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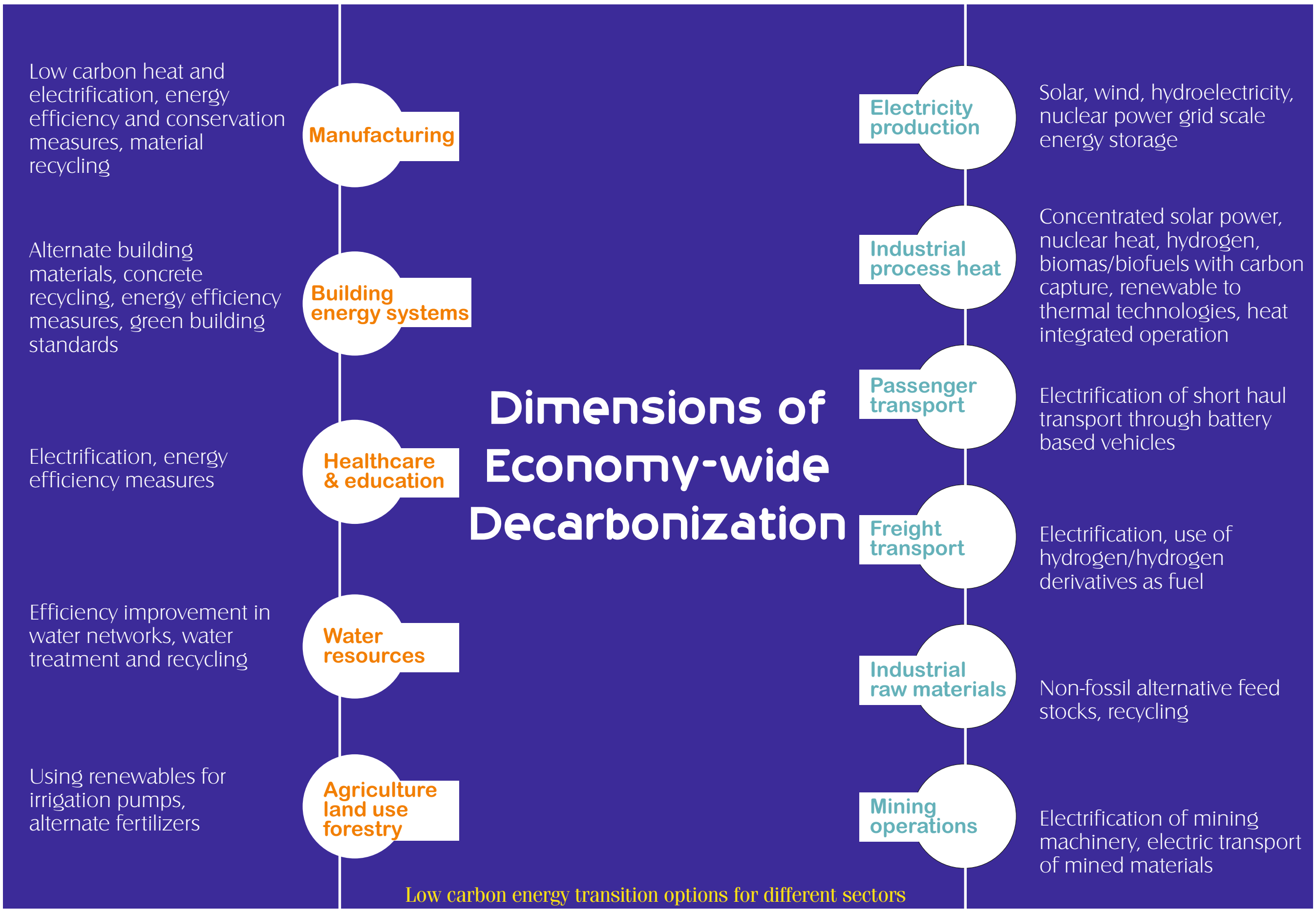
The latest series (released in 2021-2022) of the Assessment Reports (ARs) from the three Working Groups (WGs) of the Intergovernmental Panel on Climate Change (IPCC) has established without doubt the role of greenhouse gas (GHG) emissions in human induced climate change[1]. Carbon dioxide emissions reduction across all sectors of the economy and management of residual and unavoidable emissions from the hard-to-abate sectors through technological and nature-based means is the most critical need of the hour in our attempts at climate change mitigation.

Most emissions today arise from fossil energy use and industrial processes; therefore, these sectors are the focal points for practically all emissions reductions initiatives round the world. So, what are the options for sectoral decarbonization? The illustration presented in the following page tries to highlight some of the mature and near-mature alternatives as applicable to different sectors. It shows that for the electric power sector, energy transition means switching to clean/emissions-free sources of electricity generation including renewable resources, hydro-electricity and nuclear power from the current thermal power generation stations based on coal, natural gas etc, unless the emissions from the thermal power plants are fully captured and permanently stored away. For passenger transport (which is a mobile source of carbon emissions), this implies making use of clean electricity in the shift to electric vehicles from the current dependence on liquid fossil fuels like petrol and diesel.

For many other sectors, the answers are not so straight forward yet. The difficulty lies in decarbonizing certain sectors such as heavy transport, chemical synthesis industries (such as ammonia, methanol, etc production), metallurgical processes (such as steel production), glass and cement production. This is because not only do these sectors depend on fossil fuels for energy, but very often they make use of fossil fuel derived compounds as a raw material or feed stock to the process.

Therefore, electricity alone will not decarbonize these sectors, low carbon electricity must be used to produce low or zero carbon materials/energy vectors which can then contribute to decarbonization of these sectors. One such vector is clean hydrogen (produced by using clean electricity from renewable and nuclear sources and/ or heat using a carbon free feed material such as water), that has gained massive momentum all over the world. This form of hydrogen is often described as green hydrogen.

The most developed technique for green hydrogen production today is the electrolysis of water in alkaline water electrolysers or proton exchange membrane electrolysers, which can make use of any low carbon electricity source to split water into its constituent elements oxygen and hydrogen.



Low carbon energy transition options for different sectors

Energy Considerations in Hydrogen Production and Utilisation

Unlike primary energy sources like coal, crude oil, natural gas which may be designated as fuels, hydrogen does not occur freely in nature. It is a secondary energy form that has to be produced by using some primary energy form. Thus it is best designated as an energy vector or carrier and not a fuel. Let us look at the energy considerations surrounding hydrogen production by electrochemical water splitting and its uses for different applications[2]. This becomes an important decision criterion governing the ultimate applications of hydrogen for decarbonization.

The water splitting reaction producing hydrogen and oxygen may be written as follows:

$$H_2O \leftrightarrow H_2 + 0.5O_2 \quad \Delta H_R = +\,285\ \frac{kJ}{mol}\ H_2$$

It indicates that the thermodynamic minimum amount of energy required to completely split 1 mol of water to produce 1 mol of hydrogen is about 285 kJ (all products and reactants being at 298 K, 1 atm pressure). It also indicates that if 1 mol of hydrogen is burnt with the stoichiometric minimum amount of oxygen (i.e., 0.5 mol of O_2), the maximum heat that may be released is 285 kJ (this is also called the calorific value of hydrogen). These figures pertain to ideal processes of production or combustion which have infinitesimally slow rates and are therefore considered ideal.

It is thus evident that in any real system where finite rates of hydrogen production and utilization have to be accomplished, additional energy greater than 285 kJ would be needed to split a mole of water and energy less than 285 kJ would be obtained from combustion of a mol of hydrogen in oxygen. How much more or less depends on the system efficiencies and various losses and irreversibilities occurring during the process. For example, a typical industrial scale water electrolyser has an electricity-to-hydrogen production efficiency of 70 to 75%.

Thus to split water by electrolysis, one needs to spend between 285/0.75 to 285/0.7 kJ (or 380 to 407 kJ of electric energy) per mol of water split. Then, if one were to burn this hydrogen is a typical fuel cell of 60% efficiency, one would recover a maximum of 285*0.6 = 171 kJ electricity per mol of H_2 burnt. If hydrogen is burnt and used to produce electricity in a gas turbine power plant, even less electricity would be produced since these plants may have efficiencies of about 45 to 50%.

Thus, the net energy return from hydrogen applications on the energy used for producing hydrogen is always less than one. Because of these factors, hydrogen is at best an energy carrier or converter and not a fuel. So, its first uses need to be in non-energy applications and then only energy related applications of hydrogen for decarbonization should be considered.

Essential

Ammonia/Fertilizers

Food processing

Iron, steel, other metallurgical uses

Hydro-treatment/ hydro-processing applications in refineries

Methanol synthesis; semiconductors

Shipping/aviation/ long distance/heavy transport

Conditional

Long Distance Rail Transport

River/lake based local water transportation

Industrial heating/ thermal applications

Autonomous power systems in remote areas/islands

Avoidable

Renewable Energy long duration storage/ transportation

Buses, cars and other modes of urban transport

Domestic heating, cooking and other energy services

Grid balancing/ flexibility/reliability services

Classification of the uses of low carbon hydrogen [based on the conceptual framework in [3] and [4]

Decarbonization – Role of Hydrogen

Once it is established that hydrogen is a crucial component of the decarbonization journey of a nation, one needs to consider the best uses of hydrogen (based on thorough evaluation and comparison of possible alternatives) and thereby identify the priority sectors to be decarbonized by hydrogen. On the basis of alternatives available for specific sectors and their relative techno-commercial maturity levels today, these uses may be classified as 'Essential', 'Conditional', and 'Avoidable', as shown in the illustration presented above. The rationale for such categorization is provided next.

a) Under the 'Essential' category in the above illustration, many of the listed applications such as ammonia production and chemical synthesis, semiconductor and food processing industries already make use of hydrogen derived from fossil fuels (e.g. by steam reforming technology using natural gas as the feed stock). Therefore in the hierarchy of uses of hydrogen, these automatically occupy the top places, since they must mandatorily replace fossil hydrogen in their approach to full decarbonization. Low carbon hydrogen is therefore a direct or drop-in substitute for fossil hydrogen in these industrial applications. These sectors must be supported by adequate policies and incentives related to hydrogen use in the near term.

The technological alternate for these sectors is to use carbon capture technologies at the point of fossil hydrogen production so that the emissions intensity is greatly reduced. Such hydrogen is often designated as 'blue hydrogen'. But given the fact that carbon capture technologies still need to prove their techno-commercial viability at scale (vis-à-vis the maturity level already attained by electrolytic hydrogen technologies), this 'blue hydrogen' route is very likely to slow down the net zero carbon emissions journey of these sectors, not to mention keeping the end user sectors exposed to natural gas price volatility and supply security concerns (given the geo-political situation and natural gas related energy crisis already facing many countries today).

Therefore electrolytic hydrogen has a very good business case in these sectors already. The challenge would be to produce and dispatch the renewable or nuclear hydrogen to these end users, because not all these industries will be able to produce their required quantities of hydrogen at their site itself (which has usually been the case when using fossil hydrogen – the methane reformers are installed close to the ammonia plant or chemicals complex, thereby obviating the need for bulk storage or transport of hydrogen).

b) For the sectors under the 'Conditional' category in the above illustration, one needs to be cautiously optimistic about the use of hydrogen. This is because not only will adequate amounts of hydrogen have to be generated and transported, one would also need additional demand-side hardware (such as hydrogen storage and fuel cell systems or hydrogen based reduction furnaces for iron ore reduction in steel production) in order to let these industries make use of hydrogen. For example, in countries (such as India) where the railway system is already electrified, the dedicated production and use of hydrogen (which is ultimately used to generate electricity itself via fuel cells) is not advised, since it merely serves to introduce additional conversion steps and the associated inefficiencies in the overall process, along with the need for massive new infrastructure build out. Use of clean electricity is the most direct route to their decarbonization. In other applications such as small scale distributed power systems or micro grids, the use of renewable electricity and battery based electricity storage system is a techno-economically better alternative than the system. In many industrial heat applications, use of renewable electricity based heat and thermal storage in suitable media may prove to be adequate, without requiring hydrogen combustion. But in high temperature applications, in the absence of high temperature heat sources hydrogen as a zero carbon fuel may turn out to be the only viable option. But this too would need some modification in the hardware, for example in the burners or furnaces which have so far worked on natural gas or fuel oil as the heating media. Biofuels to substitute fossil fuels has been considered but unless carbon capture is also deployed alongside, the process will not be entirely carbon neutral.

c) The sectors placed under the 'Avoidable' category are currently the least attractive use cases for hydrogen utilization, given the still high hardware or capital costs for hydrogen production vis-à-vis that of battery based electricity storage for urban mobility and grid scale energy storage. The relevant alternatives are building hydrogen fuelling stations versus electric vehicle chargers and currently electric chargers are somewhat more accessible than hydrogen stations, thereby favouring direct electrification versus use of hydrogen in some transport applications.

Another such area is the use of electricity driven heat pumps for building heating applications rather than replacing previously installed oil or gas fired boilers by hydrogen fired ones. Thermodynamically, heat pumps make much more sense in most geographies with moderate to even severe winters than hydrogen boilers, due to greater number of conversion steps and corresponding losses at each level, as discussed earlier. Depending on size of the grid and any potential imbalance, the need for energy reserves can be very different. If hydrogen is used for grid balancing and long duration energy storage, very large hydrogen storage would be needed in many areas. And these areas may not have access to underground caverns, etc which have been proposed to be used for large scale hydrogen storage.

Concluding Remarks

The discussion in the above sections drives home the point that use of hydrogen should not be considered as the panacea for all the ills of a fossil fuel driven world! There are specific sectors where the use of hydrogen is mandatory for net zero emissions targets to be achieved, but there are many more sectors which are better served by direct electrification and electricity storage compared to the alternate hydrogen-hydrogen storage-fuel cell route. In many of these applications, not only must the supply side of hydrogen be taken care of, substantial revamps and retrofits on the hydrogen use or demand side will also be required if hydrogen truly has to play a part in their decarbonization. The maturity of carbon capture technologies may also make some potential hydrogen applications redundant. In any case, the major prerequisite in both cases is that only low carbon energy forms be used to harness the electricity and heat that will ultimately go into the production of the hydrogen or for carbon capture process plants. Use case selection is a very important part of a successful hydrogen economy! That must be supported by rigorous analysis that looks at near and long term considerations holistically.

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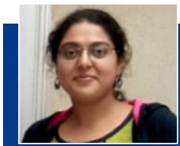

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