 2040, but also expectations that hydrogen not only will help decarbonize hard-to-electrify industries, but even be used in Fuel Cell Electric Vehicles (FCEV's) competing with EVs. The three scenarios below are high, middle and low scenarios for the future of green hydrogen.

Scenario 1: A world in which green hydrogen only plays a minimal role. The GHG savings effect of replacing thermal power is much larger. Until renewables have replaced fossil fuels, hydrogen is taking the back seat. However, small fleets of hydrogen vehicles are operated as part of technology validation and other R&D projects. Green hydrogen is produced from surplus renewable power.

Scenario 2: A world where green hydrogen has an increasing role to play in decarbonizing industries, due to its physical properties, breadth of application and complementary nature to low-carbon electricity. Areas include industry feedstock, heavy transport and blended hydrogen for heating.

Scenario 3: A world transformed by green hydrogen, where even the more difficult areas for using hydrogen are seeing an increasingly greater share of hydrogen meeting demand. Areas may include green hydrogen used for light-duty vehicles, high-grade industry heat, passenger ships and steel production. Green hydrogen is produced from dedicated renewables.

Question 1: Which scenario best describes your expectations for the global green hydrogen economy in 2040?



Consensus	Scenario 2	60%
CONSENSUS STATUS	PANEL CONSENSUS PICK	GROUP STABILITY

There was a consensus among panelists that the middle-of-the-road scenario 2 best described the expectations for the development of green hydrogen technologies.

The overall panel opinion indicates that green hydrogen will have an increasing role to play in decarbonizing industries. It will ensure smart sector integration and complement the electrification of society. Its role will primarily be to facilitate the decarbonization of sectors that are hard to electrify, a primary area being heavy vehicle transport and the maritime industry.

However, a significant part of the panelists think that green hydrogen will have a much bigger role to play. This distinction will be found throughout the survey.

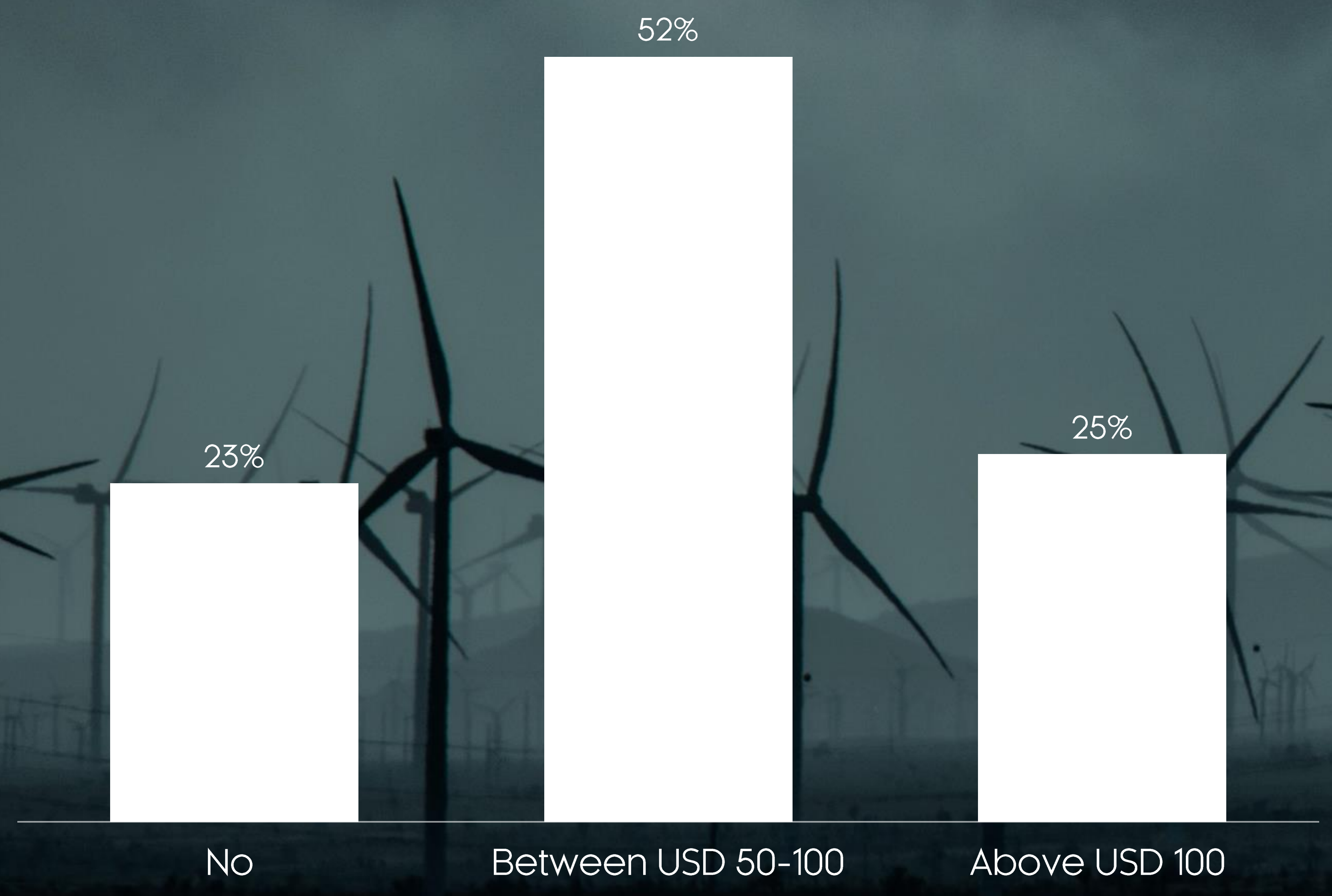
Many critics point to the non-viability of green hydrogen due to conversion losses and the high price of green hydrogen production. This study clearly supports the notion that green hydrogen will play an important part in the energy transition.

Question 1: Which scenario best describes your expectations for the global green hydrogen economy in 2040?

EXPERT PANELIST INSIGHTS

Scenario 1: Electrolyzing water to make hydrogen is a bad idea in general, due to very low round trip energy efficiency.	*Scenario 2: The explosive nature of hydrogen, along with its inherently low volumetric energy density, which requires significant investment to overcome by liquification, make hydrogen utilization in basic aspects of life unlikely. However, as feedstock and where volumetric energy density is not an issue, green hydrogen should be able to prosper as the energy vector of the future.*	*Scenario 3: It is both eminently doable and also necessary for the green transition.*
Scenario 1: The main industrial actors are not on a trajectory where their technological capabilities will be able to either handle a hydrogen transition or effectively support the hydrogen infrastructure. Hydrogen will primarily play a role as a fuel in ships, as battery capacity for large vessels never will be practical.	*Scenario 2: 20 years out will not see the necessary investments in renewable energy and infrastructure to fully convert a hydrogen economy. In the next 10, maybe 20 years, we will have a shortage of renewable electricity and thus direct use of power is more efficient.*	*Scenario 3: The technologies are becoming cost competitive, both on production and consumption technologies. The levelized cost of heat (LCOH) will fall and so will TOC (Total cost of Ownership). Electricity will of course still be a major part.*

Question 2: By 2040, we will have an effective carbon tax (above USD 50 per ton CO_2 equivalents) covering most key polluting regions?



Consensus
CONSENSUS STATUS

Between 50-100
PANEL CONSENSUS PICK

52%
GROUP STABILITY

The scenarios envisioned for 2040 rest on different assumptions that are important to understand. Chief among these are the assumptions about carbon pricing.

The panel estimated that a carbon price above USD 50 will be in force in 2040. Free text from experts who have answered 'no', indicate that many do believe that a carbon price will be present in 2040, yet either find it to be lower than USD 50 or are discouraged in regard to its geographical scope and effectiveness, thinking that it most likely will be a patchwork of regional taxes or emission trade schemes. When adjusting for this difference in assumptions, the difference in answers in question 1 on what scenario is most likely is consistent with the difference in carbon pricing assumptions, suggesting, maybe not surprisingly, that carbon price is the de facto determinant of the future of green hydrogen.

Question 2: By 2040, we will have an effective carbon tax (above USD 50 per ton CO_2 equivalents) covering most key polluting regions?

EXPERT PANELIST INSIGHTS

No: There may be a tax, but it will not be effective. The political opposition among developing countries is too strong, and there is no effective international organization capable of enforcing nor administering an effective carbon tax.	*Above USD 100: The green transition needs a helping hand and only regulations can give the final push.*	*Above USD 100: If we do not have it, it means that we have failed the transition.*

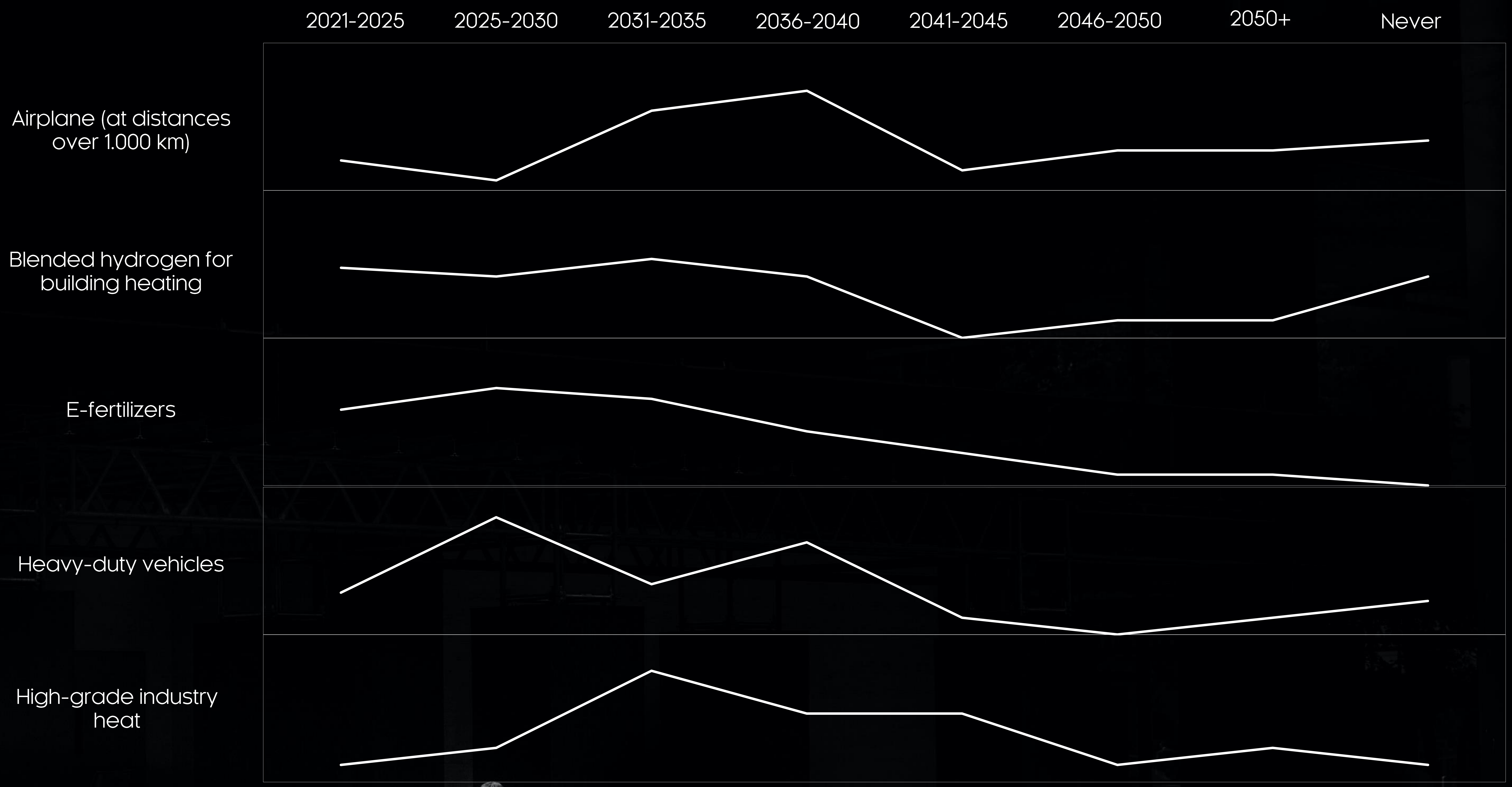
Question 3: By when do you believe that green hydrogen will reach parity with other low-carbon alternatives across key applications (based on total cost of ownership including subsidies in first-mover countries and your carbon tax assumptions)?

The hydrogen panellists are largely in agreement that green hydrogen will reach parity with other low-carbon alternatives across the proposed industry applications before 2040.

When this is not the case, as in the case of pure and blended hydrogen heating as well as light-duty vehicles, this is due to the fact that a large part of the panel has little confidence in green hydrogen ever reaching party in these areas. Of the proposed industry applications, the greatest degree of confidence is in E-fertilizers. E-fertilisers will reach parity already in 2025-2030, as will heavy-duty transport. The use of green hydrogen in high-grade industry heat and ships will follow between 2031 and 2035.

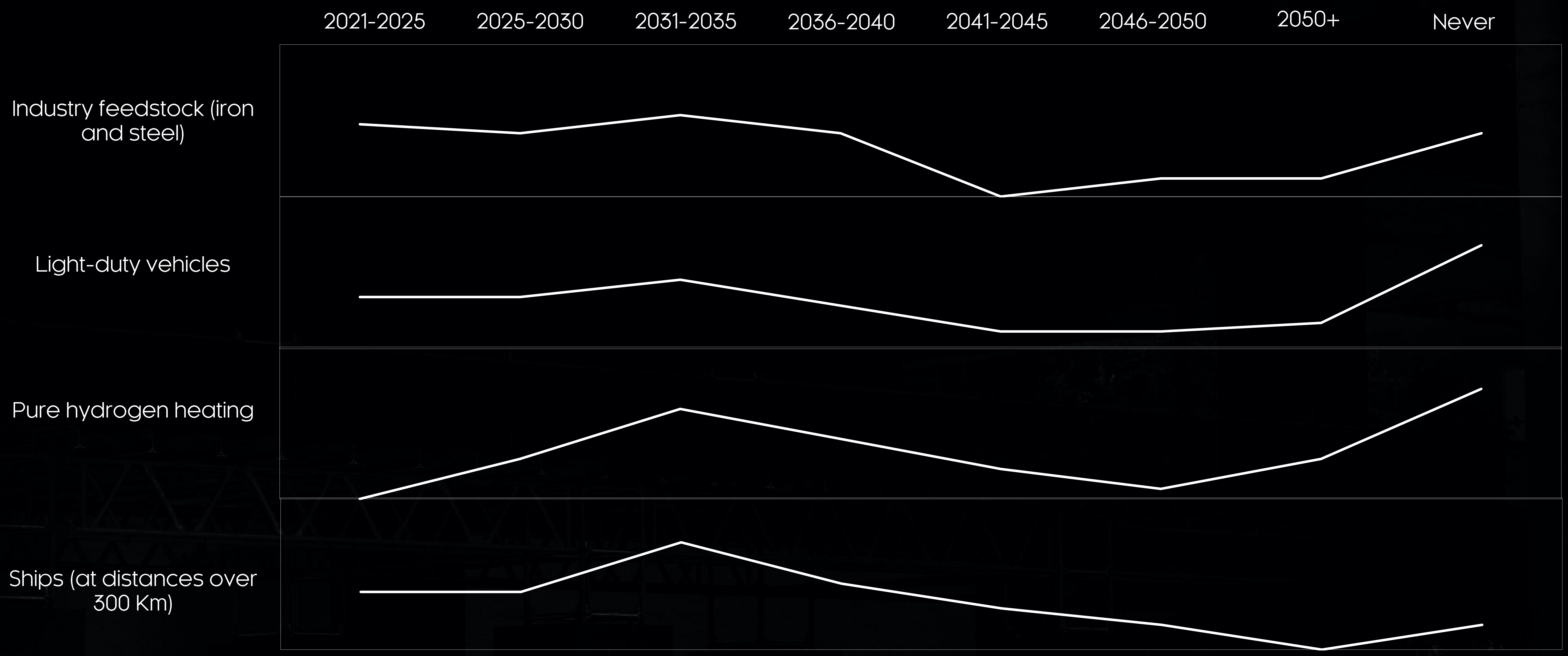
Green hydrogen reaching parity for use in airplanes is the area that most agree will take the longest time. Hydrogen for heating continues to be an area of disagreement, with a part of the hydrogen panellists arguing that hydrogen should not be burned, but rather used as E-fuels.

Distribution of answers across timeline



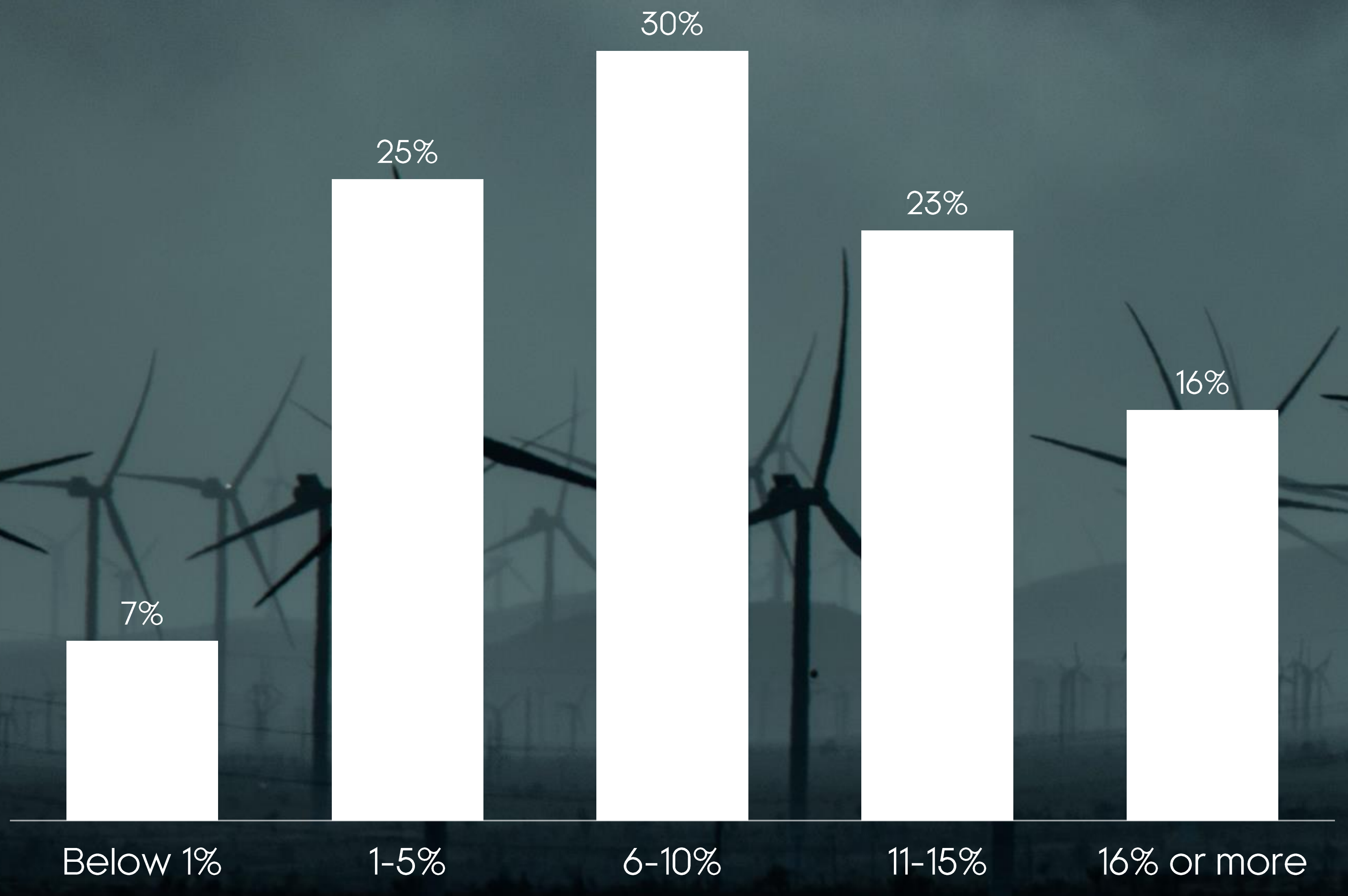
Note: On the y axis is percentage distribution between 0-40%.. The column chart has been converted to a line chart to ease overview

Distribution of answers across timeline



Note: On the y axis is percentage distribution between 0-40%.. The column chart has been converted to a line chart to ease overview

Question 4: What is the most likely size of the global green hydrogen market in 2040? (Share of total final energy consumption)



Dissensus
CONSENSUS STATUS

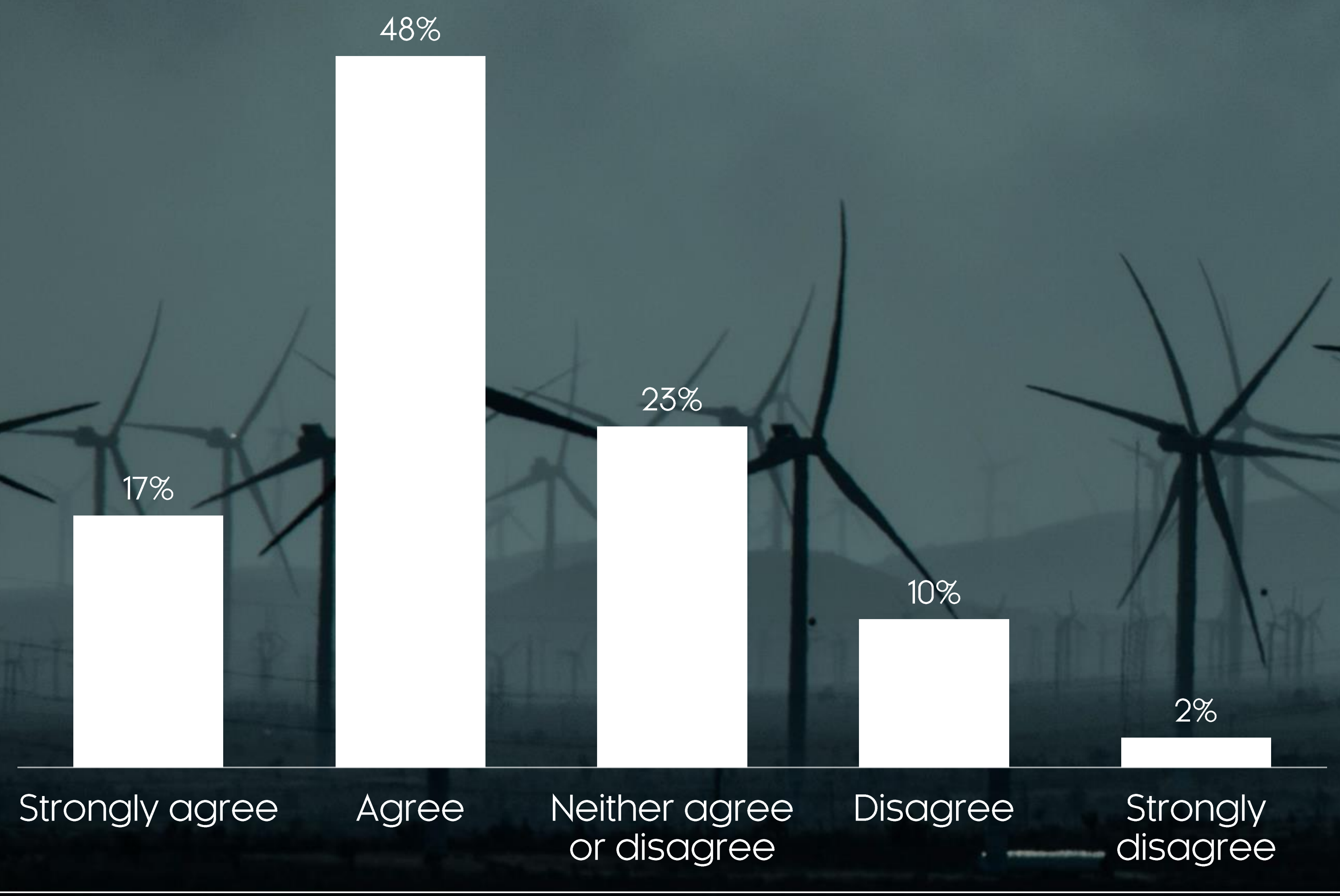
30%
GROUP STABILITY

There is a great deal of uncertainty as to the size of the hydrogen market in 2040, but the answers reflect a conviction that hydrogen will play a significant part in decarbonizing society. In fact, most experts think that due to the green energy transition, the market for hydrogen will be higher than the markets for solar and wind are today.

The time it took for past renewable technologies to reach market maturity will not be a predictor of the time it will take future low-carbon technologies such as PtX to reach maturity.

The disagreement about the market size reflects the same distribution found when asked about carbon prices, suggesting that this is the key factor behind the disagreement.

Question 5: By 2040, will the cost of global distribution of hydrogen (e.g. in the form of ammonia) have sufficiently decreased, thus paving the way for a globalized green hydrogen market?



Consensus
CONSENSUS STATUS

Agree
PANEL CONSENSUS PICK

59%
GROUP STABILITY

Hydrogen can be liquefied, transported as ammonia or in liquid organic hydrogen carriers (LOHCs). If hydrogen is to become the new oil as some have argued, it is necessary for hydrogen to be shipped overseas (over 1.500 km) at cost far lower than would be the case today. Total cost, including costs of conversion before export and reconversion back to hydrogen before consumption, would need to have reached parity with other alternatives.

A majority of the Hydrogen Panel agree that this will have happened by 2040, however the responses suggest that even among those who subscribe to a high carbon price there are fewer who believe in the viability of a global hydrogen market by 2040.

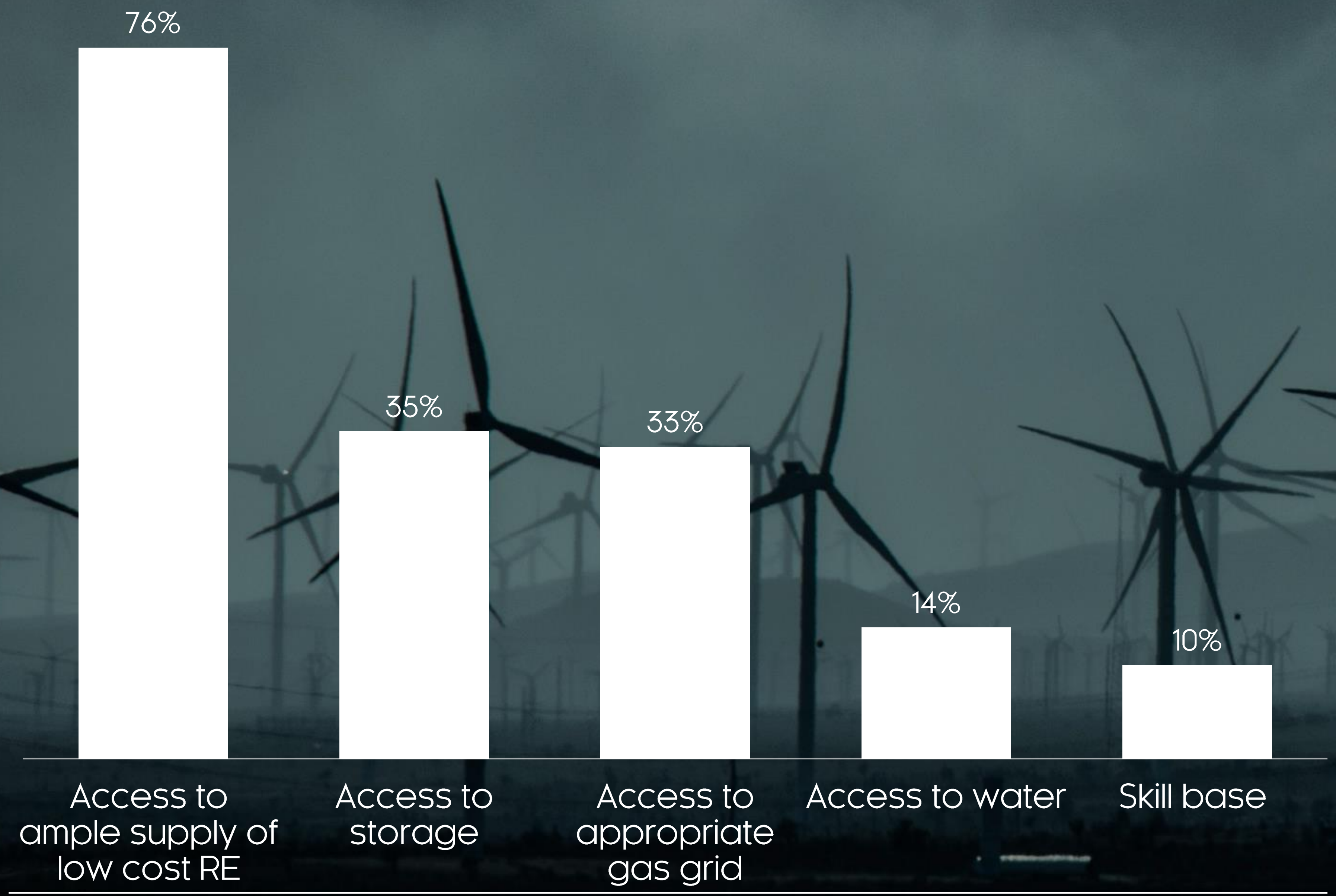
Free text submissions from experts also indicate that while it may move towards a globalized market, it may never be transatlantic and stay regional, but at distances of more than 1.500 km.

Question 5: By 2040, will the cost of global distribution of hydrogen (e.g. in the form of ammonia) have sufficiently decreased, thus paving the way for a globalized green hydrogen market?

EXPERT PANELIST INSIGHTS

Strongly agree: Ammonia is proven as an energy carrier - with 181 Mt produced in 2019, and 17.5 Mt of ammonia safely traded and transported yearly by ship, truck, and train. Green hydrogen price parity with hydrocarbons is expected in 2030, which will create a business case for switching to green ammonia in addition to the low carbon case.	*Strongly disagree: Hydrogen should never be transported and certainly not in the form of ammonia. Going to ammonia and back is way too inefficient/expensive. We will make ammonia in large quantities - BUT this will be used directly (in fertilizers) or DIRECTLY as a shipping fuel (not converted back to hydrogen).*	*Neither agree nor disagree: The cost of renewable electricity production is so low that it is more profitable to produce hydrogen locally in places. Global distribution of hydrogen is limited to certain countries or regions.*
Neither agree nor disagree: The main barrier will not be the distribution of hydrogen but rather the consonance of the global regulatory framework and its synergy with the possible CO_2 tax.	*Disagree: I do not expect cross trans-Atlantic hydrogen transport to become more financially attractive then internal in-continental hydrogen transport to a wide extent. The fact that all continents can offer the basic conditions for low-cost electricity means that the cost of local production will generally tend to be lower than the cost of foreign production + the cost of transport.*	*Disagree: There is likely to be some international trade in green ammonia, but it will not be a globalized market because the cost of transport will remain relatively high. Even the natural gas market today is regional rather than global.*

Question 6: What do you find to be the key geographical differences determining the uptake of green hydrogen (excluding access to capital and government funds)?



POSSIBLE TO SELECT 2 ANSWERS, THUS SUM OF PERCENTAGE IS 168%

According to the IEA, if all current hydrogen production was to be replaced with green hydrogen production using water electrolysis, one would need 3600 TWh, which is more than the annual electricity generation of the European Union. For this reason, it is no surprise that the Hydrogen Panel is in agreement when asked about the importance of access to low-cost renewables.

Access to ample supply of low-cost renewables is the main geographically determined obstacle for the uptake of green hydrogen, and this will define the areas in which green hydrogen production will be economically viable. However, hydrogen needs to be transported as well, meaning access to appropriate storage and distribution infrastructure is also critical.

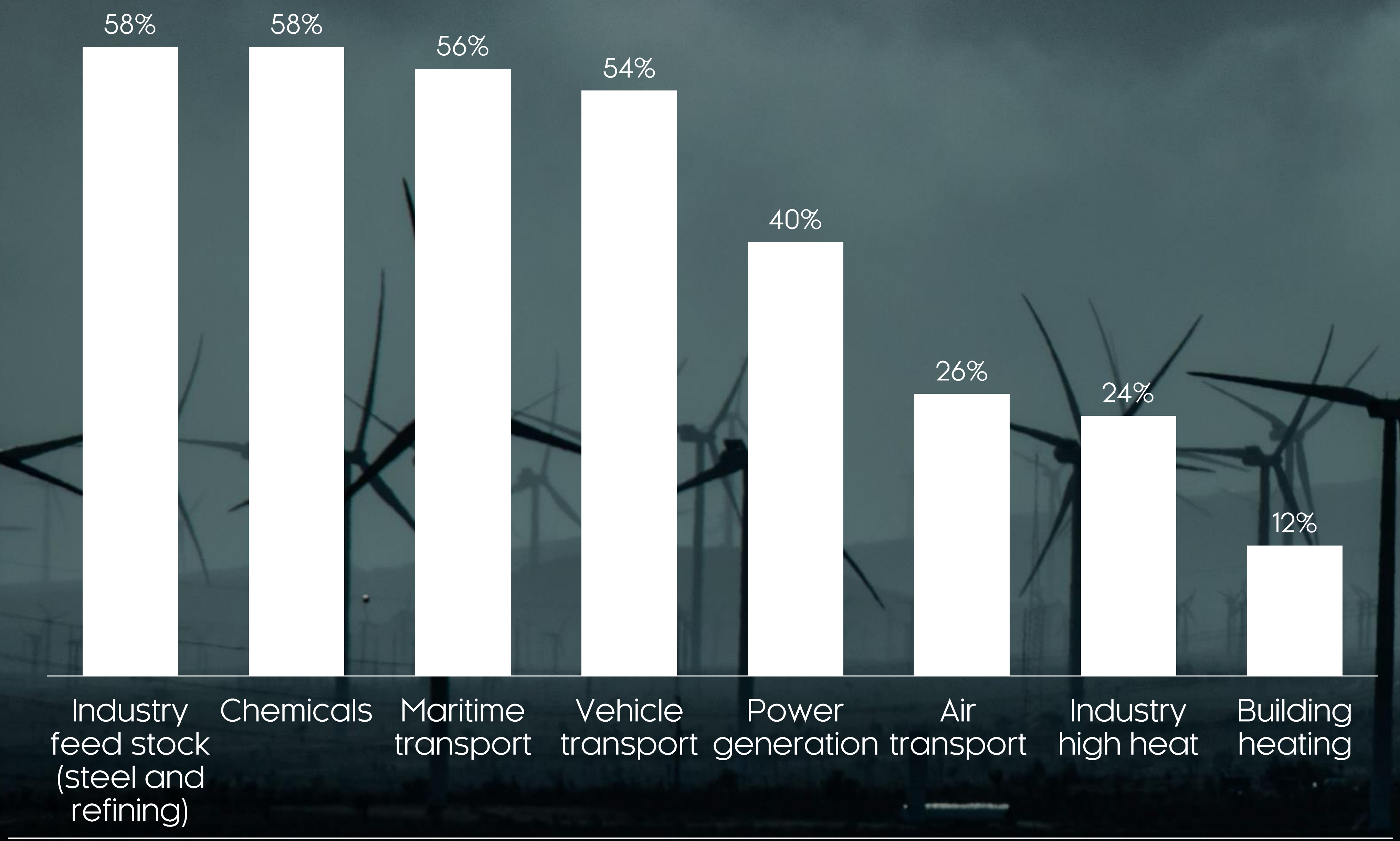
Note: The graph does not illustrate category "Other" (16,33%).

Question 6: What do you find to be the key geographical differences determining the uptake of green hydrogen (excluding access to capital and government funds)?

EXPERT PANELIST INSIGHTS

Electrolyzers are expensive today. They need access to both great wind and solar resources and to the local power markets to operate at high load factor to provide optimal value.	*Water is never a major cost issue. Cost of electricity is the most important issue. The utilization of electrolyzer heat may decrease the cost of hydrogen by 10-15%. The effect of storage is in the same range.*	*For many countries, generating sufficient renewables is impossible. Other countries that do have the conditions to generate sufficient hydrogen may lack the ability to transport it. The key challenge is to link these two, creating new value chains.*

Question 7: Which three industries/areas will primarily drive global demand growth?



POSSIBLE TO SELECT 4 ANSWERS, THUS SUM OF PERCENTAGE IS 328%.

Knowing what sectors will drive demand growth is important to investors and regulators alike. These are the areas to look for, as the they tend to drive down prices so that other more high-cost areas can piggyback on the technologies and price declines can be achieved.

The panel selected four industry applications that will drive global demand growth, these four areas will need significant volumes of green hydrogen and are difficult to decarbonize in any other way. Of the four, three already make up the majority of present-day usage of hydrogen (primarily produced from natural gas), namely oil refining (33%), ammonia production (27%) and methanol production (11%).

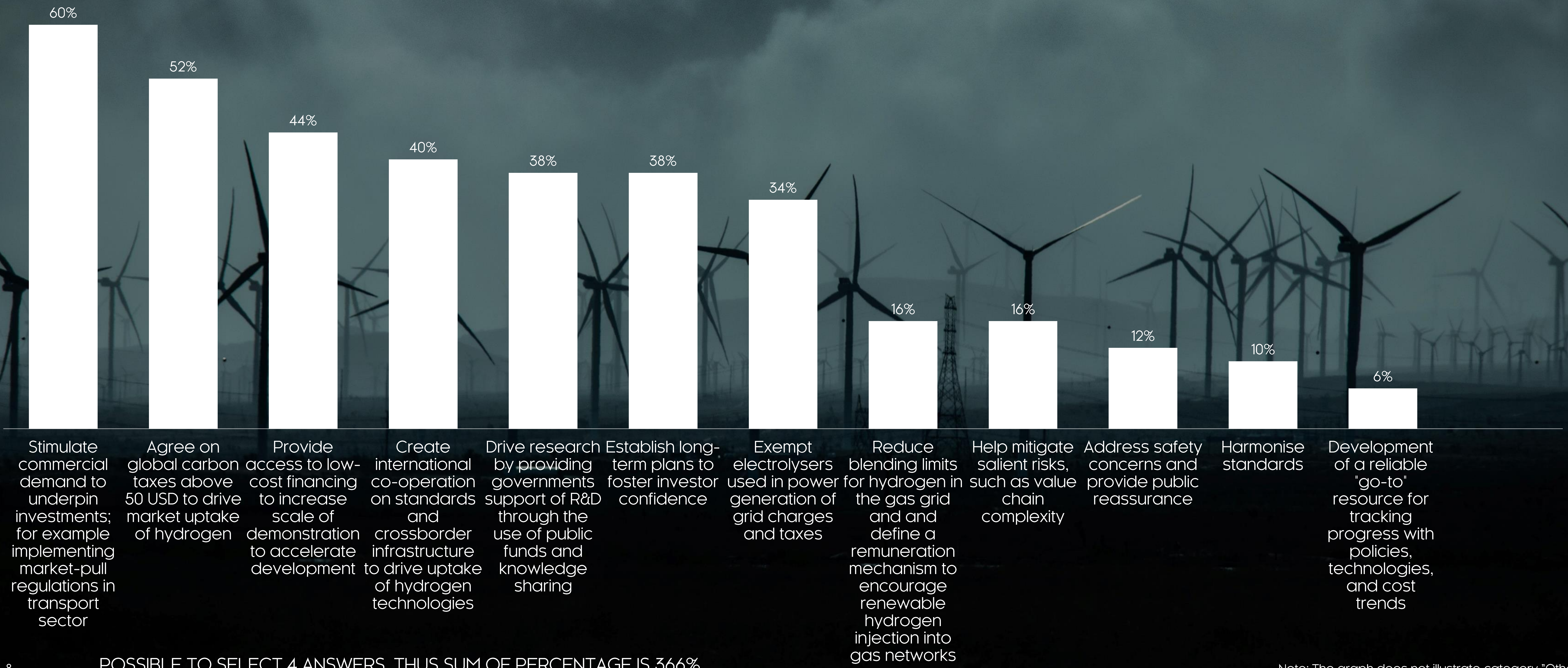
Note: The graph does not illustrate category "Other" (6%).

Question 7: Which three industries/areas will primarily drive global demand growth?

EXPERT PANELIST INSIGHTS

The whole point of hydrogen is that it can be transported, and of the four, by far maritime transport will be the biggest driver because of the lack of alternatives with extremely large engines.	*It's all about size and business case. Industry and Maritime transport are currently huge contributors to climate change. The business case for using hydrogen for building heating is nearly there (opex is already attractive, capex needs to go down).*	*For heavy-duty vehicles, hydrogen driven trains are more reliable than battery electric drive trains. Marine transport, industry feedstock and building heating are hard-to-decarbonize sectors that have a significant incentive to switch fuels once carbon taxes are introduced.*
Steel and refining as well as green ammonia production drive global demand growth the next 10-15 years.	*Heating is quite easy to electrify or gas easier to decarbonize via biomethane ... H_2 should be directed to hard-to-decarbonize sectors, not to heating.*	*Power sector: Market will be driven by biggest off takers.*

Question 8: Which of the following do you think are key change drivers to scale green hydrogen production and uptake?



POSSIBLE TO SELECT 4 ANSWERS, THUS SUM OF PERCENTAGE IS 366%.

Note: The graph does not illustrate category "Other" (4%).

Question 8: Which of the following do you think are key change drivers to scale green hydrogen production and uptake?

EXPERT PANELIST INSIGHTS

The underlying problem here – that the question does not touch – is the lack of international political will to coordinate either a tax, large cross-border investments, or international coordination on standards. Even within the EU, this will be a massive and probably impossible task.	*Enabling innovation using research investment is paramount to increasing efficiencies, thereby enabling more cost-effective production and utilization of green hydrogen. A quick way to utilize hydrogen is by injecting it into the gas grid, which will also allow for direct utilization using existing heating and power generation infrastructure to some extent.*	*In order for green hydrogen to reach its true potential prior to 2030, it will require carbon taxes, standards for the classification of technologies and renewable energy, and importantly equity funding (provided by investors) and debt funding (at a low cost). These are the key elements to drive change.*
We generally need better devices. Likewise, if a carbon tax is implemented, it needs to be globally agreed on (no exemptions like Kyoto for Schedule A vs. Schedule B).	*Hydrogen should not be blended in the traditional gas networks but instead used for decarbonizing hard-to-decarbonize industries. Hydrogen is too valuable to be used for heating.*	*Finally, relieving public fears over hydrogen is important to successfully implement hydrogen in the economy in the long term.*

Question 9: Which country/region do you think will have taken the lead in green hydrogen technology by 2040?

Consensus
CONSENSUS STATUS

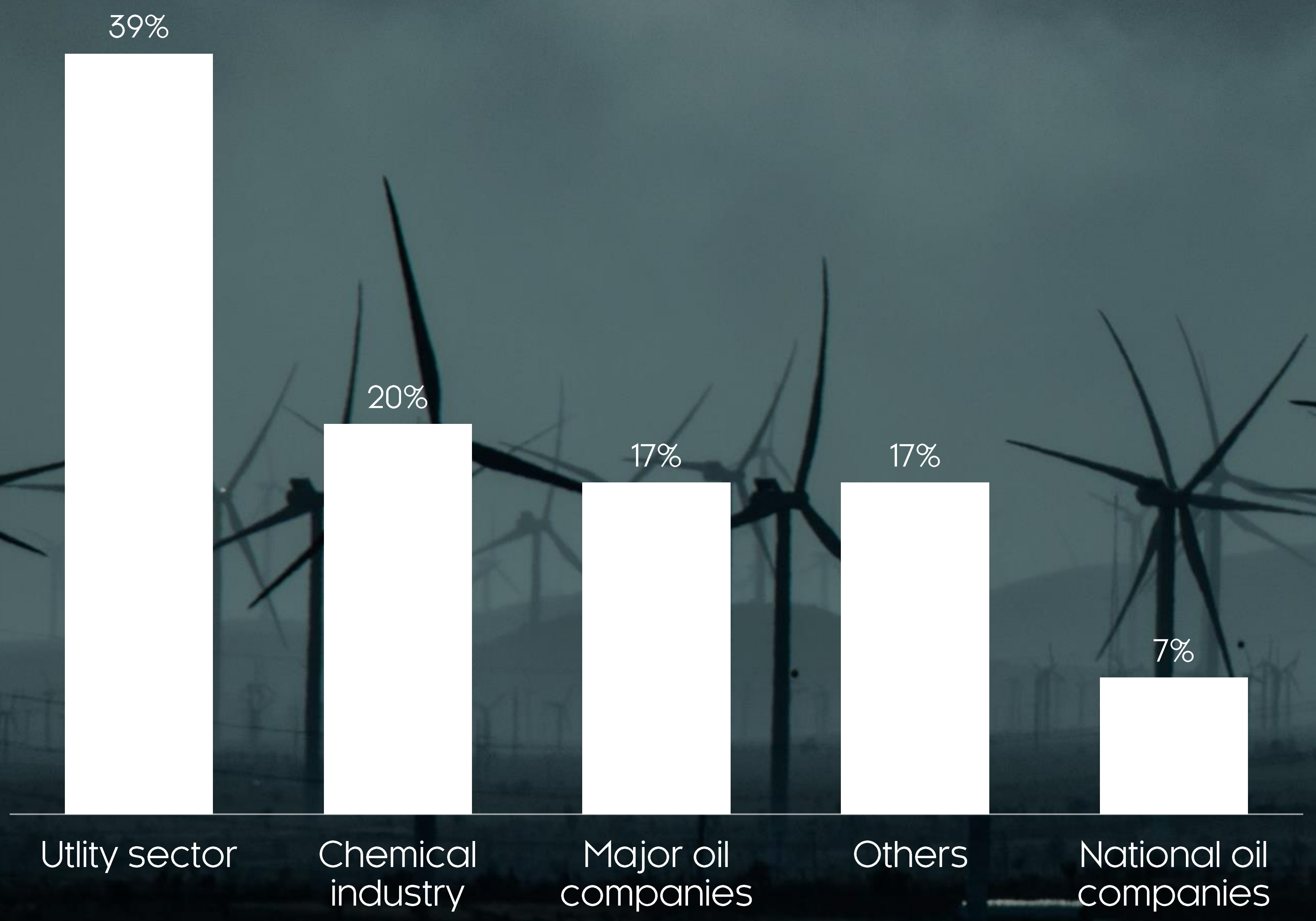
Europe
PANEL CONSENSUS PICK

62%
GROUP STABILITY

The European Commission presented the European Green Deal in December 2019, outlining the main policy initiatives for reaching net-zero global warming emissions by 2050. The EU's push for carbon neutrality by 2050 implies significant electrification in all sectors – either directly or indirectly – resulting in a massive expansion of solar and wind power, hence providing the backdrop for green hydrogen and smart sector integration. It may be for this reason that Europe was singled out by the panellists as the region that will have taken the lead in green hydrogen technology by 2040.

Given the fact that the majority of participants are from Europe, there may be a bias. However, even non-European participants have singled out Europe; notably Americans were not at all optimistic about the role of the USA in terms of taking leadership within green hydrogen technology.

Question 10: Who will be the key players in green hydrogen production in 2040?



Dissensus

CONSENSUS STATUS

39%

GROUP STABILITY

Given that 33% of current hydrogen demand comes from oil refining, it may not be surprising that oil companies and refiners have begun investigating the possibility of producing green hydrogen. With the green transition on its way, the likes of Shell, BP and Equinor have been major investors in low-carbon hydrogen solutions. Major utilities in Europe and North America are also moving in and investing in green hydrogen.

When asked about who will be the key players in hydrogen production in 2040, the Hydrogen Panel disagreed but the majority did not pick the ones currently investing the most – the oil companies. Rather, they chose the utility sector and the chemical industry. 17% said that this was basically a new market that is open to anyone with deep enough pocket to be a player in the burgeoning hydrogen economy.

Question 10: Who will be the key players in green hydrogen production in 2040?

EXPERT PANELIST INSIGHTS

Major Oil Companies: Plenty of money now, and if they don't spend them on this, they will be out of business.	*Oil companies are probably still dominant, but basically any company with deep pockets has the opportunity now to invest / acquire / develop the technologies to play a major role.*	*Others: The global energy industry is at the cusp of significant change. The best comparison is to the advent of the mass use of the internet in 1994, at which time it was difficult to predict new business models and use cases of the internet technology, which has upended many industries in 26 years. The opportunities to develop new business models that will develop out of this ecosystem are significant (largest retailer in the world is Amazon.com, most valuable vehicle company in the world is Tesla, and the one of the most valuable communications companies is ZOOM).*
Governments should do more to support new entrants, rather than rely on traditional, established companies that have a vested interest in maintaining the status quo and slowing down change.	*Chemical Industry: Looks like it will be mainly industrial gas providers such as Linde, Air Liquide, Air Products and a few selected oil majors such as Shell.*	*Oil companies will be laggards.*

Question 11: Which of the following technologies do you believe will have reached parity with other zero-carbon alternatives in 2040 (in first-mover countries)?

POSSIBLE TO SELECT MORE THAN ONE ANSWERS, THUS SUM OF PERCENTAGE IS 244%

Note: The graph does not illustrate category "Other" (7,5%).

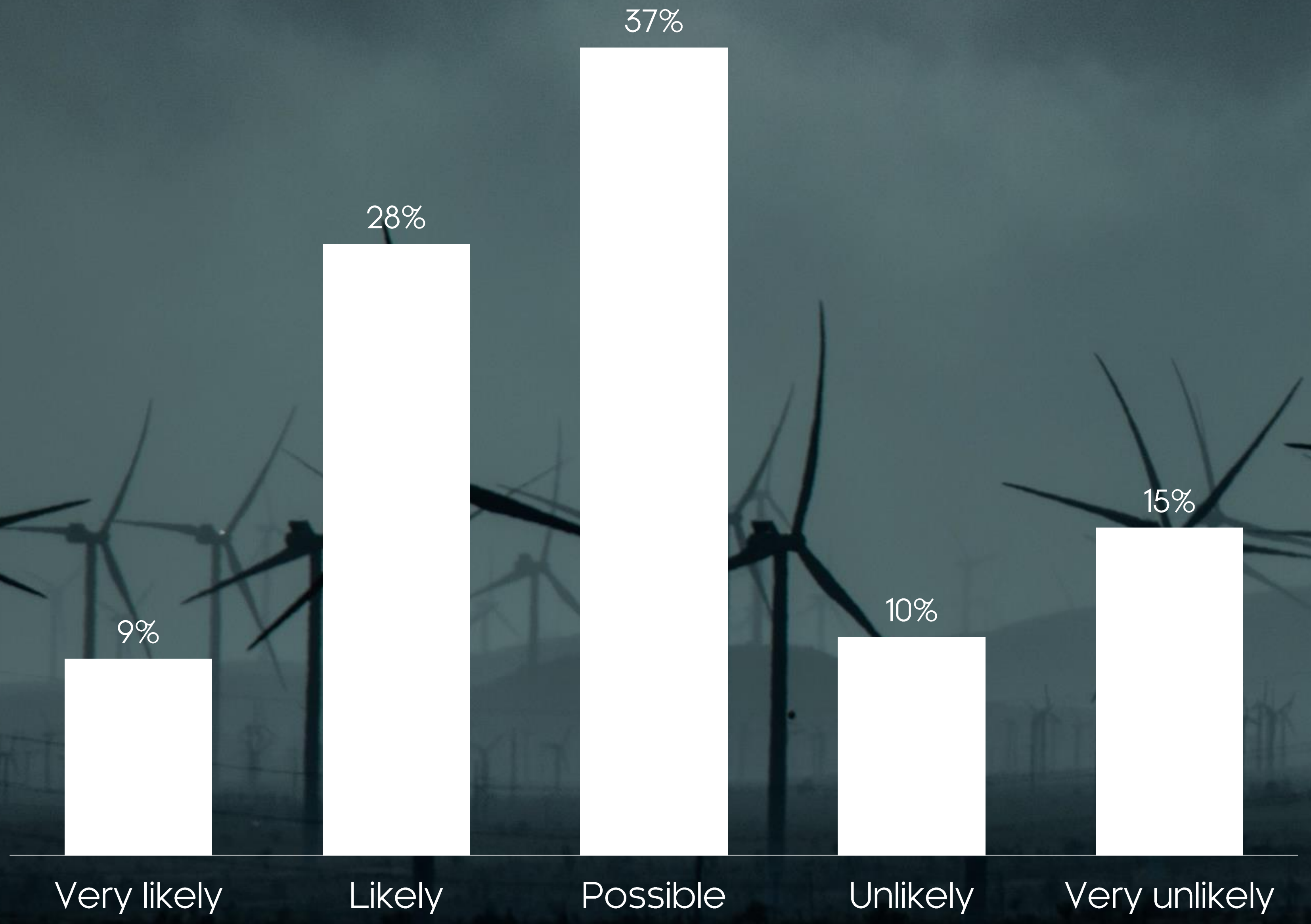
Question 11: Which of the following technologies do you believe will have reached parity with other zero-carbon alternatives in 2040 (in first-mover countries)?

EXPERT PANELIST INSIGHTS

Coal is dirt cheap, and CCS is becoming cheaper by the moment, especially with the higher reliance on natural gas, leaving vacant gas wells ready to be used around the world. While pricier, natural gas is already comparably low carbon, which could allow for it to reach zero-carbon status with more ease. Biofuel technologies of all types are either carbon disastrous (first-generation) or simply extremely inefficient (second generation). Solar-thermal is inefficient, as is photoelectro-chemical production. Considering their competition with classic photovoltaic electricity production, I see little chance of these technologies being widely used in the future.	*Turquoise hydrogen: The first commercial NG pyrolysis plants are being built with plasma ovens, not bubbling. NG Pyrolysis requires 5-6 times less green electricity than electrolysis and represents the only use of natural gas with no formation of CO_2. Cost of NG will be low as it will progressively shrink to produce turquoise hydrogen.*	*Most technologies on this list have significant scale problems. BECCS is an example. Biomass can only be transported a certain distance before the energy and economic cost of transportation ruins the economics of the plant. This forces biomass facilities to stay small. If they can only harvest inputs from a 50 or 100 mile radius, they can't be big. Small gasifiers are expensive. Small CC is expensive. Small sequestration is prohibitive. Small hydrogen pipelines to load centers are prohibitive.*
Blue hydrogen will for sure take the prize here. Energy source is "free" natural gas. None of the others can compete with that. It is however NOT A SUSTAINABLE solution.	*Bioenergy and CCS may have a change in very large scale. However, biogenic carbon is more wisely used for PtX fuels.*	*Large scale CCS on global level looks like a nice dream.*

Transport and Storage

Question 12: By 2040, how likely is it that local green hydrogen distribution in your country primarily happens through pipelines (instead of e.g. rail and truck)?



Consensus	Possible	61%
CONSENSUS STATUS	PANEL CONSENSUS PICK	GROUP STABILITY

As the IEA has noted, the distribution cost is vital to the economics of hydrogen. Today, the majority of hydrogen is transported by trucks carrying hydrogen either as a gas or liquid, but pipelines are likely to be the most cost-effective long-term choice.

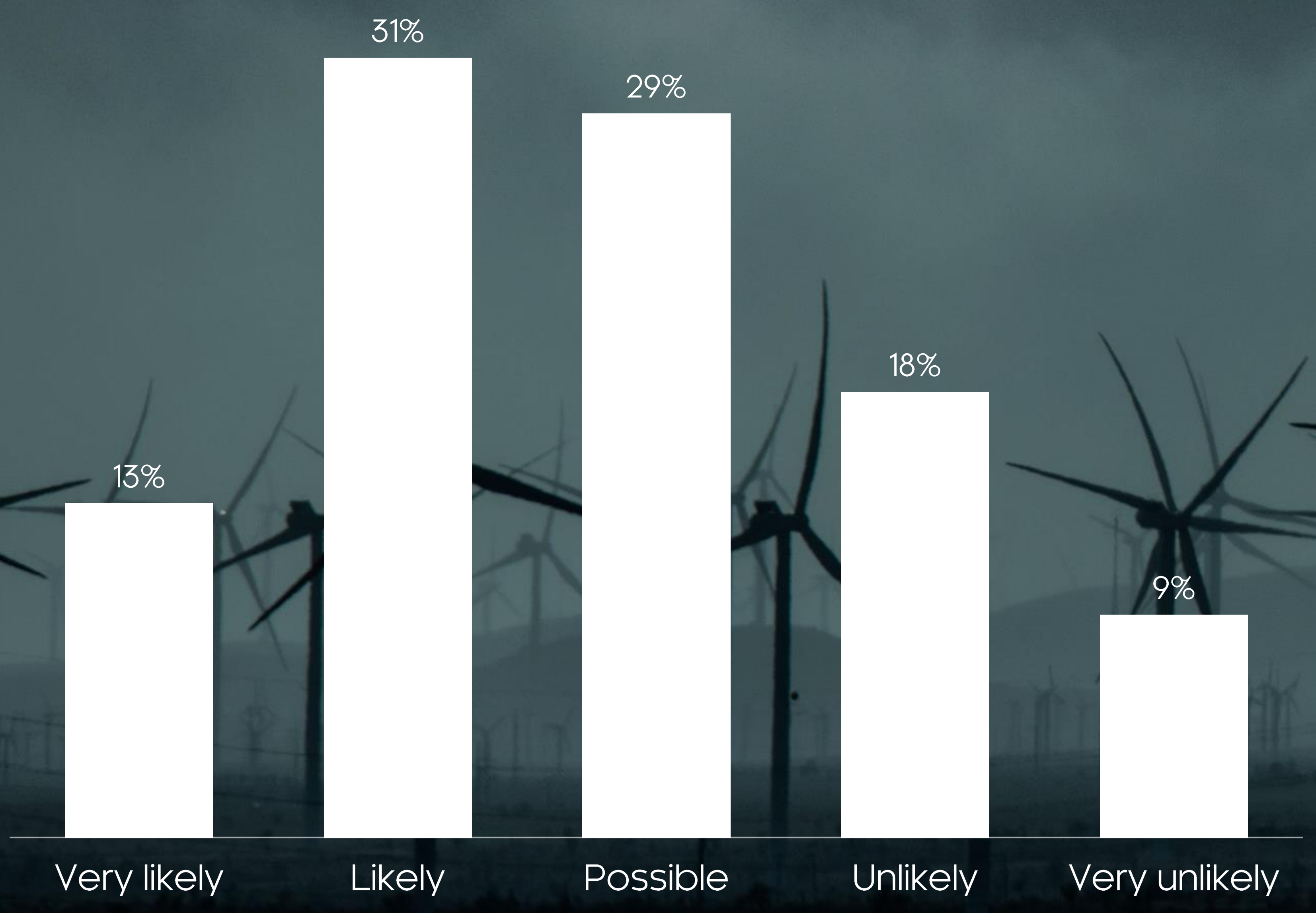
When asked, the panel is in disagreement. However, the disagreement mainly reflects local conditions. As an example, participants stating that distribution through pipelines is very unlikely are all non-European. Yet even within Europe there are vast differences in opinions. The main barriers are the high investments needed to create a pipeline infrastructure relative to the low cost of trucks. Reflecting that for pipelines to be the preferred choice for local hydrogen distribution, a sufficiently large, sustained and localized demand is needed.

Question 12: By 2040, how likely is it that local green hydrogen distribution in your country primarily happens through pipelines (instead of e.g. rail and truck)?

EXPERT PANELIST INSIGHTS

Very likely: 0.13c/kg/1000km is unbeatable. I see H2 economy similar to natural gas/LNG market today – much lower cost of long-distance transport cost via pipelines, considering that majority of H2 will be imported from outside EU.	*Unlikely: Hydrogen truck transport is very cost-efficient in Finland. Pipelines are limited for some industrial hydrogen users.*	*Possible: Denmark is small enough that pipelines can be built, in particular because of the many straits that make road and rail impractical for direct transport.*
Very likely: While the initial investment is high for hydrogen compatible piping, the lifetime investment becomes attractive compared to rail/truck transport, especially considering the harsher safety requirements for mobile transport through populated areas.	*Possible: I don't think that hydrogen should be distributed. Too expensive. Should be used at source to make the actual end product (ammonia, methanol, kerosene, etc.)*	*Possible: Technically it is possible, yet I doubt whether green hydrogen in our country will be transported as such. I would expect brown hydrogen to be blended into our existing grid and green hydrogen mainly produced and transported decentralized.*

Question 13: Considering energy-related costs, round-trip efficiency, what is the likelihood that green hydrogen will be adopted for mid to long term energy storage in your country by 2040?



Consensus
CONSENSUS STATUS

Possible*
PANEL CONSENSUS PICK

64%
GROUP STABILITY

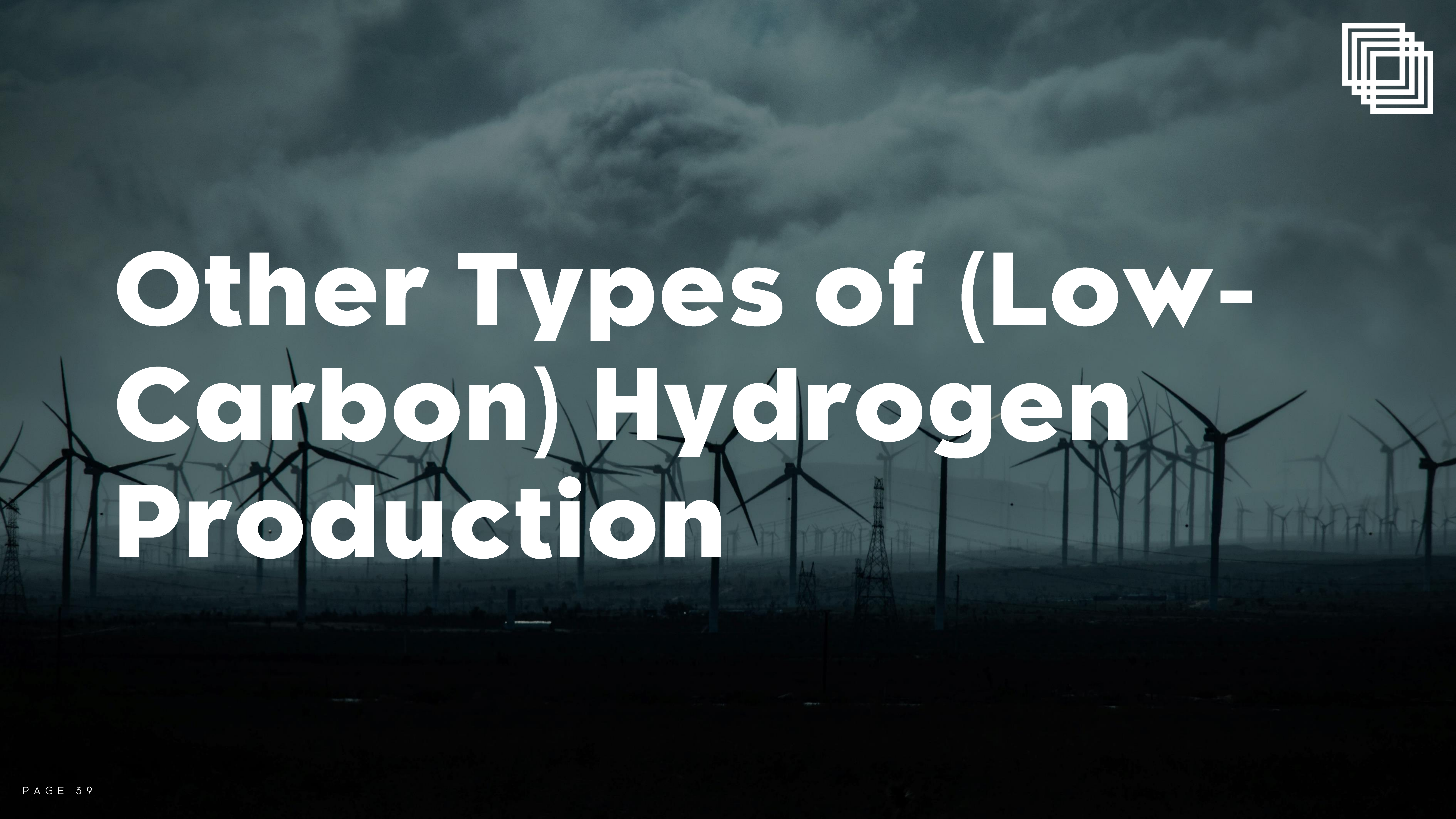
Both renewable power production and power demand exhibit seasonal variations creating a need for long-term energy storage. Hydrogen can serve as a long-term storage medium, with the capability of storing energy for several months.

When asked about the likelihood that green hydrogen will be adopted for mid to long term energy storage, the panel participants are in disagreement.

Two main objections against hydrogen used as energy storage are put forward:

1. In countries with access to pumped hydro, hydrogen is not an economic alternative.
2. Hydrogen could be used for storage to feed back into the grid, yet it would make more sense to store the energy as fuels.

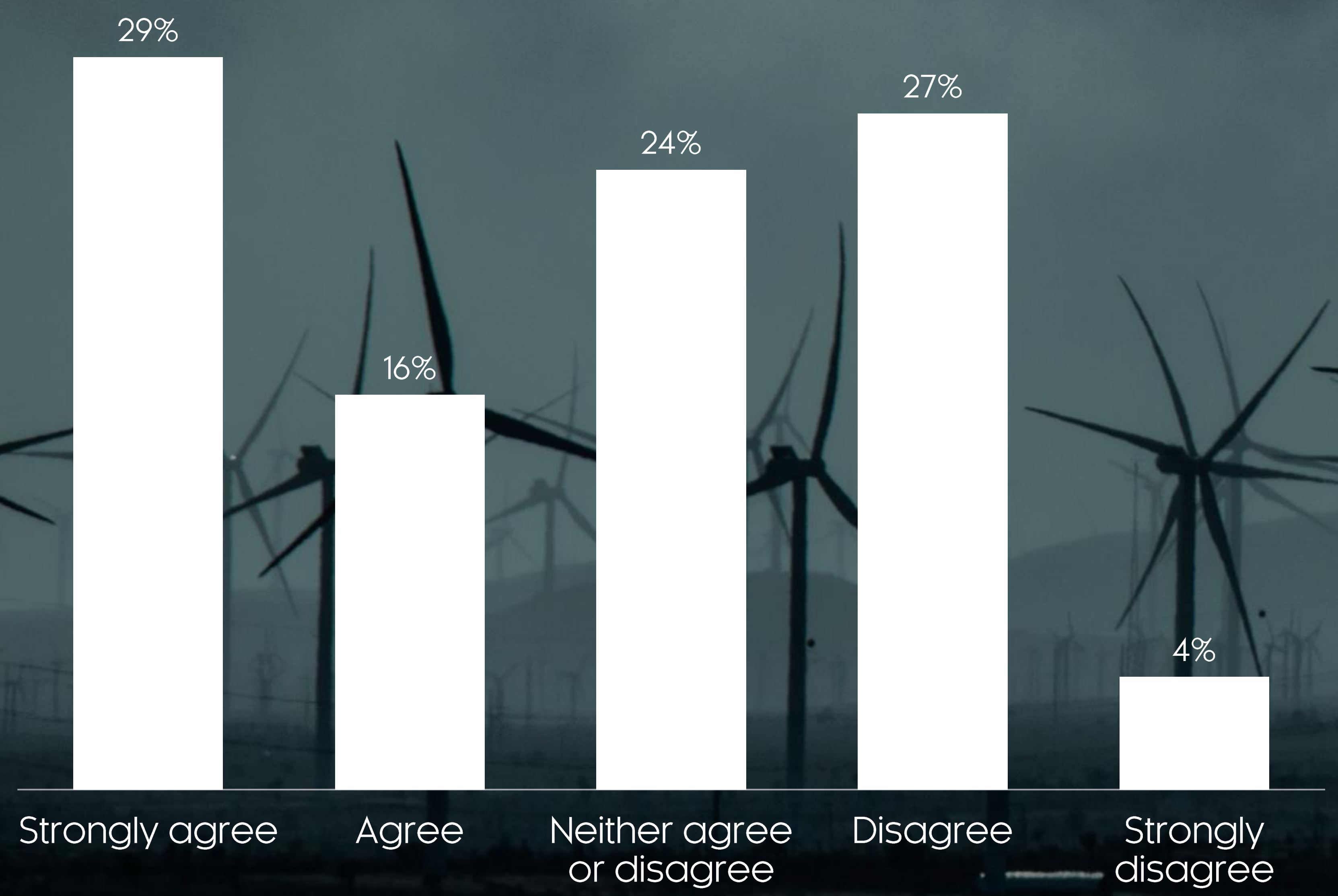
*Note: In this case the consensus pick is not the option with the highest answer distribution



Other Types of (Low-Carbon) Hydrogen Production

Question 14: How much do you agree with the following statement?

Statement: Toward 2040, blue hydrogen will be a necessary steppingstone to green hydrogen.



Consensus
CONSENSUS STATUS

Neither agree nor disagree
PANEL CONSENSUS PICK

51%
GROUP STABILITY

Blue hydrogen is produced by reforming natural gas into hydrogen plus CO_2. Some argue that realistically, blue hydrogen is a necessary steppingstone to green hydrogen, since renewable energy is best used to replace fossil power generation, where it has at least twice the decarbonization effect. Blue hydrogen could drive price reduction downstream to be ready when power generation is decarbonized. Others argue that green hydrogen should be the focus of investing from the get-go.

The panel is in disagreement on this question. On the one hand, it is argued that blue hydrogen will accelerate the development of hydrogen infrastructure, but on the other hand, it will obstruct investments in green hydrogen technologies, creating a catch 22.

Question 14: How much do you agree with the following statement?

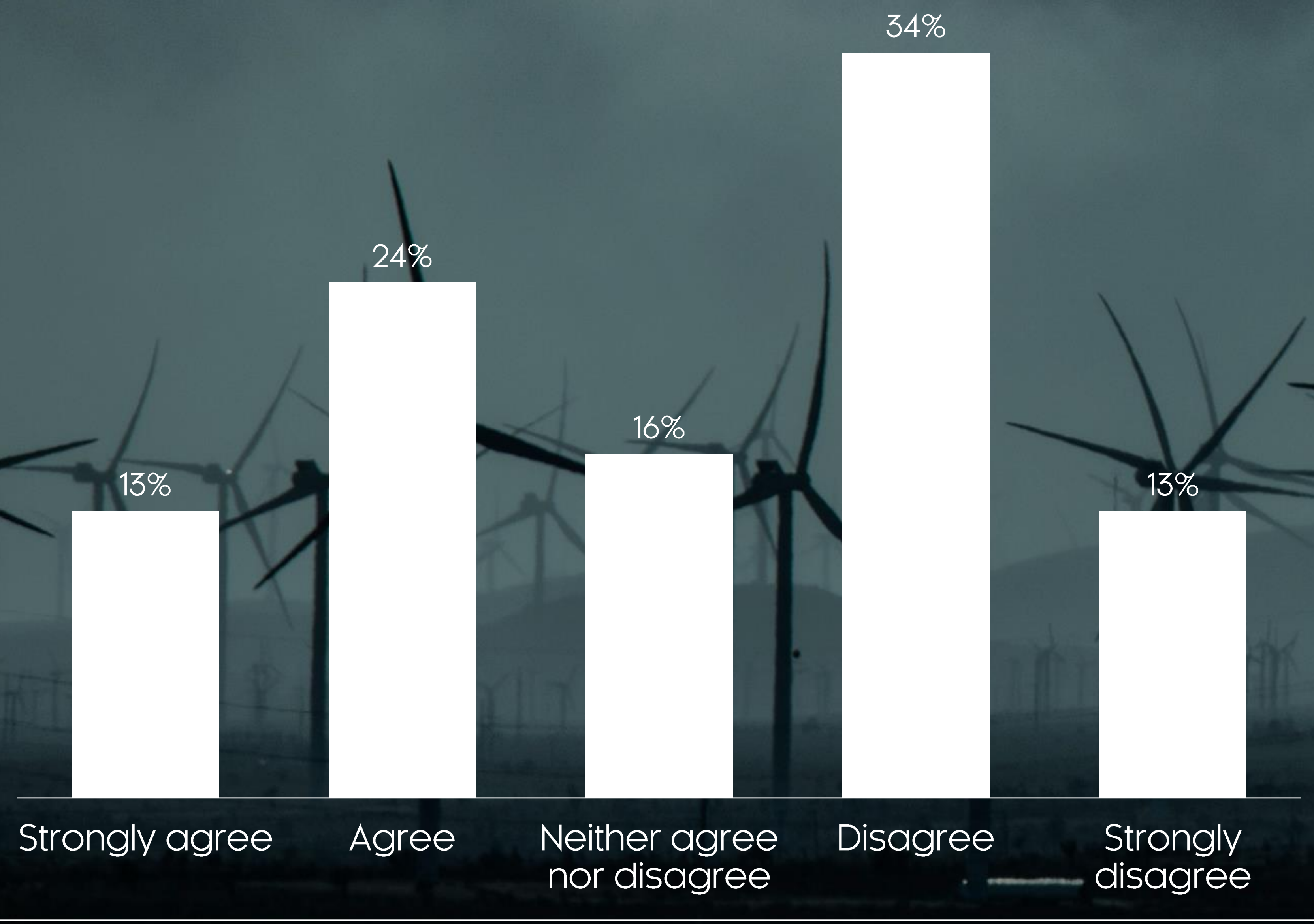
Statement: Toward 2040, blue hydrogen will be a necessary steppingstone to green hydrogen.

EXPERT PANELIST INSIGHTS

Strongly agree: We need to create a market for hydrogen first, by means of cost-effective technology.	*Disagree: The cost of green hydrogen declines, getting blue and green hydrogen very close. At the same time, consumer focus on fossil-free energy increases.*
Agree: Blue H_2 can be more easily deployed on a large scale and lead to partial CO_2 emissions reduction.	*Disagree: Increased use of natural gas for hydrogen production will increase natural gas demand. Since this additional demand is mostly covered by LNG and other production with high midstream and upstream emissions the real carbon intensity of blue hydrogen is 3-4 $kg(CO_2)/kg(H_2)$, which is not acceptable in the long term.*

Question 15: How much do you agree with the following statement?

Statement: Toward 2040, blue hydrogen will be a necessary steppingstone to hydrogen from BECCS.



Consensus
CONSENSUS STATUS

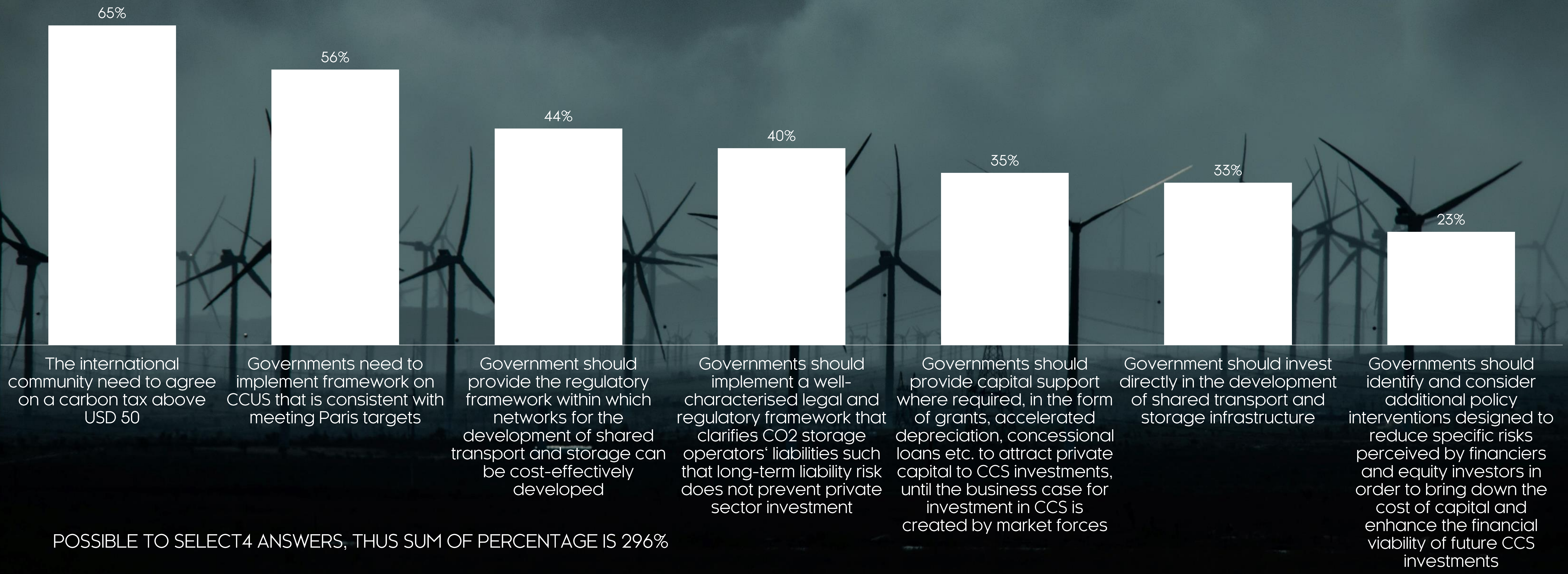
Neither agree nor disagree
PANEL CONSENSUS PICK

58%
GROUP STABILITY

Hydrogen can be produced from biomass through anaerobic digestion or fermentation or by thermochemical gasification of biomass. While anaerobic digestion to produce biogas is the most technically mature of these processes, biomass gasification has a greater breadth of application, as it can potentially convert all organic matter, and through the use of CCS provide and option for negative emission. For BECCS to be a viable option, the price of CCS will need to come down considerably.

The question to the panel was if blue hydrogen will be a necessary steppingstone to reach this objective. The panel is not in internal agreement, but a majority disagrees with the statement. Comments range from blue hydrogen not being needed to drive down cost of CCS, to BECCS should not take the focus away from green hydrogen and BECCS not being competitive nor the best use of biomass.

Question 16:What are the most important kinds of policy support needed for securing investments in carbon capture, utilisation, and storage (CCUS)?

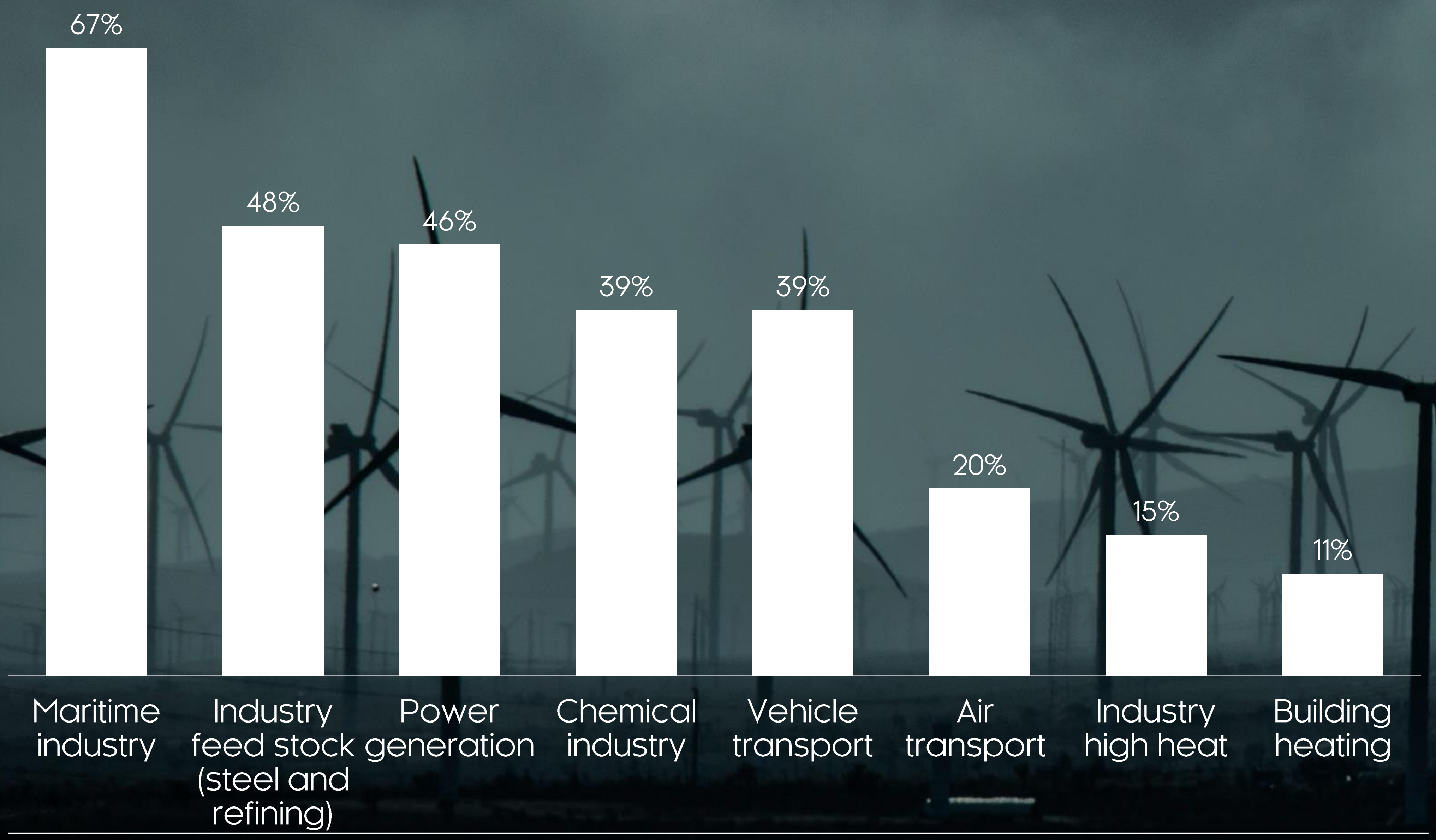


POSSIBLE TO SELECT4 ANSWERS, THUS SUM OF PERCENTAGE IS 296%

Note: The graph does not illustrate category "Other" (17,28%).

Hydrogen Market and Competitiveness

Question 17: Which industries/areas will be affected the most by the growth of the green hydrogen economy in 2040 compared to today, considering both positive and negative consequences?



POSSIBLE TO SELECT 3 ANSWERS, THUS SUM OF PERCENTAGE IS 285%

The requirements for deep decarbonization and the specific role of green hydrogen will create both risks of disruption to the business models of industries as well as their opportunities to increase market share.

For investors it is of particular importance to track what sectors will be affected, also for governments with large corporations within affected sectors the impact on employment and GDP is important so that appropriate investment into R&D can mitigate the downside or help rebuild a new competitive industry.

The panelist are in agreement that the most affected industries are the maritime industry, industries that use hydrogen as feedstock, e.g. steel and refinery, and those within power generation, with chemicals and heavy-duty transport coming in closely after.

Question 18: Which of the statements below is more likely to happen?

Statement A: Fuel cell manufacturing will be consolidated among a few key global actors.
Statement B: Fuel cell manufacturing is characterized by strong local/regional champions.

Dissensus

CONSENSUS STATUS

38%

GROUP STABILITY

It is still too early to say how the development of the electrolysis industry will look, but overall, the business case for competitive green hydrogen requires a further cheapening of the basic electrolysis process. This should call for a greater consolidation in the industry to achieve economies of scale to drive down the cost of fuel cells.

The majority of the panel finds that statement A is the statement that most accurately reflects the world in 2040. 74% find that fuel cell manufacturing will be consolidated among a few key global actors, as to some extent has been the case with solar PV modules manufacturing.

Main reason provided is that fuel cell manufacturing is no different from many other industries and the same dynamic will be at play.

Question 19: What will it take to lock in investors to the green hydrogen economy in your country?

POSSIBLE TO SELECT 3 ANSWERS, THUS SUM OF PERCENTAGE IS 266%

Question 19: What will it take to lock in investors to the green hydrogen economy in your country?

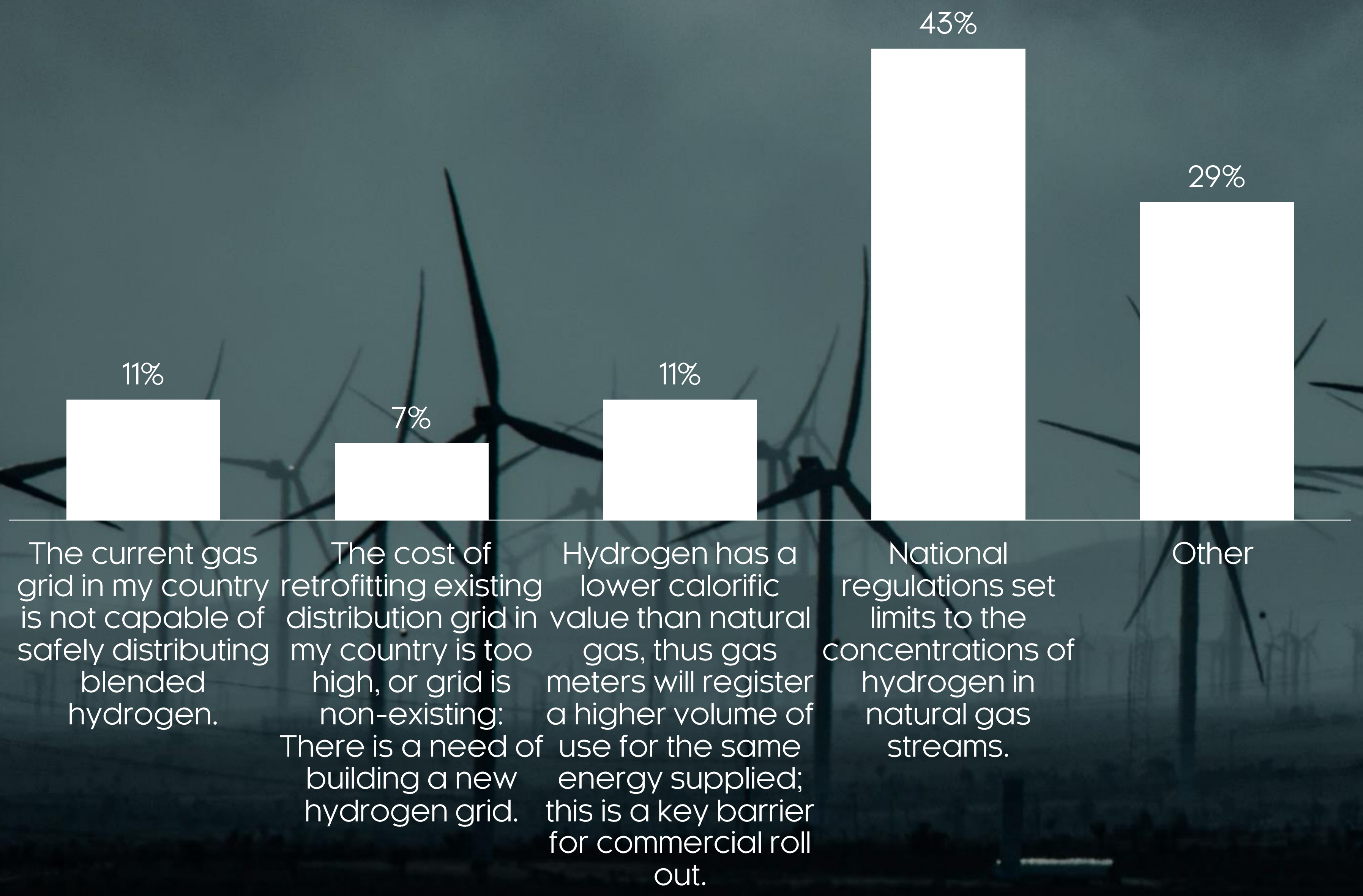
EXPERT PANELIST INSIGHTS

To unlock the green hydrogen economy, which is not cost competitive at present, will require incentives and support to enable the private sector to deploy equity capital and debt to projects. This will have the most material impact on green hydrogen investment.

Hydrogen hubs, meaning local areas with large hydrogen production and consumption, are needed. By focusing on the right areas, the amount of public support can be kept at an acceptable level.

Hydrogen End Use

Question 20: What is the biggest hurdle that needs to be overcome to use existing natural gas infrastructure in your country to deliver green blended hydrogen to end users?



Dissensus

CONSENSUS STATUS

43%

GROUP STABILITY

The EU has adopted a 55% emission reduction target for 2030. For countries like Germany, this means that heating emissions need to be reduced by half. Hydrogen has been proposed as a way to reduce emissions in heating, and that using blended hydrogen would be a way to facilitate the uptake of hydrogen in general. Opponents argue that this is not the best use of hydrogen, and hydrogen should be used in areas that are harder to decarbonize.

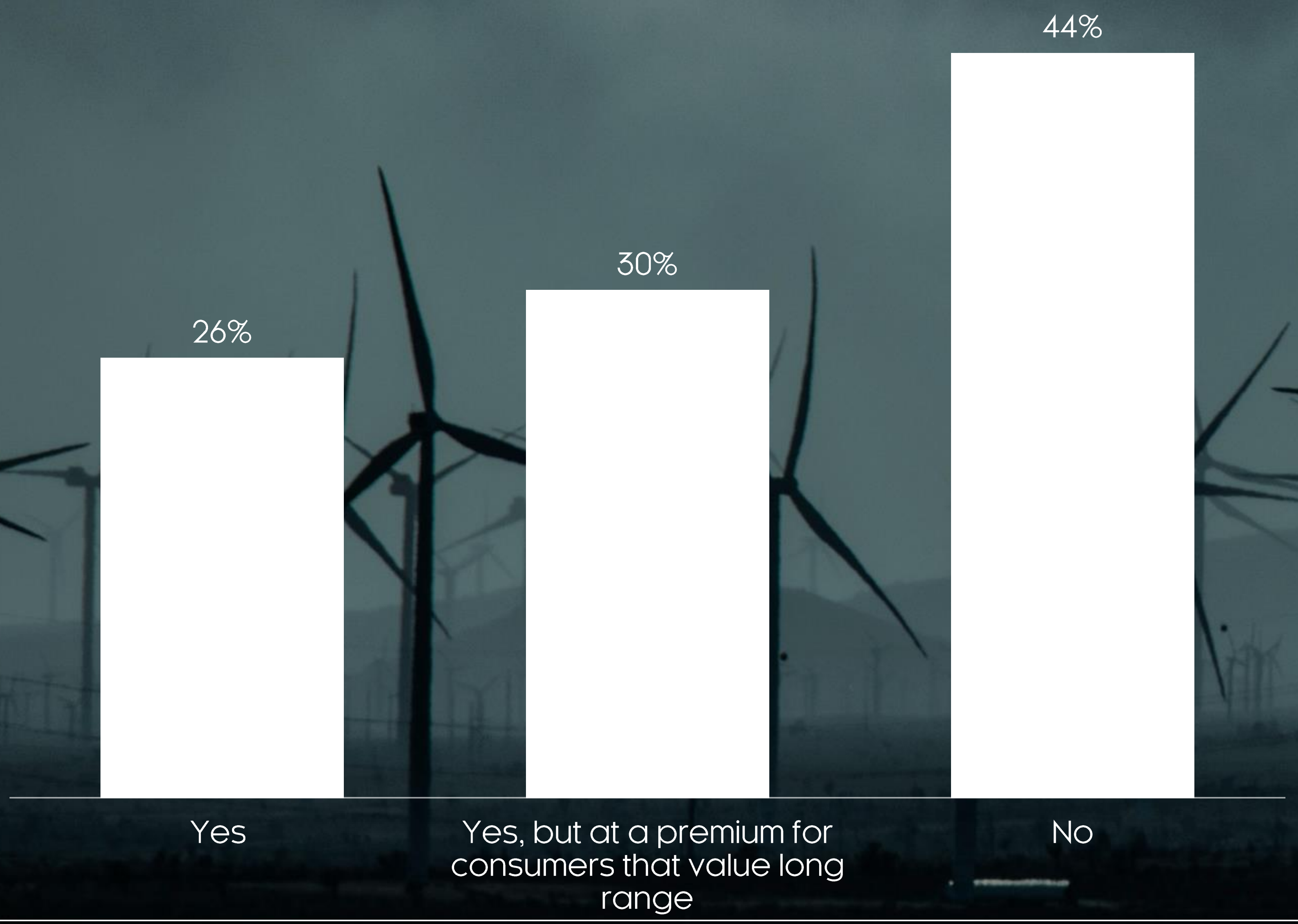
When asked, a majority of the panel sees the use of blended hydrogen as possible, yet the high "other" category and the associated answers reflect the viewpoint that hydrogen is a high-value product and should not be burned. There are too many alternatives to get heat that are more cost effective - heat pumps, excess heat from electrolysis - via district heating etc. This shows that this is still a point of debate.

Question 20: What is the biggest hurdle that needs to be overcome to use existing natural gas infrastructure in your country to deliver green blended hydrogen to end users?

EXPERT PANELIST INSIGHTS

National regulations set limits to the concentrations of hydrogen in natural gas streams: 1% (volume) limit is really low.	*Other: It is not a good idea – power to hydrogen to heat is a terrible solution. It is much better with direct electric heating.*	*Other: The gas grid will continue to serve a large amount of customers whose installations are adapted to natural gas (methane). They cannot use hydrogen due to the large difference in Wobbe Index. This is unlikely to change, and certainly not for all for the next decades.*
The current gas grid in my country is not capable of safely distributing blended hydrogen: Gas regulation within Italy and EU in general is too fragmented at the moment.	*Other: Using heat pumps with a seasonal performance factor of 3 is six times more effiicient than burning hydrogen with an overall efficiency – electrolysis, compression and other losses – of 50% or so.*	*National regulations set limits to the concentrations of hydrogen in natural gas streams: Hydrogen (not ammonia) is not well suited to our pipelines. Embrittlement alone is a killer. NH_3 will work.*

Question 21: Considering the conversion loss of green hydrogen and the price decline in batteries, do you believe that fuel cell hydrogen powered vehicles will be able to be competitive with EV (light-duty vehicles) in 2040?



Dissensus

CONSENSUS STATUS

44%

GROUP STABILITY

In 2003, the EU-backed European Hydrogen and Fuel Cell Technology Platform forecast up to 5 million hydrogen cars on the streets by 2020. Today 0,03% of that goal has been reached.

Will things be different this time around?

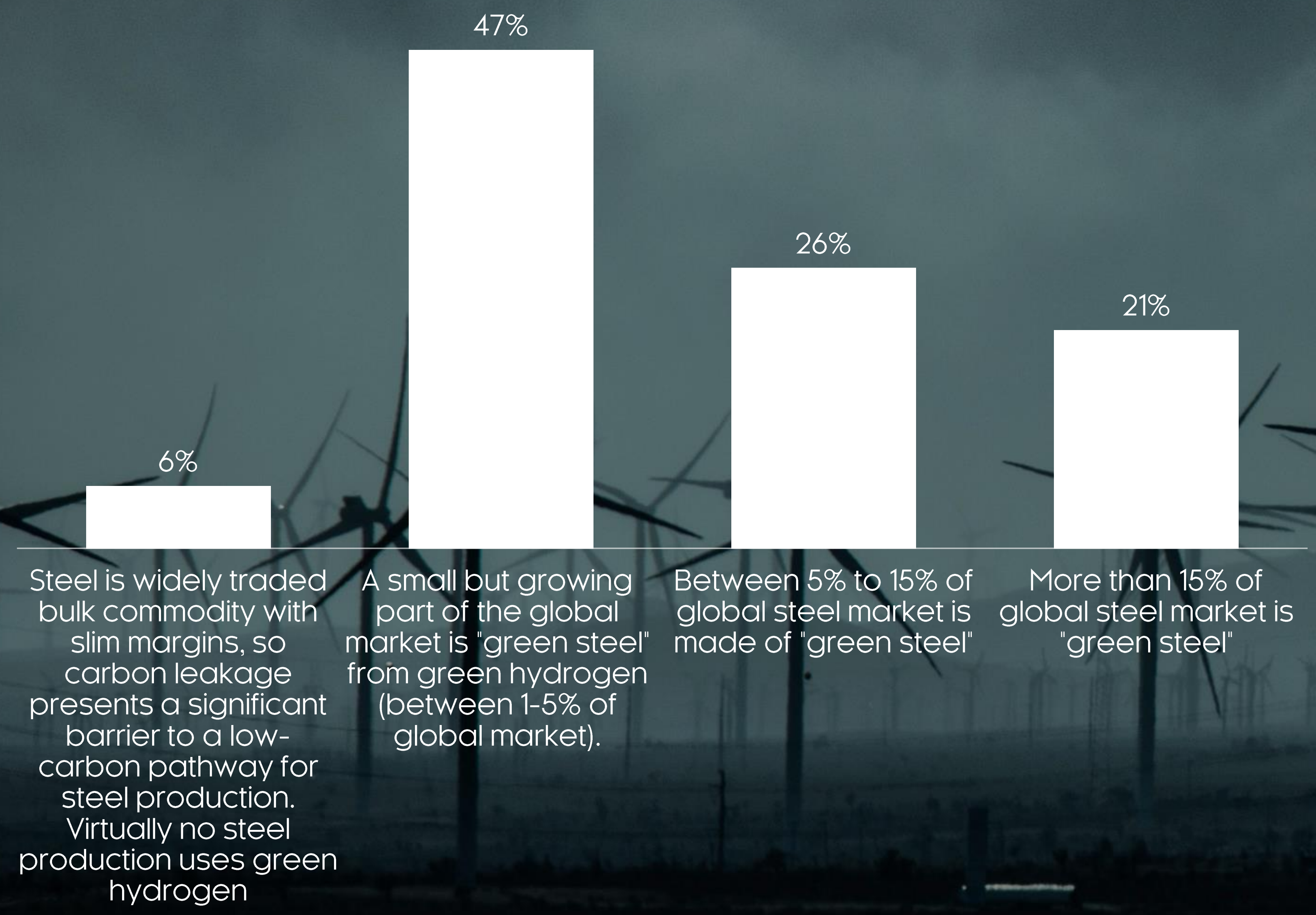
For every fuel cell car in the EU there are ca. 1.000 EVs, but even so, a rather large share of the panelist expects fuel cell electric vehicles (FCEV's) to be competitive with light-duty electric vehicles in 2040, arguing that insufficient range may still pose a problem in 2040. A majority however argue that FCEV will not be able to overtake EVs by 2040, so here, too, there is disagreement.

Question 21: Considering the conversion loss of green hydrogen and the price decline in batteries, do you believe that fuel cell hydrogen powered vehicles will be able to be competitive with EV (light-duty vehicles) in 2040?

EXPERT PANELIST INSIGHTS

Yes: FCEVs will absolutely be competitive, if not more so with the appropriate early market incentives akin to those provided battery electric vehicles. In addition, consumers making choices for personal transportation are not driven by efficiency in most cases. Consumers choose personal transportation based on it's ability to meet their personal needs (SUV, minivan, sports car, sedan, pickup truck), vehicle brand, style and price among other factors.	*No: If Tesla's next gen battery benchmarks are to be believed, it is difficult to see how hydrogen could be competitive at all in light EVs.*
Yes - but at a premium for consumers that value long range: The development of batteries has been fast and it will continue. The extra weight and additional charging time may open some market for FCEV.	*No: H_2 infrastructure is being set up ("H_2 mobility network"), but cars are being manufactured not on industrial scale - basically still hand-made.*

Question 22: What best describes your expectations for green hydrogen in the steel industry by 2040?



Dissensus

CONSENSUS STATUS

47%

GROUP STABILITY

The steel industry generates about 8% of global CO_2 emissions. Reaching zero emissions by 2050 will be difficult, but according to the IEA, it should be technically possible to produce all primary steel with hydrogen.

There is a consensus among the panelists that green steel will be a part of steel production in 2040, but disagreement about its global market share.

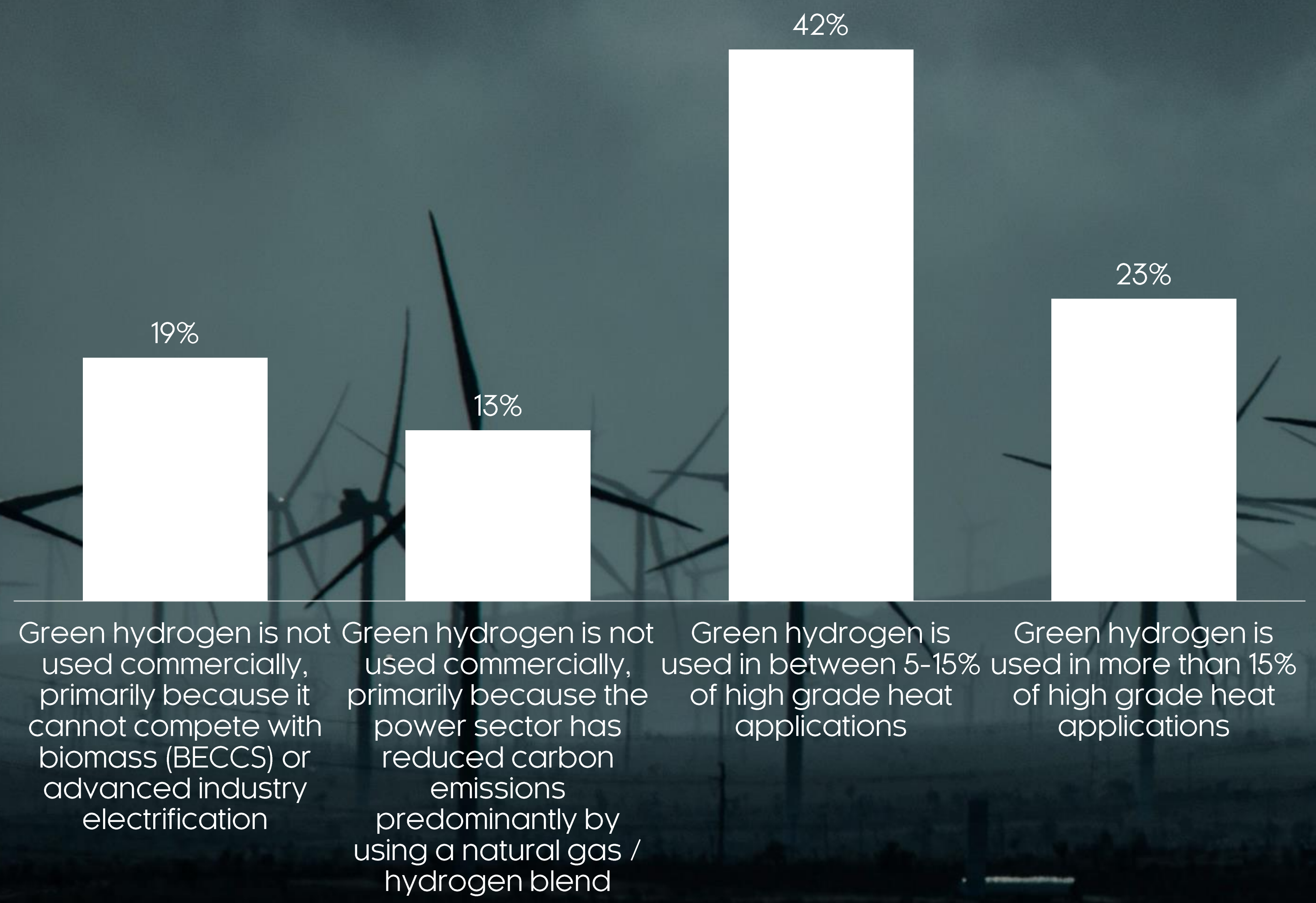
These answers may reflect the progress that has already been made. As an example, Sweden is already using hydrogen in the steel industry with the goal of decarbonizing the industry by 2035. A bigger market share for green steel would however require vast amounts of low cost, low carbon electricity and the right regulatory framework. This would likely take the form of border tax adjustments or mandatory procurement.

Question 22: What best describes your expectations for green hydrogen in the steel industry by 2040?

EXPERT PANELIST INSIGHTS

Between 1-5% of global market: *I believe that with regulation, green hydrogen will begin to be used in that industry, although it will be limited in scale due to the need for even lower prices and the time needed to integrate hydrogen in existing industries.*	*Between 1-5% of global market:* *It is a mistake to focus this question only on steel-making. Heating steel to 1200C for hotforming operations represents a viable fast way to implement hydrogen in the steel industry. Global potential is >300 million tons of CO_2 savings. This question is missed in the survey and represents a very fast way forward – with important impacts also on fuel cell viability for vehicles as well as power grid balancing.*

Question 23: What best describes your expectations for the use of green hydrogen for industrial high-temperature heat (above 400 degrees Celsius) by 2040?



Dissensus

CONSENSUS STATUS

42%

GROUP STABILITY

Excluding the chemical, iron and steel sectors, industrial high-temperature heat is responsible for around 3% of global energy-sector CO_2 emissions. Hydrogen promises to help decarbonize high heat and according to the Hydrogen Council could provide as much as 23% of high heat. According to the IEA, however, hydrogen in high heat would find it hard to compete with biofuels and would need CO_2 above USD 100/tCO_2. A 2020 study by Potsdam Institute of Climate Impact Research even suggests that as much as 99% of industry can be decarbonized using advanced electrification.

When asked, the panelists are in disagreement. A majority of 65% however, believes that hydrogen will be used to some extent.

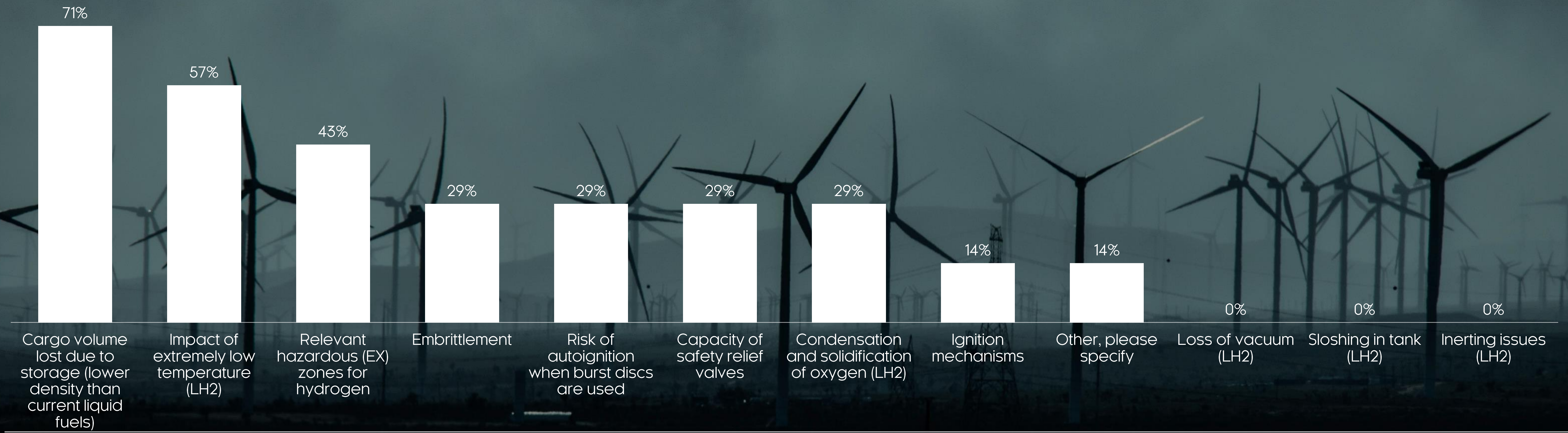
Note: The graph does not illustrate category "Other" (3,23%).

Question 23: What best describes your expectations for the use of green hydrogen for industrial high-temperature heat by 2040?

EXPERT PANELIST INSIGHTS

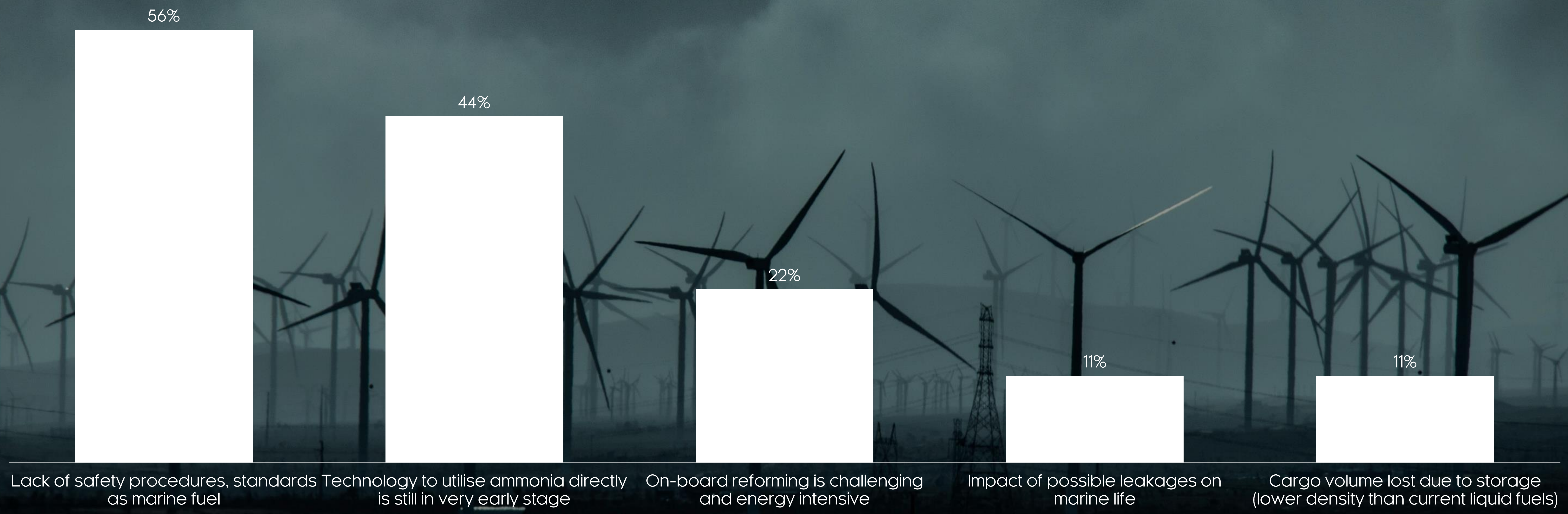
Green hydrogen is not used commercially, primarily because it cannot compete with biomass (BECCS) or advanced industry electrification: Scratch the BECCS from the option and I would more strongly agree. Please see 1414 degrees company in Australia for an example of how to do advanced industry electrification. Molten silicon can store huge amounts of energy in a small space at temperatures that are relevant to industry. The heat input can follow a dispatch signal from a local RE resource or from a market.	Green hydrogen is not used commercially, primarily because it cannot compete with biomass (BECCS) or advanced industry electrification: There might be some niches, but less than 5%. Advanced industry electrification, based on industrial heat pumps and, most importantly, a range of electro-magnetic technologies, can deliver electricity at all temperature levels. Think of methane pyrolysis: at the heart of the plasma oven, the temperature exceeds 3000°C – higher than the combustion temperature of hydrogen.
Green hydrogen is used in between 5-15% of high grade heat applications: Heating is possible to electrify up to 1000C quite well. We have done so. However, the heating up to 1200C is where hydrogen (and oxygen) can play an important role. Global potential > 300 million tonnes of CO_2 savings.	Green hydrogen is used in between 5-15% of high grade heat applications: The cost of green hydrogen will still be quite high in 2040 (1-1.5 €/kg) in most places. Blending of hydrogen to biogas and NG has become common.

Question 24: What hurdles need to be overcome to use liquid hydrogen or methylene-powered fuel cells as on-board power supply for ship propulsion?



POSSIBLE TO SELECT 5 ANSWERS, THUS SUM OF PERCENTAGE IS 315%

Question 25: What hurdles need to be overcome to use ammonia-powered fuel cells as on-board power supply for ship propulsion?



POSSIBLE TO SELECT 2 ANSWERS, THUS SUM OF PERCENTAGE IS 144%

Note: The graph does not illustrate category "Other" (33,33%).

Question 25: What hurdles need to be overcome to use ammonia-powered fuel cells as on-board power supply for ship propulsion?

EXPERT PANELIST INSIGHTS

One should NOT use ammonia with low temperature fuel cells, as these will never be able to compete with 4-stroke engines. High temperature fuel cells, which can directly operate on ammonia with a high efficiency (>60 %) might be economically competitive, but this is still uncertain.	*Ammonia is already one of the most widely transported chemicals globally, so I am convinced that the safety measures etc. are in place. The bigger hurdle here is, who is the key stakeholder can/wants/has a direct benefit in solving technical issues such as on-board reforming or direct ammonia application. That currently is still a big unknown and has to come from a consortia of stakeholders along the value chain, making this hurdle pretty high.*	*Maritime regulations don't change overnight, and I doubt large investment in technology that has not been addressed regulatory-wise will take place.*

Question 26: What enabling measures can be taken to increase hydrogen uptake for on-board power supply for ship propulsion?

POSSIBLE TO SELECT 3 ANSWERS, THUS SUM OF PERCENTAGE IS 250%

Note: The graph does not illustrate category "Other" (20%).

Bibliography

Business Finland. 2020. National hydrogen roadmap for Finland.

Department for Transport. 2019. Maritime 2050. Navigating the Future.

ENERGINET. 2019. Winds of change in a hydrogen perspective.

European Commission, 2020. A Hydrogen Strategy for a Climate-Neutral Europe.

Fuel Cells and Hydrogen Joint Undertaking (FCH JU). 2019. Hydrogen Roadmap Europe.

Fraunhofer IEE. 2020. Hydrogen in the energy system of the future: focus on heat in buildings.

HyLAW.2018.Legal-administrative procedures and barriers to hydrogen applications in the maritime sector.

Hydrogen Council. 2017. Hydrogen scaling up.

Hydrogen Council. 2020. Path to hydrogen competitiveness.

IEA Bioenergy. 2018. Hydrogen from biomass gasification.

IEA. 2020. Energy Technology Perspectives

IRENA. 2018. Hydrogen from renewable power.

IRENA. 2019. Renewable power-to-hydrogen.

Bibliography

Liebreich, M. 2020. Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side. Bloomberg NEF.

Liebreich, M. 2020. Liebreich: Separating Hype from Hydrogen – Part Two: The Demand Side. Bloomberg NEF.

Minett, S Parr, M . 2020. What is the real cost of Hydrogen. Euroactiv

The Oxford Institute for Energy Studies. 2020. Blue hydrogen as an enabler of green hydrogen: the case of Germany.

Silvia Madeddu et al. 2020. Environ. Res. Lett. in press https://doi.org/10.1088/1748-9326/abbd02

SUPERGEN. 2017. Bioenergy Hub Leaders Consultation –BECCS& Hydrogen Summary.

US Drive. 2017. Hydrogen Production Tech Team Roadmap.

Van Renssen, S. 2020. The hydrogen solution?. Nat. Clim. Chang. 10, 799–801. https://doi.org/10.1038/s41558-020-0891-0

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