Scientific Innovation Series 8

수소와 에너지 전환

Hydrogen and the Energy Transition

Transcript

In-Kook Park:

Good afternoon, ladies and gentlemen. It is my great pleasure to welcome all of you to the Scientific Innovation Series of the Chey Institute for Advanced Studies. Since its inauguration, the Chey Institute has operated on its three main pillars. First, identification of geopolitical risk. Second, scientific innovation and its risk. Third, the impact of science on geopolitics.

The Chey Institute has hosted numerous scientific innovation conferences or special lectures focusing on cutting edge topics such as nanoscience, AI, EV batteries, semiconductors, and quantum computing. On these occasions, we brought together Nobel Prize worthy scholars to share their invaluable knowledge and insight. The Chey Institute is committed to continuing its mission as a knowledge sharing platform amid unprecedented challenges and opportunities. For the second half of this year, we have planned exciting topics such as post-quantum security, the metaverse, CRISPR technology, and the New Space.

Today's webinar will highlight hydrogen energy. This topic deserves our attention as a hydrogen is gaining traction as an essential building block of the renewable energy ecosystem. Today, we are privileged to have a world-leading industry experts and scholars who are pioneering this field. I extend my welcome to Mr. Bernd Heid from McKinsey & Company, Mr. Andy Marsh, the CEO of Plug Power, and Professor Cha

Suk Won and Professor Nam Ki Tae from Seoul National University. Also, I would like to give my special thanks to Vice Chairman Jeong Joon Yu for today's participation and his whole-hearted support for our program. Finally, I would like to introduce today's moderator, Dr. Song Kyung Yeol, who is a leading hydrogen and energy solution business at SK E&S. In 2007, he led energy, chemical, and power practice as Director of McKinsey Energy Center in Korea.

Please enjoy this special session on hydrogen energy.

I thank you.

Kyung Yeol Song:

Thank you, President Park, for the kind introduction. I'm Kyung Yeol Song, and it's my pleasure to moderate today's Chey Scientific Innovation Series. I wish to thank the Chey Institute for hosting this timely webinar on hydrogen and the energy transition.

I would like to start by introducing the plenary speaker, Mr. Jeong Joon Yu. Mr. Yu is Vice Chairman and CEO at SK E&S and Director of Board at SK Innovation. Mr. Yu began his career as a Senior Accountant at the New York office of Deloitte in 1987, and later joined McKinsey & Co. to establish and found its Seoul office in 1991. In 1996, Mr. Yu joined LG Construction, where he took over a corporate planning and overseas business development role. Mr. Yu was appointed Vice President of Corporate Planning of SK Corporation in 1998. Later, he became President at Resources & Chemicals Business of SK Energy in 2008 and then served as President & CEO of SK Lubricants. Mr. Yu was President of the Growth and Global Promotion Division in SK Holdings and directed the global business including M&A activities of the whole SK Group, before being appointed as President & CEO at SK E&S in 2013. From 2018 to 2019, he served as President of Energy & Chemical Committee of SK SUPEX Council.

Today, the title of his talk is "Hydrogen: Past, Present, and Its Future."

Jeong Joon Yu:

Thank you, Dr. Song for the introduction. Good day to everyone joining us here today. I would like to thank the Chey institute for Advanced Studies for providing me the opportunity to give the plenary speech at this webinar for Hydrogen and Energy Transition.

Today, we have other keynote speakers that will provide many different insights which I'm sure everyone is keen about. We have Mr. Bernd Heid, who is the global no. 1 consultant on hydrogen. We also have Mr. Andy Marsh, CEO of Plug Power, a leading provider of turnkey hydrogen solutions who is also our partner. And lastly, two distinguish professors from Seoul national university, Dr. Cha Suk Won and Dr. Nam Ki Tae. Before the other keynote speakers provide their speech, let me begin with an introduction of the big picture that will cover hydrogen's past, present, and its future.

If we look at Page 2, so what is hydrogen exactly? I would like to talk on the key properties of hydrogen first. Firstly, hydrogen is the most abundant chemical substance in the universes, making up about 75% of the universe's elemental mass. While hydrogen is so abundant in the universe, it is not easy to find it on earth. This is because hydrogen is the lightest element in the universe. Since it is so light, Earth's gravity is not significant enough to prevent it from escaping the atmosphere.

Next, hydrogen is highly reactive and mainly exists in compounds like water (H_2O) or an organic form but rarely as pure molecule. H_2O itself is a very stable compound, but we need to apply huge energy to H_2O to get hydrogen out of it. Despite its huge energy density with carbon free option, as it is very hard to produce hydrogen, it is also the reason why it is not popular as an energy carrier.

Finally, hydrogen is a carbon-free energy with high energy density. As shown on the bottom right chart, hydrogen's energy density in terms of mass is much higher than fossil fuel. For example, hydrogen's energy density is 3X larger than crude oil or LNG and ~7X of coal. Therefore, if there is an economic way to produce & utilize it, hydrogen has the potential to replace fossil fuel as a new energy carrier in the net-zero era.

Now we know what hydrogen is, let me share when it was actually first discovered. On page 3, the first to recognize hydrogen as a discrete substance was in 1766 by Henry Cavendish an UK chemist. And In 1783, Antoine Lavoisier a French chemist, was the first to name it as “hydrogen". And did you know, in Greek, “hydrogen” means “maker of water.” Actually, most important technologies and engineering principles were already discovered & developed more than 200 years ago. For example, in year 1783, there was the first flight with a hydrogen balloon made by French inventor, Jacques Charles. In year 1800, there was the first discovery of the concept of electrolysis by William Nicholson and Anthony Carlisle, and quite surprisingly in 1839, the 1st fuel cell was constructed by Sir Robert Grove. As shown, core hydrogen technologies such as fuel cell, electrolysis, were already developed more than 150 years ago. Another interesting fact to share in the next page is the history of hydrogen economy.

On page 4, in fact, “hydrogen economy” concept was already proposed more than 100 years ago. In 1874, French novelist Jules Verne described the concept of “hydrogen economy”, for the 1st time in his novel. He said "Water will one day be employed as fuel and will furnish an inexhaustible source of heat and light, of which coal is not capable.” As we can see, his vision on hydrogen economy is being realized now. And in 1923, a more scientific theory was proposed by an UK scientist J.B.S. Haldane about 100 years ago. He provided a speech on hydrogen, which included modern scientific and engineering principles on hydrogen. For example, concepts on green hydrogen, Power to Gas (P2G), liquefaction of hydrogen and applications of hydrogen for many different areas. Today, most of the hydrogen technologies are built on top of Haldane's proposed idea which was the first proposal of a hydrogen-based renewable energy economy. Despite the early discovery, hydrogen has been a niche product until recently.

On page 5, we talk about why it was a niche product. Since the beginning, hydrogen was used for many different applications. In fact, the first major commercial production by electrolysis started in 1920 in EU and US. It was used as fuel for airships until the Hindenburg disaster in 1937. However, as shown on the right side of the page, it has been used as a niche product because its benefit-cost ratio was not high enough to justify an investment. Cost was just too high because hydrogen exists in a compound with other elements like H_2O, making it harder to produce without significant energy applied. And also, benefit was not perceived high, because hydrogen's carbon-free property was not valuable until recently.

In fact, until 2019, there was no single major report on energy industry which included hydrogen in a long-term energy mix as hydrogen wasn't considered a critical factor in our energy mix. Then, the billion-dollar question we all have will be Why Now? In the next few pages, I will further explain on hydrogen's present stage.

On Page 6, one of the main reasons on why now is because the competitive cost position of hydrogen is dramatically improving. As shown on the left graph chart, with the competitiveness of hydrogen improving, CO_2 emission will also dramatically reduce to achieve net-zero by 2050. We need to build more consensus as we need to limit global warming to 1.5 degrees to avoid catastrophic disaster. But this ambitious goal will not be realized automatically without any effort. If we are really serious about the 1.5°C target, stronger penalties and regulations on carbon emission will be inevitable, like the "carbon tax."

Looking at the right side of the page, recently, IEA published a report "Net Zero by 2050", that shows carbon price should reach at $130/ton CO_2 in 2030 and $250/ton CO_2 in 2050 to realize net zero by 2050. Actually, many countries like Korea have announced

Net-Zero target by 2050. And are starting to apply a price for carbon emission to drive and influence the need for Net zero. As a result, CO_2 emission is no longer free to offload. Which is dramatically changing the competitive landscape for carbon free environment and also improving relative competitiveness of hydrogen significantly against fossil fuels.

Next, on page 7, on the left side, it shows that cost of hydrogen reducing significantly due to renewable energy cost being more competitive against conventional resources like fossil fuel. Since year 2000, LCOE, also known as Levelized Cost of Electricity, of renewables has reduced more than 10X which was enabled by technological innovation and scale effect. Now, even in some regions, LCOE of renewable reaches in the low $20/MWh. And on the right side, combined with fast & significant capex reduction for electrolyzer, this ongoing renewable LCOE drop will make green hydrogen more competitive than grey hydrogen even without subsidy before 2030 in some regions. For projects such as offshore wind powered electrolysis in Central Europe, renewable hydrogen production costs could decline from USD $5.4/kg in 2020 to USD $2.3/kg in 2030, with LCOE declines having the greatest cost-down impact. And for projects using low-cost renewables like solar photovoltaic powered electrolysis in the Middle East, the cost of renewables-based hydrogen production could decline to $1.5/kg in 2030.

Moving onto Page 8, let's now look at how competitive hydrogen will be. On this page, it shows that with at $100 per ton of CO_2 at 2030, slightly lower than IEA's scenario of $130 per ton of CO_2, hydrogen will be cost-competitive in many applications, especially for heavy & long-range transportation. Other transportation like shipping or aviation only break even at higher costs of carbon around $170 per ton of CO_2. And end applications in buildings and power will require an even higher carbon price up to $200 per ton of CO_2 to become cost competitive.

Now knowing how competitive it will be, on Page 9, let's look at how big hydrogen demand will be. Recently, there are many reports published on hydrogen's future outlook ranging from 200 to 600 million tons. Reports show up 3 times difference and also with a range between 7% to 18% of total energy demand. This huge difference is mainly because of the different assumed scenarios due to increase in earth temperature. Under a 1.5°C scenario, it seems there is consensus that 2050 hydrogen demand will be around 500-600 million tons per year which represents about 18% of final energy demand in 2050. Clearly, hydrogen is definitely not a panacea. And we cannot completely replace all the existing energy sources with hydrogen clearly. However, we should concur that hydrogen is indispensable and will grow substantially.

After knowing how competitive it will be, on Page 10, we look at what are the key applications. This chart compares hydrogen cost competitiveness against conventional options and carbon solution. As you can see in the chart, 9 applications in the red box in upper-right area are the ones where hydrogen can become a cost-competitive low-carbon solution against fossil fuel. Thus, this does not imply that hydrogen will satisfy all this energy demand by 2030, but it does showcase that hydrogen is expected to have a significant role to play as a clean energy in the future energy mix. For a more professional explanation on the table, Mr. Bernd Heid will discuss further during his presentation.

On Page 11, we talk further on how cheap it will be. The numbers shown in the blue boxes represents year 2020. And the numbers in the green boxes forecast the cost under each value chain under an ideal scenario, in which each value chain's cost declines almost to one-third (1/3) as oppose to year 2020. Due to ongoing renewable LCOE drop and fast electrolyzer capex reduction, green hydrogen cost will reduce fast and become competitive against grey hydrogen even without subsidy before 2030 in some regions. To note, there are three main factors that contribute significantly to cost reduction: 1st is equipment cost reduction through technological improvement; 2nd is increasing utilization; and 3rd is by scale effect. As a result, hydrogen retail cost based on green hydrogen, meaning the cost of hydrogen at the pump, can be reduced from $10/kg to as low as $3/kg in optimal regions Talking about all the potential theories and facts to prove the true value and stability of hydrogen, to achieve it, what commitments and considerations do we need?

Here on page 12, I believe there are 3 major components that need to be considered: 1st is Long Term Investments; 2nd is Incentivizing policies and regulations; and 3rd is an industry standard across industries.

For investments, countries and companies need to make long term investments over a course of 10 to 20 years to provide a workable stable framework. For policies, the development of hydrogen energy needs a boost from government and policymakers. For standards, the standardization landscape for hydrogen is very complex due to the different sectors related. Harmonization of industrial standards is inevitable to maximize scale effect.

To summarize, we looked at the technical, commercial, and legal aspects. And it is prominent that all areas need to play its part to finally bring out the potential of hydrogen into our lives.

This is what I’ve prepared today and I hope I was able provide the big picture of hydrogen and also its potential to fast-track towards our net zero era. Thank you for your time and without further ado, let me hand it over to our moderator, Dr. Song and our panel of experts to further share their insights on this topic.

Thank you again.

Kyung Yeol Song:

Thank you, Mr. Yu, for the presentation. Mr. Yu has given us a brief history of hydrogen technology and told us about today's key applications as well as opportunities for growth.

Next, I will introduce the first distinguished keynote speaker, Mr. Bernd Heid. Mr. Heid is a Senior Partner with McKinsey & Company and is based in Cologne, Germany. He joined the firm in 2000 and is the global leader of the McKinsey Hydrogen Service Line, where he has led numerous projects along the full hydrogen value chain. He leads McKinsey's work on the partnership with the Hydrogen Council, where he co-authored the reports on "Hydrogen Scaling-up" and the "Cost Roadmap". He also leads the firm's Future of Mobility collaboration with the World Economic Forum.

Today, he will give us a talk titled "The Hydrogen Opportunity: Hydrogen Initiatives, Technology Roadmaps, and Outlook."

Bernd Heid:

Thank you very much for that kind introduction and also thank you, Mr. Park, for having me. I will speak about the hydrogen opportunity today, both on the global momentum with its initiatives, the technology roadmap, but also the outlook. So, the work that I will show you has been developed together with the Hydrogen Council. The Hydrogen Council is a CEO-led initiative of companies along the value chain that all pursue the development of the hydrogen economy. So, let me start first with the narrative of why we think hydrogen is important and needed and also what is different this time.

Let us look on the next page on the on the narrative. So, number one, we need hydrogen for deep decarbonization. So, hydrogen as an energy carrier is needed to decarbonize hard-to-abate sectors. Think of steel. Think of heavy industries. Think of heavy-duty trucking. So, these are all sectors, where it would be difficult to decarbonize those end-users without hydrogen in the mix. Number two is we see an accelerating global momentum. Right now, we count more than two hundred projects around the globe. This has a total of 80 billion investments. These are mature investments. So, we only count the projects that have either already FID (final investment decision) or post-FID decision.

And in addition, we also see that governments are very committed to support that transition of the hydrogen economy. So, this adds up to another 70 billion US dollar on top of what is being invested in the private sector. We see 10x growth of the use of hydrogen compared to today in the next 30 years. I will speak more about this. And number four is an important one because that is new and also enables at all that hydrogen will become an energy vector. That is, the production of decarbonized hydrogen came down in cost and will continue to fall in cost of production so that by the end of the decade we will be at levels of 2 US dollars or below for decarbonized hydrogen, that means green or blue. And the last message that I would love to convey is that hydrogen and its energy vector is something that happens in ecosystems. You often see five, six or more companies along the value chain cooperating to get parts of that ecosystem going, often in an ecosystem with the public side and also governments to support. So fairly, hydrogen is an investment that individual companies do alone. But this is really an ecosystem play that we see.

So, let's look at the next page where you see a chart that depicts proportional CO_2 emissions, in this case, Europe. The global picture doesn't look much different. It just has different sizes. But we color coded different areas on this chart, depending on which technology is in a sweet spot to help to avoid these emissions. And you see color coding light blue, where hydrogen is in a sweet spot. You see gray, where we have direct electrification. You have black, where there will be batteries dominating these use cases, and you have dark blue, where depending on the use case, you either have batteries or hydrogen. And that's also one message from this chart. This is about the coexistence of these different technology types. It's not about electrification versus hydrogen. These are very complementary technologies in an integrated energy transition. But you see on the left side, especially on the industry where we need hydrogen to decarbonize petrochemicals, chemicals, the reduction of iron ore to DR pellets or raw iron. That's where hydrogen is needed. In the middle column on transportation, you can almost think the heavier the application and the longer the distance, the better hydrogen is in a sweet spot. So, aviation or shipping, we will not be able to decarbonize with hydrogen, even if it's used in derivatives, think of ammonia, think of methanol, or think of synthetic fuel. For all of these free fuels, you would need a molecule of decarbonized hydrogen in the beginning to start this. And on transportation, road transportation, it's really a matter of if you want to travel long distance with a heavy truck, hydrogen is in a sweet spot. But even if you have a truck and you just go a short distance, let's say, in urban areas, then it even makes sense to have a battery in a commercial vehicle. So, that really depends on the individual use cases that you use.

So, let's look on the next page. There's an overview on the global projects that we see on hydrogen. This is the 228 projects I commented in the introduction and you see two patterns evolving. So, on the one hand, you see the smaller bubbles. Each represents hydrogen projects, what we call closed-looped ecosystems, where you have the hydrogen production and the uptake next to each other in applications like industry, like ammonia production, like transportation or other integrated hydrogen use cases. And they happen in markets with end-users. This is, for example, in Korea, which we see as one of the leading markets. We also see that in Japan. We see that in Europe. Note lastly that there are governments that are committed and determined to lead the energy transition. A second pattern that you see on this chart is the larger turquoise bubbles in, for example, Australia, Saudi Arabia, or Chile. Here we are talking about giga scale hydrogen production places. And this is because we have places with high exposure to sun or wind so that we have cheap and affordable renewable energy to produce hydrogen at relatively low cost. So, these markets will be future export hubs for the hydrogen economy. So, we will see hydrogen being imported from Australia or hydrogen coming from Saudi Arabia, North Africa, Latin America. And this is actually also one of the reasons why we strongly believe in hydrogen as an energy vector, is we will not be able to transport energy over long distance or store over a longer period of time if we do not convert the electrons into molecules. And that's where hydrogen has the key advantage. It's an energy vector that enables us to export sunshine and wind out of places where we have very cheap renewable power. To supplement that picture, of course, we will see over time also blue hydrogen evolving in countries or regions where we have low-cost natural gas, plus we have carbon capture and storage processes. So therefore, we will see that as a global economy on the two energy vectors.

Let us now look first at green hydrogen production. The next slide shows you the development of the electrolyzer capacity over time for the next 10 years. Today we have roughly an installed base of 200 megawatts of electrolyzer capacity, which is very tiny, and this will grow over time to 70 gigawatts until the end of the decade. And I left the timestamps on this chart so that you can see how the momentum evolves over time. So, if we had come together two years ago in June 2019, my answer would have been that we see growth of two or three gigawatts, and just a year later we were already at almost 10 times that capacity at 28 gigawatts. And today we are again at more than two times that capacity at 70 gigawatts. So, in our projection, if we see that evolving, we will be certain that we have 100 gigawatts or more until the end of the decade. And that's a massive growth. If you consider today we have 200 megawatts growing to 100 gigawatts. That is a factor of 500. And this is not unrealistic. We have governments around the globe committing to develop similar roadmaps. So, Europe alone has pledged 40 gigawatt of hydrogen electrolyzer capacity until the end of the decade. So therefore, I expect rather that number to be higher than 100 gigawatts than being lower.

Let's look at the regional distribution on the next slide, where you see where this all happens. And you see that this momentum, to a large extent, stems from developments in Asia, to a large extent in Australia, where we see hydrogen being exported to Asian regions. You'll also see Europe, with a high share of production, mainly for Europe itself. And you see also an emerging Middle Eastern production, which we expect to become far higher because the projects that you see here are to a large extent, in an initial phase. So, we will see more hydrogen production in Middle East. And we will see also more hydrogen production in North America where the momentum just unfolded. And that is driven by investors in the US putting pressure on boards to have an ESG compliance strategy. So unlike in Europe or parts of Asia where we have a strong regulatory push, we will see the private sector or the investor community, to be precise, to enable hydrogen economy also in the US.

Let us look at the hydrogen cost on the next slide, where you see the development of gray, blue, and green hydrogen over time. Gray, to share the definition, is hydrogen produced from natural gas in a process that is called steam methane reforming. And this process is CO_2-emitting because you split up the natural gas into its ingredients and CO_2 is one of the end products out of this process. The reason why the cost of gray hydrogen goes up is, we assume implied carbon taxation onto these processes. So just the pure production cost would be a flat gray line at around 1 to 1.7 US dollars. And that depends on what's the cost of gas that goes into that process. Blue hydrogen is 50 US dollar cents more expensive. The delta comes from the carbon capture and storage process that you add on top of the gray hydrogen production to capture the CO_2 sequestered and store it, for example, in caverns or use it in other processes.

And then you have green hydrogen that today is somewhere in the range of 4 to 6 US dollars per kilogram, again, depending largely on where on this planet you are. But the important message here is that the cost of green hydrogen from renewables will fall by 60 percent to reach levels of 2 US dollars or below until the end of the decade. And that comes from three factors. So, number one, the most important factor is the cost of renewables that go into that process. That's also why you see that high variation, depending on the endowment of solar and wind in these regions. Renewables costs have fallen 80 percent over the past decade. They will continue to fall not as much, but this is one important driver. A second one is the capex of electrolyzers that I will show you on the next slide. And the third factor is the utilization factor of electrolyzers.

So, let's look at electrolyzer technologies. What you see here are the three dominant technologies. You have alkaline electrolysis (AWE). That's a very mature technology that has existed for decades and now is being used to also produce hydrogen. You have the

PEM electrolysis, which is a fairly new technology. And that's also why you see the high cost decline from levels of 1,000 US dollars per kilowatt of electrolyzer capacity coming down to levels of 400 and below. And you have solid oxide electrolyzers (SOEC), which is a technology that is even more nascent. That's why it's more expensive today as it's produced in smaller batches. But also, here we see the cost decline over time. And for all of the data that I showed you, this is not just a McKinsey projection. We here use data from the member companies of the Hydrogen Council. So, think of that as like a clean team process where we collected in a clean team, data from member companies and were able to develop that with real industry data. We used a ring-fenced anti-trust compliant way. So that's how we get this data. And while we see this cost decline of electrolyzers, we also strongly believe that there will be co-existence of electrolyzer technologies next to each other. Think of alkaline as the best technology. If you need large-scale production volume, PEM has an advantage because it builds far smaller. So, if space is the constraint, you can basically modularize PEM technology in a far smaller space and you can also stack it in containerized solutions. So that is a better solution if you are space constrained. And then solid oxide is a great solution, if you have excess heat of processes available. You see in the small round bubbles the efficiency of these processes and solid oxide technology can happen in 20 percent higher efficiency. Think of that as the utilization factor of energy in transforming that into molecules. And the reason for that is that solid oxide operates at high temperature. Think of 800 degrees Celsius. So, if we have excess heat like in steel-making or like in synthetic fuel production, where you have subsequent processes like Fischer-Tropsch that give you exothermic energy that can be used to be recycled in the solid oxide process, then solid oxide is the best way to go. So, we firmly believe that we will see these technologies next to each other, coexisting in this ecosystem. And this is really an important message that the cost for all of these technologies come down, and that's not because we see new technologies evolving over time like we have seen for battery technology, for example, here it is mainly the point in the scaling up of these technologies. Think of you produce today, electrolyzer at smaller scale in individual batches. And as you go, you introduce slow processes and produce at larger scale. That is what brings down the cost dramatically.

Let us look briefly on the next slide at the demand outlook for hydrogen. And what you see here is the uptake from today somewhere around 2,700 terawatt-hour equivalent of hydrogen. That's corresponding to 90 million tons of hydrogen that we already use each year that is used in in refineries. This is used in ammonia production of feedstock in other chemical or petrochemical processes. And you see on the one hand that the growth of hydrogen goes up to level 21,800 terawatts. That's equivalent to 18 percent of the global energy demand. And that's massive. And you see new applications come into play in transportation from road transport, trucks, cars, but also including trains, aviation or marine applications. You also see the industry as a large sector to use hydrogen. You have it in certain areas where you have power generation. Think of peak power. You also have that for building heat and power. Think of backup power for data centers. But we also use it in existing feedstock and also to decarbonize existing feedstock. Think of the hydrogen we use today in refineries that create hydrogen. And if we convert that to blue or we replace it with green hydrogen, that's where we also will decarbonize over time the 90 million tons. And all the applications that come on top of today's application will by definition be decarbonized, because it doesn't make sense to use hydrogen that is produced with a CO_2-emitting process, if you want to decarbonize end-use. So, think of if you use hydrogen for truck, why would we do that? We might as well stick to current diesel, or we stick to natural gas. So, it only makes sense if all of the hydrogen applications are in fact also decarbonized applications.

And let me show you on the next slide where we did an assessment of different TCO calculations. We model two ways. On the X axis, you see, 'Is hydrogen more or less competitive than the conventional technology?' The Y axis depicts whether hydrogen is more or less competitive than the next low carbon solution. Think of hydrogen versus battery. Think of hydrogen versus biofuel.

And here what you see, and let's flip to the next page where you have the real applications. We modeled 35 different applications and you see in the upper right corner applications where the hydrogen is in the sweet spot. You have heavy duty trucking, you have forklifts, you have taxi fleet, you have cranes, but you also have applications like steel-making or refineries or ammonia that goes into fertilizers. And the upper left corner presents applications from marine, from back-up power, blending hydrogen in the grids, cruise ships, aviation or methanol production. The message here is hydrogen is the best way to decarbonize these applications, but it comes at a cost. That's why they are to the left of the vertical line. So, think of that you almost have ISO lines. The further left you go, the more implied cost of CO_2 abatement you need to have. And it's a simple math that for some of the applications,

It will come at additional cost to decarbonize, but if society is willing to decarbonize these end users, then hydrogen is the best way to go. And also, just to do the back testing, we have, for example, compact urban cars in the lower left corner, which also makes sense because for smaller cars that go short distance, of course, battery is the most efficient way to go because it has a higher efficiency in the energy conversion and lower losses. So that's why it shows up as batteries are better use than hydrogen for small cars.

Let us look at the next page on the global distribution of various hydrogen sources. You have two world maps, the left one where you see hydrogen being produced from low cost renewables, wind or solar. Dark green means that we can produce hydrogen at levels of 2 US dollars or below. And here you see Australia, you see India, China, you see Middle East, North Africa, parts of Europe like Iberia, and you also see Chile, or parts of the US. And on the right side, you see a similar map just with places where cheap blue hydrogen can be produced. So, these are all places where you have relatively low-cost natural gas that you can use to produce hydrogen and then recycle the CO_2 and put that in a carbon capture and storage process. And these are places in Southeast Asia. And again, we have Middle East and North Africa. But you also have countries like Russia that come into the mix or you have parts of Canada and the US. Think of the Permian Basin or the Bay Area in the US where you could produce low-cost hydrogen. And this also explains why this is a global economy. This is not about individual countries, but we see that that we have a new distribution of energy sources around the globe and other societies that are in demand of energy. And Korea belongs to that. Japan belongs to that. And Europe will also be a net importer of decarbonized energy. So, this drives this global momentum between export and import of hydrogen in the future. And while this takes a while, we will not have, for example, liquid hydrogen shipping at scale available for the next few years, we will see a lot of ammonia export happening for the simple use that we can use ammonia as the next best proxy for hydrogen already today.

And just shortly before I finish off on the next slide, I would love to undermine the point that this is happening in ecosystem and here we just selected a handful of projects like you have seen the 228 on one of the earliest flights. And the message that I would love to convey here is a lot of that happens in ecosystem of players along the value chain, that is happening around industrial clusters or ports, that is being used for feedstock in, for example, ammonia production. We see it in the steel sector. We see it in the transportation sector on powering hydrogen trucks. And we see it also in large scale development projects where hydrogen is being produced for future export.

And to finish off on the last slide, I would just love to visualize a small hydrogen economy or ecosystem and we will see more copies of that evolving, where you have, on the one hand, hydrogen production from either renewables or from decarbonized sources of natural gas. We have a transmission system evolving off pipelines together with shipping, and we will have also hydrogen in industrial clusters. Think of methanol production, ammonia, think of refinery decarbonization and then all end users of the likes that that I have shown earlier, from transportation to heat and power, industrially created heat and also applications as feedstock. And that together is what we what we call hydrogen economy or hydrogen society. And that happens on a national level. But that also will happen internationally. And that's also the reason why we see hydrogen as a real energy vector, not just a technical solution. I thank you very much for your attention and thank you for having me.

Kyung Yeol Song:

Thank you, Mr. Heid, for your comprehensive and insightful speech on the current status of hydrogen ecosystem and opportunities ahead.

Now our next speaker is Professor Suk Won Cha. Dr. Cha is Professor of Mechanical and Aerospace Engineering at Seoul National University. He has also served as Associate Dean at the College of Engineering and Office of International Affairs. In the past decade, Prof. Cha pioneered optimal energy management strategies for automotive fuel cell systems and innovative vacuum fabrication process for electrolyte and electrode materials. Among his 150+ writings, Prof. Cha is well-recognized for his co-authorship of the world-wide bestselling book, Fuel Cell Fundamentals. Prof. Cha is the recipient of the Springer Award from International Journal of Automotive Technology as the most cited author.

The title of his talk is “The Fundamentals of Hydrogen Fuel Cells Technology.”

Suk Won Cha:

Thank you for the nice introduction. My name is Suk Won Cha and I'm a professor at the Department of Mechanical Engineering at Seoul National University. It is my great pleasure to give a speech on the hydrogen fuel cell technology today. Here's a little brief introduction of myself. Again, I'm a professor at the Department of Mechanical Engineering, and some of the materials that presented today is actually borrowed from my textbook. So, let me refer to it later as your reference.

OK, so when you talk about the hydrogen economy, everything starts from hydrogen. Ok, so hydrogen will may come from the like green powers, wind, solar, hydro, and then the electricity will through the electrolysis, it'll make hydrogen. And then when we make hydrogen, we will deliver it to the like the buildings or even for the, your homes or the automotive. And the fuel cell actually will exist in those buildings and your cars. And then you will turn that hydrogen energy into electricity and then can be used for your convenience. So, fuel cell is actually a fit as a power source, actually power generator in this hydrogen economy. And then, the most developed countries in the world actually have a really aggressive hydrogen vehicle roadmap. And then recent announcements of all these like examples of these hydrogen vehicles, which uses the fuel cell, has getting popularity. And then you may see around yourself, there's some hydrogen fuel cell cars are driving around you. And then, by like 2030 or 2050, we will see millions of fuel cell cars dispatch around you.

And then, also Korea government has a very aggressive hydrogen roadmap. This is borrowed from the Korean government roadmap. And then, for example, like hydrogen vehicle, okay, we are talking about like 80,000 or some six million in like 20 years. And then also like in four year, the power source for your buildings and your homes, we're talking about some gigawatt range of installations in our future.

So, why we're so interested in the fuel cell? So, a fuel cell actually is famous for, known for high efficiency. And also, it uses hydrogen, so emission you have only water. So, it's clean energy. And also, hydrogen can be renewed so you can generate hydrogen from the renewable energy source. So, we're talking about this use of hydrogen as a fuel and the fuel cell will power your like buses, automotive, personal vehicles, trains, large-scale power station or small-scale power station, even drones and ships around us.

So, let me discuss a little bit more into the fuel cell itself. OK, so what is fuel cell? Fuel cell, you can think of it as a black box. We put hydrogen and oxygen, then it generates water and electricity. So, basically, it's so-called electrochemical. OK, so energy device, a conversion device, that means it converts chemical energy of hydrogen and oxygen into electricity. So, when you talk about like heat engines, which drives your automotive these days, the hydrogen chemical energy turns into the thermal energy. So, that's why it's called heat engines. And then, the thermal energy turns into mechanical energy, and then it turns into electrical energy through the generator. So, the losses are associated in each of these conversion steps. But fuel cells directly convert this chemical energy into electricity. So that's why it's famous for its high efficiency.

Here's a little cartoon. OK, compares the fuel cell versus battery versus the combustion engine. Again, this is a combustion engine, convert this chemical energy into heat energy and then mechanical energy, then it turns into electric energy. Fuel cells basically convert chemical energy directly to the electrical energy, so has high efficiency. Actually, the battery does the same thing. So, it also converts the chemical energy into the electrical energy. But the major difference between the battery technology and the fuel cell technology is like this. This cartoon explains it. Battery actually has the fuel inside this closed case. So, when you have the reaction in the battery, the electricity goes out. So, it's a closed system. But the fuel cell is so-called open system. So, you have the fuel tank, okay, and then fuel cell. So, it's similar to combustion engine, which has the engine and then thank. So, you use the fuel from the fuel tank and then it is supplied to the fuel cell, or you can supply to the engine and then you make electricity or mechanical work. So, a fuel cell is close to combustion engine and then it's an open system. So, it's open and the fuel can be provided. So, this is like a major difference between and then the similarity between the battery and fuel cells. So, fuel cell itself is somewhere in between technology, between battery and then our combustion engines.

And then, if you compare the photovoltaic or solar cell – it is also well known as renewable energy source – and then the fuel cell, then both of the system is the open system because you provide sunlight, the photovoltaic device, and then it'll generate the electricity. Fuel cell also provides fuel, then it generates electricity. The major difference is fuel cell has higher, basically, power density. That means it requires a smaller area or a smaller footprint. So, like the area, like a city area, fuel cell has much more advantages just because it provides more power from the small volume or space.

Okay, let me talk about a little bit on the efficiency of fuel cell, because the fuel cell is famous for its high efficiency. This is an example of the hydrogen fuel cell. Around room temperature, according to thermodynamics, it turns out that the Gibbs energy, the ratio between the hydrogen reaction and the Gibbs energy versus the enthalpy gives you the efficiency. Typically, you'll have something like close to 80 percent efficiency if your fuel cell is ideal. The Carnot cycle means it's a heat engine. So, the efficiency of heat engines depends on the heat source. But if you go to a higher temperature, also like this ideal heat engine, you can have a higher efficiency. But anyway, the fuel cell is inherently directly converting, OK, so has a high efficiency.

But in case the real fuel cell is not a true story because the ideal hydrogen fuel cell, OK, like 80 percent efficient hydrogen fuel cells are supposed to generate something like 1.2V. And then, this is typical characteristic of fuel cell. Fuel cells generate electricity directly from chemical energy. So, it has the voltages and then it has the current. So, it's like operation of a battery. If you have ideal fuel cell, it should have generated like fixed 1.2V, regardless of your, the current, how much current you draw from your fuel cell. But because there is some internal, inherited internal losses, typical fuel cell behaves something like this. So, the difference between the ideal voltage and this actual voltage is the loss inside the fuel cell. So, if this is ideal, should show 80 percent efficiency, but typical fuel cell reduced, the efficiency reduced down to something like 50 percent, around 50 percent. So, that's the real power fuel cell.

And also, the fuel cell generates power. So, from your physics class, I think if you remember still, the power, OK, is current times voltage. So, if you multiply the current and then voltage value here, you will get a new curve something like that. And then, this is the power curve represented at this line. So, fuel cells generate power. That's the basic operation of the fuel cell.

OK, this is the first hydrogen fuel cell, OK? Actually, it dates back to like more than 100 years ago. So, the first fuel cell from this old drawing was invented by Sir William Grove, a scientist from England in 1839. OK, so this is his first patented design. So, during that time, he invented this first fuel cell, which has this sulfuric acid as the electrolyte and then has the platinum rod as an electrode. So, there is two electrodes on your left and right. And then for one electrode we provide hydrogen and then the other electrode we provide air or oxygen. Then what happens is, at the hydrogen side, which call, we call it anode, OK, the oxidation happens, which loses electrons. OK, so hydrogen turns into proton and electron. The ion of the hydrogen is basically proton. So, it loses electrons and then when it loses, turns into, the hydrogen turns to protons and electrons, hydrogens travel through this electrolyte, which is sulfuric acid. So, this electrolyte is basically ionic conductor. OK, so in this case the proton can conduct. And then electrons, OK, go through this electrode and then go to outer circuit and then do the work, and then return to the oxygen side, which we call it cathode.

And then, at cathode side, the chemical reaction called reduction happens. So that means it gains electron. So, oxygen here, the oxygen bubbles and the proton, hydrogen ion combines with electron and that turns into water. So, if you add these two reactions together and then you just simply have the entire reaction of hydrogen and oxygen, they meet together and combine and becomes water. So, it's a very simple device. But through this chemical reaction, somehow you reroute the electron and then make electrical work. So here what we can see is the electrolyte, which is the ionic conductor and then electrode, which is where this reaction happens, right? This oxidation or reduction happens at the anode and the cathode. So, this electrode and the electrolyte is very important key device in the fuel cell structure.

But the modern fuel cells, it is a totally different story. So, because these are all the liquids, and then this is bulky, and the handling is tough, and also, it's a very large device. So modern fuel cells, we have something called membrane-electrode-assembly (MEA). So, we have the membrane, which is basically the electrolyte. It's very thin and solid membrane structure. And then we have also the electrode. We need electrode. OK, the anode hydrogen side or cathode oxygen side. So, we have a really thin structure. In modern fuel cells, to increase the power density, we have a very small and thin structure. So, example of the, when the electrolyte is polymer made with the carbon electrode or some of the, famous, the solid oxide fuel cell (SOFC) company made by Bloom, I have the oxide, this kind of oxide-based MEA. So, modern fuel cells have more like a very thin membrane structure.

But also, fuel cells have to be large because it's a power device. We need a large area and big device. So, all these MEAs, OK, these NEAs, anode, electrolyte, and cathode structure is combined together with some sealing gaskets for hydrogen sealing and oxygen sealing, and some of the flow-providing structure which is called bipolar plate. They are assembled together, and then they make something called a fuel cell stack, which is a very large device like this. And then in this fuel cell stack, each of the fuel cells are serially connected. So, I said like, a fuel cell may generate something like hydrogen fuel cell, may generate something like 0.6V, then they are serially connected in like 50 or even 100 cells and then they generate a very high voltage.

Let me discuss a little bit on the fuel cell types in modern technology. OK, so this sounds like me like an alien language, or fuel cell people use all these observations, something called like PEMFC, PAFC, or AFC, or MCFC, or SOFC. FC means fuel cell, but this PEM, all these PA means the name of the electrolytes that each fuel cell uses. For example, PEM means proton exchange membrane or polymer electrolyte membrane. So, it basically uses the polymer membrane as an electrolyte. PAFC means that it's phosphoric acid. So, it has liquid phosphoric acid utilized as an electrolyte. Alkaline fuel cell AFC means that it uses alkaline liquid as an electrolyte. MCFC means that it's a molten carbonate. Molten carbon is used as electrolyte. Or, solid oxide, which is a solid oxide or a ceramic material is used as the electrolyte. So, all these different electrolytes have different ionic conduction through the electrolyte. And then these fuel cell types are basically determined by the use of the electrolyte, so named after the electrolyte. And then because of all these different electrolyte technologies, the operating temperature is sort of optimized, determined for the proper operation for the electrolyte. So basically, electrolyte determines the traveling ion species and all the operating temperatures, and all the rest of the materials. The components of the fuel cells are decided by basically this operating temperature. So, electrolyte basically determines the types of fuel cell.

And then let me briefly explain a little bit on the details on each technology. For example, phosphoric acid fuel cell. It's already well-commercialized and then has some moderate success. So, this is the example of actually the power plant site in South Korea. And then it's a relatively easy technology and then it has well demonstrated up to a large scale. So, it's widely used as like stationary power plant.

And then, alkaline fuel cell, it has some disadvantage because it uses liquid electrolyte of the alkaline solution. It may react with carbon dioxide. It has very high limitations of using pure oxygen without any carbon dioxide. So, it has limited success in space shuttle missions.

Molten carbonate fuel cell also has a long history. And then some of the large scale up to the megawatt power plant has been demonstrated, and also, it's commercialized. It has a low power density but is suitable for the hot, because it operates at a very high temperature. It has a very high efficiency using the combined heat as a combined heat power system, so has a very high efficiency, and so has a moderate success also in the power plant market.

Solid oxide fuel cell. It uses the solid oxide electrolyte and then it operates at very high temperature, something like close to 800 Celsius, and then it uses all different types of ceramic materials. And then recently, it is gaining popularity as a power source like some of the stationary power source, for the buildings, Bloom Energy or even some STX Korean company is producing like small-scale and large-scale stationary power systems.

And then, PEMFC is basically made of the polymer electrolyte, and it has the highest power density. So, it's very suitable for like automotive application, mobility application, and also the small-scale stationary power generation. So, its market is growing really fast for these proton exchange membrane fuel cells.

OK, so far, I have explained some basic information about the fuel cell technology, but the one thing that you have to remember is that fuel cells have to be large because it is a large-scale device, power generation device. But fuel cell also needs to be small. So, I'll explain this concept with some of the actual research that I have been conducting for the past decades. It’s about ultrathin solid oxide fuel cell.

For example, in fuel cell structure, you have the electrolyte, I explained it as MEA, electrolyte, and then this catalyst, electrode structure. So, typically, this conventional electrolyte, for example, as a solid oxide fuel cell have some like tens of micrometer scale thick. The problem is, when you have this thick electrolyte, we will have some internal loss, so-called Ohmic loss. The ions have to trouble through this electrolyte and then there is a voltage drop. So, when you have the thick electrolyte, you will have more voltage drop. OK, so the idea is you can decrease the electrolyte thickness up to like a nanometer range. So, it will greatly reduce the internal loss. And then also, when you talk about the electrode, when we have these large-sized particles versus very small-sized particles, the electrode structure, then these small particle structure has much higher surface area. So, we are talking about like from the micrometer-range size to nanometer-range size. Then also it has a similar effect. You will reduce the internal loss, or internal voltage drops coming from the electrode. Also, you can increase the voltage and then make the fuel cell operate close to the ideal voltage.

So, here’s some example, which was that my laboratory has developed. Compare this conventional solid oxide fuel cell structure versus this thin film structure. So, from the like 20 to 200 micro range, to like 28 nanometers to one micro. So, it's like about 100 times scale reduction. So, we'll have definitely some advantages. The question is how you can do it.

So, what we have adapted is basically the nanoscale thin film process. Actually, the various thin film processes have been developed from the semiconductor industry. So, we are adapting those technologies. For example, the physical vapor deposition technique or the pulsed laser deposition technique or even atomic layer deposition technique. So, all these thin film technologies can deposit metals and the oxidized material in a vacuum environment, and then we can physically deposit or atomic layer deposition worth in the chemical deposition method.

So, here’s some example of what I've developed. OK, so all the structure, OK, you can see the cross-section, you can see that it's in hundreds of nanometer range. So, hundreds of nanometer scale electrode supported by the porous anode structure which resides in the porous substrate and also the cathode structure and the interlayer. So, we have some details of the materials and solid oxide filter materials, which are going to skip for the moment.

What you can see, like even if you make like a very thin film structure, this is some example of the like, the poorly made structure versus well-made structure. If you make, have like some process parameter is not adjusted properly, you can have something like very coarse structure which is not suitable for as electrolyte structure. But in this case, we utilize something called atomic layer deposition technique, and then we generate really fully dense. Even in nanometer scale, you can see all the structure is very dense and is suitable for as a dense electrolyte.

And also, the electrode, OK, by technique called co-deposition technique, deposit metals and oxide together in the vacuum-assisted environment. And then you can make this kind of very interesting structure like in nanometer range. It has a very high surface, like a flower-shaped structure mixed with oxide and metal from the surface. And this is a cross-section view. So, these types of structure actually exhibit extremely high activity and then reduce the internal loss. So, some of the test has been conducted. So, it's like the voltage and the current curve. And then we use the hydrogen fuel or even methane fuel. Methane fuel is reported as like, can be operated a really high temperature, something like 700 to 800 Celsius. But we can because of the high activity of such the catalyst, we can reduce the operating temperature to something like 500 Celsius. So, 200 Celsius below the normal operating temperature. Also, if you compare the performance between the hydrogen and the methane, it’s very similar. So, we can see this, the activity of the catalyst and electrolyte, such a thin film structure shows a very high performance through a very thin film and thin film structure.

And another example is the, we added another, on the MEA structure, we added something called reforming. So, it will turn the methane into the hydrogen and then the hydrogen fitted into the fuel cell. So, it's like two devices combined together. And then if you look at the performance, such a thin film structure with a high surface area, the catalyst or electrode material shows a really high performance, one of the best reported in the world. And also, with the help of such a high surface, the catalyst structure, the electrode structure with the thin film process, we can also make this, turn that methane into the hydrogen at very low temperature and also with a low temperature. And then it also showed one of the best results reported in the world. OK, so thank you very much. Thanks for listening.

Kyung Yeol Song:

Thank you, Professor Cha, for your insightful presentation on the principles of fuel cells, their types and implications.

Our next speaker is Professor Ki Tae Nam. Professor Nam is Professor of Material Science and Engineering at Seoul National University. His research interests are bio-inspired nanomaterials and artificial photosynthesis. He spent three years at the Lawrence

Berkeley National Lab as a Postdoctoral Fellow, working on the peptide mimetic materials, before joining Seoul National University in 2010. Recently, he was awarded "Young Faculty" Presidential Award.

The title of his talk today is "Hydrogen Production Inspired by Nature."

Ki Tae Nam:

Thank you for the nice introduction by Dr. Song Kyung Yeol. So, first of all, I would like to thank the Chey Institute for arranging such a nice global opportunity for the discussion about our hydrogen. Truly, I believe that for the hydrogen economy, we need global collaboration to facilitate the hydrogen economy. Also, it was a very nice presentation by Bernd Heid from McKinsey. Also, we will have a good presentation from Andy from the United States. Interestingly, Germany, the United States, and Korea are the most active countries in hydrogen research. So, I'm very excited to be part of this nice discussion about hydrogen economy. So, today my talk is about the simplest but most important reaction. That is, water splitting for hydrogen production. It's a very simple reaction. However, we need a scientific breakthrough in this research field. So, I'm a material scientist. So, today I will show you how material innovation can be useful to make some cleaner and cheaper hydrogen. So, my research is inspired by a biological system. Today, I will show you how biological principles can be translated into the synthetic technology.

So, I want to start my talk with CO_2, because I believe that the hydrogen economy is necessary and mostly driven by the CO_2 issue. So, today we produce a lot of CO_2. Globally, we produce about 8 billion tons every year. That's a lot. So, if you convert that value, in Korea every person produces 1 ton of CO_2. So, if you imagine the volume of 1 ton of CO_2, that's a spherical balloon with 10m in diameter. That's such a large volume. So, question is for the carbon neutralization, 'Is there any way to convert that CO_2 or to capture that CO_2?' For example, there is a lot of discussion about CO_2 capturing, but I think that CO_2 capturing may not be the ideal solution. So, for the CO_2 capturing, we can use carbonate or you can use amine. For example, if you convert CO_2 into the calcium carbonate, in New York City, we have to make such a big mountain-like calcium carbonate deposit. So, I want to say is that CO_2 capturing is an intermediate solution, but for the carbon neutralization, it may not be an ideal solution. So, if you break down the emission of CO_2, 45% is from the burning of fuel and the 28% is from transportation. When you drive a car for 1km, every car produces about 100 grams of CO_2. So, to reduce the CO_2 emission, we need some breakthrough in the transportation system and the energy system. So, in this regard, the hydrogen economy as should come to convert CO_2 or to make a new breakthrough in our transportation system based on the hydrogen car.

Today, there are many methods to produce hydrogen. One of them is blue hydrogen, which is a very promising method. But I want to emphasize that blue hydrogen still produces CO_2. So, blue hydrogen is based on a simple chemical reaction starting from methane and then reacting with some steamed water to produce hydrogen. But as you can see, that figure always results in the production of the CO_2. Of course, that~~'s~~ CO_2 is centralized, so if we have some good CO_2 capturing system, you can efficiently remove CO_2. But as I said, it's not a fully environmentally friendly or sustainable chemistry. Because of that reason, there are a lot of discussion about green hydrogen. That's the simplest reaction. The history is a very, very long. Even in 1833, there are some reports in the literature. This figure shows Faraday. Faraday is a famous scientist who discovered electricity and developed a lot of the laws about electricity. So even in his book, he has a very detailed description about the detailed mechanism and the detailed setup about water electrolysis. So, water electrolysis is a very simple reaction. In Korea, even in elementary school students do that experiment. It is based on two reactions. Two electrodes, the cathode and the anode. At the cathode part, the proton is reduced to generate hydrogen. And at the anode part, water is oxidized into the oxygen and the proton. It’s a very simple reaction. Because of its simplicity, long time ago, even 200 years ago, we had a very successful demonstration of hydrogen production from water electrolysis. But what's the problem? The problem is the cost. We need energy, especially we need electricity to split water. Because of that cost issue, still we don't see a lot of green hydrogen from water.

Let's do some simple calculation. It's a graph. I can explain very easily, very simply. So, this is a typical electrochemical data. The x-axis shows you, I will show you, the potential. And the y-axis is the current. You can understand that. So, when you apply a potential, above a certain potential, we get some current. It means that the reaction starts happening. So, a current is flowing through the circuit. The current indicates that some reaction is happening at the cathode and the anode. That's hydrogen production and then oxygen production. So, if you multiply the x-axis and the y-axis, you get power because voltage multiplied by current is power. We have watts. And then, if you know how long we operate that electricity, we get the total energy. And the y-axis is directly corresponding to the hydrogen production. So, if you develop a good catalyst, the curve on this graph is moving to the left side. It means that at a lower potential, you get the same amount of hydrogen. So, it means that you can decrease the total energy required to produce a certain level of hydrogen. Based on that simple calculation, we can calculate how much energy is required to produce hydrogen. So, the DOE (Department of Energy) target in 2021 is about 43 and we expect that we will produce hydrogen in 2050 at 42 to produce 1kg of hydrogen.

Let's do a simpler analysis about that equation. It's an equation but not difficult, very simple math. In order to get that kilowatts per kilogram of hydrogen, we need power, voltage multiplied by current, and current is corresponding to hydrogen production. And from that simple math, we can easily find out that the energy efficiency is directly depending on the potential. A potential has three components. One is the thermodynamic potential. And then there are three more components of the potential, the cathode, the anode, and then the systematic potential. So why is this necessary? In order to get cheaper hydrogen, we have to decrease the potential. That's our scientific challenge. And then in order to do that, we have to understand the origin, and then we have to decouple each factor. That's our approach. Thermodynamics suggests that for water splitting, we need 1.23V. If you only consider that thermodynamic value, the theoretical minimum energy required for hydrogen production is 32kWh. What is the price of the electricity in Korea? At my home, 1kWh is about 10 cents. And if you plug that number, you can easily find out that in Korea, in order to get 1kg of hydrogen, you need about 3,000 Korean Won. It is about three dollars, which is very expensive. But that is only considering thermodynamics. There is another component of potential, the cathode and the anode. But interestingly, although our focus is about hydrogen production, most of potential is applied in the anode part, about 70% or 80%. I want to remind you that at the anode, water oxidation is happening. So, the counterreaction is determining the overall efficiency. So that's the reason a lot of people are working on the anode to get cheaper hydrogen in electrolysis.

So, to tackle that problem, we have to think about the way to couple our electricity with sustainable energy sources, including the solar cell. So, we can do some simple math. For example, the x-axis shows what's the price of the electricity generated from the solar cell, and the y-axis shows the kWh/kg that I mentioned in the previous slide, so if you multiply these two numbers, we get how much money is required for the production of hydrogen. A few years ago, solar cell electricity was about 0.1 dollar per kilowatt hour, and then that electricity performance is about 50 something, in this case, about 4 or 5 dollars to produce a kilogram of hydrogen. But as the price of electricity produced by solar cells keeps decreasing, you can see the price of the hydrogen from the sustainable energy source has become economically feasible. For example, there is a line, which is about 2 dollars. We think that's the point where green hydrogen can compete with blue hydrogen. In our group, a few years ago, as an effort to couple these two technologies, we made a world record in solar-to-hydrogen conversion efficiency. Our record is about 20% solar-to-hydrogen conversion efficiency. But although it looks very simple, it's not easy. For the efficient coupling between solar cell and then water electrolysis we have to have very careful engineering about the interface, including the DC/DC converting system.

But that discussion is about just electricity. But there is another issue in material cost. The anode material is mostly composed of ruthenium and iridium, and also titanium. Titanium is a cheaper material. Commercially available anodes are very expensive. They are about 4,000 dollars per $1m^2$. That's very expensive. Why? Because of the prices of ruthenium and iridium. Specially, iridium is very expensive, much more expensive than platinum. But in commercially available electrolyzer, we cannot make electrolyzer without iridium. That's the problem. Because iridium guarantees good stability and good efficiency. But why is iridium expensive? I expect the iridium price to keep going up. Why? On our Earth, the total iridium deposit is 400 tons only. Annually, we require 7 tons of iridium. Iridium is also a very useful material for OLED production. So, as OLED production is going up, I think the iridium price will be going up. And iridium is mostly produced in South Africa, in that area. That's the big issue.

So, to tackle that problem, there is an economic issue, and there is a material issue, science is very important. We should understand the molecular level and from the molecular understanding, we can make a breakthrough. So, the current electrode is based on a very simple reaction. The water molecule is coming in, as I show you, and it generates an oxo in combination with another water molecule. Scientists already know that the O-O bonding is the rate-determining step. However, if you compare all the materials for the OER, oxygen evolution reaction, at the anode, and the HER, hydrogen evolution reaction at the cathode, PT (platinum), iridium, and ruthenium are good. And for the past 20 years, science did not make a big breakthrough in this development of a new catalyst. We can make a transition-metal-based catalyst, but it's not sustainable. Not sustainable means it’s not stable. After a few months, it will degrade very quickly. Still, platinum and iridium are the winners. So, what can we do?

We can learn lessons from biological systems. Why? Biological systems evolve gradually and they optimize reactions. So, from photosynthesis, we can learn a lot of things. Here are two examples. So, the left image is the bacteria, and the right is a leaf. From the photosystem, we can get a lot of energy. So, plants and bacteria convert solar energy into glucose, and we eat them. So where is the source of those electrons? Those electrons are from water. If you look at the details, there's a membrane, a very complex structure. There are a lot of energy systems and there is also the photosystem. And our focus is on this part. That is one of the most exciting systems existing in biology. Why is it interesting? That's the best water oxidation catalyst to convert water into oxygen. As I said, it's a counterreaction for hydrogen production. Interestingly, biology uses only 4 manganese and 1 calcium surrounded by protein, that is carbon. Although our synthetic technology, we use platinum and iridium. But biology uses manganese and then performance is much better than Iridium and Ruthenium. That's the beautiful part for biology. So, very difficult problem. So, what can you do?

So previously, I showed you the water oxidation mechanism in our synthetic catalyst, but this is a mechanism that happens inside a biological system. They have 4 Manganese, the 4 manganese keep moving then continues to change the valency and then, the water molecule is inserted between the 2 manganese. Very beautiful mechanism. In the world, no one has ever successfully demonstrated or mimic that kind of mechanism in synthetic technology. So, I believe that that's the most important reaction for the future. So, what can you do?

So, it's a very difficult problem for scientists. When you face that difficult problem, we have to a breakdown each question. So, that's the several lessons that I want to address. And for the past 10 years in my group, we made some slow progress about this approach. So, lattice distortion is important, entropy is important, controlling the manganese valency is important, and controlling the activation of lattice Oxygen is very important. I think that also others groups made another list of lessons.

So, to translate that principle, my group started from the Manganese Oxide (MnO) Nanoparticle. It has heterogenous character and homogenous character. So, it's a hybrid catalyst. Like heterogenous catalyst, we can easily deposit it on the surface of the nanoelectrode. And then like a homogeneous catalyst, we can do very fine tuning at the atomic level. This is an example of our Manganese Oxide Nanoparticle. So now, you are looking at each nanoparticle using the transmission electron microscopy. So, let's take a closer look at it. It's beautiful. What can you see? Each dot is a manganese atom, and then inside the bulk has a very symmetric crystal structure. However, if you look at the surface, this is a very distorted crystal structure. I discovered that that distortion of the manganese atom is very similar to the manganese calcium cluster that exists in the biological system. So, using that interface, we do some science. We do some surface modification. So, I will show you some example about some beautiful science.

So, this is our approach. So, different some synthetic catalyst, usually human beings are working on the symmetric crystal environment and that's the conventional approach. But if you look at the biological system, it has a very distorted structure. And in order to realize that distortion on the surface of our nanoparticle, we do some surface chemistry. Now, based on that, we found some experimental evidence that using this platform, we can really mimic the biological system. So, here is some example. On top of nanoparticle, you can see some bright dot. Each dot is an individual atom. Now, you are looking at the atom using the transmission electron microscopy. So, for the detailed analysis, (I will show you some brief example) we decorate our manganese oxide nanoparticle with Nickel. So, using very simple chemistry on top of the Manganese Oxide nanoparticle, we decorate a single atom of Nickel. Based on this approach, for the first time, we discovered a low-spin Manganese IV. So, before this work, all the people only observe the high-spin Manganese IV. So, spin is electron. So, low-spin means that compared to high-spin, the total spin number was decreased a lot. What is the science here? So, using the spectroscopy technique, we got some clear evidence of the low-spin. So, why is it important?

So, in biological systems, spin configuration is the one of the most important principle used in biological systems. So, we demonstrate low-spin synthetically in our catalyst. So, this is some evidence.

So, there are two possibilities for the low-spin, depending on the energy level. So, we can do some spin analysis. So, we discovered, different from those symmetric octahedral geometry, we can compress into the z-direction. As a result, the energy level was split. So, different from the conventional high-spin state in synthetic catalyst, for the first time, we realized that low-spin configuration in our system. So, I believe that this is a starting point. There are many, many opportunities to generate different orbital structure in our system. So, using the DFT calculation, we confirm our understanding. And then, after analyzing this detailed molecular mechanism at the atomic level, we develop some other theory.

So, in catalyst design, resistance to the system is also important, as I showed you before. So, we can deposit our electron on top of our Manganese Oxide nanoparticle. So, as you can see, you can see some array of nanoparticle. So, electron and proton should move through that interface. So, why scientists do that? So, from that understanding, we can significantly enhance the catalyst activity. So, we made some deposit in our nanoparticle, the manganese oxide. We developed very simple circuit model composed of resistance and capacitance. And using this simple circuit model, we can apply to some AI algorithm to understand the proton electron transport and the cooperation of that proton electron transport is very important. And then from that analysis, we can significantly lower the overall resistance that applied inside our electrode. So, based on there, we can identify important kinetic parameters: resistance, capacitance, reaction intermediate. And then, I want to say that all of them is from the simple AC measurement. I want to emphasize that that kind of AC impedance analysis is also important for lithium ion batteries; it is generalized for the other electrochemical system. That's a good starting point. And based on that, we can identify kinetic parameter. And then from there, we can also observe turnover frequency and then we can compare the turnover frequency with other Lithium and Ruthenium material.

And then, in addition to that kind of analysis, also in our group these days, we are working on entropy. So why is entropy important? So, to increase the efficiency, some high temperature or elevated temperature electrolysis operation is also important. So, Gibbs Free Energy is delta G = delta H - T delta S. So, if we look at 'T', 'delta S' is important. So, in order to predict some Gibbs Free Energy change depending on the temperature, understanding of entropy is important. But if we look at the biological system, entropy is controlled very precisely. I want to emphasize that aspect. So, for the electrolyzer system, also, we have to consider that entropy in addition to the enthalpy. That enthalpy analysis has been done for the past 50 years. So, based on that kind of engineering and scientific innovation, so our Oxygen Evolution Reaction (OER) Catalyst is world-best, much better than Iridium Oxide. So, our overpotential is below 300mV. So, we have a world record, but there is a lot of room for improvement. So, we have to solve that stability issue.

So, from my talk, I will deliver that lesson. So, water electrolysis still requires scientific breakthrough. And then, water oxidation is kinetically the slowest reaction. And then, in order to improve the catalyst activity, in addition to the catalytic cycle, electron transport and entropy effect are all important. And then, my challenge is that our ideal thermodynamics suggests that 32kWh is a limit. So, the question is, within 10 years, is there any scientific breakthrough to set our new target, for example, 30kWh. That's our target. I want to make some breakthrough for that analysis. I like to acknowledge all my collaborators and students. So, again, I'd like to give thanks for giving me such a great opportunity to share my research. And then, thank you for listening.

Kyung Yeol Song:

Thank you, Professor Nam, for the presentation. Many of our audience are interested in breakthroughs in water electrolysis, and nature continues to inspire us in this area as well.

Now, let me introduce our final speaker, Mr. Andy Marsh. Mr. Marsh has served as President and CEO of Plug Power since April 2008. He identified material handling as the first commercially viable market for Plug Power's business in hydrogen economy. Today, the firm's fuel cell solutions are leveraged by world leaders such as Amazon and Walmart, to power industrial hydrogen electric vehicles. Mr. Marsh continues to spearhead hydrogen fuel cell innovations, and his ability to drive revenue growth 300 percent has landed Plug Power on Deloitte's Technology Fast 500 list in 2015 and 2016. Internationally, Mr. Marsh represents Plug Power in their role as supporting members of the Hydrogen Council, a global initiative of leading energy, transport and industry companies.

The title of his talk is "Get Ready for the $10 Trillion Dollar Hydrogen Economy."

Andy Marsh:

So, you know, today I'm going to provide you an introduction to Plug Power. Probably everyone in Korea doesn't know about what Plug Power has accomplished. And look, I know a lot of the speakers went through the importance of hydrogen infrastructure for the carbon neutral society in the future. I'm an engineer, not a scientist, like some of the distinguished speakers before me. And I like to talk about the applications that make hydrogen real today. And look, it's not a skate to the end world. There are opportunities and challenges in the present and future energy market for hydrogen. And I'd like to take a moment to speak about that. But let me start off by talking about my favorite subject, Plug Power. And Plug Power for those who don't know, is located in upstate New York, real close to where Edison started working on electricity back many, many years ago. We've been around for 24 years. We have 180 patents. Lots of employees, 1,400 folks focused on fuel cell and hydrogen. I think the item that really distinguishes us is that we have operated our fuel cells in some incredibly tough applications as we've developed, as the introduction mentioned, the first commercial market for fuel cells. Putting them on forklift trucks for customers like Amazon, Walmart, Home Depot, General Motors. And now there's over forty thousand of those units running around the world. And in the United States during the COVID crisis, more than 25% of retail food moved through Plug Power products.

But the number that always strikes me is we use over 40 tons of hydrogen daily. We are the largest user of liquid hydrogen in the world, surpassing NASA about two years ago. We've deployed over 110 fueling stations and distribution centers, which are used and we are adding another 60 this year. And as I mentioned earlier, we touched almost every citizen in the United States during the COVID crisis. But we're much more than material handling. During that journey, we developed a full slew of capabilities. And that slew of capabilities included to manufacture our own MEA (Membrane Electrode Assemblies) and we're building a Gigafactory in Rochester, New York, which will be the largest MEA production facility in the world. And we plan to duplicate another one in South Korea with SK. And that facility will not only make PEM (Proton Exchange Membranes) MEAs for fuel cells, but for electrolyzer and comes online in August of this year. On top of that, we have products for mobility. We have products for large scale stationary products. We also made two big bets last year which have been rewarded by the market. One of those bets was we bought the first private company to build a large-scale liquid hydrogen plant. And we also bought the company which is renowned for its electrolyzer PEM technology. Now, having worked in the space for over 47 years with NASA and other deployments, that company, if you go to look at the DEO website for work that's been done by Giner, is renowned as having the world's best 10 electrolyzer technology. And you know, Plug has developed the first commercial market and we intend to be a leader in this hydrogen transition. We're not going to do it all alone. But as you can see, we're deeply involved in power generation. We're deeply involved in transportation and hydrogen generation.

Just to talk about a few partners. Group Renault, which has deployed hundreds of thousand light commercial vehicles in Europe using BEB (battery electric bus) technology and Plug came together to form a joint venture core idea, which is the first products will be leveraging their master brand product to develop products that will be used for moving goods, as well as products that are meant for moving people, like at airports. This JV with Renault, which is a vehicle JV, not just a fuel cell JV, is focused on by 2030, Europe is targeting over 500,000 light commercial vehicles on the road and our JV idea is targeting over 30% in that market. It's real. It's today. And that JV has been born. In Spain, we're working with Acciona. As many folks know, Spain has many, many low-cost renewable assets based on the sun shines a lot. And with Acciona, a large utility provider in Spain, we're looking to provide 20% of the hydrogen energy required in the Iberian Peninsula. It's an exciting program. What's really interesting is some of that hydrogen which will be developed for Acciona will also be filling light commercial vehicles manufactured by JV in Spain. And our good, good partner, SK, we have a wide range of opportunities we're looking at. Everywhere, from stationary products, to on road vehicles providing engines, to fueling stations that are electrolyzer offering. In my mind, we couldn't have picked a better partner for Asia than our friends at SK, who also made a substantial investment in Plug Power and owns over 10% of our company today.

One of the items that really excites me and actually really excites our investors is we're building the first green hydrogen network across the United States. We're looking to leverage hydro power, solar power, wind power. One of my favorite projects is actually in New York, where we're looking to leverage Niagara Falls power, just like George Westinghouse did, to develop the first Large-Scale Electrical Network in the United States to use as the feedstock to power Plug Power electrolyzers to build the largest green hydrogen plant in the world. And that system/network will generate 45 tons of liquid hydrogen, which will be distributed across the United States to many of our customers.

We recently announced a green hydrogen project in Camden, Georgia. Out a little bit west of Fort Worth, we're building a green hydrogen plant using wind power, which will generate 45 tons of liquid hydrogen a day. And over on the West Coast, we brought top property to build a solar farm in California, which could generate between 45 to 60 tons of liquid hydrogen day. By 2025, Plug Power will have a network across the United States that will provide over 500 tons of green hydrogen a day to meet our customers' needs like Walmart and Amazon. So, really exciting work going on. And globally we're targeting by 2028 to have over 1000 tons of green hydrogen capacity. And Plug Power has the balance sheet to make this all happen with at the end of the first quarter, close to five billion dollars on the balance sheet and strong support, especially here in the United States, to build out this network.

So, let me turn to something that I know that most of your audience has heard about a lot this morning, the importance of hydrogen infrastructure for carbon neutral society. But I don't know if one of my friends showed this or not, but this is a slide that shows four significant items to reduce global emissions: from power to transport to industry and building. And hydrogen and Plug Power has a position in all these areas. With SK, we hope by 2025 to develop over 400 megawatts of stationary power. In the United States, to just have a feel, I was doing a discussion with my employees yesterday, we over have over a hundred opportunities in the funnel for our stationary products today. It's a significant market opportunity for Plug and for this industry. In the transport, I talked about work with Renault. And I'm sure I know our speakers and I heard Bernd talk about it. But there are certain applications - fertilizer manufacturing, steel manufacturing, concrete manufacturing - in the industrial space where the only roadmap to reduce global emissions by 24% for CO_2 is by leveraging hydrogen. And finally, we're beginning to do some of this work here in the United States and globally, that looking to inject hydrogen into the natural gas pipeline to start moving in that long-term trend of decarbonizing building heat as well as other functions.

And, you know, I think this is a real estate. So, when you think about everything I talked about with hydrogen, producing hydrogen with our electrolyzers and distributing hydrogen, even though we're not a large company, in some aspect I have more assets in the field here in North America to back up facilities with hydrogen than any other company in the country. With over 170 fueling stations by the end of the year, we're also obviously experts in dispensing. And what really has surprised me is we're actually more sophisticated in monitoring/maintaining your hydrogen network than traditional industrial gas companies. When I think about green hydrogen, it is the great accelerator of many applications.

And here is our picture of work that we're doing with people like Amazon. In the lower right-hand corner, what you see is a material handling equipment, which is moving goods in their warehouse. And it could be robots, Plug Power low power fuel cell technology. We're building outdoor fueling stations for companies today where they can pull up and fuel vehicles, which leverage Plug Power fuel cells. And that vast green hydrogen network, from distributing hydrogen to generating hydrogen, Plug Power already in that business today. And we have massive expansion plans to support this rapid growth in green hydrogen. And you know, I just like to mention we have the products that can do it today. And in our fuel cell products, we leverage our ProGen module.

And I think a lot of discussions have been scientific today. Let me tell you how I think about fuel cells and all of these applications. I think a lot about how the diesel generator market development. The diesel generators that backup data centers also generators that run class A trucks, the diesel engines that run trains, are actually the same technology and the same building block. It's really how one is attacking the market for fuel cells for five based platforms that can provide low power all the way up to large scale modular stationary power systems. And plug has all this technology to deploy and we've done work in all of these areas. It's a business that, without this capability, without having these modular, scalable offerings, you're not able to produce a scale. But also, it limits your ability to innovate. Now, when I look at one market that we're doing a lot of innovation in today, it really is our technology platform, is really looking at the aerial aircraft industry. We have opportunities today where Plug Power has actually made investments in regional aircrafts to convert them to fuel cell and hydrogen. In regional aircraft fuel, fuel cells because of their lightweight higher energy density make a lot more sense than batteries. But we're actually using that as a platform to advance our technology. As you look at how you develop lower weight technology, higher density technology, that technology we're developing for the aerial space ultimately will leverage into on road vehicles and other applications across the board because of the value of high efficiency, high power density and light weight is always an attractive feature when you're talking about power. And I can tell you, I'm a power electronics engineer, and that mantra has been the same for over 40 years.

We also have a full range, again, when you think about how we think about these markets. We think about platforms. We have platforms which can build megawatt scale plants, which we're using in Genesee County. We're using 135 megawatts of our electrolyzer platform, designed and built in a scalable fashion, to support our customers. We have small scale deployments. I have one megawatt of electrolyzers today operated at customer site to support their hydrogen needs for material handling and on road vehicles. And, Plug has a wide array of technology and three base platform, just like we do in fuel cells, to kind of grow and scale this business.

So much of what Plug Power does is really focus on commercialization. And look, the huge opportunity. Just thought, may you look at words that Goldman Sachs has put out. Bank of America believes 24% percent of world energy will come from clean hydrogen. When you look at Bloomberg, they talk about cut up to 34% of global greenhouse gas emissions, you need hydrogen. Hydrogen is a huge opportunity for Plug Power and certainly many other companies. But, you know, let's not think there aren't challenges.

And I think we talked about some of them today, how to deliver hydrogen at cost and scale. So, I think one of the items, just to talk about how we think about how to make sure hydrogen is cost competitive with natural gas to generate hydrogen, we've been able to do our deals where we're buying electricity for the meters. So, we do not have to pay transportation costs. And that's a huge advantage for Plug Power and that you're in striking distance of having green hydrogen that is cost par with natural gas generating hydrogen. And if you look at the bills around the world, and I'm very familiar, I'm also the chairperson of the Fuel Cell and Hydrogen Energy Association here in the United States, a lot of the government work that's going on today is in laws that are looking to be passed in the Senate and House, supported strongly by the President, is looking to provide significant tax credits for the usage of green hydrogen up to three dollars a kilogram. When I think about kilogram of hydrogen from a real point of view, it's equivalent to 2 gallons of gasoline. So, I think that's significant.

Now, when it comes to cost and scale for fuel cells. Plug Power has been on a journey for the last 13 years. We've been on a journey. And during that journey we've seen the cost of fuel cells decline at 24% every time we doubled the number of units in the field. So, I grew up in the wireless industry. I can remember where we were in 1983 and where we are today. You know, those cost reductions have been dramatic as technologies become more sophisticated and as we scale. I think it's really important. You have to listen to customers. But it's more than listening to customers. It is really translating customers into markets and what they need in the future. There is no such thing as a fuel cell to put in a forklift truck until Plug Power decided that was the right application. And we were able to show customers how they could move goods easier and quicker. And I think it's really important for us in the industry to make sure that we're always talking to customers and listening to customers, but also thinking through what we're being told and really what that means for future products.

And finally, being the CEO of a public company, there's a lot of criticism talked about hydrogen fuel cells. You've been doing it for 24 years, why isn't it commercial yet? And I think one of the big myths is that people don't really realize how this technology has continued to grow. I joined Plug Power in 2008. We were a technology company. We had about one million dollars in revenue. Now we're commercial. This year, we'll do 475 million dollars. It is a commercial technology product today and it will continue as costs come down, as the quest to decarbonize the world comes down. Hydrogen is really the solution for the future. And I think it's not only Andy Marsh, the CEO of Plug Power, saying that. You're hearing that from people like Bloomberg and Bank of America and Goldman. Large swaths of people believe hydrogen matters. Now and finally, I really like to say, I really appreciate the opportunity to talk to you today. We're leading, and with others, leading the efforts to help decarbonize society for future generations. We're proud of our work. We think hydrogen is critical for long term success. And we're going to be a leader around the world with great partners, like SK and others. I really appreciate the time and the opportunity to speak with you today. So, thank you. And I appreciate that. I look forward to the Q&A session. So, thank you, everyone.

Kyung Yeol Song:

Thank you, Mr. Marsh, for giving an extensive industry perspective on hydrogen infrastructure and applications. This concludes today's presentations.

Now, we will invite our four keynote speakers for a discussion. As today's moderator, I will be presiding the discussion session. We have received hundreds of questions in advance from our audience. In this discussion, we will address some of these questions.

So basically, for each question, I like to allocate it to each panelist, but there are some questions which may sound arguable and debatable. For those questions, if you don't mind, after allocating each question to each panelist, I will open those questions for other panelists for more active discussion as well. The first question is on the role of international environmental regulatory bodies for hydrogen industry, and if you don't mind, Mr. Heid, I would like to ask this question to you. As we all know, the role of international bodies is important in order for renewable energy and hydrogen industry to grow sustainably, to become a meaningful source of global energy mix. Until recently, however, it seems like those bodies have not been fully effective from the viewpoint of hydrogen economy. What role should the international bodies take to accelerate global energy transition toward net-zero energy? How can they regulate carbon emission and promote transitional technologies such as renewables and hydrogen?

Bernd Heid:

Thank you very much for that question. And I would love to start with commenting on your question of how effective the role of international bodies has been. And I must say, this is a very complex value chain from production, distribution. We touch, as we heard from many of the speakers, on different parts of the of the end users. So, I think getting that coordination together takes some time and also some effort. So therefore, I see a lot of momentum happening there.

I see six different roles that international bodies, especially also governments, can help in that energy transition. Number one, I think the stability in the offtake of the end use of hydrogen is an important one. So, if we want to make these business cases work, we need stability in the usage of hydrogen and stable offtake agreements is certainly part of it. Number two, I see support in clean hydrogen investments along the value chain, that is green hydrogen production from renewables, electrolyzer capacity, but that's also blue hydrogen in the sense of carbon capture, that is infrastructure for distribution and fulfilling. So, we see a lot of government plans right now investing into these clean technologies. Number three, it's something that in Europe we call, for example, Carbon Contracts for Differences (CCFD), where governments make up for that economic gap between the production cost and the cost that is required to break even in terms of hydrogen.

And on the contrary, that is also as a fourth element, I see the role of CO_2 taxation important, as you have seen earlier in the conversation, for many of these applications, there is required willingness to pay a premium from society. So only if society is willing to pay that that premium, we are able to enable that. And that in essence, is the carbon tax on certain of the applications. And the two final ones are more on the coordination side. As we are dealing here with molecule that is now in the hands of many parts along the value chain, the whole question of safety codes and standards is important. How do we handle this molecule in a safe manner? I think that is not only a national question, but also an international coordination question, that we have same codes because this molecule travels across the globe and should be handled in a similar way. And the final remark I would love to make is that coordination of getting that economy working. And you heard me say that a lot of that happens in ecosystems. Many of those ecosystems are between the private sector side, the public side, and also the investor community and having a coordination of what happens, when, and where. I think these are all topics where an international coordinated action of these bodies can be helpful.

Kyung Yeol Song:

Thank you, Mr. Heid, for sharing your great insights. All the six rules you just described make a lot of sense. Especially, the importance of CO_2 tax seems quite important to accelerate the energy transition toward net-zero society. The second question is specifically for Mr. Marsh. Mr. Marsh, there was a question from audience about your motivation and the decision process that helped you see opportunities in material handling equipment as the first application for fuel cell innovation. What was the decision process that helped you see opportunities in those areas and in the long run, I'm wondering whether you expect the scope of business to continue to grow much beyond that?

Andy Marsh:

That's a good question. I joined Plug Power in 2008. At that time, Plug Power was doing experiments in six different applications. I was looking at a mix of three different fuel cell technologies and I was hired to build a business. And I went around and visited for about six months, really went out to study the fuel cell space and talked to potential users. And often when I spoke with people, they were looking to use fuel cells because quite honestly, they thought it was interesting. But they really couldn't describe the business paths. When I went and spoke to a number of folks like Wal-Mart who were doing trials with three or four forklift trucks at the time with fuel cells. They could define to me how fuel cells could create value in their operation. You eliminate the battery change-out process, which could take 20 minutes. You had fast fueling, which could take just a few minutes versus hours to charge batteries. The trucks could run long. So, in reality, they said we could save labor with fuel cells and the numbers that they put around that were in the 8 percent range. So, you step back and said, hey, you could create value for the customer if you were really interested, when you really listened to that description, it was a description of asset-intense applications where fuel cells made sense. That I think that, you know, is the bane of this industry. I think we were really one of the first ones to see that industrial application where you had centralized fueling that the value proposition was simpler because the cost of the hydrogen infrastructure was not nearly as large when you thought about spreading it around 300 forklift trucks.

So, you had an application, which was a fleet vehicle application, which many people think were the right applications today for on-road vehicles and ports in other areas, coupled with the fact that you could enunciate that value proposition. And we married the two together. And that's really why we went into the material handling market. And as I mentioned during my presentation, during COVID, you know, we moved 25 percent of the retail food here in the United States. We have four pedestal customers that are known around the world, Wal-Mart, Home Depot, Amazon, General Motors. And we actually have a fifth one, which we haven't announced yet, which will be buying over 25 million dollars of product this year and another 25 million dollars next year for the deployment of fuel cells for material handling equipment. It's a big market opportunity. By 2024, we believe we'll be doing a 750 million to 850 million dollars of sales in this market. And I think that this green hydrogen becomes more and more available, which I really believe is the great accelerator in these applications. With customers who want to have a zero-carbon footprint, green hydrogen fuel cells in this industry, in material handling, and all the other work, we expect to have growth rates which are astronomical, for the foreseeable future.

Kyung Yeol Song:

Thank you, Mr. Marsh, for sharing your story. As Professor Cha presented during his talk, the basic theory of fuel cells has a more-than-100-year history. But how to engineer it to make it work in real life is another story. And from that angle, I really respect Plug Power as well as other innovative companies who are working very hard to make the dream of hydrogen fuel cells come true. And what Mr. Marsh just mentioned is naturally connecting to the next question, which is about technological competitiveness of fuel cells against others. If you don't mind, Professor Cha, I would like to ask this question to you. As we know, fuel cell technologies have a long history and have been in use for a while, but were not able to reach parity price probably due to its high cost. So, Professor Cha, based on your experience and knowledge, what do you think is the main reason for this? And would it be a reasonable statement to say that this problem has been already fixed? Can we say now that the hydrogen fuel cell technology is cost competitive against other competing technologies in the market? If not, when do you think that will happen? And what is the most important technological breakthrough to make it happen?

Suk Won Cha:

Thank you for the question. So, in my opinion, when a technology makes success in the commercial market, first, the technology has to be mature enough. That means the it should satisfy all the requirements from the customers. So that's the first thing. For the fuel cell point of view, it actually took a long time to reach that point because the fuel cell itself is like, I think I mentioned a little bit in my talk, it uses some of the very sophisticated nanotechnologies in electrolytes and electrodes, but also from the system point of view, it also requires some really nice system integration. So, both of these technologies have to be combined together. So, it took a long time actually to mature the technology itself. So, I think we reached the point where the technology is mature enough. The other point we have to think about is, 'Can we produce on a massive scale?' So, I think nowadays, fuel cells are going into this stage of mass production. And when we think of this mass production, actually because the fuel cell system is a very complicated system, it requires really complicated supply chains, from the raw materials to the system integration level. So, to be successful in the market, actually, all those industries throughout the supply chain also have to mature at mass production scale. So actually, what we are seeing these days is actually the maturing of the supply chain and it is growing really fast. So, I think what we'll see in the near future will be the more mass production of fuel cells, and the we'll see more fuel cells in the market. So, I think the breakthrough actually at this point has to be really that we have to reduce the cost down through this mass production scale. So, I think that's the important thing that we have to consider at this point.

Kyung Yeol Song:

Thank you, Professor Cha, for sharing the great insight. On top of fuel cell technologies, there is another important factor in hydrogen economy, which is how to make hydrogen in a cost-effective way, at the same time, carbon free. So, this question is about the evolution of different types of hydrogen production methods in the future. And I would like to ask this question to Professor Nam. But at the same time, what I also realized during the four keynote speeches today is that there is one important common theme, which is green hydrogen, as well as H_2 production methods. So, after Professor Nam shares his perspective, I would like to also open this question to other panelists as well. Probably, Mr. Heid or Mr. Marsh can share your views as well, based on your deep industry insights. So, Professor Nam, the question is about, again, the evolution of different types of hydrogen production methods in the future. So, as we discussed today, basically there are three different types of hydrogen production methods which are gray hydrogen, blue hydrogen, and green hydrogen. Probably, we don't need to repeat the definition of each color of hydrogen here. But based on your perspective, what is your view on the different types of hydrogen production methods, their future evolution in the next 10 years, and also at the same time in the next 20 to 30 years? Also, personally, I was very inspired by your presentation today, which is quite innovative hydrogen production technologies. And personally, also, I like to hear your view on when your technology will be successfully commercialized in the future as well.

Ki Tae Nam:

Yeah, thank you, Doctor Song. So, you asked a lot of good questions about hydrogen production. So today, Bernd showed a very nice cost analysis in the graph to compare the prices of green hydrogen, blue hydrogen, and gray hydrogen. It's all about the price. But personally, I hope that green hydrogen should come very fast, very soon, because of the environmental issue. So, I think the hydrogen economy will come not because of the cost issue, but because of the environmental issue. We want to reduce CO_2. Also, we want to replace the current fossil-based chemical industry. That's the major driving force. So, I agree that green hydrogen is still very expensive. So, how can we make green hydrogen to be cost-effective? It depends on the price of the electricity. So, in my opinion, the price of electricity is important. 5 cents per kilowatt hour, that's the key or guideline. So, if we can get electricity below that value, below 5 cents, and then I think that green hydrogen will be cost competitive. So now, these days, we see a lot of price reduction in the sustainable energy. And also, using other sustainable sources using the heat, so we can decrease electricity cost. So, I predict that green hydrogen should be coupled with sustainable energy sources. That's my prediction. And then based on that efficient coupling, we want to bypass that period of blue hydrogen and go directly to green hydrogen. Also, in addition to the cost of the hydrogen, we have to think about value addition in using hydrogen for other applications. Today, Bernd mentioned iron reduction chemistry. So, steel companies are using coal, but using hydrogen, we can reduce iron oxide to iron. But still it's expensive, but the good thing is that by using hydrogen, we can add value. So, hydrogen can be useful for other chemical reactions and by using hydrogen for other chemical reactions, we can add value. And based on that value addition, also we can make green hydrogen come very fast. That's my expectation.

Kyung Yeol Song:

Thank you, Professor Nam, for sharing your insight. Probably, there are some other opinions in the audience who may prefer blue hydrogen to green hydrogen, especially considering the environmental limitations that Korea has. Probably, we can discuss that question a bit later. But Mr. Marsh or Mr. Heid, any additional comment that you want to share on the future evolution of hydrogen production technologies?

Andy Marsh:

Yeah, so let me comment first. I think very interesting comments by the professor, and I think it is depending upon where you are in the world. So that 5-cent number, none of the green hydrogen plants that I'm building am I paying that high of a price for electricity. I'm seeing electricity pricing in the 2.5 cents to 3.5 cents per kilowatt hour range. And that makes green hydrogen very, very competitive. And I think what one has to then step back and think about is you have to think about it is a system. All the deals that I'm doing are actually behind the meter. So, I don't pay transmission costs. And by buying electricity at very high demand behind the meter, those kinds of pricing the professor mentioned is possible here in the United States. And I would say in North America in general. And so, Plug Power is surely betting on green hydrogen in North America. I do know around the world that carbon capture technology and other approaches in blue hydrogen make a great deal of sense just because of the cost of the feedstock. And to me, it's really tied to what's the cost of feedstock when you're thinking about what's the most competitive solution. And then finally, I want to add, and I think a real good point made by professor is, you know, in the end, it's up to customers. And, you know, I think the lower the CI (Carbon Intensity) Score, the more attractive it's going to be to customers.

Kyung Yeol Song:

Thank you, Mr. Marsh. Mr. Heid, I understand that you already shared a very insightful analysis during your presentation about the cost comparison among gray and blue and green hydrogen. Could you share your additional comment about the future evolution, about the different types of hydrogen product and technologies as well?

Bernd Heid:

So, in terms of pathways, I see that there's a debate going on, is green a better source for hydrogen than, for example, blue. By the way, there are also other technologies out there, pyrolysis, we could produce hydrogen from biomass and others. So, it's not only these two decarbonized ones, but think of them as like the two major decarbonized sources of hydrogen. I think in the end, for this planet, it's important to avoid emitting CO_2. And if blue is a pathway where we can we can make use of natural gas feed sources, then at the same time capture, sequester and store the CO_2, we will see countries and companies exploiting that potential. So, I have a very realistic view of this world. While Green sounds most promising because we do not emit CO_2 the first place, I think as long as we have natural gas resources and we have the availability of CCUS (Carbon Capture, Utilization and Storage), we will see also blue happening at the same time. And think of just of countries in Middle East, North Africa, think of Russia, think of Southeast Asia, think of parts in the US where you have availability of natural gas resources, we will also see the push to do so. And in the end, it's a matter of competitive position. Foremost, it's important that this is the decarbonized molecule. Second, it's then important to have that available and also at low cost. And that pretty much depends on where on this planet you are. And what of the endowment of energy, be it renewable energy or natural gas you sit on. And that determines the longer-term mix. And whether society over the long run, decides on green as the better alternative to decarbonize, I would not be able to judge this today. This has a lot to do with consumer sentiment. I am certain this will take more than 10 or 15 years to find out. But for most where we are now, we should be excited that we see that momentum happening in this industry. So, think of that as we are just at the starting point. So, I am less worried about the individual pathways as long as we make this hydrogen society happening. And then let's sort out over the time on which part of the planet, which pathway is the best.

Kyung Yeol Song:

Thank you for sharing your perspective. The point you mentioned about the blue versus green is very insightful and relevant. This is probably one of the most arguable and debatable questions in Korean government and business sector these days because in an ideal world, it would be great if we can have access to an abundant amount of green hydrogen. But in reality, in Korea, our concern is that the cost competitiveness or renewable energy is unlikely to reach out to below 5 cents per kilowatt hour, which is the criteria that Professor Nam just described. From that angle, I think this is the natural next question, which is about what's the best way for Korea to secure clean hydrogen in the future. So, as we discussed today, the Korea government has a very strong ambition to realize the hydrogen economy in the next 20 to 30 years. And what we have not concluded at this moment is how to secure that hydrogen. So, after a lot of discussion and debate, it looks like there are two different paths. The first path is blue hydrogen, which is gray hydrogen plus carbon capture, and the second path is importing green hydrogen from some other countries with great solar radiation environment, probably Australia. So, if you don't mind, Professor Nam, I like to ask this question first. And also, I'd like to open this question to other panelists as well because it's a very important agenda for Korea's hydrogen economy. So, Professor Nam, based on your expertise, which seems to be more feasible and a better option for Korea to secure carbon-free hydrogen, between these two options we just talked about, especially considering the limitation and drawback of each option. For example, blue hydrogen definitely has a limitation about the cost competitiveness of carbon capture technologies, and at the same time, importing green hydrogen from some other countries also has a fundamental drawback and limitation in terms of cost of liquefaction and shipping. So, based on this limitation and fundamental challenges, any advice from your side on Korea’s strategy on clean or carbon-free hydrogen would be appreciated.

Ki Tae Nam:

The second question is also very difficult, and I think that there will be a lot of debate. And before we discuss about the cost of electricity also I want to emphasize to consider material sustainability. So, as I mentioned in my talk, platinum and iridium prices keep increasing. And for hydrogen storage and hydrogen production, we need a certain element. That should be considered. So, we have to think about the price of platinum, and also, we have to think about how to replace the platinum that is useful for a lot of fuel cell devices. So now, instead of the global issue, focusing on our Korean issue, as Dr. Song suggested, here in Korea, sustainable and renewable energy sources are very limited. So, in that sense, because we don't have enough solar power and our wind power reserve is also not enough, I'm looking at the possibility to use the sea because our Korean peninsula is surrounded by the sea. And then interestingly, we have a very good capability for the chlorine evolution, or the chloro-alkali process, around the Korean peninsula. We produce a lot of chlorine and use it for our chemical reaction. So, our chlorine evolution is from the seawater. That's the anodic reaction, and during the chlorine evolution, also we can get hydrogen. So, I want to emphasize that we only focus on the price of hydrogen, but by utilizing or by coupling with alternative energy reactions, such as chlorine or biomass oxidation, or other organic chemical reaction, we can add value to green hydrogen. So, we can sell green hydrogen, and also, we need some electricity but by selling products from anodic part, we can create a new economic value chain. So, I am thinking the Korean situation is something special. Also, for the Korean situation, I think that the production of hydrogen is not easy. However, we have a very small country and we are all connected together. And so maybe to install hydrogen stations will be much easier. Because also we have a good success in the network systems using the wireless because we the Korean Peninsula is a very small, so in that sense, hydrogen stations can be easily installed in all over the area in our Korean peninsula. That would be our strength and that would be the innovative platform to see fast growth in the hydrogen economy.

Kyung Yeol Song:

Thank you, Professor Nam. Since this is such an important topic, if you don't mind, I would like to ask this question to each panelist as well. Hopefully, you can imagine that you are meeting with the Korean President in an hour and you need to provide your advice on what's the best way for Korea to secure carbon-free hydrogen. So, it'd be great if you can share your advice not only for the Korean President, but also the Korea society as well. So, Professor Cha, why don't you start.

Suk Won Cha:

Yes, actually this is a complicated question and Dr. Song mentioned about methane before me, which is a carbon sequestration. Really the problem with Korea is Korea is also importing methane and usually the methane is coming to South Korea in a liquefied form. So, compared to European countries and the US who are delivering methane in pipelines, for example, from Russia to Europe, Korea has this liquefied methane gases delivered in the ship. Actually, the cost is almost double of that of pipeline delivery. So, that also gives us the problem of methane delivery and he production of hydrogen, which increases the cost. So, maybe some option will be that we can directly import through pipelines from Russia. That may reduce the hydrogen cost. But also, we have some problems with that. And then also the scarcity of renewable resources in South Korea is also problematic. So, we have to actually work on the cost-effective process to produced hydrogen. And maybe something that we may consider in the future will be using electricity from nuclear power plants. Because Korea has good technology of building cheap electricity from nuclear power plants, so those nuclear power plants can be utilized. And also, there are some high temperature processes to produce hydrogen. So that could be some option in the future. But the thing is, we have to think about diverse resources. I think one or two resources may not be enough to match the demand in South Korea. So, we have to think about all directions. And then even though we have to think about the cost competitiveness, in some sense, I think we have to go with a variety of options together for now.

Kyung Yeol Song:

Thank you, Professor Cha. Especially, I like your opinion that putting all the eggs in one bag is very dangerous. Probably, portfolio is very important. Mr. Marsh, what kind of advice would you provide to the Korean government on the hydrogen strategy?

Andy Marsh:

First, I think it's maybe a little presumptuous for an American to tell the South Korean government what they should do, but I'll give you my opinion first. Energy is a national security matter, as well as how you meet your CO_2 goals. I think you can discuss leveraging the natural capabilities South Korea has. For example, how do you leverage your chloro-alkali production to take waste streams to generate hydrogen? I think that should be given very, very high priority. I think when you think about Korea's position, I would suggest that wind power may be an opportunity for renewables for South Korea to grow and expand their renewable position to help energy independence. I think also one has to think about your nations, which are partners, the United States or Australia. And when I was sitting back here listening to the discussion and importing energy from around the world, for example, here in the US, we expect there's going to be a significant tax credit for the generation of green hydrogen. Thinking about what's going on in Australia, I think how to leverage your partners around the world who have the same value system, who care about and can help Korea become energy independent. I think this is a national security issue, an economic issue for countries around the world. And I think that Korea, because where it's located, especially treacherous, and that would be my thoughts to share with the Korean government. With absolute knowledge that I'm not a Korean, I have a lot of respect for what people in their own countries think about the best approach for their future.

Kyung Yeol Song:

Thank you, Mr. Marsh. As CEO of a global leading hydrogen company, your advice will be highly appreciated by our society. And also, I would like to ask the same question to Mr. Heid, especially considering your role in the Hydrogen Council as well as your contribution to the Hydrogen Council, your advice will be also very important, especially not only to me, but also many colleagues on my team. My colleagues are highly inspired by the recent McKinsey report on hydrogen's future. So, from that angle, Mr. Heid, any advice or recommendation about Korea's strategy to secure clean hydrogen?

Bernd Heid:

Thank you very much. And also, I would see in a similar way. I feel very humble in giving any advice to you in Korea. First of all, I must say, the world looks a lot on to Korea. So, in terms of technology, there's a lot what we can learn in the rest of the world from what you have achieved. So therefore, I think Korea is one of the leading pioneers in this hydrogen society. So therefore, as much as you might learn from others, there's certainly a lot we can learn from Korea. So, let me comment on pathways of hydrogen and how you could secure your hydrogen position. There are more or less two steps that we need to combine. The one is the hydrogen production. And where can we produce decarbonized hydrogen at low cost? That's the energy vector. And the second one is the logistics portion. And being a peninsula with your position, you will be a net importer of energy. And of course, the cheapest way of logistics is always if you locally produce. Unfortunately, you are not as endowed with cheap renewable power. Your offshore wind is certainly more expensive than solar in other places. There is a high likelihood that there will be a fair portion when logistics faces a hole. As Professor Cha mentioned, certainly pipelines are the cheapest form of distributing hydrogen, especially if you use existing natural gas pipelines and retrofit them so that they can be used for hydrogen. That's the cheapest form. Think of my keynote earlier, I mentioned that we have places where we can produce hydrogen at 1.5 to 2 US dollars per kilogram. We made a calculation, if you ship hydrogen via a pipeline that only adds up to 1/2 US dollar cent to the distribution. We in Europe can certainly do that. Think of North Africa to places like Germany or France. Think of places from Russia, from northern Netherlands, we can do that by a pipe. I think for you that option is not a viable one. So, you will be left with shipping imports that can be done in the form of liquid hydrogen. It's a nascent technology and probably takes 10 more years to be fully commercialized. But shipping liquid hydrogen would add roughly 2 US dollars to the cost of production. So, we are still at total landed cost of around 4 US dollar in Korea. For the lack of liquid hydrogen shipping today, we could still use ammonia as a carrier because ammonia is commercialized. It's a traded commodity. So, the advantage of ammonia is like you can ship it already today. So, we could import hydrogen in the form of ammonia. The good thing is it's easy to transport. It's also probably less than two US dollars on the cost that you add to it. However, you either use it as ammonia in the sense of co-firing in a power plant in ammonia production as the marine shipping fuel.

Bernd Heid:

But if you need it, for example, for transportation in the fuel cell, back cracking of ammonia will not be pure enough to be suitable in the fuel cell. So, that is not an option. So therefore, that's the one part that's the logistic cost that we need to add. And then in terms of production, I would certainly keep all options open. And that's like, well, could you from other countries import hydrogen at the lowest potential cost? Certainly, Australia would be one exporting hub. I think there's an option to get blue hydrogen from places like Southeast Asia nearby. You could import either blue or green from places like Middle East, or you could even import green hydrogen via the Pacific route from Chile, where in Chile we probably have some of the lowest cost of renewable energy of less than 1.5 US dollars per kilowatt hour of energy, so therefore the cost of producing hydrogen can be as little as 1.5 US dollars per kilogram. And if you then add, let's say, 2

US dollars for the logistics, you are still very competitive, even if you import that hydrogen. So therefore, I would love to separate these two things of what is an ideal carrier to import versus do you have different pathways and partnerships of how to secure the supply with decarbonized hydrogen?

Kyung Yeol Song:

Thank you, Mr. Heid. All the comments you mentioned are very relevant and insightful. Probably, our President will deeply appreciate all the comments that all our panelists provided. I just realized that we are already running out of time and I have more than 10 percent on my list. But given the limitation of our time today, this will be our last question, which I really want to discuss as well. We so far, we talked about hydrogen production technologies and the role of global regulatory bodies in accelerating the energy transition. And what we have not touched so far is the evolution of fuel cell technologies across different value chains. In addition to competition between blue versus green hydrogen, which fuel-cell technology is the ultimate winner, is another very important at the same time debatable topic in Korea's sector. So, if you don't mind, I would like to ask this question to Professor Cha, and also, I would like to open this question to other panelists. Here is the question. So, Professor Cha, you provided a great speech on different types of fuel cell technologies like PEMFC, SOFC, MCFC, and PAFC. So, considering the advantage and limitation of each technology, what's your view on the evolution of different types of fuel cell technology in the future? So, do you think one specific technology will dominate the market eventually, maybe similar to solar, where crystalline technology is dominating the market, or electric vehicle at this moment where lithium ion technology dominates the market as well? Or do you think several fuel cell technologies continue to coexist and compete each other for different applications? Or another possibility is that is there any chance that a completely new innovative fuel cell technology, which you have not described today, will emerge in the future, like solid-state battery in electric vehicle?

Suk Won Cha:

Thank you for the great question. So, I think the key of the success of this fuel cell technology is actually the cost, including the capital cost and also the operational cost like maintenance. And then, if you look at the evolution of the fuel cell technology, I think as I introduced. phosphoric acid fuel cell (PAFC) or MCFC were commercialized much earlier. I think the reason is because they use liquid electrolyte and PEMC, SOFC, which use solid electrolyte, come in a little bit later stage. So, the movement actually of these technologies is actually to win this battle. The technology that is mass-production-friendly will win, I think, this game. But if you look at the history of this industry, it doesn't take a few years, even 10 years. It takes a really long time to have the proper supply chain and then have this mature technology. So, what I think is for now, all these different fuel cell technologies will co-exist together, but eventually the technology that wins the cost reduction game will win the market. In that sense, PEMFC is moving really fast because of the application in mobility, but also the solid fuel cell technology is catching up slowly. But I think sometime later it will also be a competitive technology. So, I think it will take some time until we see who the winner is. But for now, I think all these technologies will coexist.

Kyung Yeol Song:

Thank you, Professor Cha. So probably, Mr. Marsh, as CEO of a global leading PEMFC player, you have something to add about the future technology evolution?

Andy Marsh:

Well, I'm not going to sit here and say I don't think PEM is going to win in the end. I think that would probably be a poor position for the CEO of Plug Power to be taking. That being said, on a serious note, I think the cost trends for PEM. First, I want to take a step back. I've never been a purist when it comes to renewable energy. I believe that there are attributes of solid oxide, with high temperature and constant performance without variable load. If you're using solid oxide for electrolyzers, if you have a continuous energy source, I'll step back and say there may be the right application for the right price, for the right product. I don't think it's fair to say that you just can't look at the cost of the fuel cell system or the electrolyzer system. You have to think about everything that surrounds it. SOFC working from a nuclear power plant, generating hydrogen with a constant load, even if SOFC costs higher, it may be the right solution just because of the characteristics of the product. That being said, I think in a renewable world, the PEM technology has unique advantages with electrolyzer because of the ability to low track, because of its fast response time, the same advantage that it has in any mobility application, where I think PEM is the winner because of the huge transients that the devices have to go through. If you work in a high temperature, that's just going to be challenging both from the materials point of view and from the performance point of view. So, I think the other real advantage PEM has from a cost perspective, you're going to much more easily marry the cost structure of PEM fuel cells and electrolyzers. When you look at what we're doing at our Gigafactory, the same equipment, the same line that makes PEM MEAs for fuel cells is making MEAs for electrolyzers. It's a pretty powerful combination when you look at the scale mobility that's going to allow you to drive costs dramatically down. I believe in the end, PEM will be the dominant. I would not be focused on PEM, if I did not believe that.

Kyung Yeol Song:

Thank you for sharing your story about PEMFC, Mr. Marsh. Probably, I also want to ask the same question to Mr. Heid, since he has been looking at hydrogen industry and fuel cell technology for multiple years. And we will appreciate your perspective on the future evolution of fuel cell technology.

Bernd Heid:

So first of all, I agree to what other panelists have said earlier. I do not believe that it's a winner-takes-it-all game. Like you heard me say earlier, we will see probably different technologies for electrolyzers coexisting at the same time. I also think that this is a similar discussion. What is the end use you use it for? Is it stationary? Is it a mobile application? Then, technologies have that sweet spot. What I would love to add to that is I think cost reduction and scale-up is a super critical vector for this discussion. We could use fuel cell at 250 US dollars per kilowatt as of today. And the scaling of this technology and we heard it earlier, in the panel discussion, it's a manufacturing challenge that we are having. It's less a technology challenge, but really the scaling up of production capacity to something like, our calculations show, 100,000 units, 200,000 units a year, that bring you into ranges of 100 US dollars per kilowatt. And that's then also a competitive cost level. So, I think next to the technology question, we should also ask this scaling question of these technologies along with it, and not to forget that the cost of the system is not the only factor in this equation of how fast and how quickly the hydrogen society comes. But there are topics like infrastructure out there, often fuel cells are compared to the pure electric drive train. And also, the logic is, think of what is the most effective infrastructure that we add to it that goes beyond the pure technology question of the fuel cell, but certainly adds to the to the total viability of such business case. And do we have that energy, clean energy available? That's also a factor that plays a role. So therefore, I'm a big believer in the coexistence of multiple technologies, both along the fuel cell side, but also vis-a-vis other applications. So therefore, I also do not see, for example, battery electrics being a competitor to fuel cells. But I think these are very complementary technologies and we will see both of them evolving over time at scale.

Kyung Yeol Song:

Thank you, Mr Heid. Personally, I really want to continue this question. I think 40 minutes is too short. Hopefully, I thought this could be a four-hour or even four-day discussion and debate. But unfortunately, today, to honor the time allowed for today, we need to conclude our discussion here. But before we wrap up, if you don't mind, I'd like to suggest that each panelist share the final concluding comment about the hydrogen technology and hydrogen economy as well. So, Professor Nam, if you don't mind, could you start with your concluding comment for today's webinar?

Ki Tae Nam:

Yes, in Korea now, it is a very late night and yet we have Andy from the United States and Bernd from Germany. So, yeah, that's reason why all of us together here. Because hydrogen economy will come through global collaboration. So globally, we act together for clean energy source. So, although I cannot meet with some of our panelists directly, but using this webinar system, we had a lot of very useful and informative discussion. I look forward to further collaboration, so all of us want to work together for a sustainable future. Thank you.

Kyung Yeol Song:

Thank you, Professor Nam. Professor Cha, could you also share your concluding remark?

Suk Won Cha:

Thank you. I think all the panelists have mentioned all the great details about hydrogen technology. I think this hydrogen technology problem is really a worldwide scale problem. There have been some uncertainties in the technology in the past. So, it's difficult to push this technology to the limit in a larger scale with that uncertainty. But after 30, 40 years of development, I think this uncertainty has been decreasing. So that's why I think we are now finally seeing the hydrogen technologies working in like large and global scale. And also, the nations are pushing it, too. So, I'm expecting a really exciting future from now on. And I'm really happy to see that. Thank you.

Kyung Yeol Song:

Thank you, Professor Cha. Mr. Marsh?

Andy Marsh:

Yes, I had the wonderful opportunity in my career to live through the communication revolution. I worked in wireless in 1983 and broadband in 1988 and the opportunities we used to talk about what the world would be like and how everyone could communicate and work around the world. And we would have discussions like this. And, you know, I would think, you know, I maybe had an overly optimistic view of what was possible. I do believe a renewable world is possible. I do believe that we can achieve the goals and powers, as we mentioned, working together globally, and I do strongly believe that hydrogen and fuel cells are part of the solution. And we're doing this, you know, just like in wireless communication, we've made farming easier in India and Bangladesh. And we're going to make a better world, not only for this generation, but future generations. And it's so exciting that I lived through one revolution and to be part of the second revolution as we change how people think about energy around the world.

Kyung Yeol Song:

Thank you, Mr. Marsh. Mr. Heid, please.

Bernd Heid:

First of all, I must say, I'm excited to be here in an international panel with you in Korea, my friend, Andy in in the US, and see that momentum unfolding. I'm now more than 10 years in that sector, and I'm absolutely convinced that this momentum that we see will be triggering the biggest change across sectors that we ever have seen. There was not such a thing that will fundamentally change the industries and energy sector like this. What I would love to add to the conversation, I think in many ways we talk about individual applications. And I would love to highlight the systemic view of what we are about to face here. Think of hydrogen as an energy vector that starts with a level playing field. We can debate a lot about what is the most effective way in the conversion of energy and end application. And often you hear the argument that pure electricity is simply more efficient because it has less energy losses. But it doesn't help if you do not have availability of that of that energy at any time, any place on this planet. And that is where hydrogen comes in. And see how exciting that is that we start with a level playing field of a new form of energy, and we more or less make energy in places where today this energy is not exploited or used. And that's the renewable energy in places like Africa, Middle East, Australia, Chile, where we were not able to extract that energy and make it available to the rest of the world. And now we have a carrier in this molecule that enables us to export sunshine and export wind to other places where we are in in search and in need of energy.

And that, I think, is the fundamental revolution that we see here. We more or less found a molecule that is existed ever since the world was there. But we found new use of this molecule and that it can carry it can carry sunshine and wind and other forms of energy across the world. That's what I get a lot of excitement out of.

Kyung Yeol Song:

Thank you so much, Mr. Heid. It's very unfortunate to say that this concludes today's webinar. We really appreciate those of you who have stayed around so far. And we hope that this has been an informative session for you. Thank you so much.