PRIORITIZATION OF MULTIFACETED CRITERIA FOR THE DIFFERENT CO_2 REMOVAL TECHNOLOGIES FROM BIOGAS USING ANALYTICAL HIERARCHICAL PROCESS

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ABSTRACT

Biogas and its derived forms may be considered as the most extensive source of Biomass energy. Raw biogas, which is usually generated from different type of biomass wastes, is primarily be made up of CH_4 (55%-65%) and CO_2 (35%- 45%). Raw biogas has the calorific value of 22- 25 MJ/m3. After CO_2 removal, the CH_4 gas has a calorific value up to 39 MJ/ m3, Purified biogas has much broader and greater value applications. Packed Tower Absorption (Water Scrubbing), Packed Tower Absorption (Amine Scrubbing), Pressure Swing Adsorption, Chemical Reaction with Lime, Membrane Separation and Cryogenic Separation are the main available Technologies for the removal of CO_2 from Biogas. Each type of Technologies has its merits and demerits. In order to select the most appropriate Technology among them are very important to gain the optimal benefit. To deal with such complex decision making problems, The Analytic Hierarchy Process (AHP) a Multi criteria Decision Model introduced by Thomas Saaty, is an effective tool. The AHP helps to capture both subjective and objective aspects of a decision by reducing complex decisions to a series of pair wise comparisons and then synthesize the results. In this research, prioritization of multifaceted criteria like Technology Maturity (Technical Aspects Only), Technology Availability (In India), Initial Investment Cost, Operation Cost, Process Efficiency and Process Emissions (Air, Water & Ground) is done by using AHP (Super Decision Software) for the prioritization of most appropriate CO_2 Removal Technology from Biogas.

Key Words: Biogas, CO_2 Removal Technologies, Analytical Hierarchical Process, Multifaceted Criteria, Super Decision Software

I. INTRODUCTION

India depends heavily on coal, oil and natural gas for meeting its energy demand. Demand for energy will continue to increase and potential of energy resource will continue decrease. This mismatch denote to energy crisis. For removal of this disparity between energy demand and availability, the renewable energy is promoting as alternative energy source. Various renewable energy sources such as wind energy, geothermal energy, solar energy and biomass energy etc. are available readily in India [1, 2, 3].

Biomass is regarded as the prominent source of renewable energy. Biomass energy is a potentially sustainable and comparatively environment friendly source of energy. Rapid rate of fossil fuel usage releases huge amount of CO_2. Conversely, biomass absorbs the same amount of CO_2 in rising that it releases when burned as a fuel. Biomass is carbon dioxide neutral source on sustainable basis utilization. In addition, biomass contain negligible amount of sulfur so they have a minimum contribution to acid rain. Therefore, biomass use as substitute of fossil fuels for energy Production will result in a net reduction in green-house gas emissions [4]. Biomass energy resource is comparatively uniformly available in India likened to other renewable sources. Recognizing the potential of bioenergy progression, the Ministry of New and Renewable Energy (MNRE), India has started several biomass programs, with promoting Degree of success [5].

Biogas and its derived forms may be considered as the most extensive source of Biomass energy. Biogas is a product of bio-methanation process when fermentable organic materials are subjected to anaerobic digestion in the presence of methanogenic bacteria. The main constituents of produced gas from the anaerobic digestion mainly contain CH_4 and CO_2. It also contains some other gases and vapors contents [6].

Raw biogas, which is usually generated from different type of biomass wastes is primarily be made up of CH_4 (55%-65%) and CO_2 (35%- 45%). Raw biogas has the calorific value of 22- 25 MJ/m3. After CO2 removal, the CH_4 gas has a calorific value up to 39 MJ/ m3. Purified biogas with methane content above 96% can have the similar property as natural gas, which can substitute fossil gas and has much broader and greater value applications. Thus, it is essential to promote purification techniques for biogas upgrading [7]. The majority of biogas purification methods are derived from conventional gas separation technologies and many of them have been successfully applied for natural gas purification. Normally used methods are Packed Tower Absorption (Water Scrubbing), Packed Tower Absorption (Amine Scrubbing), and Pressure Swing Adsorption, Chemical Reaction with Lime, Membrane Separation and Cryogenic Separation. Each type of CO2 removal from Biogas has its advantages and disadvantages, so that selecting the most appropriate removal Technology among them is very important to gain the best possible option. The Analytic Hierarchy Process (AHP) a Multi-Criteria Decision- Making (MCDM) model introduced by Thomas Saaty, is an effective tool for dealing with such complex decision making.

MCDM is a branch of a general class of Operations Research models which deal with the process of making decisions in the presence of multiple objectives. These methods can handle both quantitative and qualitative criteria. In AHP, a multiple criteria problem is structured hierarchically by breaking down a problem into smaller and smaller consistent parts. The goal (objective) is at the top of the hierarchy, criteria and subcriteria at levels and sub-levels of the hierarchy, respectively, and decision alternatives at the bottom of the hierarchy. The best alternative is usually selected by making comparisons between alternatives with respect to each attribute. This type of method has been used in Renewable Energy planning [8].

In this research, we have selected and ranked multifaceted criteria like **Technology Maturity (Technical Aspects Only), Technology Availability (In India), Initial Investment Cost, Operation Cost, Process Efficiency and Process Emissions (Air, Water & Ground)** using **AHP (Super Decision Software)** for the prioritization of most appropriate Removal Technology of CO_2 removal from Biogas in Indian context.

II. VARIOUS REMOVAL TECHNOLOGIES OF CO_2 FROM BIOGAS

Removal of CO_2 from Biogas can be accomplished by using a number of different Technologies like Packed Tower Absorption (Water Scrubbing), Packed Tower Absorption (Amine Scrubbing), and Pressure Swing Adsorption (ZMS), Chemical Reaction with Lime, Membrane Separation and Cryogenic Separation. Factors that influence the choice of removal process are: the quantity of biogas available, the ultimate application of energy, environmental norms and economic viability. The brief discussion of the CO_2 Removal technologies from biogas is given below:

2.1 Packed Tower Absorption (Water Scrubbing)

Packed Tower Absorption (Water Scrubbing) is the most commonly used method for the purification of biogas. It is fundamentally based on the principle that the solubility of CO_2 and H_2S is higher in water as compared to CH_4, thus separating both CO_2 and H_2S simultaneously from biogas with a high efficiency is easy. To increase the absorption of CO_2 and H_2S, Biogas is usually compressed to 900–1200 kPa and a packing media which has a high surface area is used. Within the scrubber, the flow of biogas keeps counter currently with respect to water flow that is sprayed from the top of scrubber, and the absorption primarily occurs on the surface of the packing media. Cleaned biogas can contain >96% CH4 after drying [9]. The liquid effluent contains a high concentration of CO_2 and a low concentration of CH_4. CH_4 is recycled in the flash tank where pressure is lowered to 200–400 kPa. Finally, water is regenerated in the stripper at near atmospheric pressure with air blown into the stripper. The advantages of this method include no need for chemicals and simultaneous removal of CO_2, H_2S, and other impurities which are soluble in water, e.g. Dust and Ammonia (NH_3).The main challenge of this method is that its demand of water is very high. Current studies on PWS mainly focus on applying high pressure, reducing water usage, and optimizing water pH. Water pH affects absorption of H_2S. Solubility of H_2S decreases with decreasing pH .At elevated pressure, the solubility of gases increases, which reduces water demand in the scrubber. The method provides 100% pure methane but the purity is dependent on many factors i.e. dimensions of scrubbing tower, composition of raw biogas, water flow rates, gas pressure, and purity of water used[10].

2.2 Packed Tower Absorption (Amine Scrubbing)

Amine solvent has been often used to separate CO_2 from gas streams because of its high absorption selectivity of CO_2.The solvents which are generally used are alkanol amines, such as mono ethanol amine (MEA), diethanol amine (DEA) or methyl diethanol amine (MDEA), among which MEA is the most widely, employed solvent for low pressure absorption. These solvents not only enhance CO_2 absorption capacity but also reduce corrosion problems [10]. The reactions during adsorption and desorption processes are shown below.

Absorption of CO_2: $RNH_2 + H_2O + CO_2 \longrightarrow (RNH_3)^+ + (HCO_3)^-$ (i)

Desorption of CO_2: $(RNH_3)^+ + (HCO_3)^- \longrightarrow RNH_2 + H_2O + CO_2$ (ii)

Where R is an organic component. For example, R is – $(CH_2)_2OH$ for MEA. The above reactions are mainly governed by pressure and temperature. Lower temperature and higher pressure favors absorption, while higher temperature and lower pressure promote desorption. Biogas is usually compressed at 600–700 kPa before feeding into the absorption reactor. In the absorption phase, CO_2 and some H_2S gas dissolve into the solvent, while high-purity CH_4 gas leaves the reactor. The cleaned biogas usually contains high purity CH_4 (96–98%). Also, due to the fact that amine solvents have a much higher solubility of CO_2 over CH_4, CH_4 loss can be very low during this process [12]. Thus, amine absorption is preferred where strict environmental regulations on CH_4 emissions are applied.

2.3 Pressure Swing Adsorption

Pressure swing adsorption (PSA) uses the adsorbent's differences in gas adsorption rates to capture preferred gases (e.g. CO_2, O_2, and N_2) at a high pressure, and then releases the adsorbates at a low pressure to regenerate the adsorbent for a subsequent adsorption cycle. Usually the adsorbents which are used in PSA are carbon molecular sieve, zeolite, silica gel, and activated carbon, due to their low cost, large specific area and pore volume, and excellent thermal stability [13]. These adsorbents are designed to have a specific pore size thus enabling selective adsorption of molecules that are smaller than the designed pore size. The molecular size of CH_4, CO_2, O_2, and N_2 are 4.0, 2.8, 2.8, and 3.0Å, respectively, at standard conditions. Therefore, an adsorbent with a pore size of 3.7Å is able to capture CO_2, O_2, andN_2, but not CH_4, thereby cleaning the biogas [14]. The major concern of the PSA system is its toxicity and over-loading of adsorbents. Sticky gases, such as H_2S and NH_3, may irreversibly attach to many adsorbents and reduce their available surface area for adsorption, while water competes with other adsorbates for adsorption spots. Therefore, H_2S and water need to be removed from biogas before the PSA cleaning process . PSA method is preferred over the other purification technologies because of low energy requirements and low capital cost in comparison with other separation methods [15].

2.4 Membrane Separation

The Separation principle of membrane permeation is that under a certain pressure, gases with high permeability (e.g. small molecular size and low affinity) can be transported through the membrane while gases with low permeability are retained. High permeable impurities, such as CO_2, O_2, and H_2O, pass through the membrane as permeate; while low permeable CH_4 is retained [16].General criteria for evaluating membrane separation are CH_4 loss, selectivity, pressure drop across membrane, and membrane life span. Comparing the performance of a poly sulphone membrane and a cellulose acetate membrane on purifying biogas which was generated from a sewage plant unit, and it is noted that the permeability of CH_4 and CO_2 of both membranes was generally increased with temperature, which led to decreased separation efficiency. Stern et al utilized membranes made from “glassy” polymers, such as cellulose acetate and polyimides, to separate biogas generated from a municipal waste water treatment plant, and showed that CH_4 content higher than 90% can be obtained, while organic impurities may be act as a poison for the membrane. Based on this outcome, pretreatment of biogas to remove organic impurities prior to membrane separation is generally recommended. Along with the development of bioenergy in latest years, an increase in the interest in large-scale membrane separation projects has been found [17].

2.5 Cryogenic Technology

The cryogenic process of refining biogas includes the separation of the gas mixtures by fractional condensations and distillations at the condition of low temperatures. This method has the benefit that it allows regaining of pure constituent in the form of a liquid, which can be transported appropriately. Cryogenic technology takes advantage of the different boiling points of gases (CO_2: -78.5^{0}C, CH_4: -161^{0}C) by progressively cooling the raw biogas under pressure and, consequently, obtaining high purity CH_4. High purity CO_2 is produced as a valuable byproduct. This method is also used for liquefied biogas (LBG) production. In a cryogenic process, crude biogas is compressed to almost at 80 bar. The compression is made in several stages with inter- stage cooling. The compressed gas is dried to ignore freezing throughout the cooling process. The biogas is cooled with chillers and heat exchangers top which is at -45^{0}C, condensed CO_2 which is removed in a separator. The CO_2 is treated further to recover dissolved CH_4, which is recycled to the gas inlet site. By this method more than 97% pure methane is achieved.

2.6 Chemical Reaction with Lime

Maizirwan Mel1 et. al (2014) used Aqueous solution of Ca $(OH)_2$ as chemical solvent to demonstrate its ability and effectiveness in absorbing CO_2 and H_2S from biogas. Different operating parameters which include concentration of limewater solution and flow rate of biogas were used. Removal efficiency and absorption capacity of CO_2 were analyzed based on the results obtained. Biogas concentration before and after treatment with limewater solution, Ca $(OH)_2$ aqueous were determined using a biogas analyzer. Different percentage of compositions after purification was obtained.CO_2 especially was seen to be absorbed into the limewater solution to a great value for each concentration. With the concentrations of limewater increasing, the CO_2 reading dropped drastically to a significant value indicating CO2 absorption into the limewater solution. Using data obtained (by taking the CO_2 reading before it is saturated and its CH4 reading) from the gas analyzer after six minutes of contact, CO_2 removal efficiency and CH_4 enrichment were calculated. It was found that the concentration of limewater plays an important role on the CO2 removal efficiency.

III. SELECTION OF MULTIFACETED CRITERIA AND METHODOLOGY

In the Analytic Hierarchy Process a decision problem is structured as a hierarchy with a goal node at the top, criteria influencing the goal in the level below (there may also be several additional levels of sub-criteria), and the alternatives of the decision in the bottom level. The Selection of multifaceted criteria for CO_2 Removal technologies from biogas is very crucial step of this process. Various criteria like **Technology Maturity (Technical Aspects Only), Technology Availability (In India), Initial Investment Cost, Operation Cost, Process Efficiency and Process Emissions (Air, Water & Ground)** are selected from the literature review and discussion with experts from different sectors that are related to the problem improves the effectiveness and correctness of the decision.

The benefit of the proposed model is that it increases the effectiveness of the decision by allowing participation of different experts. Multiple decision makers are often preferred rather than a single decision maker, to avoid bias and minimize partiality in the decision process. Since decisions made in the energy sector affect all society and sectors, these decisions should not be made by the initiative of one man or through one sector. The criteria will be pairwise compared for importance to establish their priorities with respect to the goal. The removal technologies will be pairwise compared for preference to establish their priorities with respect to each criterion. The results of all these comparisons will be combined to give the best alternative with the highest priority. The goal and criteria are one comparison group with the goal as the parent and the criteria as the children. The criteria will be pairwise compared with respect to the Goal for importance. Each criterion connected to the alternatives forms a comparison group with that criterion as the parent and the alternative as children [19, 20]. The alternatives will be pairwise compared with respect to the criterion for preference as shown in Fig. 1 given below.

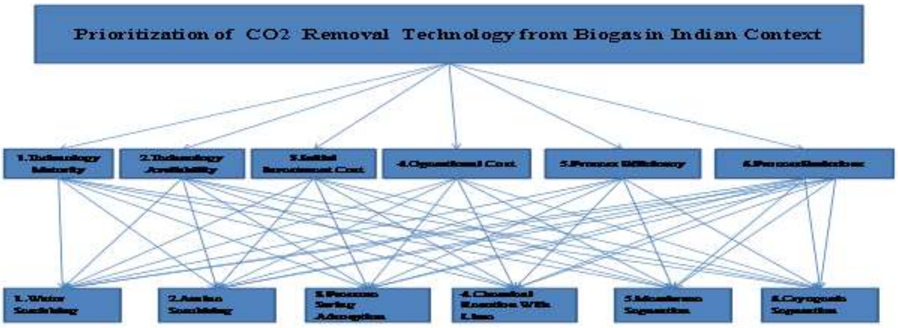

Fig 1: The Hierarchy of Biomass Priority

In this research Super Decisions software designed by William J. Adams is used for the implementation for decision making. It decomposes a problem systematically and incorporates judgments on intangible factors alongside tangible factors. In this software a decision model is made up of clusters, nodes and links. Clusters are groupings of nodes which are logically related factors of the decision. Connections are made among nodes to establish comparison groups and when nodes are connected links automatically appear between their clusters. In a hierarchy the links go only downward: from the goal node to the criterion nodes and from each Criterion node to the alternative nodes. Below is a screenshot of the CO_2 removal Technologies Hierarchy as it appears in the software in Fig. 2

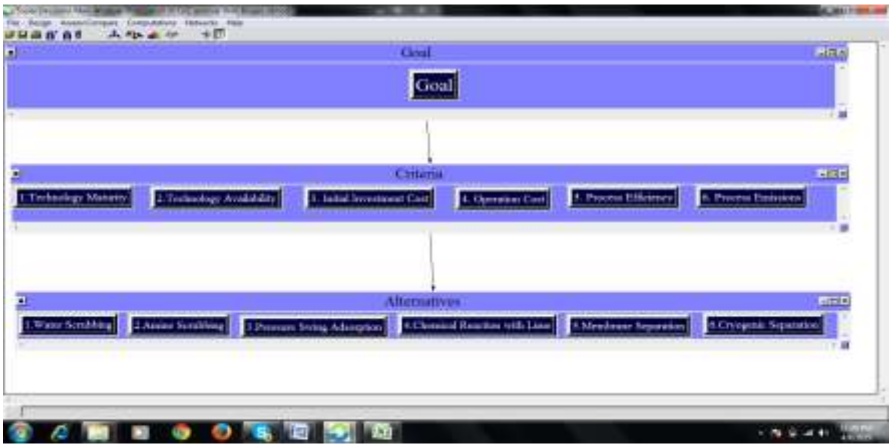

Fig 2: The Hierarchy of Links in Super Decision Software

The pairwise comparison judgments are made using the Fundamental Scale of the AHP and the judgments are arranged in the pairwise comparison matrix. The pairwise comparison judgments used in the AHP pairwise comparison matrix are defined as shown in the Fundamental Scale of the AHP given by Thomas Satty below in Table 1.

Table .1: The Fundamental Scale of the AHP

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another

7	Very strong importance	An activity is favored very strongly over another
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Used to express intermediate values	
Decimals	1.1, 1.2, 1.3, …1.9	For comparing elements that are very close

The numbers in the cells in an AHP matrix, by convention, indicate the dominance of the row element over the column element; a cell is named by its position (Row, Column) with the row element first then the column element. Only the judgments in the unshaded area need to be made and entered because the inverse of a judgment automatically entered in its transpose cell. The diagonal elements are always 1, because an element equals itself in importance. If the number of elements is n the number of judgments is $n\ (n-1)/2$ to do the complete set of judgments .The Pairwise comparison of multifaceted criteria as discussion with experts from different sectors that are related to the problem is shown in Table-2

Table 2: Matrix showing Pairwise Comparison of Criteria with respect to Goal

Goal	**1.Technology Maturity**	**2.Technology Availability**	**3.Intial Investment Cost**	**4.Operation Cost**	**5.Process Efficiency**	**6.Process Emissions**
1.Technology Maturity	**1**	**3**	**4**	**5**	**4**	**7**
2.Technology Availability		**1**	**3**	**4**	**3**	**6**
3.Intial Investment Cost			**1**	**2**	**4**	**5**
4.Operation Cost				**1**	**3**	**4**
5.Process Efficiency					**1**	**2**
6.Process Emissions						**1**

It is clear from above table only $n\ (n-1)/2$ judgment are required while rest of judgment are done with the help of SuperDecisions Software to do the complete set of judgments as shown in table-3.

Table 3: Matrix showing Pairwise Comparison of Criteria with respect to Goal

	1.C1	2.C2	3.C3	4.C4	5.C5	6.C6
1.C1	1	2	3	6	8	3
2.C2	0.5	1	2	5	7	3
3.C3	0.33333	0.5	1	5	6	2
4.C4	0.1667	0.2	0.2	1	2	0.25
5.C5	0.125	0.1428	0.1667	0.5	1	0.2
6.C6	0.3333	0.3333	0.5	4	5	1

Priorities for the criteria are obtained by calculating the principal eigenvector of the above matrix. A short computational way to obtain this vector is to raise the matrix to powers. Fast convergence is obtained by successively squaring the matrix. The row sums are calculated and normalized. The computation is stopped when the difference between these sums in two consecutive calculations of the power is smaller than a prescribed value.

The priorities of an AHP pairwise comparison matrix are obtained by solving for the principal eigenvector of the matrix. The mathematical equation for the principal eigenvector w and principal eigenvalue λmax of a matrix A is given below. It says that if a matrix A times a vector w equals a constant (λmax is a constant) times the same vector, that vector is an eigenvector of the matrix. Matrices have had more than one eigenvector; the principal eigenvector which is associated with the principal eigenvalue λmax (that is, the largest eigenvalue) of A is the solution vector used for an AHP pairwise comparison matrix. $Aw = \lambda max\ w$.

The *SuperDecisions* software uses a special algorithm to remember and display additional priorities in the Limit supermatrix that appeared in successive powers of the matrix and give useful information. The final overall priorities for the alternatives, in raw unnormalized form, appear in the column beneath the goal. The priorities for the criteria in the goal column, when normalized, are the original priorities derived by pairwise comparison. The weighted supermatrix is raised to powers until it converges to the limit supermatrix which contains the final results, the priorities for the alternatives, as well as the overall priorities for all the other elements in the model. It happens that the weighted supermatrix is the same as the unweighted supermatrix for an AHP hierarchy, so raise the matrix above to powers [21].

IV RESULTS AND DISCUSSION

Six types of multifaceted criteria **Technology Maturity (Technical Aspects Only), Technology Availability (In India), Initial Investment Cost, Operation Cost, Process Efficiency and Process Emissions (Air, Water & Ground)** have been evaluated to determine the most appropriate one for the prioritization of Technology for CO_2 removal from Biogas in Indian Perspective . A selection methodology based on AHP (Super Decision Software) is used. This methodology involves a procedure for the aggregation of expert opinion using the six selection criteria that are appropriate for India.

Experts involved in the assessment found that the **Technology Maturity** is the most important criteria having the priority of **0.4189** followed by the priorities of **Technology Availability and Initial Investment Cost** as

0.2469 and 0.1444 respectively. While other criteria **Operation Cost, Process Efficiency and Process Emissions** have lower scores **0.0973, 0.0575 and 0.0347** respectively.

The Results above mentioned is shown below in Fig.3, the screenshot from super decision software.

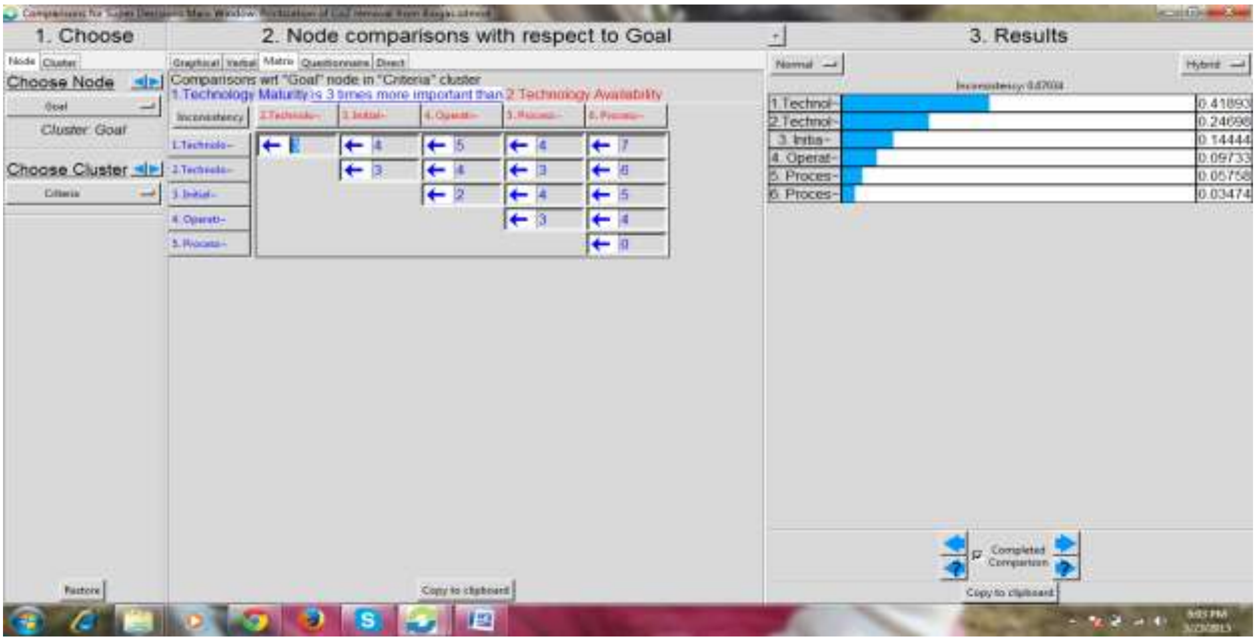

Fig.3: The screenshot from super decision software

The results of the above decision can also be shown as below in Table 4.

Table 4: Priorities of Different Criteria

Inconsistency	0.07034	
Name	Normalized	Idealized
1.Technology Maturity	0.418933375	1
2.Technology Availability	0.246977191	0.589538112
3. Initial Investment Cost	0.144443978	0.344789855
4. Operation Cost	0.097330098	0.232328347
5. Process Efficiency	0.057575502	0.137433553
6. Process Emissions	0.034739856	0.082924537

It is very clear from the above results that the criteria related to **Technology Maturity and Technology Availability** are more important than any other criteria.

V CONCLUSION

As the India is currently moving fast towards industrial and technical advancement, energy sources have become an important concern. Currently, the major energy supply is from fossil fuel containing carbon sources. Though, these sources produced from non-renewable type of energy and are said to be depleted soon. The combustion of the fossil fuels contributes to the emission of the largest greenhouses gasses like carbon dioxide into the atmosphere which could cause global warming.

Biogas is preferred over fossil fuels sources as it is much cheaper and environmentally friendly. The sources for biogas production could be from readily available raw materials like cow manure, fruit and vegetable waste, food processing industries (poultry) as well as municipal solid waste (MSW). The gases in biogas can be combusted or oxidized with oxygen. The energy released, which is about 22 MJ/kg allows biogas to be used as fuel for heating purposes such as cooking or to power motor vehicles.

However, before the biogas could be supplied for energy application, it needs to be purified as there is the presence of entities like CO_2 and H_2S which can affect the performance of the whole system for biogas production. Upgrading biogas to natural gas quality is a multiple step procedure. A range of technologies are available in order to remove contaminants or trace elements from biogas being produced, leaving purified biogas.

It was found that there are sufficient removal Technologies are available but each option has its own limitations. In such a complex situation; Multi criteria Decision Making (MCDM) methodologies increasingly popular in decision making for sustainable energy systems because of their ability to integrate the multi-criteria and complex nature of these systems. One of possible methods is AHP method, which offers a frame of effective tools in complex decision situations, and helps to simplify and speed up natural process of decision making. In AHP method Selection and ranking of Criteria is most critical and important step. In this study an overview of various Removal Technologies of CO_2 from Biogas is presented and Ranking of Criteria for prioritizing various Removal Technologies of CO_2 from Biogas has been done. An AHP (Super Decision Software) model is developed to meet out the purpose.

From this Research, it can be concluded that the experts involved in the assessment found that in the criteria related to **Technology Maturity, Technology Availability and Initial Investment Cost** are more important than any other criteria. The benefit of the proposed model is that it increases the effectiveness of the decision by allowing participation of different experts. Since decisions made in the energy sector affect all society and sectors, these decisions should not be made by the initiative of individual or through one sector. In terms of Biogas Energy Utilization, the ranking of Criteria involved in this study is useful to Energy Planners in determining the priorities in the field of Biogas Energy. The method used and the results obtained from this study can be used in the further research.

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