Hydrogen Energy: Production, Storage, Transportation and Safety
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Lecture - 55
Overview of Storage Methods and Economics

Now, that we have fair idea about the different methods which can be used for hydrogen storage and the different technologies involved, let us have a quick overview of the different methods and economics involved in the different processes. Now, when it comes to the economics or the cost competitiveness the scaling up or economies of scale this is a significant or a key driver in the cost reduction.

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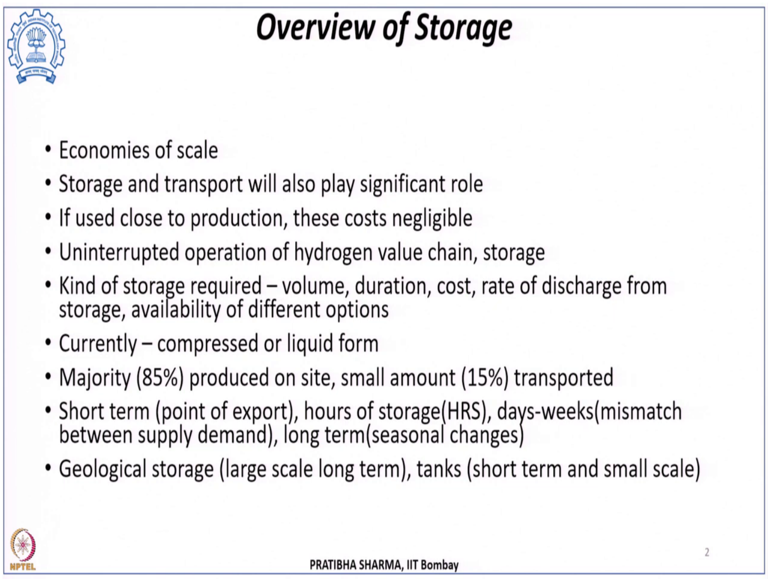

Now, this is significant player such that, it can result into an early cost reduction compared to the major technological breakthroughs that can impact bringing in. We need to understand that not only the hydrogen production, but the storage and transport also plays a significant role in the cost competitiveness of hydrogen. For example, if hydrogen is being produced at a point where it is used itself, so it is like onsite hydrogen production in that case, the costs involved in the storage and transport are negligently small.

However, if it has to be transported over larger distances and large-scale hydrogen is being carried over longer distances, then that may involve significant cost. And, at times, it has been found that this cost could be even three times the cost of hydrogen production. Now, when we are considering the increased demand of hydrogen, the increased usage of hydrogen in the global energy mix.

So, for smooth operation of large-scale hydrogen value chain, the storage becomes essential. We have seen the various methods of hydrogen storage. We have seen that there is a method geological storage wherein we can store tens of thousands of tons of hydrogen and that is already in operation.

Now, which method of storage we will be using that depends upon several parameters like, how much amount of hydrogen we want to store? What is the capacity of the storage system we are looking at? For how long we want to store that? And, all this will be decided by the end use application. What is the cost that can be afforded for that storage method?

At what rate we want the discharge from storage unit to the rate at which hydrogen is discharged from the storage based on the end use application? And, this is in case of geological storage, its availability at different regions for the different options. So, now, currently if we see in the today's scenario most of the hydrogen is being stored in its compressed form or in its liquefied form.

So, these usually these are in the tanks for stationary and mobile applications. Now currently if we see majority of the hydrogen which is being produced that is utilized on site. So, 85 percent of the total hydrogen being produced that is utilized on site. Only a small amount that is 15 percent of it is being transported and that transportation is done by means of either trucks or pipelines.

Now, depending upon how long we want to store? What is the scale at which we want to store? There can be different options for storage. And, then, currently as we see that most of it is being stored in compressed or liquid state and these are in the tanks. So, that the future predictions will depend upon several points like which will be the better method for storage. So, these are the parameters as we have seen which will decide on which method will prove promising under different conditions.

For example, if we see, if we want a very short-term storage and this is at the point of export. So, at an export port, where it will be shipped further in that case what we require is a short-term storage; however, if we want to store it for hours and a typical example could be a hydrogen refueling station for vehicles refueling. In that case, we may require hours of storage. We may require days to weeks of storage, if you want to bridge the mismatch between the supply and demand so, that the users they could use it uninterrupted.

Or it could be a long-term storage, large-scale and long-term storage and that could be used to bridge the seasonal changes that could occur and when it is combined with the electricity or heat demand and that could provide the system resilience. So, depending upon capacity, duration of storage, there could be different choices that could be made.

For example, if we want large-scale long-term storage then the option that could be used could be geological storage; however, if short-term and small-scale storage is desired then it could be in the tanks. The different storage tanks, compressed hydrogen tanks or liquid state storage tanks.

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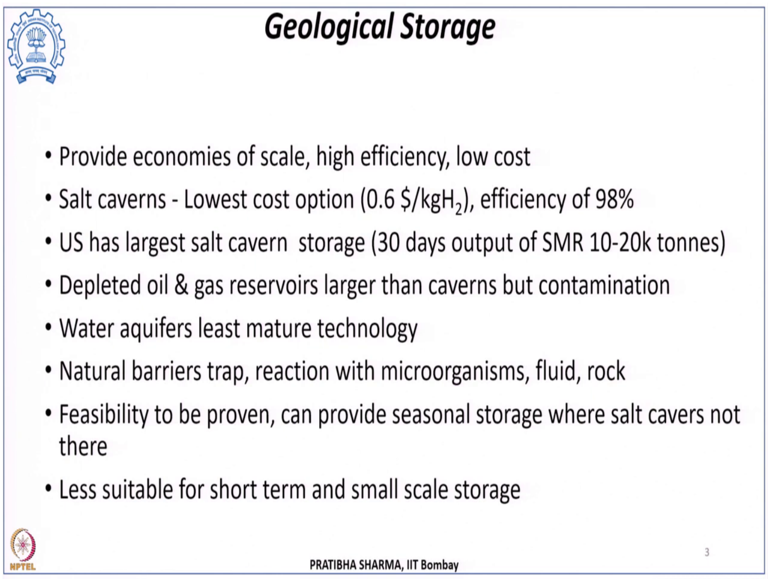

Now, when it comes to geological storage, the natural gas storage in the geological structures has been well proven and it has been widely used, this particular method of storage that provides economies of scale. It has high efficiency, low cost, it has low land cost lower footprint requirement above ground. And then we have also seen that there are different ways or geological structures in which we can store hydrogen like it can be in salt caverns.

And, there are salt caverns-based storage which we have been using since 1970s like in UK. In USA these called salt caverns have been used for storing hydrogen from since 1980s. And this has proven to be in spite of the low density of hydrogen as against the natural gas, still this particular method of storage is the lowest cost option.

So, if hydrogen is stored in salt caverns the cost predicted is comes out to be 0.6 dollars per kg of hydrogen being stored. With an efficiency of 98 percent at the same time in salt caverns the risk of contamination is very low.

At the same time, it can we can get higher delivery rate because of the high pressure at which it is stored; like in the salt caverns even in like their USA there are the largest salt caverns which can even store for 30 days the hydrogen which is being produced from an SMR plant and that output is of say 10 to 20,000 tons of hydrogen being produced from this plant.

Now, there are other plants in these salt cavern storages in UK, which can store like 1,000 tons of hydrogen and then there are certain other plants which are coming up which can store 3,500 tons in Germany.

Other than salt caverns among the geological structures we have seen the other choice could be depleted oil and gas reservoirs. Although their size is higher compared to the salt caverns, but then there are challenges like they can the hydrogen which is stored in these depleted oil and gas reservoirs may get contaminated.

And, thus, if the hydrogen which is released or taken out from these storage wells, from storage reservoirs is to be used for fuel cell then a separation and purification will be desired. The another technology for geological storage would be water aquifers and this is the one which is the least mature technology and then there are differences in the capacity, capability for utilization for hydrogen storage.

Along with oil and gas reservoirs and these aquifers there are challenges like there could be natural barriers which could trap hydrogen and then there could be a loss of hydrogen. There could be reactions that can occur with the microorganisms in the under the ground, with the fluid, with the rocks and all these can lead to loss of hydrogen. And, the feasibility of this particular method of storage that is water aquifer is still to be proven.

Although, they can provide seasonal storage; both the depleted oil and gas reservoirs as well as aquifers can provide seasonal storage large-scale storage, long-term storage at places where salt caverns are not available. But these particular methods are not suitable for their storage of hydrogen when it is required to store on small-scale and for short terms. So, when it comes to short-term small-scale storage, it can be stored in tanks either as compressed hydrogen or in the liquefied state.

Now, let us consider the second method of storage that we have seen that was compressed hydrogen storage. Now, this particular method of hydrogen storage in compressed hydrogen tank has high efficiency and we can get a high discharge rate.

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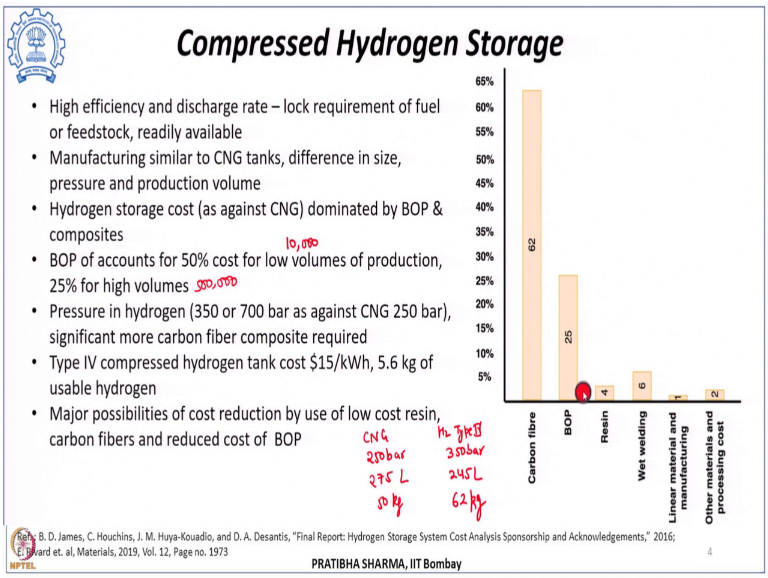

So, depending upon the requirement of fuel and feedstock, we can achieve the required efficiency and discharge rate. At the same time, these can be readily available wherever it is required. Now, the compressed hydrogen tanks they are manufactured in the same manner as the compressed natural gas tanks, like we use type IV tanks where these are made up of inner liner and with a completely wrapped fiber resin composite.

As such, these are similar to CNG tanks, the differences are in terms of size, the pressures at which they operate, they store and the production volume. Now, unlike the compressed natural gas tanks, the hydrogen storage cost it is primarily dominated by the balance of plant. So, the major contributor in the hydrogen storage in compressed hydrogen tanks is dominated by the balance of plant and the required composites for fabrication, for the manufacturing of the tank.

If we consider the small volume of production, when we talk about small volumes that mean 10,000 units of production per year or when we consider the production as in high volumes like 500,000 units of production per year.

Or when it is considered balance of plant accounts for 50 percent of cost when it is low volumes of production considering like 10,000 units of production or when it is say higher volumes say 5,00,000 units of production per year then 25 percent of the cost goes for balance of plant.

Now, if we compare the compressed natural gas tanks which hold natural gas at a pressure of 250 bars as against the hydrogen which stores at 350 bar or 700 bar a significant more amount of carbon fibers is required. Say for example, if we see natural gas tanks at a pressure of 250 bar, 275 liters it will require 50 kg of composite compared to a hydrogen storage type IV tank, let us say it stores 350 bar pressure, it may require a volume of 245 liters and will require a composite weight of 62 kg.

So, depending upon the requirement of carbon fiber composite the price also varies. So, type IV compressed hydrogen tank, it is found that the typical cost is around 15 dollars per kilowatt hour and the tanks can store 5.6 kg of usable hydrogen for vehicular application. Now, the major cost that comes in the compressed hydrogen tank is the cost of we can see carbon fiber, 62 percent of it is carbon fiber.

This is when the volume of production is higher that is 5,00,000 units, balance of plant 25 percent, resin cost is 4 percent, wet welding is 6 percent, linear manufacturing and material cost is 1 percent and the other cost of the material and processing cost is 2 percent; however, the major cost reduction chances are when we could use the resin cost lower, the fiber cost could be reduced or the balance of plant cost could be reduced.

And there will be a possibility of reduction a major possibility of reduction of cost if we could look at alternates wherein, we can get lower cost carbon fiber and balance of plant cost could be reduced.

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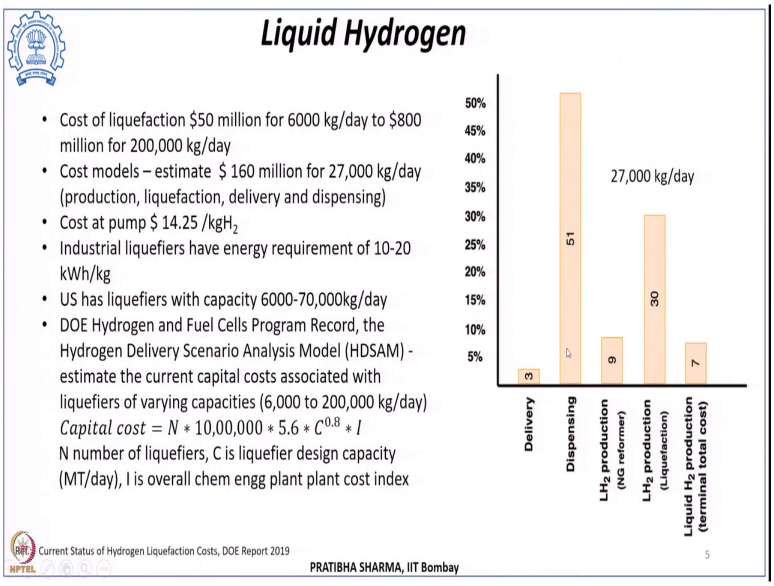

Now, the another option for storage is in the liquid form. Now, the cost of liquefaction depending upon the capacity like if it is 6000 kg per day or if it is 2,00,000 kg per day the cost could be in the range of 50 million dollars to 800 million dollars and there has been several studies which has been carried out. There have been different cost models including all the production, liquefaction, delivery and dispensing cost being included to and that has estimated that.

If it is liquefiers of size 27,000 kg per day the cost estimate is roughly around 160 million dollars. Considering all these production, liquefaction, delivery and dispensing charges, the cost at which it finally, is obtained at pump is roughly 14.25 dollars per kg of hydrogen. Usually, these liquefiers we know that this is a highly energy intensive process.

The energy required in industrial liquefiers is about 10 to 20 kilowatt hour per kg. And there are variety of capacity liquefiers which are available like for example, in US there are small liquefiers which have capacity of 6000 kg per day liquefaction and a larger liquefiers having a capacity of 70,000 kg per day of liquefaction.

There has been several studies which has been carried out under DOE programs projects like DOE hydrogen and fuel cells program and there they have used several models to find out the cost associated with the liquefiers of different capacity like ranging from 6,000 to 2,00,000 kg per day of liquefaction capacity. And they have found that the capital cost is equal to $N \times 10,00,000 \times 5.6 \times C^{0.8} \times I$.

Where, N is representing the number of liquefiers such that each liquefier is having a capacity of 2,00,000 kg per day of liquefaction. Here C is a liquefier design capacity where $5.6 \times C^{0.8}$ is obtained by best fitting the data which is available with them and this is in units of MT per day, I is the overall chemical engineering plant cost index.

And, if we see the cost breakup for hydrogen liquefaction like considering a plant of capacity 27,000 kgs per day, then we can see the major cost is dispensing. 51 percent of the cost goes in dispensing. Production cost if we see a certain percentage is for the reformer 9 percent, then another major contributor is in the liquefaction 30 percent of the cost goes in hydrogen liquefaction.

Then the terminal total cost is 7 percent and finally, delivery cost is 3 percent another method that we have learnt. So, far was solid state hydrogen storage method and this can be either in adsorption-based materials or absorption-based materials.

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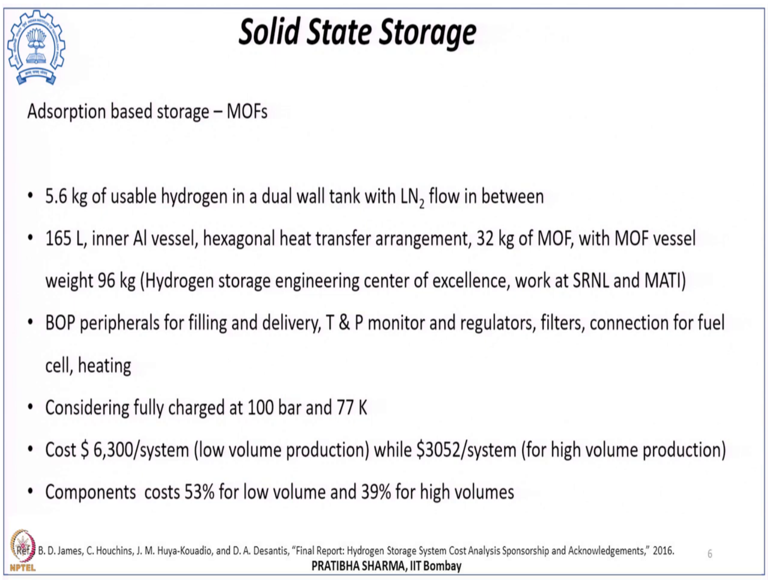

Now, if we consider the adsorption-based storage say for example, with metal organic frameworks, these systems are made up of because we have learnt that adsorption materials, they store hydrogen at liquid nitrogen temperatures.

So, considering a tank, let us say a 5.6 kg of usable capacity usually these are having double wall tanks, wherein inner tank is made up of aluminium and in between the two tanks is a liquid nitrogen that flows. So, considering a tank of say size 165 liters with hexagonal heat transfer arrangement that has been reported in the strategic analysis report with the studies from hydrogen storage engineering center of excellence work.

They have incorporated a hexagonal heat transfer arrangement system inside the tank and stored 32 kgs of metal organic framework. Now, without the metal organic framework the tank weight was 96 kgs. And then there were several other balance of plant peripherals that were incorporated like these were for filling the tank, for discharge of the hydrogen, release of hydrogen from the tank, temperature and pressure monitors and regulators.

Then there were filters, there were several connections required for connecting it for usage, there were heating arrangements so as to get hydrogen at the desired temperature. And, then these, metal organic frameworks were considered found to be fully charged at a pressure of 100 bars and 77 kelvin, the cost of such tanks that was obtained was found to be with the work done at SRNL that HEX COM type of structures.

And it was found that the cost per system at a lower production volume again considering 10,000 systems being produced, it is roughly 6,300 dollars per system cost and considering higher volume cost production 5,00,000 units being produced this is 3,052 dollars per system; however, there was another study which was MATI study and that was found a slightly different numbers.

But at that same time the amount of metal organic framework used the size of the vessel, the weight of the vessel was different and they found that this was 5777 dollars per system and this was roughly around 2,945 dollars per system.

Now, among the total cost it is found that the other components other than the tank that incorporates about 53 percent of the total cost, when it is low volume production. And, that corresponds to about 39 percent of the total cost when the production is at a higher volume of these systems.

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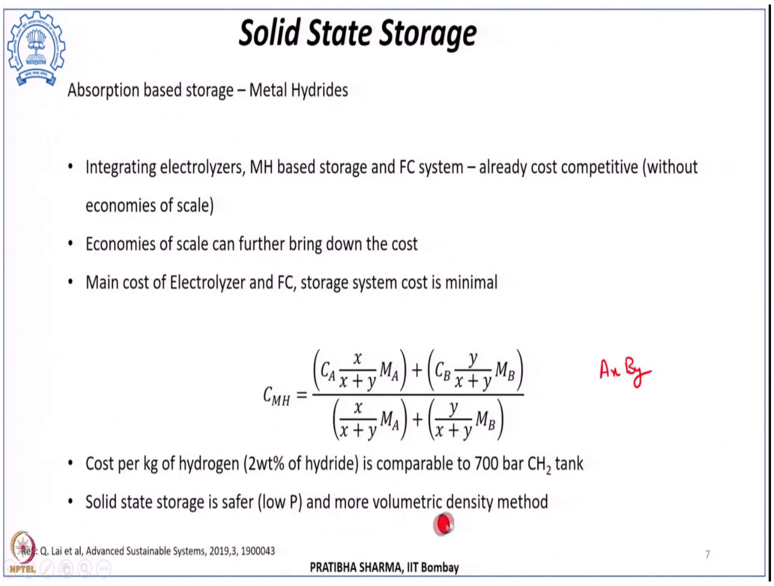

Now, when absorption-based systems like the metal hydride-based storage systems are being considered. It is found that these are at par with the compressed hydrogen tank. So, there has been studies carried out where in integrating electrolyzer with a metal hydride-based hydrogen storage system and fuel-cell system it is found that these are currently at par they are already cost competitive with the 700 bar compressed hydrogen tanks.

And this is considering that there is no large-scale manufacturing of such tanks, no manufacturing of such tanks is going on without considering any economies of scale at present they are cost competitive with the type IV tanks. If, there is economies of scale being considered the cost will further come down. It has been found that in such combined systems where we consider electrolyzer integrated with metal hydride-based storage systems and fuel cell the major cost component in such systems are the electrolyzer and fuel cell.

The storage system cost, metal hydride-based storage system cost is minimal. We can even find out the metal hydride cost if we know the elements being used and their atomic and their ratios the amounts being used like the cost of metal hydride can be given by the cost of individual elements like A, if it is a metal hydride of type AxBy, then (C_A(x/x + y) molar mass of A) + C_B the second component (C_B(y/x + y) molar mass of B) divided by [(x/x + y) molar mass of A) plus (y/x + y) molar mass of B)].

So, this is a metal hydride which is of composition AxBy. Now, if we consider that a metal hydride which is having a gravimetric capacity of say, 2 weight percent is used, then the cost per kg of hydrogen being stored in such a metal hydride-based system is comparable to 700 bar compressed hydrogen tank.

With the advantage of this particular method of storage being since we are storing hydrogen at a lower pressure, much lower pressure close to ambient, then this method of storage is comparatively much safer and volumetric density is far better than compared to the other methods of storage using the absorption-based metal hydride based storage system.

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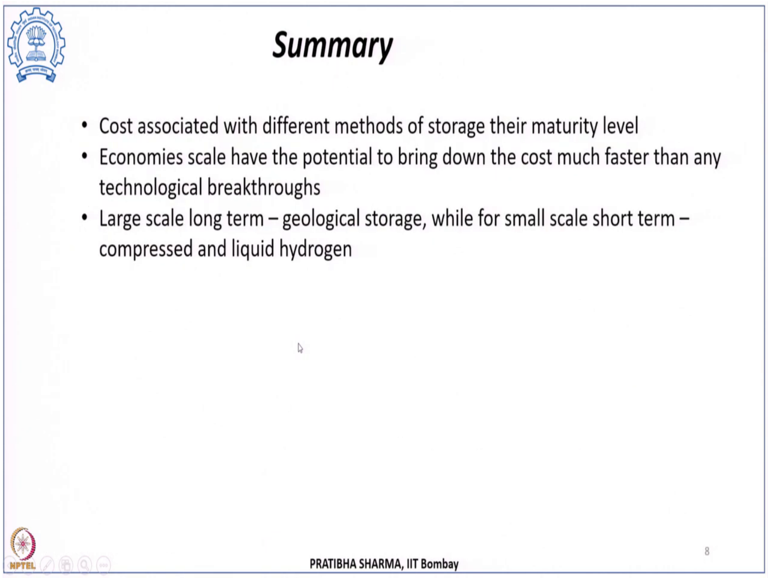

Now, to summarize this particular part, we have seen the cost associated with the different methods of storage. We have seen that different methods are at different maturity level like the geological state storage, salt cavern-based storage have been being operational; however, the aquifer-based storage these are still much more studies are required, at the same time solid state hydrogen storage these are still at laboratory scale and the economies of scale has not yet arrived in the method of storage.

We know that economies of scale definitely have a very bright potential to bring down the cost as compared to and that can bring down the cost much faster earlier than that could come from the technological breakthroughs. We have seen large-scale hydrogen storage required and long-term storage, then the geological storage would be the best option. When it comes to small-scale short-term storage then either the compressed or liquid state storage would be the better choice.

Thank you.