Energy Resources, Economics, and Sustainability

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Week – 06

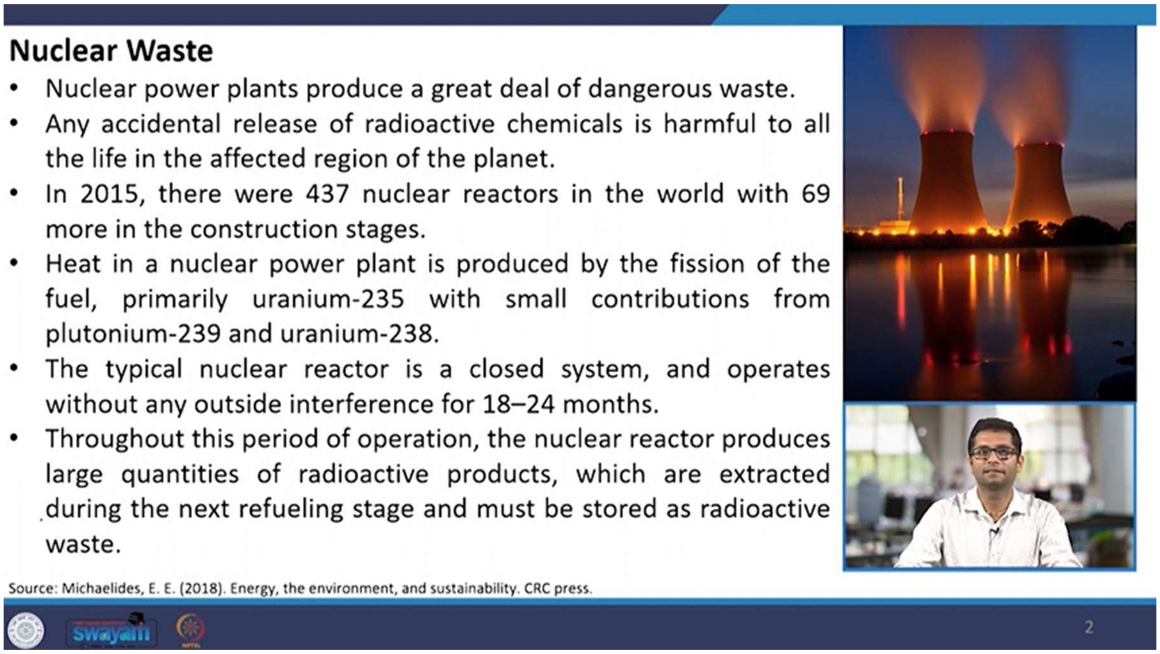
Lecture – 03

Lecture 29 - Nuclear Waste and Thermal Pollution

Hello everyone. Welcome back to the course Energy Resources, Economics and Sustainability. In the past few classes, we have been discussing the problem of global climate change. We have been discussing the main reasons behind this problem. We have also been discussing some of the myths and realities that are associated with the problem to gain a better understanding and gain different perspectives to this very problem. But the problem of climate change is not the only problem that is associated with the use of energy resources.

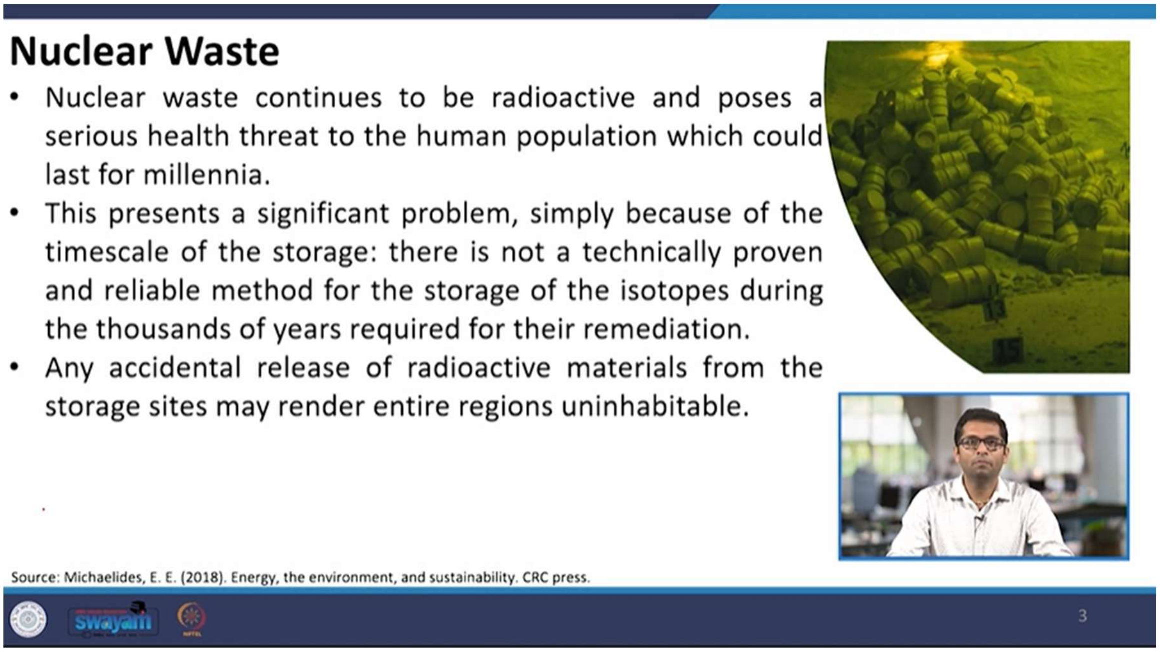
There are other problems which include the nuclear waste as well as thermal pollution. These are a few problems that are not talked about much but they continue being some of the major issues that need to be taken in the future. And this is what is going to be the focus of today's class. We will try to understand the problem of disposal of nuclear waste as well as something called as thermal pollution.

So, let us go further. So, we understand that nuclear power plants are again a major pathway for the production of energy throughout the world. They have been contributing significantly to the electricity production in different countries. We have countries like France where a majority of electricity or energy is being generated through nuclear power plants. So, if we talk about the globe almost like in 2015 there were around 437 nuclear reactors and 69 were still being built.



And the underlying principle, we won't go much into detail, is the splitting of the uranium molecules into other molecules and during this process we have a loss in mass and the generation of energy. And a typical nuclear energy system to say is a closed system. When the fission process is started and the process remains closed to the outside world and the process continues for around one and a half to two years without any interference from the outside. So, once it has been initiated it stays on for quite long. And quite differently from the operations of conventional power plants, be it coal based or natural gas based, nuclear power plants are very difficult to ramp up or ramp down.

And that is the reason they are normally used as base load so that the reactors are working in a consistent manner. You are not playing around much with the type or the electricity that is produced. One of the major issues and that is associated with the use of nuclear energy which seems to be very good energy because it does not seem to emit any CO2 on the face value is the disposal of the radioactive products that are formed throughout the life cycle. So, radioactive products are formed during the production of fuel and also there is significant quantity of waste products that are again in a radioactive range that are produced once the reactor has been shut down and they need to be disposed of properly.



So, if you talk about a conventional nuclear power plant, normally these kind of spent fuel would be like a packed in canisters something like that you can see in the figure and would be made to stay under water so that if there is release of any heat the water can absorb that and this is how the storage is normally carried out.

There have been a lot of advocacy regarding selection of suitable sites where the nuclear waste could be stored for long term. By long term you mean a couple of hundred or thousands of years because that is the time that it would require for the particles to become somewhat benign for the environment. But no major success have been found in that and the focus mainly has been on short term storage and this has aggravated the concern that suppose there is an accident or there is some kind of attacks that happen and that might spoil the storage it can lead to serious consequences. So, this is one of the issues related to nuclear power the disposal of the waste that is created from the process as well as we also have significant amount of nuclear waste being created during the enrichment of the isotopes that would be required as a fuel.

Nuclear Waste Isotopes and Their Characteristics

Isotope	Half-Life, Years	Radioactivity, Bq
Americium-231	433	11.84×10^{10}
Americium-234	7,900	0.7×10^{10}
Iodine-129	17,000,000	5.9×10^{6}
Plutonium-239	24,400	0.23×10^{10}
Plutonium-240	6,600	0.81×10^{10}
Technetium-99	210,000	6.29×10^{8}

The 2011 nuclear power plant accident in Fukushima Dai-ichi, where the stored nuclear waste was exposed and contributed significantly to the pollution in the region underscores this environmental problem.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

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So, just to give you an idea like in the figure you can see the typical half-lives of different kinds of isotopes that are produced as a product and it varies from like almost few hundred years to maybe 17 million years or it can go as I have and there is a difference between the radioactivity as well.

So, radioactivity is normally given in the terms of units of backqueral which means one splitting per gram per second. So, more is the radioactivity is more is the amount of radiation that you can expect to see in the future. Further if you remember the Fukushima disaster that happened in the year 2011 in the country of Japan one of the major reasons of exposure of the outside world to nuclear radiation was the stored nuclear waste that was exposed to the outside environment and that happened because of the accident that happened there. So, storage of this nuclear waste is indeed a big concern.

Treatment of Waste

- ***Concentration*** of the waste, where its volume is reduced by concentrating it into a smaller volume.
- ***Vitrification,*** or ***glassification,*** of the radioactive waste is a common method for stabilization before storage: The nuclear waste is mixed with sugar and heated until all the water and nitrates in the waste evaporate. The mixture is then combined with glass and heated to a higher temperature until the glass melts. This melt is poured into stainless steel containers, where it solidifies and forms a glass-like substance.
- ***Production of Synrock,*** which is a complex chemical material like concrete: The components of Synrock bind and immobilize the isotopes in the nuclear waste in physicochemical bonds that are similar to the bonds in vitrification.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

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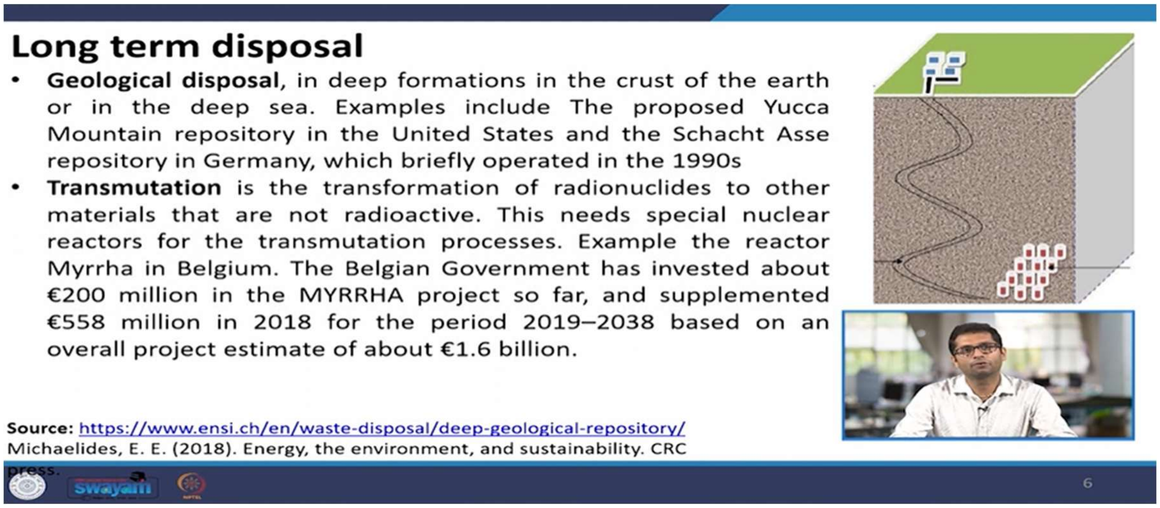
Then what could be the likely pathways for treatment of waste? So, there are three major pathways that are being currently adopted. First one is the concentration of the waste. You would normally go with some types of iron compounds that would help in concentrating the waste into high grade waste and a low grade waste. So, the high grade waste needs to be disposed of properly whereas low grade waste could be mixed with ash or other kinds of particles and is expected not to cause much of the trouble. The aim again here is to reduce the volume because the concentration of these of the reductive elements in the final product could be quite less. So, you would want to further increase the concentration and decrease the volume.

So, once you would have reduced the volume you can go for a process like vitrification or glassification. What it means is like the waste are first made to mix with sugar and water syrup and heated until like the nitrates of in the water are or the in the waste evaporates and once that happen the mixture is combined with glass and heated to a very high temperature so that the glass melts. The whole solution is then put up in stainless steel containers and made to solidify. So, what happens is this whole the radioactive material which have been concentrated earlier is made to solidify in a glass like form and this kind of structure is then stored at a location and it is expected to be like this for coming hundreds or thousands of years. An alternate pathway to this would be the production of syn rock.

So, the methodology is quite similar to the earlier process which was vitrification or glassification. What happens in here is like you form a complex chemical material something similar to concrete and then embed the concentrated mixture into this material and it is expected to stay something like for many hundreds of years something similar to vitrification. The only thing is the use of the different kind of chemical here and since we have been using nuclear fuels almost for a century we are not sure about the long term effects of this because we have not had the experience of storing the nuclear waste for more than couple of hundred years. So, that is again a reason why people are fearful like what would happen because the nuclear material would be continuously giving up radiations increasing the temperature and it is people are not 100% sure that what could be the result with the corrosion of these kinds of material in the future could there be some leakages. But since we have not seen it no one is sure about this.

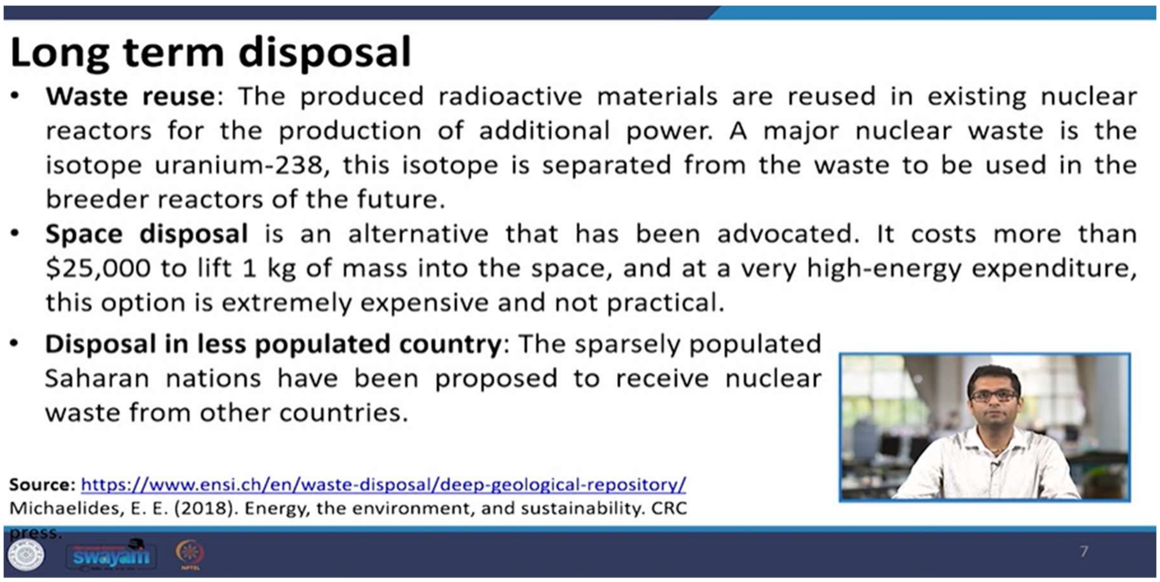
So, what happens when you have prepared a concentrated solution like this maybe glassification or syn rock you would not have to dispose it properly at some locations. So, for this there have been many kinds of pathways.



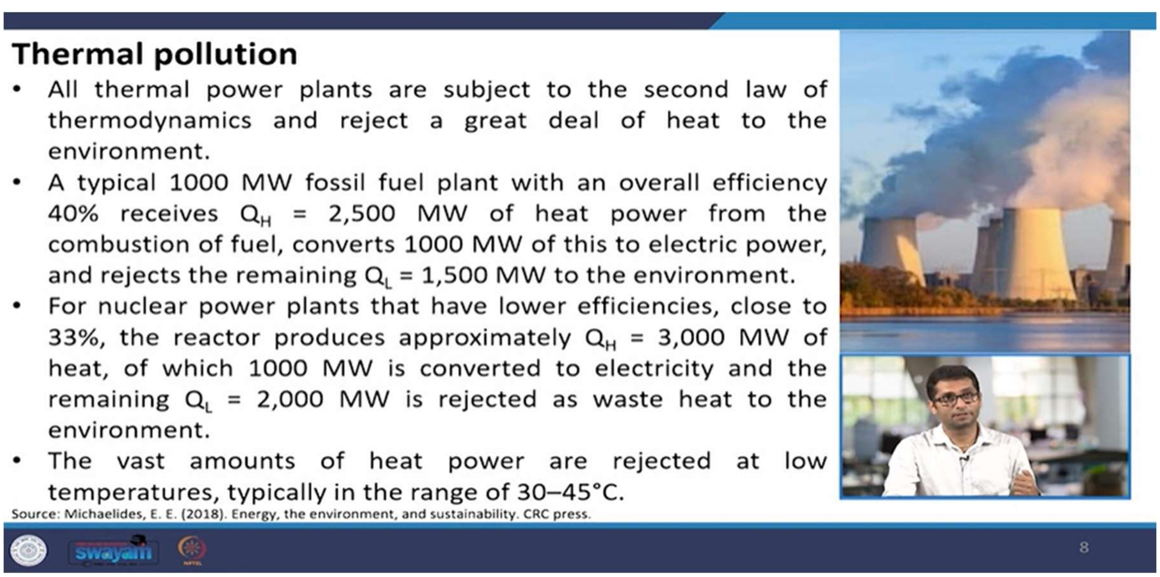
One particular pathway that has been suggested is the geological disposal. You would have many mines or fields which are deep under the sea or in the bed of the earth which are no longer being used and they could be used as a suitable repository for storing of the spent fuels. A few example could be the Yucca mountain repository in the US and then we have a similar one in Germany which was briefly operated and this is one of the ways people are or the countries around the world are exploring.

And also need to be made sure that these kinds of entities do not have any water leakages or because any contact of water with nuclear radiation can later lead to the nuclear radiation going into the water tables and putting an exposure to a great amount of people which is not something that is desirable. Another thing that is one is being explored is the transmutation. Transmutation refers to the conversion of this radioactive material into some other materials which are not radioactive in nature through the further use of some kinds of nuclear reactors. The research was initially initiated in the US but later on stopped. The reason behind this was because plutonium was one of the by-product of these kinds of conversion pathways and plutonium is also one of the feedstock to save for the nuclear weapons.

So that was one of the reasons why this kind of research was stopped. Further something similar is still being carried out in Europe specifically in Belgium. So they are looking at one of the reactors which is named Myra and they are putting some amount of money in the project is expected to have a total outlay of around 1.6 billion dollars and till date they would have spent around 200 millions and around 550 millions in two different trenches where they are again exploring that if the radioactive material that is produced in the spent fuel could be further converted into materials which are not radioactive in nature. Then another pathway that is talked about a lot is the reuse of the waste and the produced radioactive materials could be reused.

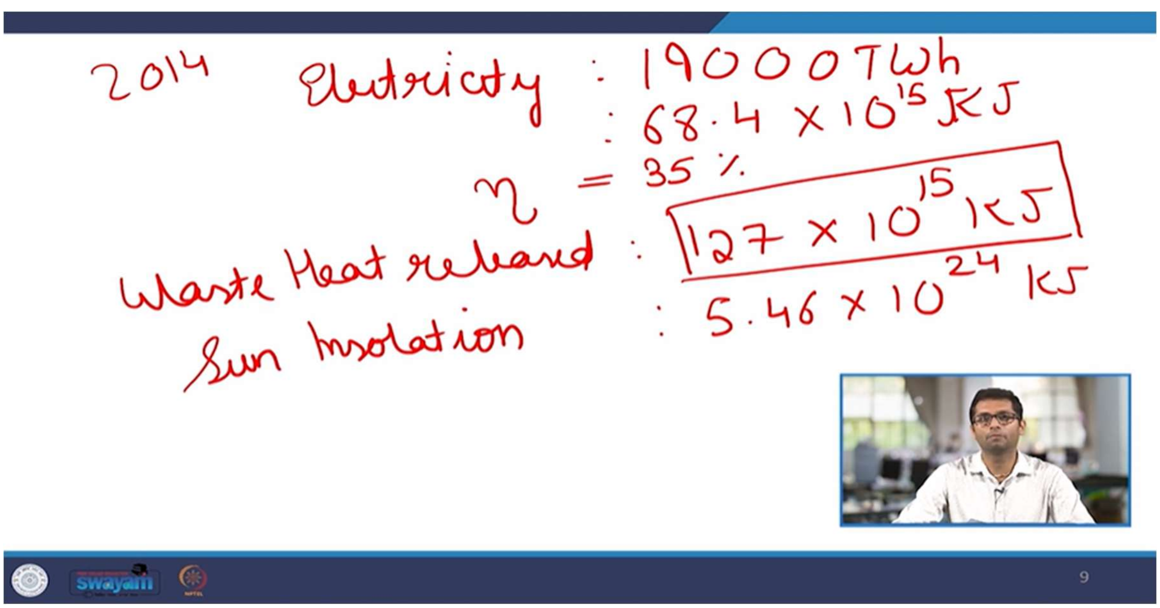


A major nuclear waste that is produced again is the isotope of uranium 238 and if this isotope is successfully separated possibly it could be used in other breeder reactors for the production of more energy and this is something that is being carried out. Then there are also aims to space disposal where they would want to pack the used nuclear material into some kinds of concentrated packing and raise the whole thing into the space and leave them in the space. So the typical cost that is estimated for an activity like this would be around 25000 dollars per to lift 1 kgs of mass of waste. So it comes out to be very expensive all the people are talking about it but it is way too expensive to be practical. Further there is also a danger that we have a lot of satellites and other space material that are doing and there is a lot of space debris already in the space. So one cannot rule out that there could be a possible collusion and there could be further not so good consequences of such an expedition. Further there is also a pathway which is like the developed countries dumping some of their nuclear waste into some of the less populated and not so affluent countries which might be in the need of some kind of economic incentives. A typical example is given of the sub-Saharan nations most of which are poor nations which would normally agree to in terms of some economic incentives that the affluent countries which would be producing their nuclear energy might would want to give their nuclear waste to these countries and store it there so that their people are safe. Now this is a very controversial issue and it has a lot of like debate going on it around. One of the specific things that is being discussed is the stewardship cessation means once the nuclear waste has been transported to a third country does if and if the country is not able to maintain the due standards as well as the safety of those radioactive material and there happens to be some kind of accident who would be the responsible party. Will it be the country who produced the waste in the original place or will it be the country who have taken in the waste for due economic incentive. So one thing that major countries are talking about is that like once they have sold in their waste to third country they are no longer involved their stewardship towards the protection of that particular waste cease to exist whereas there is another lobby which says about perpetual stewardship saying that the producer of this waste remains responsible for the safe handling throughout the lifespan which can be perpetuated in some of the cases and there is a strong debate behind this and also there are social factors and a lot of economic factors that are involved. So this is another thing that is being discussed but again it is a bit controversial. Further another kind of waste that not many people talk about is one of thermal pollution.

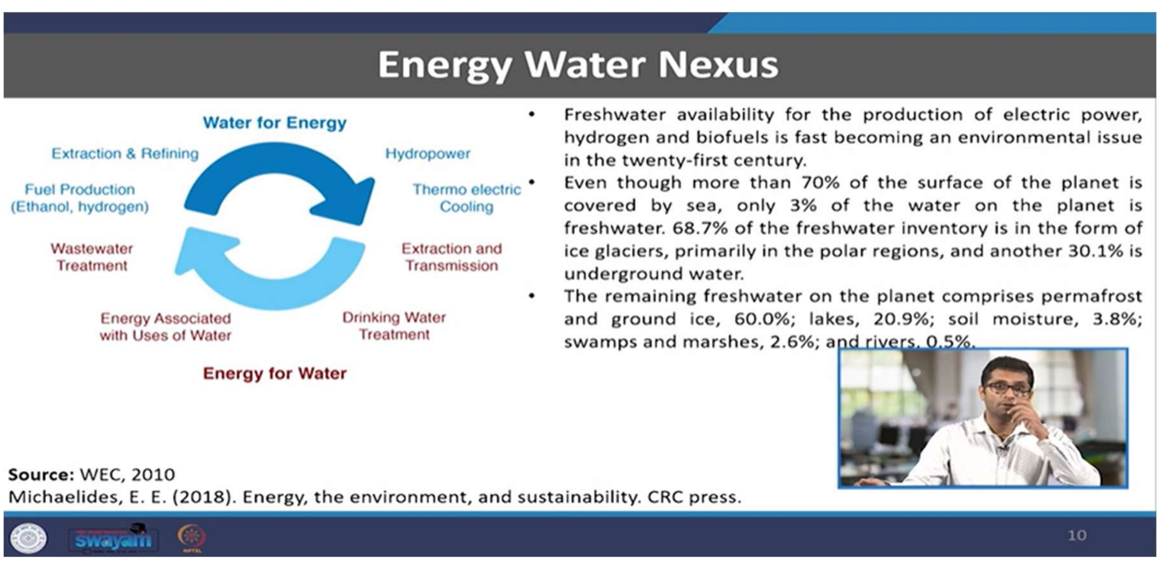


So what do I mean by thermal pollution? So we have learnt in the previous classes that all thermal power plants run at a specific capacity and specific efficiency and we also have a great deal of heat that is lost. So if I talk about a typical 1 gigawatt fossil fuel power plant it might have the latest ones might have an efficiency of around 40% which means it would be consuming an input power of roughly 25,00 megawatt or 2.5 gigawatt and it is effectively converting this 2.5 gigawatt into just 1 gigawatt of electricity. What happens to the remaining 1.5 gigawatt? This heat is normally released to the environment and it is not much of use although people have been saying that we can increase the efficiency but we have thermodynamic limits to it.

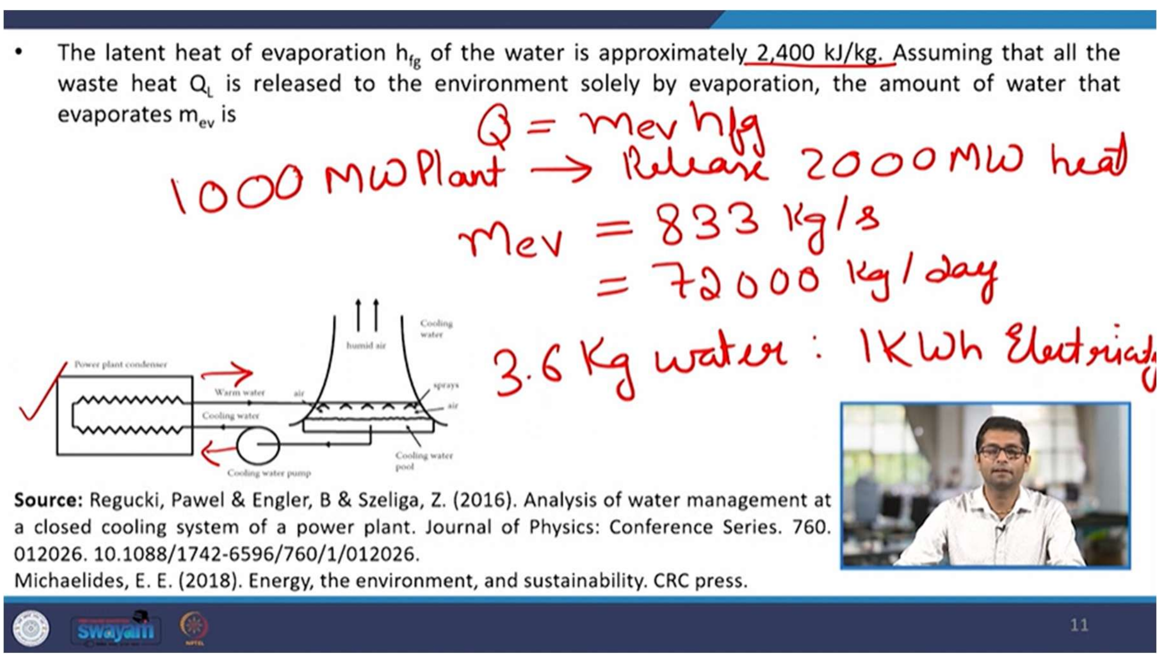
Most of the heat that is available to the environment is a very low grade heat somewhere around 50 degree Celsius or so which is not potentially a source of great power although it could be used for building heating applications or some other small heating applications but you cannot derive much of the power from this amount of low grade heat. Similar example could be seen in the case of a nuclear power plant which can be expected to run at an efficiency of 33%. So for every 1 gigawatt hour or gigawatt of electricity produced you had an input of around 3 gigawatt or 3000 megawatt and the remaining 2000 megawatt energy is again rejected as waste heat to the environment and typically this heat again would be less than 50 degree Celsius or so. So that it is very difficult to make use of this heat and this is where the thermodynamic second law come into play and you cannot make 100% efficient systems.



So if we are to look at the global electricity consumption. So if I consider the year 2014 the electricity consumed in that particular year was roughly 19,000 terawatt hour in terms of the energy units and this would be roughly equal to 68.4 into 10 to power 15 kilojoules of energy that is released. So maybe we can get kilojoules of energy that is released in the atmosphere and if I take the efficiency typical efficiency of the conversion processes to be around 35% the input electricity and the amount of heat that would be released from these kinds of processes as waste heat or I can say the waste heat released from this particular operation would be of the order of around 125 into 10 to power 15 kilojoules of heat. So one would suggest that this is a very great amount of heat and this could be a significant contributor to global warming as well so and there are some kind of communication that state this is again a major cause of global warming. But we need to understand that comparing this with the sun's insulation that reaches the earth. So if I take out the typical sun's insulation that reaches the earth it's about 5.46 into 10 to power 24 kilojoules. So there is almost 6 to 7 order of difference between the heat that we are continuously reducing receiving from the sun and that which is being again radiated back from the earth. So again this being a great source of heat but if to say that this is also major contributor to global warming might be an exaggeration of course the absolute amount of heat is too high but again if you compare that with the sun's insulation that is many orders of magnitude lesser. But that doesn't mean it doesn't have consequences and this is something we will discuss in the future slides but if we consider the effect of thermal pollution to global warming this could be said to be minimal.



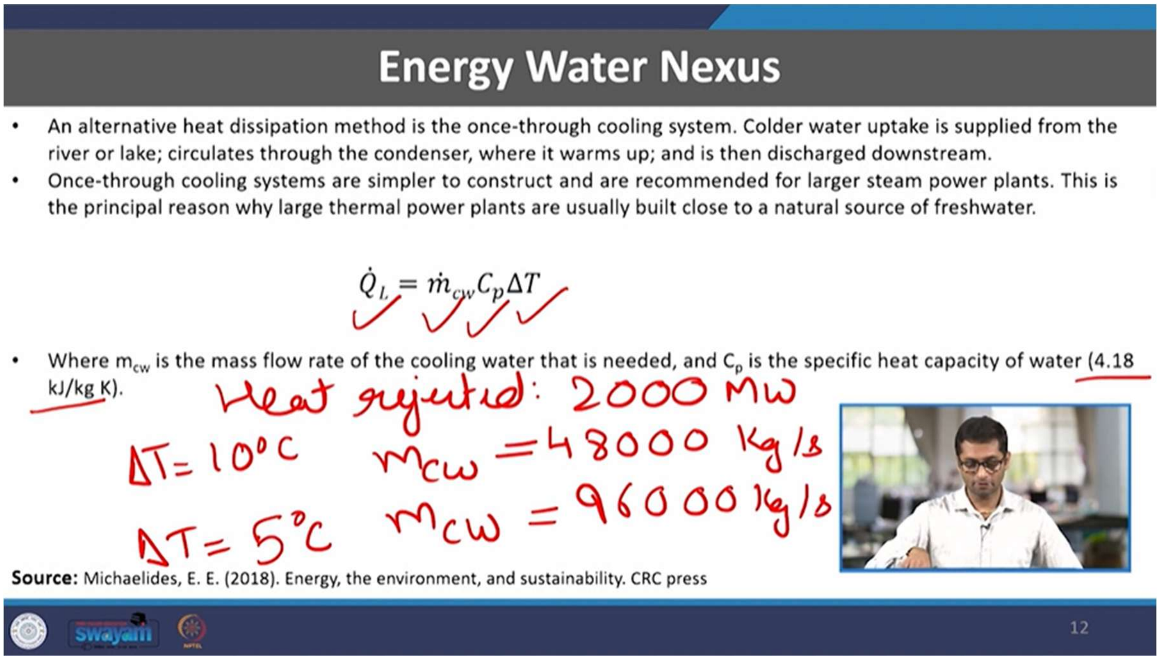
Now let's go further and try to understand this in much more detail. So what would be the likely effect? Now much of these plants would rely on fresh water for cooling of the condensers where this heat is released and we need to understand that earth although it has 70% of its surface covered with water bodies most of it is in the form of oceans which are saline in nature and almost 3% of the water that is available would come under the category of fresh water. Even among this 3% 67% or 68% or more is in the form of the glaciers, polar regions and underground water which we don't have direct access to. The remaining water that is left again is available in the form of the ground ice, lakes, moisture, marshes and rivers. So if I see the lakes, lakes is just 20% of the remaining fresh water and rivers is just 0.5%. So the fresh water that is available to us is a very small percentage of the total water that is available on the planet earth and that's a commodity that we need for our day to day survival that we need for the crops to grow that we need for the ecosystems to survive the different kinds of animals and plants to survive and it's not something we should be willing to sacrifice for some of the cooling applications. So just let us try to estimate the amount of water that would be needed in a typical cooling operation for a power plant.



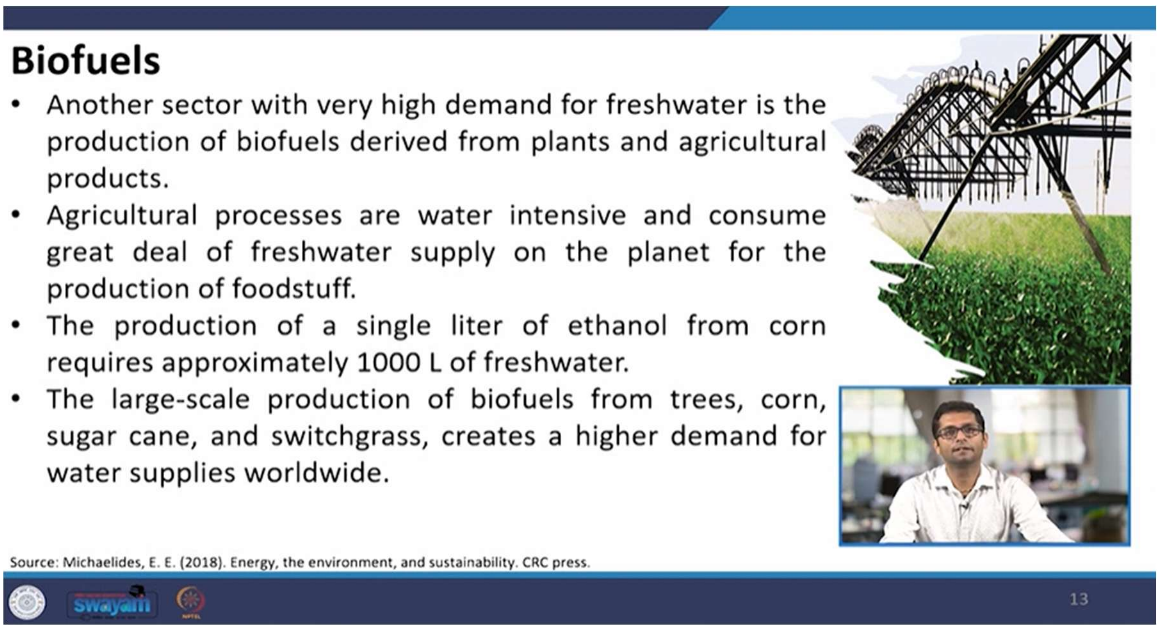
So there are two ways to understand it like one is that like we can consider a standard power plant where the heat would be released from the condenser. So this is the power plant condenser where you would be cooling down the steam and normally you would have the cooling water entering which would be at ambient temperature and in the process of cooling the steam that is used to run the turbine we will warm up the water. So the water gets heated and to further cool down this water it is normally spent to the cooling towers, the huge cooling towers which are basically used to depict the power plants in many of the figures even in the first slide if you refer we have shown this cooling towers which are big in size.

So what happens here is like the water is made to fall and you would have the air blowers in it and because of the effect some amount of water would evaporate and because this consumes energy it would cool down the remaining amount of water. So the equation that could be said is like the heat that would be absorbed in this process in the cooling tower would be the mass of the water that would evaporate and multiplied by the heat of evaporation of water or the latent heat of evaporation. The latent heat of evaporation of water is known to be roughly of the order of 2400 kilojoules of energy per kg and if we consider a typical power plant maybe 1000 megawatt plant and that is something we are considering it would basically release or 2000 megawatt of heat to the environment and if I put in like these values in this equation and calculate the mass of water. So the mass of water that would have evaporated for this rather typical power plant would be almost 833 kgs per second. If I take that in terms of day this would come out to be around 72000 kgs in a day or this would be roughly 72 tons of fresh water being evaporated to the environment on a daily level.

And as a rule of thumb or as an average we can consider that 3.6 kg water would be lost for every 1 kilowatt hour of electricity produced. So this water loss could again be a big consequence for any water scarce country specifically in India also we do not have much of the water resources of course we have many perennial rivers but again their availability of water given the huge population that we have to feed. It is a big concern that should be discussed the amount of water that is lost in the process of cooling in the case of conventional thermal power plants. Another thing that is normally adopted for saving the evaporative water is using once through cooling systems.

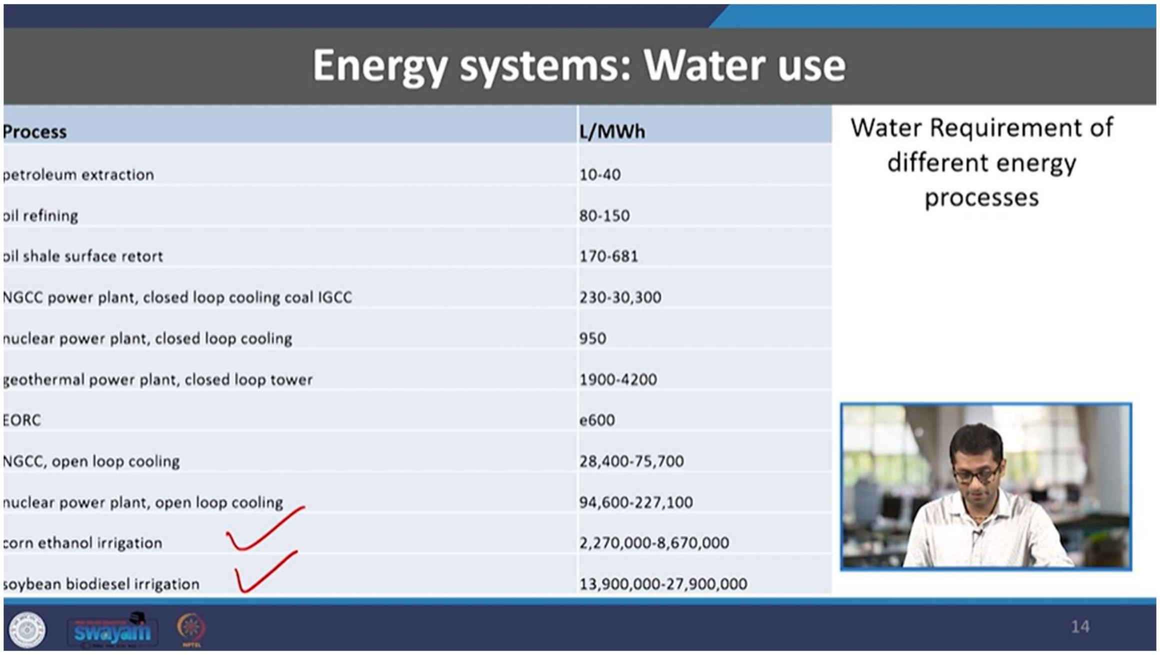


So what happens in a once through cooling system is that you do not have the water evaporate but you take the water from a stream of water might be a river or a lake and use that for cooling and then supply the water back to the lake or the river. So you take the water upstream of a river use it for heating and supply somewhat of the heated water back to the river. So in that case you do not expect much of the evaporation losses also one cannot deny there is no evaporation because the water as such would be absorbing some amount or a great amount of heat. So there would be some amount of absorption but a great amount of heat is absorbed in the form of like the quantity of heat absorbed by water would be equal to the mass of the water multiplied with the heat capacity of the water and multiplied by the temperature difference which is basically the potential difference for which the heat is being transferred. So let us take the similar example so if I consider the same case of the heat rejected being around 2000 megawatt and if I use the same equation with the CP of water being 4.18 kilo joules per kg kelvin and if I assume a delta T or temperature difference of 10 kg celsius which means the difference in the temperature from the source from the like if the water is taken in from the upstream and going to the downstream the water requirement or the cooling water mass flow rate would be roughly 48000 kgs per second. So remember in the earlier case this was around 833 kgs per second so there is a huge increase in the amount of water that would need to be circulated. Further if this delta T is assumed to be around 5 degree Celsius I do not want to raise the temperature of the water much this same mass flow rate would be almost doubling to around 96000 kgs per second. So you would have somewhat increase in the amount of water that you would be consuming in absorbing the same amount of heat. So again this remains a question like should we be using such amount of water for these kinds of application and again this is also the reason that you would find a majority of the big power plants in the vicinity of some kind of fresh water source. Throughout the world if you see the location of the major coal based power plants or nuclear based power plants they would be located in the vicinity of big rivers or big reservoirs of water so there is so that there is a sufficient supply of water which is used as cooling water.



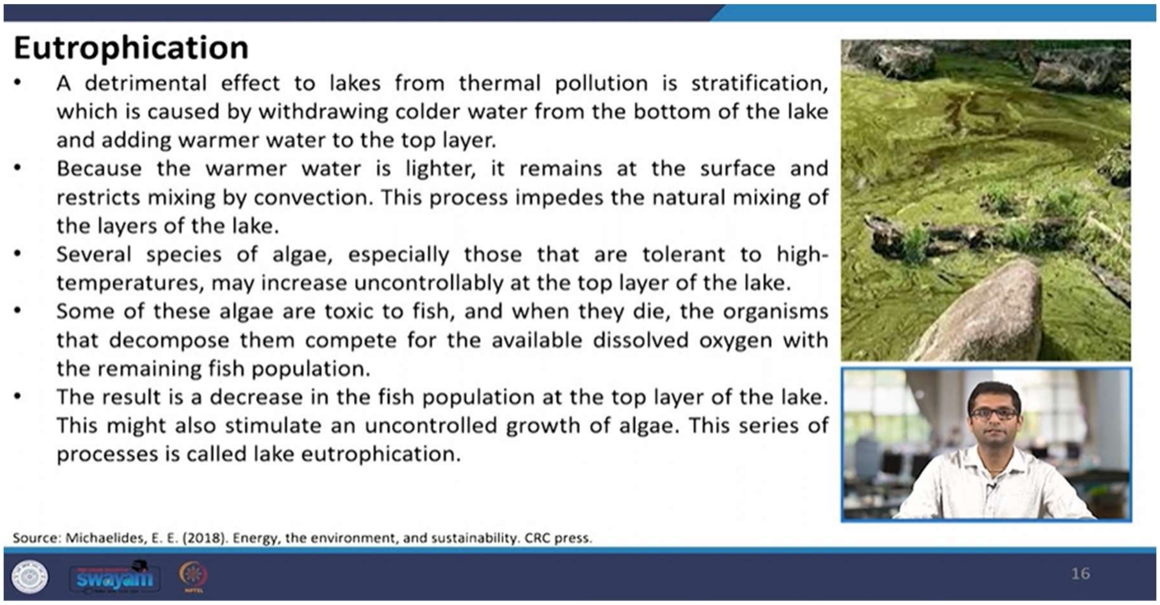
Another area where water use is a lot of concern is in the production of biofuels. So biofuels is a fuel that is derived from a biomass source something similar to biodiesel, bioethanol or like coming from biomass source where you grow the biomass and then use it through different types of conversion process to replace a fuel that is already being used in the market. And one of the major issues with respect to biofuels is the amount of water that would be consumed during the growth and harvesting of the biomass that you are growing. Because if you see the conventional farming we use a lot of water and this water goes into the growth of the biomass and further this biomass is used as a fuel.

So if you see the amount of water that goes for production of 1 litre of bioethanol it would be almost 1000 litres of fresh water that goes. So the water footprint of any biofuel could be huge and that needs to be understood. Of course it is understood like biofuels could be the future it could help in bringing down the CO2 emissions but one of the major consequences of use of biofuels is that they are huge water consumption.



Just for the sake of comparison we are referring to a study which has done analysis on the litres of water that is consumed per megawatt hour of energy produced and we find that the production of corn ethanol and soybean based biodiesel consuming almost like 13 million to 27 million litres of water per megawatt hour of electricity produced. Comparing that with a conventional power plant and this could be a typical range of course this would depend upon the technology.

But biofuels tend to use a lot of water and given we are living in a country which has a huge population to support and not blessed with a lot of water resources and diseases like this should be made taking into account that of course there could be pathways which could have a low CO2 emissions but the water footprint of different kinds of fuels should also be taken into account.

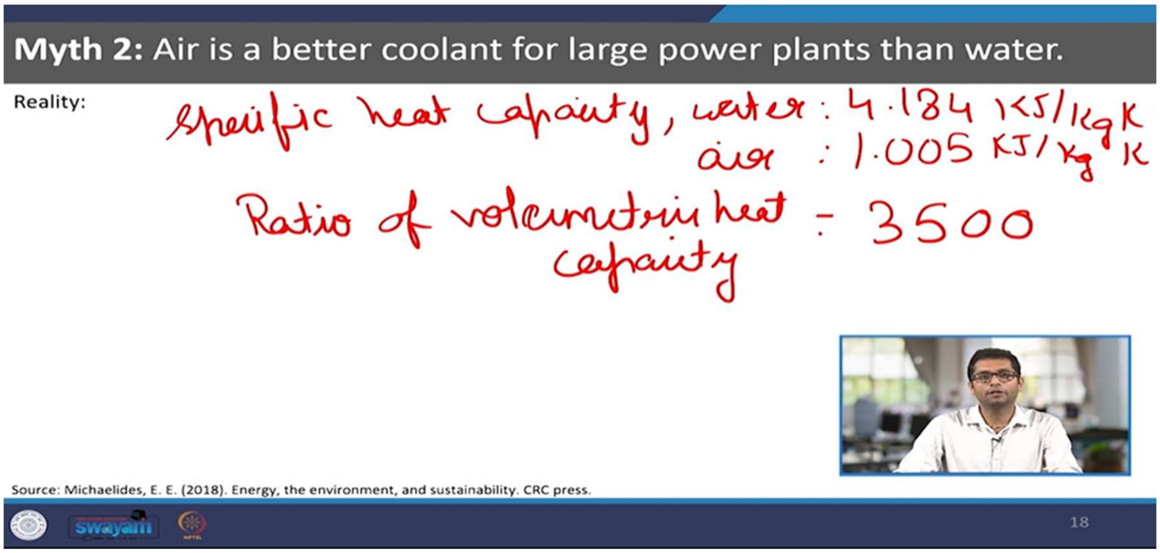


Further this rejection of heat as we have discussed in the earlier slide to the water bodies could also have significant consequences on the aquatic life because what we are essentially doing is we are raising the temperature of the water in the downstream process where we are releasing this heated effluents and what normally happens is because of this change in the system the dissolved oxygen concentration tends to reduce and there is also an increase in the order of some of the reactions which are important for the aquatic ecosystems and these kinds of changes could result in like reproduction changes or growth patterns of certain organisms which might lead to increase of certain organisms and decrease of some of the organisms. So the ecosystem changes from these kinds of systems of course they would be system specific but could lead to significant changes and this is something that should be kept in mind as well. Further there is another important thing because to be understood that one of the detrimental effect that happens from the thermal pollution is the stratification or the eutrophication. So most of the water that would be taken in or would be used from the upstream would be from the bottom of the lake whereas the release of the water normally happens to the top of the lake.

Also the warm water being less in density tends to stay in the top and this also hinders the mixing or the natural mixing of the different parts of the lakes. So normally the lakes are aquatic ecosystems with specific systems going in and because of the human intervention of taking in water for cooling purposes and giving back heated water somewhat heated water maybe at a delta of 10 degree Celsius they hinder the natural processes of the different nutrient cycles that are there in the lake and it also gives rise to the increase of algae which are the greenish kind that you can see in the figure in here. Because of this green the algae growth tends to limit the oxygen available for the other life species which leads to degradation of the other organisms and spoils the lake ecology and this kind of effect is also called as eutrophication where we have an uncontrolled growth of algae and one of the reasons for that has been attributed to this is the flow of the different kinds of chemicals that come from the fertilizers and pesticides and insecticides. Another major reason that has been attributed is the release of the heated water into the water bodies that can have an effect like this. So with this let us also try to understand some of the facts as well as myths with respect to water because that is an important thing.

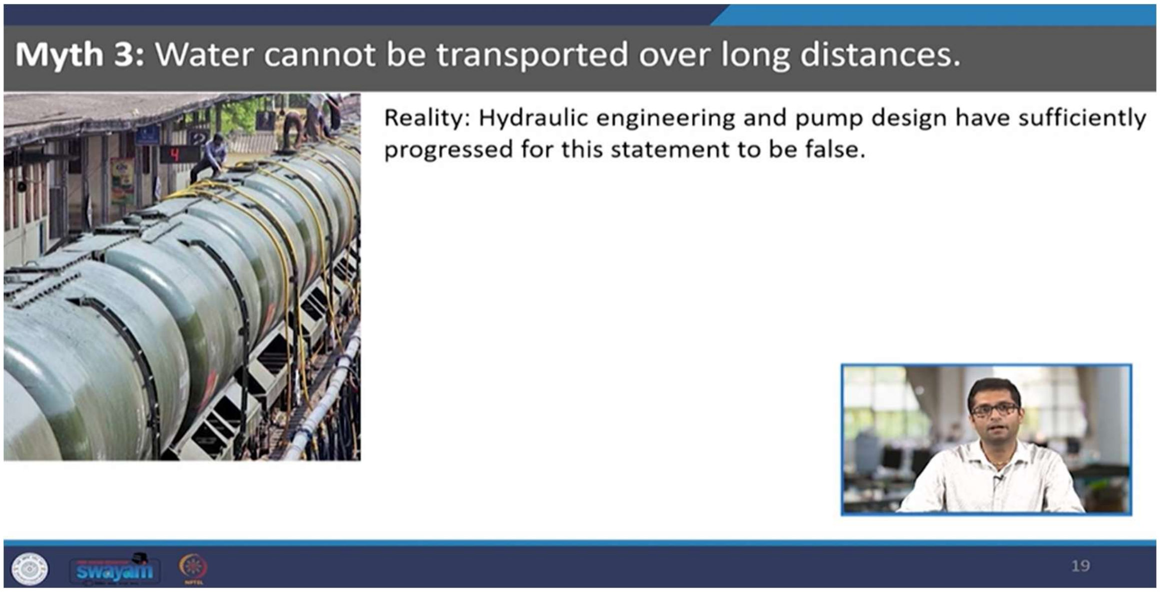
So one of the myths that we normally come across that water has become a very scarce commodity. Now a scarce commodity is something that would have a very limited supply and a very high demand. So normally a commodity that falls from the sky every few months and in abundance would not be called a scarce commodity. Also given the technologies we have the membrane technologies that can help convert a lot of sea water into drinking water.

A lot of Middle Eastern countries are relying on that. They convert this saline sea water into drinking water. So water as such cannot be said as scarce commodity because there is a huge amount of water available on earth. What it is normally is it is an economically scarce commodity. What we can say is the ability of the different countries to give the normal population water at an economic rate might be limited because the water needs to be transported or the water needs to be converted from other sources to be a portable form. But as such to say water has become a very scarce commodity might be a misnomer.

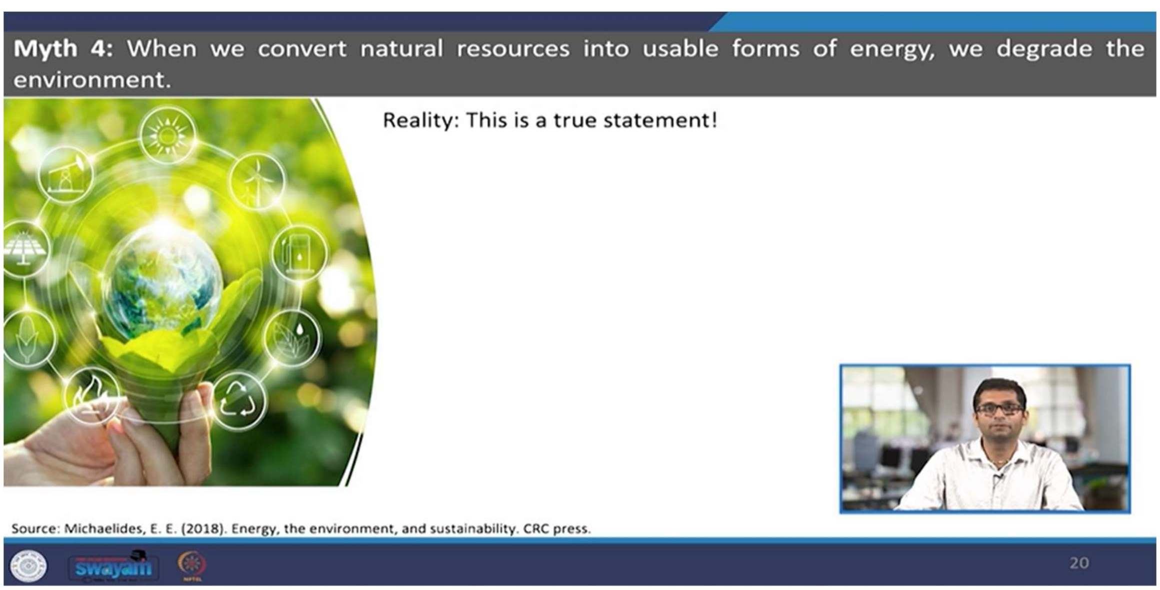


Another myth that one can come across is why do not we use air as a coolant in the large power plants and why are we wasting drinking water for it. Air can also basically do all the function that water is currently doing. So let us try to understand with the help of certain data. So if I talk about the specific heat capacity of water this would be almost of the range 4.184 kilojoules per kg kelvin. If I see the same value for air this would come around to be 1.005 kilojoules per kg kelvin. Also if you see the rate so we see water has 4 times the specific heat capacity in terms of the weight of absorbing water as compared to air. We can also compare the volumetric heat capacity and give you the ratio. If I see the volumetric of water and air this would come around to be almost 3500 because the density of water is much higher than that of water.

So if you see the volumetric heat capacity water makes better sense and if I also talk about the thermal heat capacity so the thermal heat capacity of sorry the thermal conductivity of water is roughly 0.63 watt per meter kelvin. Compare that with that of water it is 0.024 watt per meter kelvin. So it always makes economic sense to use water instead of air because you would require a very good amount of air and for water you do not need much of the compression as well. And this is the reason why water has been used because it is abundantly available. But this needs to be discussed in the future can we go in with the use of water given that water has other applications as well.



And then there is also myth that people understand that water cannot be transported over long distances but we in India have seen that there have been trains running for transporting water and also like with the advancement of hydraulic engineering and pump designing we know that sufficient amount of waters could be transported for 300 or 400 kilometers. So water transportation of course like it could be expensive but water can be transported over long distances.



And finally people say that when we convert natural resources into usable forms of energy we degrade the environment. Well this one is a true statement whenever we are producing energy from the natural resources we are doing some kind of problem or degradation to the environment. It could be in the form of CO_2 emissions, it could be the form of the water, it could be the form of different kinds of chemicals released into the environment. And this is what is going to be the discussion for the next class where we are going to discuss the different kinds of problems that are related with different kinds of energy production pathways conventional and non-conventional, renewable and non-renewable so as to get an understanding like what could be the likely problems. So of course we have discussed one of the major issues of CO_2 in the past but there are many other issues which we will be highlighting in the next class. With this we end today's class. Thank you.