**Hydrogen Energy: Production, Storage, Transportation and Safety**
**Prof. Pratibha Sharma**
**Department of Energy Science and Engineering**
**Indian Institute of Technology, Bombay**

**Lecture - 57**
**Other Options for Long Distance Hydrogen Transmission**

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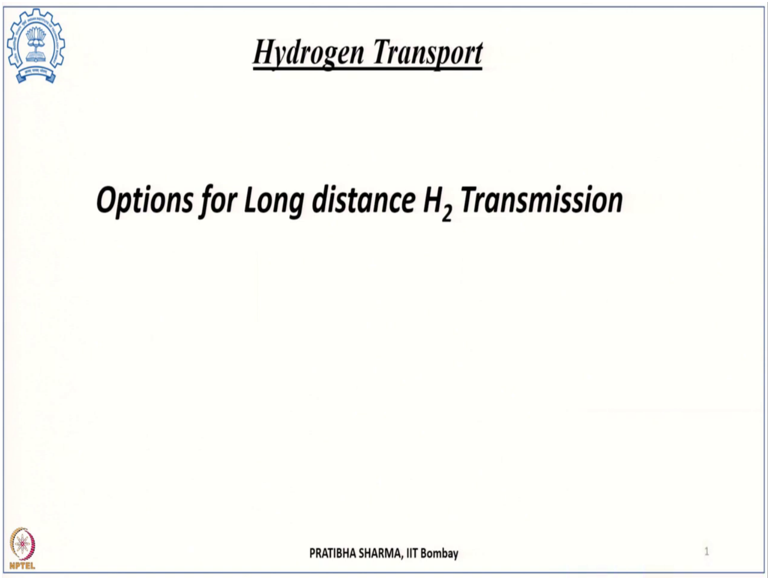


In the previous class we have studied Hydrogen Transport via hydrogen dedicated pipelines. Now, hydrogen pipelines these are the most cost effective method for hydrogen transport, but only when it is large volumes and transmission over a longer distance.

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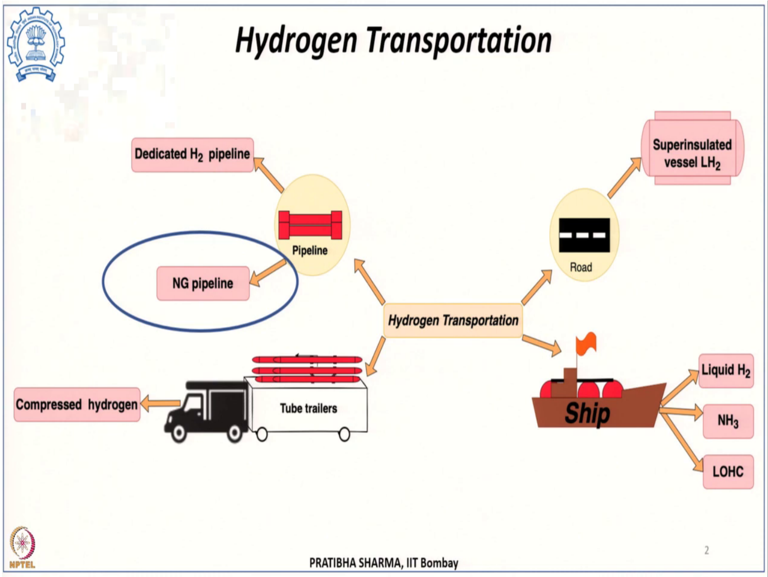


However, if the transport of hydrogen by this hydrogen dedicated pipelines laying down the pipeline is highly cost intensive. So, it is very expensive and it may take a lot of time in completion of such pipeline projects. It's not only the construction of the pipeline, but at the same time the various approvals, the legal regulations, the rights of ways all that processing requires a lot of time.

So, the alternate way could be we can have either transporting hydrogen via road by means of tube trailers or super insulated vessels. So, these modes we will see in the next class. Or the other option could be blending of hydrogen with natural gas and then transporting it through the existing natural gas pipelines.

Now, this particular method of transporting hydrogen by a blending in the existing natural gas pipelines has advantages that it not only saves in terms of the cost. But, at the same time this can also save time because the time that will require for constructing a hydrogen dedicated pipeline will be saved at the same time this can serve as a long term future additional means of delivery of hydrogen. At the same time, it can also serve to transport hydrogen during the initial hydrogen market growth when the demand of hydrogen is going to increase.

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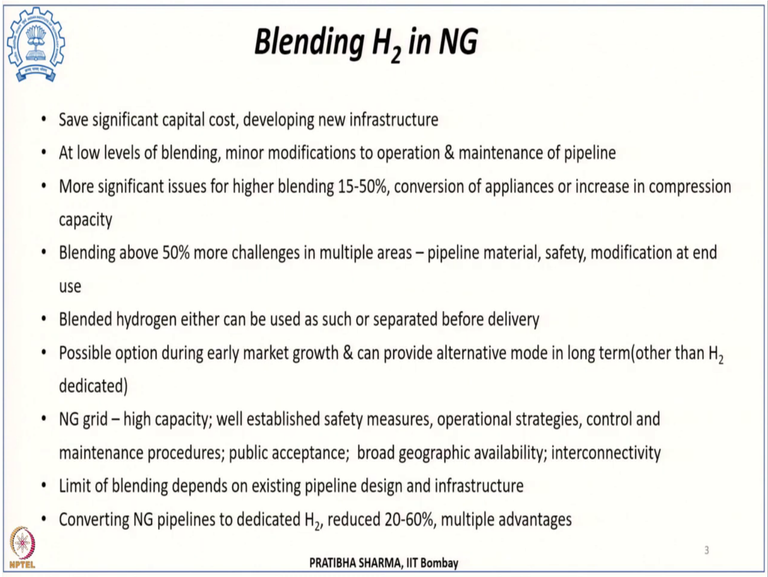


Now, we will see this particular method of hydrogen transportation; wherein hydrogen is blended with natural gas and transported in the existing natural gas pipeline. Now, this blending will save significant capital cost as against laying down hydrogen dedicated transmission and distribution pipelines. Now, if we blend hydrogen in a lower concentration in that case the energy that goes or the consumers that may have to pay slightly higher amount, but that will in fact, result into lower carbon dioxide emissions.

At the same time these blending standards currently there are different regulations in the countries and these have to be clearly spelled out. At the same time there is a requirement of a harmony between the cross borders for having similar standards throughout. If this blending is to be done in a smaller concentration at lower level, then it will lead to minor modification in the operation and maintenance of the natural gas pipelines.

If this blending is done at a percentage level of say 5 to 15 percent, then it’s not going to cause a significant change in the existing infrastructure. However, if blending is to be done at a higher level like 15 to 50 percent then there are more significant changes that needs to be carried out in terms of conversion of the end use appliances or increase in the compression capacity that will be particularly for the industrial users.

Now if the blending has to be further exceeded say above 50 percent. In that case the challenges will be in multiple areas. So, we have to deal with the pipeline material we have to see what kind of pipeline material is being used whether it is compatible with the hydrogen at a percentage level of 50 percent or more.

We have to also look at the safety issues, modifications will be required at the point of end use as well. Now this hydrogen blended with natural gas there are two options either it could be used as such at places, at end use facilities, at utilities which can handle certain percentage of hydrogen in natural gas or else the blended hydrogen has to be separated before the delivery for the end use application. And that will again add up to the cost.

Now the benefit of existing natural gas pipeline network that will come if hydrogen is blended with natural gas that will be like in terms of the high capacity. If we compare, then about 5000 kilometers of hydrogen dedicated pipeline exists globally as against 3 million kilometers of natural gas pipelines. And also there is a underground storage facility of natural gas which is about 400 billion cubic meters globally.

So, high capacity of natural gas transmission at the same time storage facilities are already available and since we have been using the natural gas infrastructure for quite some time for decades.

So, there is already well established safety measures operational strategies and control and maintenance procedure at place which can be further extended. Already there has been a public acceptance towards the use of natural gas and these infrastructures, the pipeline grids they are available geographically over broad location. And then there is an interconnectivity which is desired.

So, the important thing that lies is how much should be the quantity of blending that should be permissible. So, that limit of blending that may vary and it may depend upon what is the existing pipeline design and infrastructure. Like what is the design and construction of the pipeline, that falls into like what is the integrity of these pipelines what are the dimensions of the pipelines, what is the capacity of these pipelines, what are the materials with which these pipelines are made up of.

At the same time the design and construction of the other peripheral components other equipments that are used with the pipelines. Like the compressor stations it also will depend upon the design and construction of the end use appliances which are using that blended hydrogen. Now, there has been several studies that has been carried out globally like some of the studies in Germany that has also revealed that if we convert natural gas pipelines to dedicated hydrogen pipelines.

So, completely on to the hydrogen pipelines that may reduce cost by 20 to 60 percent and not only reduce the cost, but it may have multiple advantages one is definitely the cost reduction, but another one will be like say it could be the existing pipelines which have like the right of ways they have already the legal regulations that can be converted to hydrogen and that could save a substantial amount of time.

At the same time this may have a benefit in the sense in long run. For example, if the demand of hydrogen grows in future and the renewable integration policies may change and if the demand of natural gas decreases with time in future in that case these natural gas pipelines which will be assets may get stranded and using this blending or this conversion that may utilize those assets in future as well.

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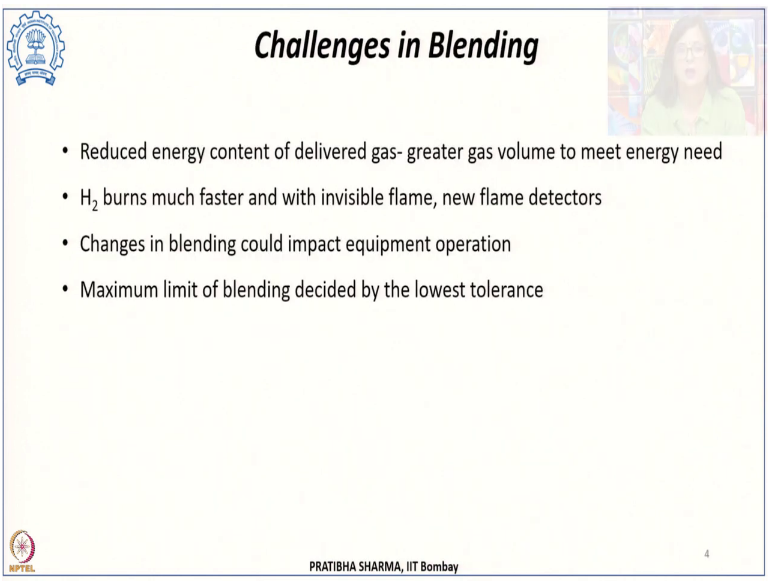


Now, there are not only advantages, but there are challenges in blending of hydrogen in the natural gas, these challenges are like one of the challenges we know that hydrogen has a lower volumetric energy density. Now when hydrogen is blended then the amount of energy or the energy content of the delivered gas to the end user will decrease and; that means, the end user will have to use greater gas volume to meet the similar energy requirements and not only the end users, but the end users could be industries.

Like the chemical industries and all wherein they also they may have a requirement of the carbon which is present in the natural gas and for that purpose they will again will have to use larger gas volumes to meet the requirement. Another challenge could be we know that hydrogen has different properties than natural gas; we have already seen when we studied the properties of hydrogen we know that it burns faster and it burns with an invisible flame.

So, there will be safety considerations that needs to be taken care of they will require new flame detectors. So, as to identify to avoid any hazardous situation also the volumes the change in the volume of the gas, they may affect the operation of different appliances. For example, some of the appliances they may be able to handle a certain range of gas composition and if the gas composition goes beyond that particular level then that may impact its operation. So, as such in that case this blending may not be suitable for those appliances.

The upper limit of blending that could be allowed that; however, may depend upon the utility. So, it may depend upon the appliance it may depend upon the different industrial sector and its utilization, now that will be decided on case by case basis, but in the entire network of blended hydrogen natural gas pipeline, the determining factor would be the appliance which has the lowest tolerance and that will decide the maximum limit of blending. So, these are the challenges which could be faced when hydrogen is blended into the natural gas.

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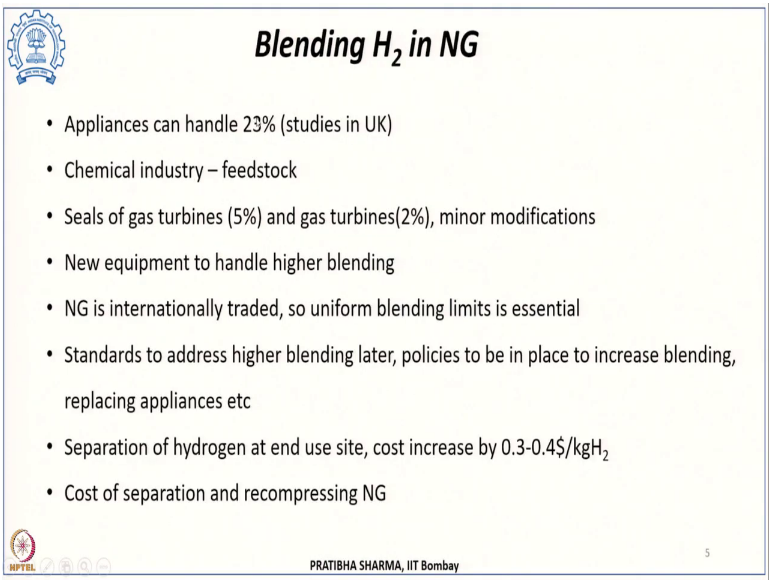

Now, there have been studies in UK which has been carried out to show that the existing natural gas pipelines can be used for hydrogen transportation. And the underground storage like salt cavern based storage can be used for hydrogen storage as well. In some of the appliances this blending percentage that could be handled could be much higher.

Like 23 percent could be handled by some of the appliances. So, this is another extreme a higher blending level could be acceptable like for appliances which could be used for heating or for cooking. But on the other hand there could be utilities which may not handle a higher percentage for example, the chemical industry where say natural gas is used as a feedstock. So, there if hydrogen is blended.

So, that particular industrial segment may not be able to handle a higher percentage of hydrogen at the same time if it is to be used for gas turbines then the seals of gas turbines can handle say 5 percent, the gas turbine itself can handle 2 percent. So, the handling percentage may vary, but in gas turbine seals it is possible that a minor modification in these can increase the blending percentage or can increase the acceptance towards the higher blending percentage.

It is also possible that in future in order to handle a higher blending level new equipments needs to be designed and deployed. Now, this thing is not new or it is not an unprecedented event like passed also in 1960s or 1970s several countries including UK, US, Austria and others when there was a shift from use of town gas to natural gas they converted millions of equipments using billions of dollars of funding to make it operating on natural gas they replaced those equipments.

So, this can also be done in future if required. Besides we need to also understand that natural gas is a commodity it is internationally traded. So, what is required is this blending percentage these regulations standard should be uniform. So, the blending limit should be uniform throughout. So, that it could be easily transported and that is essential.

Besides the standards which are developed it should be considered that in future with the knowledge which is gained with the changes with time, it may be possible that the utilities may be able to handle a higher percentage of blending. So, these standards should be flexible to address higher blending levels in future at the same time the policies should be in place.

So, that they could allow increased blending in future or policies towards replacing appliances in future that should be considered. Now as mentioned either hydrogen blended with natural gas could be used as such at depending upon the application or if the demand for the utility is pure hydrogen in that case separation of hydrogen from the natural gas becomes essential at the end use site.

Now, this separation can be through different methods we have already studied hydrogen separation in purification, pressure swing absorption, membrane based separation method could be used, but that again will depend upon what is the blending percentage. However, that separation of hydrogen from the natural gas will increase the cost of hydrogen, but it is nominal like 0.3 to 0.4 dollars per kg will be the increase or the additional cost associated with separation of hydrogen at the point of use from the natural gas.

Not only the separation cost will add up, but then once hydrogen is extracted from the blend in that case the natural gas needs to be recompressed to the desired pressure levels and that will also add up to the cost other than the separation cost.

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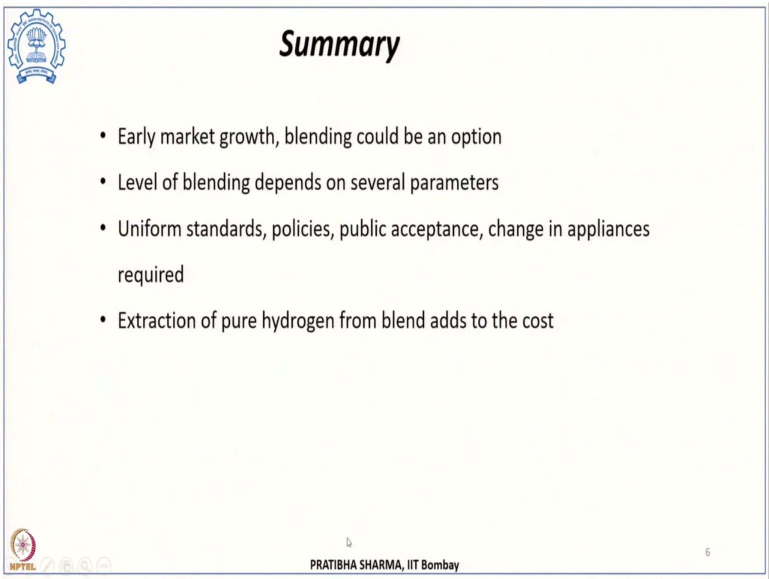


To summarize this particular portion, we have seen that the requirement for the early market growth or the increasing hydrogen demand. The one way of transport could be blending of hydrogen with natural gas. Now, these blending levels currently depends upon several parameters and currently there are not uniform standards and policies.

Although public acceptance is already there for natural gas and there may be in future requirement of changing of appliances, the extraction of hydrogen from natural gas from the blends that may add up to the cost.

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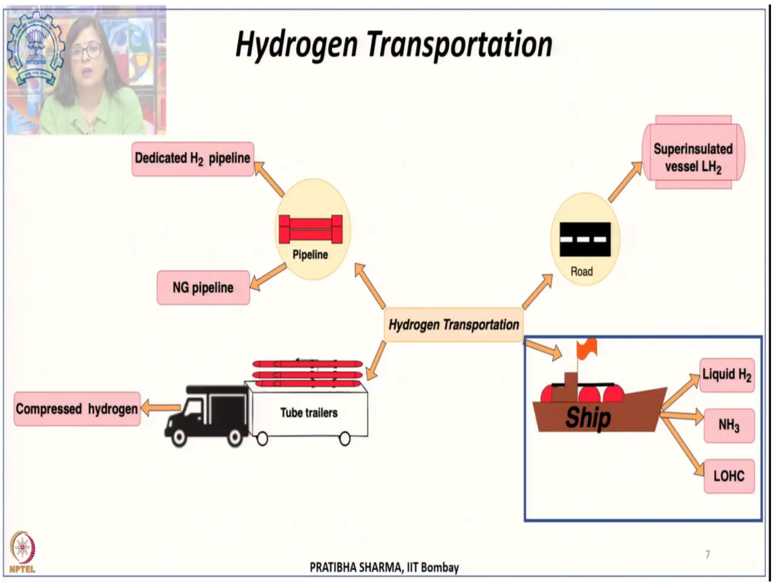


Now, the another method for hydrogen transportation other than blending in the natural gas could be transportation by a means of liquid hydrogen via ships or in the form of ammonia or liquid organic hydrogen carrier.

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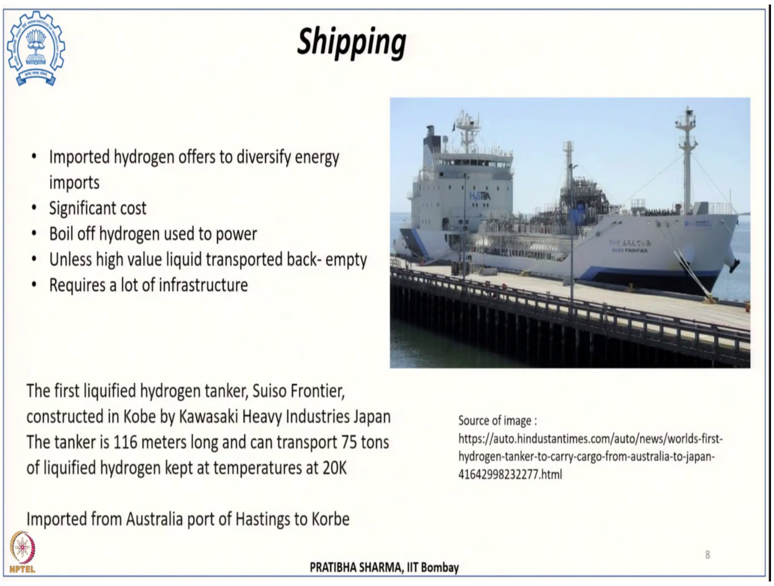

Now, the imported hydrogen allows several countries to diversify their energy imports and that is why a lot of interest has been there towards shipping and transporting hydrogen via ship. Although this particular method of transportation that increases the cost significantly.

So, it is not only the liquefaction cost that adds up, but the shipping cost also increases. So, that increases the overall cost. At the same time the interesting thing is the disadvantage that we have seen was the boil off of hydrogen in the liquid state storage that hydrogen which gets boiled off can be used to power the ship.

So, about 0.2 percent of the cargo can be consumed per day to power the journey of the ship. Now the another challenge that remains is once the liquid hydrogen has been transported from the import terminal to the export terminal from the between the terminals in that case it has unloaded the liquid hydrogen, on its return back until and unless a high value liquid product is transported back it will come empty and that will again and add up to the cost.

And then definitely a lot of infrastructure will be required for liquefaction for the storage, for the different peripheral equipments, super insulated vessels, all that will be required for carrying liquid hydrogen on ship. Now the world’s first liquid hydrogen tanker that is Suiso Frontier, so, the source of this image is mentioned here.

So, this carrier is Suiso Frontier and that started its journey on 21st January 2022 this year. And this was built by Kawasaki Heavy Industries Japan and it carried the liquid hydrogen from Australian port of Hastings to Korbe. And this is a tanker which is 116 meters long and can carry 75 tons of liquid hydrogen at 20 kelvin temperature.

So, this is the first liquefied hydrogen tanker ship which is carrying liquid hydrogen between Australia and Japan. Now this is being imported from Australia to Japan port Korbe and in Australia it is being produced by brown coal gasification.

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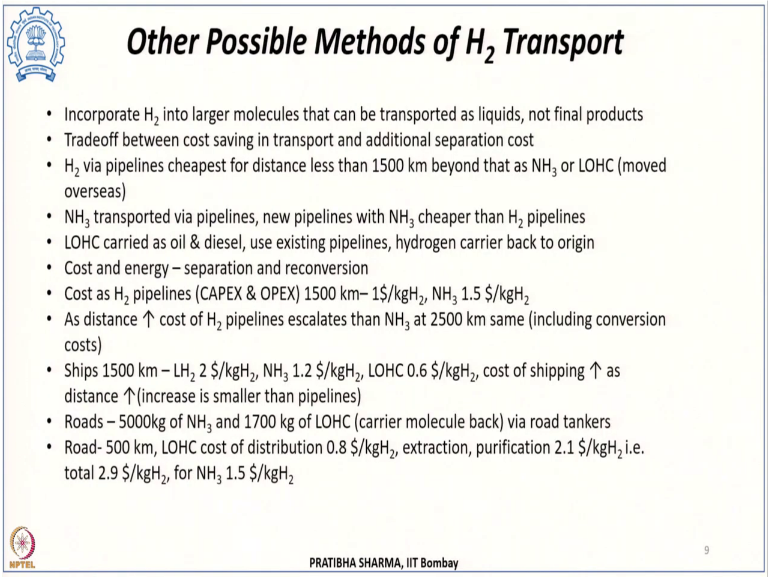


So, this is the first of its demonstration now; other than shipping the other possible method of hydrogen transport could be that hydrogen can be incorporated into the larger molecules. And it could be readily incorporated and then it could be transported as liquid. Examples could be like ammonia or liquid organic hydrogen carriers.

So, this ammonia or liquid organic hydrogen carriers they are much easier to transport as compared to transporting hydrogen, but we need to remember here that these are not the final products which could be used by the consumers. That means, we need to liberate hydrogen we need to extract hydrogen from these carriers the larger molecules and then use hydrogen after extraction that adds up to both cost as well as energy requirements.

So; that means, there will be a trade off. Trade off, but in terms of how much is the cost savings when we could save by saving in terms of transport instead of transporting hydrogen and how much additional we have to spend in separating hydrogen from these carriers. So, that trade off will decide which particular method will be better for hydrogen transportation.

Now, we have already studied that hydrogen if transported via pipelines could be cheapest option for distances which are less than 1500 kilometers. Now, beyond this particular distance it can be transported as ammonia or liquid organic hydrogen carriers especially when it is moved overseas this is considering the cost of conversion from hydrogen to ammonia, liquid organic hydrogen carrier and reconversion including all the cost still it may become economical above the distance of 1500 kilometer.

Now, if we see currently ammonia can be transported via pipelines and there exist pipelines or however, new pipelines can be laid down for transporting ammonia. But laying down these new pipelines for ammonia transport these would be cheaper than transporting via hydrogen pipeline or the cost involved in laying down hydrogen pipelines is more compared to laying down ammonia pipelines.

Liquid organic hydrogen carriers these can be carried like oil and diesel and they can use the existing pipelines which are currently being used. But the major problem lies is in liquid organic hydrogen carrier once hydrogen is being extracted the energy carrier has to be taken back to the point of origin for its recharge.

So, either that energy the hydrogen carrier in the liquid organic hydrogen carrier has to be bought back via road or a parallel pipeline will be required to take it to the point of origin. So, that may add up to the cost significantly. Now considering all these both cost and energy will be associated for separation like getting a hydrogen from liquid organic hydrogen carriers and at the same time converting it back once it is separated from hydrogen that carrier needs to be converted back to LOHC.

So, that reconversion process will require both cost as well as energy. Now the cost of hydrogen pipelines we have seen both including CAPEX and OPEX for around 1500 kilometers of pipeline. The cost of hydrogen transportation by pipeline comes out to be 1 dollar per kg of hydrogen. Transporting via ammonia is cheaper like 0.5 dollars per kg, but an additional cost of 1 dollar per kg is for conversion from hydrogen to ammonia.

So, a total of 1.5 dollar per kg is required for transporting in the form of ammonia for around 1500 kilometers. Now, beyond this 1500 kilometers if we further increase the distance. Now, as the distance will increase the cost of hydrogen pipeline we know will increase, but the relative cost of increase in laying down the hydrogen pipeline is much higher than transporting in the form of ammonia or ammonia based pipelines.

So, the cost of laying down pipelines beyond a distance of 1500 kilometer is much higher than transporting it as ammonia and that breakeven point comes at 2500 kilometer. So, at 2500 kilometer the cost becomes same for transporting via hydrogen pipeline or by ammonia based pipeline and that includes for ammonia both conversion costs. Now, the cost here becomes for both 2 dollars per kg. Another option could be if the distance to be transported is say 1500 kilometers via shipping route.

Then for liquid hydrogen this cost via ships is 2 dollars per kg of hydrogen being transported, for ammonia it is 1.2 dollars per kg. For liquid organic hydrogen carriers, it is 0.6 dollars per kg and this cost of shipping will increase if the distance goes beyond 1500 kilometers. So, this cost of shipping increases as the distance increases and this increase in cost of shipping this is smaller compared to; the cost that will increase if we have to transport it via pipelines via hydrogen dedicated pipelines.

Now, other option could be transporting via road. So, via road we can carry about 5000 kg of ammonia or 1700 kg of liquid organic hydrogen carrier. And other than the carrying it we have to bring the carrier molecule back to its original point via road tankers.

Now, if it is say 500 kilometers then the cost of liquid organic hydrogen carrier for distribution it is 0.8 dollars, but then extraction purification that adds up to 2.1 dollar making it 2.9 dollars per kg for a distance of 500 kilometers via road. But for ammonia this cost is 1.5 dollars per kg. So, these are other optional methods.

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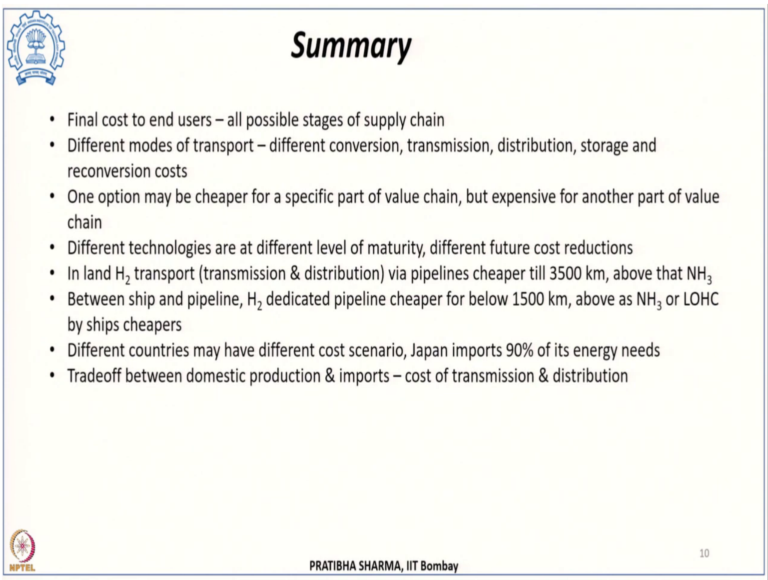


To summarize in this class, we have seen that when it comes to finding out the final cost at which hydrogen will be delivered to the end user. We have to consider all the possible stages of the supply chain and when we compare the different modes of transport for hydrogen we have to include the different conversion, transmission, distribution, storage and reconversion costs.

So, all these needs to be included while calculating the cost for a mode of transport. It is possible that one particular option could be cheaper for a specific part of value chain, but it may prove to be expensive for another part of value chain, at the same time the technologies which we have seen for long distance transmission they are at a different maturity level. And when we say the cost will come down with economies of scale; however, we need to consider that since the maturity level is different there may be different levels of cost reduction in future.

Now, when it comes to hydrogen transport that is transmission and distribution while pipeline. Pipelines are still cheaper till 3500 kilometers above that we can carry it by ammonia between if we have to decide between ship and pipeline then hydrogen dedicated pipeline will be cheaper below 1500 kilometer and above that it could be transported via ship either as ammonia or liquid organic hydrogen carrier.

So, below 1500 kilometers as dedicated hydrogen pipeline would be cheaper option and above that either ammonia or liquid hydrogen carried by a ship could be cheaper options. Now different countries they may have different cost scenario. For example, if we consider Japan, then Japan imports 90 percent of its energy needs. Now, if we see in domestic green hydrogen production it would be 6.5 dollars per kg as against importing hydrogen from Australia which will be 5.5 dollars per kg.

So, importing for Japan is 1500 cost effective is cheaper compared to domestic production in Japan; however, this may differ. So, depending upon the trade routes there will be different options for some places domestic production would be more cheaper option compared to importing.

So, that depends upon how much is the cost offset compared to the required cost for transmission and distribution. So, the trade off lies between what is the cost for domestic production and if it is to be imported what is the cost of transmission and distribution from other place.

Thank you.