

“ECONOMIC FEASIBILITY ANALYSIS OF PRODUCTION OF HYDROGEN FROM BIOMASS”

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**“ECONOMIC FEASIBILITY ANALYSIS OF PRODUCTION OF
HYDROGEN FROM BIOMASS”**

A thesis submitted in partial fulfillment of the requirements for the
Degree of Master of Technology (Gas Engineering)

By

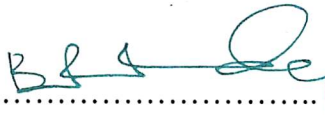
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CERTIFICATE

This is to certify that the work contained in this thesis titled "Economic Feasibility Analysis of Production of Hydrogen from Biomass" has been carried out by Vinod Dimri, M.Tech (Gas Engineering), UPES, Dehradun under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

In today's scenario the increase in the price of fossil fuel greatly affects the final hydrogen cost, at the same time global warming and green house gases are our major problem. So we have to find out an alternate source of renewable energy.

In the thesis we did the economic feasibility of hydrogen production from biomass gasification and steam methane reforming (SMR) using natural gas as the feed stock. The significance of doing this is that the increase in the price of natural gas day by day and at the same time by burning the fossil fuels emission of green house gases increases our environment temperature, so we are using biomass for making hydrogen because it is clean, easily available in abundance, efficient and completely pollution free fuel and possibly the best substitute for the fossil fuels.

In this thesis we find the capital cost and manufacturing cost of hydrogen production using the biomass gasification process and SMR for natural gas process. We use the data of 2002 for the calculation of capital and manufacturing cost of hydrogen. After that following cost was converted to the current year cost by using the producer price index using the formula:

$$\text{Cost of 2007} = \text{Cost at 2002} (495/394.3)$$

The estimated capital cost for the biomass gasification was Rs 210 crore and for SMR for natural gas was Rs 111 crore for the base capacity of 150000 Kg hydrogen per day. For other capacities the capital cost is finding out by the following equation:

$$\text{Capital costs (B)} = \text{Capital cost A (capacity of B) / capacity of A}^{0.7}$$

After finding the manufacturing cost we did the sensitivity analysis. In the sensitivity analysis we find the following conclusions:

- Effect of variation in capacity on annual capital cost of hydrogen production shows that the capital investment in SMR was much lower than the biomass gasification.
- The effect of variation in capacity on manufacturing cost of hydrogen production

shows that for 50000 Kg H₂/day capacity the manufacturing cost is equal for both the process i.e. Rs 6 crore/yr. and below this capacity biomass gasification is economic and above this capacity SMR for natural gas is economic.

- Effect of variation in capacity on per Kg cost of hydrogen production shows that for lower capacities the production price is less for gasification process and for higher capacities the production price is less for SMR process.
- The major component of capital cost in biomass gasification i.e.62% and in SMR for natural gas i.e. 61% is of total equipment cost. Therefore there is a need of making new designs of the equipments so that the throughput can increase which can reduce the capital cost.
- The component of manufacturing cost of hydrogen production for the base capacity shows that its 30% part is of power cost and 20% part is of plant maintenance for biomass gasification. Similarly the component of manufacturing cost for SMR for natural gas consists of 38% of power cost and 22% is of feed stock cost. Therefore there is a need for further research and development for the equipments to use power in more efficient way.
- Effect of increase in price of feed stock shows that in future, production of hydrogen from biomass is economically viable from biomass gasification process.

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“Economic Feasibility Analysis of Production of Hydrogen from Biomass”

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ASSUMPTIONS

- Hydrogen base capacity is of 150000 Kg/day capacity
- Calculation of capital cost of B = capital cost of A (capacity of B/capacity of A)^{0.7}
- Cost at 2007 = Cost at 2002(chemical engineering Cost index of (2007/2002))
- Natural gas price = Rs 23/Kg (10-12 \$ / Kg)
- Biomass Price = 1 Rs /Kg
- Investment Conversion factor = 0.7 for U,S.A & 0.9 for U.K

Installation and erection cost.....	12% of equipment cost
Piping and insulation.....	20% of equipment cost
Instrumentation.....	6% of equipment cost
Miscellaneous.....	4% of equipment cost
Building cost.....	35% of equipment cost
Administration cost.....	10% of equipment cost
Electrical cost.....	8% of equipment cost
Taxes.....	4% of equipment cost
Overhead field construction.....	20% of total equipment cost
Engineering cost.....	10% of total equipment cost
Contingencies.....	10% of total equipment cost
Working capital.....	20% of total equipment cost
Local Taxes.....	1.5% of total direct cost
Insurance.....	0.5% of total direct cost
Administration cost.....	25% of working capital
Plant maintenance.....	6% of total capital investment
Patent.....	3% of total direct cost
Depreciation.....	6% of (total capital cost – working cost)
Interest on working capital.....	11% of working cost

ABBREVIATIONS

ASU	air separation unit
ATR	auto thermal reforming
BDT	bone-dry ton
Btu	British thermal unit
FC	fuel cell
gal	gallon
H ₂	molecular hydrogen
ICE	internal combustion engine
kg	Kilogram
kg/d	kilograms per day
O&M	operating and maintenance
Pox	partial oxidation
PSA	pressure swing adsorption
psig	pounds per square inch gauge
SMR	steam methane reforming
FCI	Fixed Capital Cost
TDC	Total Direct Cost
WC	Working Capital
DC	Direct Cost
IDC	Indirect Cost
EC	Equipment Cost

CHAPTER 1

Introduction

Renewable biomass and biomass-derived fuels could be readily gasified to produce a hydrogen-rich gas or hydrogen. Among the biomass energy conversion schemes gasification produces a product gas, which based on its properties could be used either to co-produce value-added byproducts or hydrogen. As a readily renewable fuel, biomass may become a significant component in the global sustainable energy mix as fossil fuel resources begin to deplete. In addition, biomass utilization can expedite mitigation of greenhouse gas emissions and carbon sequestration cycles and promote "green" industries with associated growth in rural economies. Hydrogen or hydrogen-rich gas produced from biomass could be readily used in most of the present natural gas or petroleum derived hydrogen energy conversion devices and also in advanced systems such as fuel cells.

Background

Upon the introduction of the steam engine in the 1860s, society began to change dramatically as fuels such as wood, coal, oil, and gas were utilized. As time continued, the world developed an economy based on fossil fuels. This economy facilitated technological improvements and helped increase the standard of living. However, the use of fossil fuels is not without consequences –global problems have developed both economically and environmentally as a result of using these fuels. The greenhouse effect, ozone layer depletion, acid rain, and pollution are just a few of the environmental problems caused by the utilization of fossil fuels. One of the main pollutants produced is carbon dioxide. It is reported that carbon dioxide accounts for over 84% of the greenhouse gas released into the atmosphere and originates almost exclusively from the utilization of fossil fuels (Energy Information Administration, 1998). Furthermore, the Energy Information Administration (EIA) estimates that if current trends continue, worldwide carbon dioxide emissions will increase from 1,559 to 2,237 million metric tons equivalent (1.5% annual change) by the year 2025 (Energy Information Administration, 2003). The steady increase

predicted will adversely affect the world if changes in our energy sources are not made. The continuing carbon dioxide pollution to the environment would result in global warming – in turn affecting forests, agriculture yields, ecosystems, as well as human health and well-being. The use of fossil fuels not only poses environmental and health risks, it also affects the economy as prices rise. The world population is continuing to grow and industrialize; as a result, the world energy demand is increasing. Although the demand for energy is increasing, the supply cannot increase indefinitely as there are finite amounts available. Many have attempted to forecast how long the fossil fuel reserves will last with varying results, but the same general idea is conveyed – fossil fuel production will increase for a time, peak and then begin to decrease as the supply is depleted. Therefore, in the future, availability of fossil fuels will be a problem while demand is very high resulting in high energy prices. Because of the problems fossil fuels pose, it is important to seek out new sources of energy. One fuel that is expected to play a role in the mid to long-term future of the energy sector is hydrogen. Hydrogen is a desirable fuel source for several reasons:

1. Simplest and most abundant element on earth.
2. Has the highest energy content per unit weight.
3. Clean burning , only heat and water are produced when utilized.
4. Can decrease the India's dependence on foreign oil imports.
5. Convenient fuel for transportation.
6. Can supply the energy needed for transportation, electric power as well as thermal needs.
7. Efficient utilization and conversion – Fuel cells can convert 40- 65% of hydrogen's energy to electricity (as compared to IC engines 15 – 20%).
8. Safer to work with then gasoline if used properly.
9. Renewable energy source.
10. Can be produced from numerous feed stocks.

Hydrogen is a product that is fully capable of sustaining the world's energy needs now and in the future. If renewably produced, hydrogen would be a fuel used that does not contribute to environmental damage (pollution) and supports the human well being.

Hydrogen Production Technologies (current)

Hydrogen energy is belonging to the secondary energy. On the Earth where the human beings depend upon for life, although hydrogen is the richest element, the natural hydrogen exists extremely few. Therefore, the hydrogen gas can be obtained after possessing the hydrogen-contained matters. The richest hydrogen-contained matter is water (H₂O), next is various fossil fuels (i.e. coal, petroleum, natural gas) and biomass. So in order to develop and utilize this ideal clean energy, it is necessary to exploit the hydrogen resources, that is to research and develop the diverse hydrogen production methods. From the long perspective, producing the hydrogen by use of water as raw materials is the most promising methods due to the fact that the raw materials will not be run out, and the energy released by the hydrogen combustion can also generate products---water, which will not create the environmental pollution. The current main methods to produce hydrogen are via various fossil fuels that are limited in reserves and will pose the environment pollution in the course of production. Other methods to convert diverse hydrogen-contained matters to produce hydrogen are now on the stage of secondary position or under the development. However along with the expanding of hydrogen applications, the requirement will be increasing and it will be another approach to supply hydrogen resources.

Steam methane reforming (SMR)

Steam methane reforming (SMR), methanol reforming, and gasoline reforming are based on the same fundamental principles with modified operating conditions depending on the hydrogen-to-carbon ratio of the feedstock. SMR is an endothermic reaction conducted under high severity; the typical operating conditions are 30 atmospheres and temperatures exceeding 870°C (1,600°F). Conventional SMR is a fired heater filled with multiple tubes to ensure uniform heat transfer.



Typically the feedstock is pretreated to remove sulfur, a poison which deactivates nickel reforming catalysts. Guard beds filled with zinc oxide or activated carbons are used to pretreated natural gas and hydro desulfurization is used for liquid hydrocarbons. Commercially, the steam to carbon ratio is between 2 and 3. Higher stoichiometric amounts of steam promote higher conversion rates and minimize thermal cracking and coke formation. Because of the high operating temperatures, a considerable amount of heat is available for recovery from both the reformer exit gas and from the furnace flue gas. A portion of this heat is used to preheat the feed to the reformer and to generate the steam for the reformer. Additional heat is available to produce steam for export or to preheat the combustion air. Methane reforming produces a synthesis gas (syngas) with a 3:1 H₂/CO ratio. The H₂/CO ratio decreases to 2:1 for less hydrogen-rich feed stocks such as light naphtha. The addition of a CO shift reactor could further increase hydrogen yield from SMR according to Equation 2.



The shift conversion may be conducted in either one or two stages operating at three temperature levels. High temperature (660°F or 350°C) shift utilizes an iron-based catalyst, whereas medium and low (400°F or 205°C) temperature shifts use a copper based catalyst. Assuming 76% SMR efficiency coupled with CO shift, the hydrogen yield from methane on a volume is 2.4:1.

There are two options for purifying crude hydrogen. Most of the modern plants use multi-bed pressure swing adsorption (PSA) to remove water, methane, CO₂, N₂, and CO from the shift reactor to produce a high purity product (99.99%+). Alternatively, CO₂ could be removed by chemical absorption followed by methanation to convert residual CO₂ in the syngas.

Partial oxidation of heavy hydrocarbons (POX)

Partial oxidation of heavy hydrocarbons (POX) utilizes hydrocarbon feed stocks (e.g. residual oil from the treatment of crude oil) and catalytically reacts (around 600°C) the feed with superheated steam and oxygen to convert it into a mixture of H₂, CO, and CO₂. The mixture is then subjected to a shift reaction to increase the hydrogen content of the final gas and is finally separated to form the hydrogen product stream. The external

energy required to drive the process is obtained through the combustion of the feedstock itself. As a result, pollutants such as NO_x, SO_x and CO₂ can be generated in the process; to minimize the production of NO_x, the air input to the process must be separated so that pure oxygen is supplied to the reformer. This results in the need for an air separation plant which increases the capital cost of the POX plant and results in a gaseous hydrocarbon feed stocks. Overall, the POX process has an efficiency of about 50%.

Hydrogen Produce by Fossil Fuels

To produce hydrogen via coals, petroleum and natural gas as the raw material has been the primary method so far. The produced hydrogen gas can be used mainly to be the chemical raw material, for example to generate compound ammonia, and compound methanol. Sometimes, some of the hydrogen-contained gases can be used as gas fuels to supply for the municipal coal gas. The hydrogen production by fossil fuels include the procedures of hydrogen-contained gases manufacturing, transformation reaction of the content of CO in gases and purification of hydrogen gases. China has achieved mature technologies of this method and established industrialized production plants.

1)Hydrogen Gas Production by Coals as Raw Materials

The hydrogen-contained gas production by coals as raw materials has mainly two catalogues: one is to carbonize the coal (or called high-temperature carbonization); another is the gasification of the coal. The carbonization refers to produce the carbon and coke oven gas as by-products in the temperature of 900°C to 1000°C under the circumstance that the coal is separated from the air. Among the composition of coke oven gas, hydrogen covers 55-60% (in volume), methanol 23-27%, carbon monoxide 5-8%. 300 –350m³ coal gas can be obtained from each ton of coal as the municipal coal gas or the raw material to produce the hydrogen. The gasification of coal means that the coal is to react with gas agent and transformed to gas products under the condition of high temperature and normal pressure or pressurization. The gas agent can be water steam or oxygen (air). The gas products contain with the composition of hydrogen gas, with its content various along with diverse

gasification methods. The gasification aims to produce the chemical raw material or municipal coal gas. Large-scale industrial gasification oven is generally a kind of fixed bed-type gasification oven. The produced coal gas is composed with hydrogen representing 37 to 39%, carbon monoxide 17 to 18%, carbon di-oxide 32%, and methanol 8-10%. China has large-scale oven, with each production reaching 100,000m³/h. Another innovative oven is the gas current bed gasification oven, taking coal-water slurry as raw material. China has lunched the research and development from the 1960s and so far has established industrial production plants to produce compound ammonia, compound methanol raw material gas of which coal gas is composed with hydrogen of 35-36%, carbon monoxide of 44-51%, carbon oxide of 13-18%, methanol of 0.1%. Its characteristic is the low content of methanol. China has a lot batch of medium and small-scale compound ammonia factory, taking coal as raw material. After gasified, the produced hydrogen-contained coal gas can be the raw material of compound ammonia. This is one kind of method to obtain the hydrogen resources with the Chinese characteristic. To employ OGI fixed bed-type gasification oven can produce the coal-water gas in an intermittent way. This plant can be invested with few inputs and is easy to operate, of which gas products are composed with hydrogen and carbon monoxide, among which hydrogen gas can reach more than 60% and can produce pure hydrogen after being transformed. For the hydrogen production method by gasification, its equipment expense covers the main part of the investment. The coal gasification under the earth has also attached the attention in recent several decades. This technology has the advantages of high utilization rate in coal resources, and decline or avoiding the destruction of surface environment. Mr. Yuli of China Mining University developed and perfected the new technology of coal-water gas production. Among the coal gas, the hydrogen content reaches more than 50%. It has been industrially test run in Tangshan, with the daily production of coal-water gas of 50,000m³. If it can be further transformed or purified by pressure swing adsorption method, cheap hydrogen gas can be produced. This method has a promising market penetration in China.

2) Hydrogen Production by Taking Natural Gas or Lightweight Oil as Raw Material

The method to produce the hydrogen is under the circumstance that the catalyzer exists and is to react with the water steam. The reaction can be conducted under the temperature of 800 to 820°C. Among the gas produced in accordance with this method, the hydrogen gas composes 74%. Its production cost primarily depends upon the price of raw material. The majority of large-scale compound ammonia and compound methanol factory are employed the natural gas as the raw material to catalyze the water steam to be converted into hydrogen. China has made lots of cutting edge research in this field and established a batch of industrial production plants. China has been developed and employed the intermittent type natural gas and steam conversion process to produce hydrogen, and prepare the raw material for the small-scale compound ammonia factory. In this method, it is not required to adapt the high temperature alloy conversion oven, with the low investment input on plant.

3) Hydrogen Production by Taking Heavy Oil as Raw Material and Partly Oxidation

The raw materials of heavy oil include the residual oil in normal pressure or pressure declining or the combustion oil after the petroleum has been deeply processed. The hydrogen gas can be obtained after heavy oil is to be reacted with water steam and oxygen. While part of heavy oil is combusting, it can provide the heat required by the conversion and heat absorption reaction and a certain reaction temperature. The gas product composes by hydrogen covering 46%, carbon monoxide 46%, carbon oxide 6%. Among the hydrogen production cost in this method, the raw material expense covers 1/3. Due to the cheap price of heavy oil, as a consequence, this method has drawn much attention. China has set up large-scale hydrogen production plant to partly oxidize heavy oil, utilizing for preparing the raw material of compound ammonia.

Grid Electrolysis

Hydrogen production by electrolysis has been one of the current methods that is applied broadly and has become more mature. The hydrogen production by water as the raw material is the reverse process to combust hydrogen and oxygen to generate water. Therefore, it is only required a certain energy with a certain type to split out the water. The production efficient to split out the water by supply of

electricity can be fixed from 75% to 85% generally, with the simple process and no pollution but heavy consumption of power. So its application was restrained. So far the process and equipment for water electrolysis are increasingly improved. The pole material for the electrolysis reactor has been meliorated. The electrolyte was used to employ strongly alkaline liquid. In recent years, solid-state high polymer ion exchanging membrane was researched and employed as electrolyte. And this membrane can also play the function to separate the pole in electrolysis tank. The parameters such as high temperature and high pressure are employed in the electrolysis process so as to be useful for the proceeding of reaction. But the energy consumption for water electrolysis is still comparatively higher, with the power consumption of 4.5 to 5.5kWh for producing per cubic meter hydrogen gas. The electricity can be supplied by various primary energies, including fossil fuels, nuclear power, solar energy, water energy, wind energy and ocean energy. The nuclear power, water energy and ocean energy are abundant which can be utilized in a long term. The hydropower abounds in China. Therefore, it has promising penetration by use of hydropower to produce hydrogen. The solar energy is unexhausted. The method to produce hydrogen by use of photo electricity is called solar-hydrogen energy system of which research has been conducted in foreign countries. Accompanying with the improvement of solar cell conversion efficiency, decline of cost and prolonging of service life, its promising is invaluable. Moreover, the solar energy, wind energy and ocean energy can also produce hydrogen by electrolysis, and utilize the hydrogen as carrier to adjust and store the converted energy making the energy supply for the consumer more convenient and flexible. The rich electricity of the power supply system in the valley can also be used to produce hydrogen so as to store the energy. There are hundreds and thousands of hydrogen production plants in diverse scale in China, primarily with small-scale hydrogen production plants, aiming to produce the hydrogen to be raw material other than energy.

Regarding the tasks of pole process and material in the electrolysis reaction, Nankai University and Capital Teacher's Training University have once organized the research. Along with the expanding of its applications, the hydrogen production

methods by electrolysis will be increasingly developed. The hydrogen production method to split out the water in the thermo-chemical circle by use of water as raw material avoids the high temperature (higher than 4000K) requested by the thermal destruction directly using the water, and can reduce the energy consumption, which has attached great importance. This method is to add an intermedium in the water reaction system. After seeing diverse reaction stages, the water is finally decomposed to hydrogen and oxygen without consuming the intermedium. The reacting temperatures in each stage are quite lower. In recent years, more than 20 kinds of thermo-chemical circulation methods have been researched and developed, of which some have been test run.

The photochemical hydrogen production is to catalyze and decompose the photo to produce hydrogen by use of water as raw material. The process to catalyze the photo refers to the reaction system contained with catalyzer under the sunlight to prompt the water destruction to generate the hydrogen due to the existing of catalyzer. There were research reports in overseas from the 1970s. Units such as the sensitization institute under Chinese Academics of Science have also imitated the research. This method is promising, but still on the stages of basic research so far.

Hydrogen Production Technologies (future)

Hydrogen Production by Biomass

Gasification is a versatile process similar to partial oxidation with two main differences: First is that the oxidation and gasification occur at much higher temperatures (1100-1300°C). Second the process uses a wide range of solid feed stocks (coal, heavy refinery residuals, biomass). In this process, a dry or slurried form of the feedstock is subjected to elevated temperature and pressure conditions which lead to an efficient and clean conversion of carbonaceous substances into syngas (carbon monoxide and hydrogen). Depending on the feed, any inorganic materials remaining are removed as a molten slag from the bottom of the reactor. The hydrogen content of the process is

increased with the same water-gas shift reaction used in both the POX and SMR processes. Coal is the most abundant fossil fuel. Gasification of coal offers higher thermal efficiencies than conventional coal-fired power generation and also has less impact on the environment. Low-grade coal types can be effectively used in coal gasification, expanding the available fossil fuel options. Coal gasification is the oldest method known for the production of hydrogen. Two coal gasification processes commercially in use are The Koppers-Totzek process, which is operated at atmospheric pressure, and The Texaco process, which is operated at a pressure of about 5.5MPa. Both processes result in hydrogen product streams with purities of at least 97%. The biomass resources are abundant and it is also an important renewable energy. Hydrogen can be obtained by way of gasifying the biomass or by use of microorganism.

1) Hydrogen Production by Gasifying Biomass

The hydrogen-contained combustion gas can be produced by compressing the raw material of biomass such as core wood, sawdust, straw or haulm to make the gasification or cracking reaction in the gasified oven or cracked oven. Certain of results have been achieved in the field of biomass gasification technology. Guangzhou institute of energy conversion has conducted the research of biomass gasification for many years. Among the gasification products, hydrogen represents about 10%, with the thermal value of 11MJ/m^3 , which can be used as fuels in the countryside. However, the content of hydrogen is still lower. In overseas, due to the improvement of conversion technology, the gasification of biomass can be large-scale produced coal-water gas, with increasing content of hydrogen.

2) Hydrogen Production by Microorganism

The hydrogen production technology by microorganism also draws the right consequences. The hydrogen gas can be produced by use of microorganism to make the enzyme catalysis reaction under the normal temperature and normal pressure. It mainly has two catalogues, including nourish microorganism by energy conversion and photosynthesis of microorganism. The former includes various fermented

microorganisms, such as anaerobic and facultative aerobic bacteria. The original ground substance is various carbohydrate and protein. So far there is hydrogen production patent by use of carbohydrate ferment, and its produced hydrogen can be used as energy to generate electricity. The hydrogen production process between the photosynthesis microorganism such as micro-algae and photosynthesis bacteria has related to the photosynthesis, thus called hydrogen production by photosynthesis. In the early of 1990s, the microorganism institutes under Chinese Academic of Sciences and Zhejiang Agricultural University have once conducted the separation and selection research on hydrogen-produced purple non-sulfur photosynthesis bacteria, and research on hydrogen production in the process of sewage treatment by fixed type photosynthesis bacteria. Results have been achieved. In foreign countries, a kind of optimized biology reactor applied to produce hydrogen by photosynthesis bacteria has been designed, with the scale of daily production of 2800m³. In this method, various industrial and domestic organic wastewater and waste materials of agricultural products are applied as the ground substance and the photosynthesis bacteria are continuously cultivated. Whilst producing the hydrogen, wastewater can be purified and unicellular protein can be obtained. Therefore, it has great prospect.

Hydrogen Production by Hydrogen Contained Matters

In foreign countries, research has been made to produce hydrogen from the sulfureted hydrogen. H₂S resources abound in China, for example among the natural gases exploited in the Zhaolanzhuang oil and gas field in Hebei province, the content of H₂S is higher more than 90% and the reserves reach several ten million tons. It is a precious resource. There are different methods to produce hydrogen from the sulfureted hydrogen. From the 1990s, China started extensive research. For example, the Petroleum University conducted the research on hydrogen production under dual reaction system by indirect electrolysis and sulfur. Progress has achieved and the expanding experiment is undergoing. The sensitization institute under Chinese Academic of Sciences has also organized the research on sulfureted hydrogen decomposed by multi-phase enzyme catalysis, and research on hydrogen production by decomposing the sulfureted hydrogen by microwave plasma panel. All of these

research results will create conditions to take full benefits of the precious resources, to provide clean energies and chemical raw materials.

Recovery of Hydrogen as byproducts in various Chemical processes

Large amount of byproducts---hydrogen gas will be released in various chemical processes, such as salt-electrolysis alkaline manufacturing, ferment wine process, compound ammonia in chemical fertilizer industry and petroleum-refined industry. If appropriate measures can be applied to separate and recover the hydrogen gas, billions of cubic meters of hydrogen gas can be obtained in each year. This is an indispensable resource, which should be recovered and reused.

CHAPTER 2 LITERATURE REVIEW

Renewable Energy

The term “renewable energy” describes any source of energy that is constantly replaced as it is utilized. Renewable energy sources include solar, wind, geothermal, biomass, hydropower, and ocean tides. All of these sources provide a supply of energy that is renewable and with technology; can be used to provide the world energy needs. From the current fossil fuel infrastructure, environmental problems such as the greenhouse effect, ozone layer depletion, acid rain, and pollution have developed. The need to reduce the environmental impact of fossil fuels in combination with the knowledge that the fossil fuel supplies are finite, leads to an important conclusion – it is important to develop sustainable renewable energy sources for the future. With the implementation of a sustainable renewable energy source (such as hydrogen), air polluting emissions will be reduced and the quality of life in many cities will increase.

Current Barriers to Utilization of Renewable Energy

Renewable sources are often neglected today due to several reasons. First, renewable energy tends to be an intermittent source of energy leaving many to feel that it is unreliable. For example, solar energy is only available during daylight hours and therefore during storms, at night or on cloudy days, this source of energy is not available this seems to be a problem - however, with new storage technologies (e.g. hydrogen, batteries) the energy can be stored during plentiful days for nighttime use and times when the solar energy is blocked significantly. Another reason renewable energy has not become wide spread is cost considerations. Initially, renewable technologies tend to be more costly than standard construction, which leads many to judge the technologies based on a first cost analysis rather than a lifecycle costing method. After the initial construction costs, the renewable systems are generally self sufficient and can pay for themselves within a few years. After that, the systems save the consumer considerable amounts of money. If consumers are willing to look to the long-term future rather than the short-term, it will become apparent that money can be saved and the environment will be benefited by pursuing renewable technologies and advanced storage technologies such as hydrogen.

Renewable Hydrogen

Renewable hydrogen can be categorized as follows:

(1) Hydrogen produced using technologies that directly utilize the supplied renewable energy to generate the hydrogen product (thermo chemical, photochemical and biological methods are a few examples).

(2) Hydrogen produced by electrolysis with renewable energy supplying the electrical input. In general, renewable hydrogen includes any technology that produces hydrogen with all energy requirements supplied by renewable energy. Using solar power to electrolyze water produces hydrogen via a renewable energy source. The solar radiation is collected and converted into a useful form, usually heat or electricity, and then used to power an electrolyzer. This is an environmentally friendly process by which hydrogen is generated via a feedstock that will not be depleted from an energy source that is renewable. For hydrogen production by electrolysis to become a completely renewable technology, the power used must be solar generated. Currently, many solar methods of generating electricity from solar radiation exist – such as photovoltaics, and solar thermal power systems using parabolic troughs, central receiver systems, and dish/Stirling systems. A brief description of these technologies is given below. Additionally there are a number of new developments that have the potential to dramatically reduce costs or improve the conversion efficiencies. Two such developments, antenna solar energy conversion and a new combined power/cooling thermodynamic cycle. These technologies are also summarized below.

Photovoltaics: Photovoltaic (PV) solar cells directly convert solar energy into electricity. They are constructed from semiconductor materials, with crystalline silicon (c-Si) being the leading commercial material. The cells are well developed and commercially available. Silicon Photovoltaic cells have shown efficiencies of over 20% (Bolton, 1996a), and with present electrolysis technology, one can obtain electrolysis conversion efficiencies up to 95% (Hijikata, 2002). So, in the present scenario we can Obtain an overall solar-to-hydrogen conversion efficiency of around 18% with PV assisted electrolysis. Bansal et al. (1999) has reported overall solar-to-hydrogen conversion efficiencies of 7.8%.

Dish/Stirling systems: Dish/Stirling systems use parabolic dishes to focus the solar

energy onto a centrally mounted receiver/absorber engine that transfers heat to a working gaseous fluid of an attached Stirling engine. The solar energy heats the engines working fluid and drives the engine. A single system can generate up to 50kW. (Al-Sakaf, 1998). However, by grouping many of these dishes together, more power can be produced. This technology is attractive as an ideal Stirling cycle has the same efficiency as that of a Carnot cycle operating between the same temperatures. This allows for real systems based on this cycle to have potential high efficiencies. Solar-to-electric conversion efficiencies in excess of 29.4% (Strachan et al,1995) have been demonstrated. If this electricity were to power an electrolyser operating at 95% conversion efficiency, the overall solar-to-hydrogen conversion efficiency would be approximately 28%.

Solar thermal power plants: Several types of solar power plants exist today, including solar tower plants and parabolic trough power plants. A central receiver solar tower consists of a central receiver surrounded by a field of flat mirrors called heliostats that track the sun. The heliostats reflect the solar energy to the receiver/absorber where a working fluid (for example, water, molten salt, or air) is heated to temperatures around 570°C (DeLaquil et al, 1993). This fluid can be stored or used to generate steam for electricity generation using the Rankine power cycle. It is reported that solar tower systems can achieve annual solar-to-electric efficiencies of 15% (Eisenbeiss, 1996). With electrolysis efficiencies reaching 95%, a solar tower powered electrolysis plant could have solar to hydrogen conversion efficiencies of up to 14%. Unlike the solar tower power plant, parabolic trough power plants use parabolic trough reflectors to heat a fluid. The fluid flows through a receiver tube located on the line of focus for each of the parabolic troughs and reaches temperatures in the range of 150-350°C (Goswami et al,2000). The heated fluid is used to generate steam for use in a Rankine power plant. It has been reported that the solar electric generating systems (SEGS) plants in Southern California operate at an overall solar to electric efficiency of 12% and a cost of 8-10 \$/kWh (cost to produce electricity or cost of electricity)(Kolb, 1995). With electrolysis efficiencies reaching 95%, a parabolic trough powered electrolysis plant could have solar to hydrogen conversion efficiencies of up to 11%.

Combined power/cooling cycle: This cycle is a unique combination of the Rankine

and absorption refrigeration systems developed by Goswami (1995). This new thermodynamic cycle improves the cycle efficiency and resource utilization by producing power and refrigeration in the same cycle. The new cycle uses a binary fluid as the working fluid; in this case an ammonia-water solution is utilized. Ammonia vapor is generated and then superheated prior to entering the turbine. The superheated, high quality ammonia vapor is expanded thru a turbine. The expansion of the ammonia in the turbine lowers the working fluid temperature allowing the fluid to provide a refrigeration effect in a heat exchanger. Finally, the expanded ammonia vapor is absorbed into a weak ammonia/water solution, and the cycle repeats. This cycle has several benefits:

(1) The cycle can operate using low-grade sensible heat such as waste heat or solar thermal energy; (2) Both power and refrigeration are supplied. In the case of hydrogen production, the power could be used to generate H₂ via electrolysis and the refrigeration could be used to pre-cool the H₂ prior to liquefaction.

(3) Second law efficiencies greater than 60% are possible.

Nanoscale antenna conversion: Solar radiation may be converted directly into electric power using the rectenna (antenna plus rectifier) concept (Fletcher and Bailey, 1973). This device would have to efficiently absorb the broadband electromagnetic radiation to create an AC field that is coupled to an optical frequency rectifier to provide a DC electric output. The antenna length should be in the order of a few microns while the diameter of antenna should be in the sub-micron to nano range. The efficiency limits imposed on the photovoltaic cell by the band gap are not applicable to solar antennas. As discussed previously, maximum theoretical efficiency for a multijunction photovoltaic cell is 42%, whereas conversion efficiencies greater than 85% are theoretically possible for solar rectenna array (Goswami et al., 2001). The concept of antenna is well developed for millimeter wave frequencies. The feasibility of solar antenna has been further strengthened by the fact that reception and conversion of the microwave radiations were demonstrated to work at efficiencies as high as 90% (Brown, 1977; McSpadden et al, 1997; Suh and Chang, 2002). The idea proposed by Fletcher and Bailey (1973) seems to be simple; however rectification problems at such high optical frequencies (100-1000 THz) and the small scale of antennas have hindered the development of the solar antenna converters in the past. In addition, antenna design

needs to be optimized to effectively absorb the randomly polarized broadband spectrum of solar radiation. However, with the recent advances in nanotechnologies, the concept is feasible.

According to the Department of Energy, total petroleum consumption is projected to grow from 20.8 million barrels per day in 2004 to 26.1 million barrels per day in 2025. Figure 2.1 shows both the historical data (up to 2004) and projections of the India's energy consumption. The growing demand for fossil fuels and petroleum in particular, will result in higher energy costs and greater reliance on imported oil given the current crude oil capacity. This can have a potentially negative impact on the nation's economic growth as rising commodity prices are closely tied to inflation rates. The combustion of fossil fuels contributes to increased levels of greenhouse gases which can have a severe environmental impact. Renewable energy offers the opportunity to lessen fossil fuel consumption. Energy derived from solar, wind, hydroelectric, geothermal, and biomass sources are considered renewable. Because most forms of renewable energy are derived either directly or indirectly from the sun, there is an abundant supply of renewable energy available, unlike fossil fuels. The use of renewable energy also provides environmental, economic and political benefits. The scope of the work discussed in this report pertains to energy derived from biomass, specifically, hydrogen gas. Biomass energy encompasses a broad category of energy derived from plants and animals as well as the residual materials from each. Hydrogen gas is an effective energy carrier which burns cleanly producing water as the only product. Hydrogen produced from a renewable source such as biomass provides

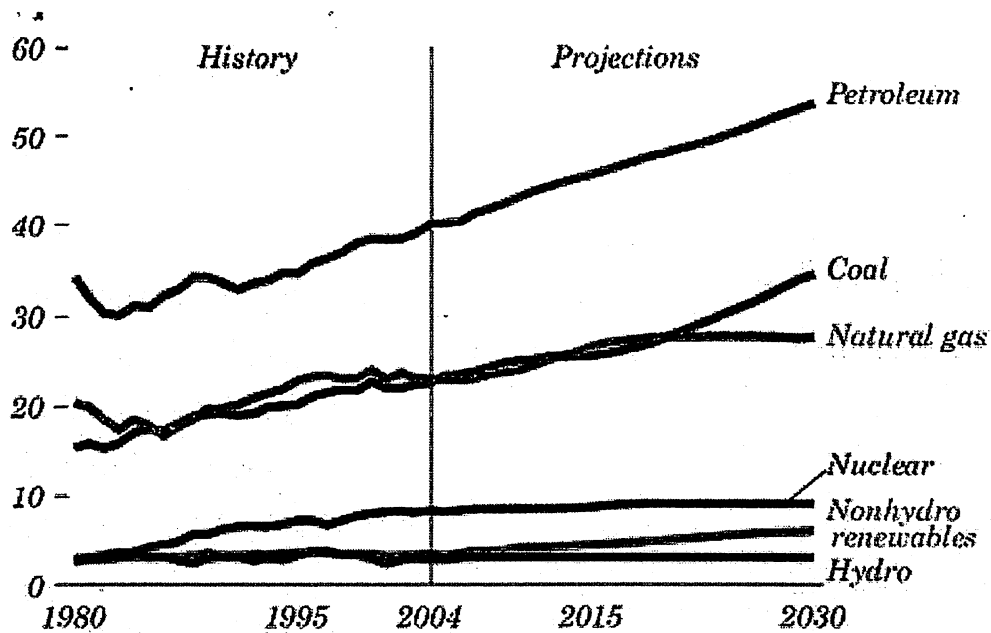


Figure 2.1- Energy consumption by fuel, 1980-2030 (quadrillion BTUs)

HYDROGEN:-

Hydrogen is the most abundant element on the Earth. While not commonly found in nature, molecular hydrogen (hydrogen gas, H₂) can be produced from a wide variety of domestic resources using a number of different technologies. Having the highest energy content on a mass basis, hydrogen can be used as a storage medium. Hydrogen can also be used in combustion processes and fuel cells to provide a broad range of energy services.

Benefits of Hydrogen:-

The widespread use of hydrogen in this country could address issues concerning energy security and air quality. When combined with fuel cell technology, hydrogen offers the following benefits:

Strengthen National Energy Security: By utilizing hydrogen in addition to other alternative energy sources, the India can reduce its oil imports. The India uses 20 million barrels of oil per day and, according to the DOE, the use of biomass can reduce that amount by 30%.

Reduce Greenhouse Gas Emissions: When hydrogen is produced from renewable sources such as biomass, there is no net increase in CO₂ emissions.

Reduce Air Pollution: The combustion of fossil fuels from electric power plants and vehicles is responsible for most of the smog and harmful particulates in the air. Fuel cells powered by pure hydrogen emit no harmful pollutants.

Improve Energy Efficiency: Fuel cells are significantly more energy efficient than combustion-based power generation technologies. A conventional combustion-based power plant typically generates electricity at efficiencies of 33 to 35 percent, while fuel cell plants can generate electricity at efficiencies of up to 85 percent, when fuel cells are used to generate electricity and heat (co-generation).

Limitations of Hydrogen:-

While hydrogen presents an attractive alternative to fossil fuel, there are several economic barriers and technical challenges to overcome before the “Hydrogen Economy” can become a reality.

Production and Infrastructure Costs: Approximately 95% of the hydrogen produced today is done so by steam reforming natural gas. This method of production is more expensive compared to conventional fossil fuels. To realize the benefits of using hydrogen to become more energy independent, hydrogen would need to be produced from a variety of sources. By producing hydrogen from natural gas, the environmental benefits are also lost as CO₂ is still the main byproduct. Developing technologies that utilize renewable sources such as biomass can address some of these issues. Another cost barrier to hydrogen utilization is the lack of infrastructure. While hydrogen gas has the highest energy content on a mass basis, it has one of the lowest on a volume basis. This makes transportation and distribution of hydrogen difficult and costly. Several distribution scenarios have been proposed ranging from “centralized production” (large production facility with distribution network) to a “distributed production” (several smaller spread out production facilities) and everything in between. As hydrogen production technology develops, hydrogen feed stock availability may dictate how the infrastructure pans out.

Fuel Cell and Storage Technology: Currently fuel cells offer the most efficient use of hydrogen energy. However, precious metal catalysis and proton exchange membrane (PEM) materials contribute to the high costs of fuel cells. There are other technical barriers, including durability, temperature resistance, and catalyst poisoning, which are

being addressed with ongoing research. Because hydrogen has such a low energy density on a volume basis, effective storage must be developed. Research is currently being performed on metal hydrides and nanostructures as possible solutions to optimize storage.

What are the future applications of biomass?

Because biomass energy systems can be based on a wide range of feedstock and use many different conversion technologies to produce solid liquid and gaseous fuels, the spectrum of their future applications is large. The EU already obtains a significant fraction of its energy as heat and electricity from biomass. In addition to the current applications, in the future, biomass could play an increasing role throughout combined heat and power (CHP) and transport applications. Biomass could be a basic element of the world's future renewable energy system. In the long term, biomass has the potential to produce 20% of the energy supply. To reach both the shorter term targets as set out in the White Paper and the long term targets, Europe needs to optimize the use of the agricultural and forest residues, to introduce energy crops and to adopt cost-effective, environmentally friendly processes, which are attractive to investors and acceptable to planning authorities and the general public.

What are the research requirements?

The principal objective for future research should be to develop cost-effective integrated approaches from biomass collection to fuel production and use, which take sustainable biomass procurement and market opportunities into account. Sustainable biomass should be taken into account in any future development. The Commission has targeted priorities for future calls for research projects in this area and recognizes the need for greater cohesion between efforts made by different countries. It has also identified the need for further investigation into the socio-economic and environmental impacts of biomass energy.

How can we develop a stronger market for biomass technology?

If biomass is to play a strong role in the energy market this will require an adequate infrastructure in order to assure a steady supply. At present, significant residues are available for emerging biomass energy schemes. However, as they are insufficient, an investment is needed to encourage biomass production. Financiers and planners need

to know where best to direct investment and how to respond to, and overcome, objections. The public need to be aware of and accept the benefits of energy from biomass schemes. There are still technology challenges to achieve the mass commercialization of bioenergy in some sectors; e.g. co-firing, CHP and transport. Moreover, researchers and developers have to recognize the key issues to be addressed so that systems with improved conversion efficiencies and better economics can reach the market place.

Areas of Research and Development

Feed stock preparation: For thermo chemical routes, variety and nature of feeds for high temperature and pressure reactors. For biological routes, pretreatment to increase accessibility.

Gasification gas conditioning: Key to utilization of H₂ in fuel cells. In Gasification presence of hydrocarbons, N₂, sulfur, chlorine compounds must be addressed not only for end use applications shift gas reaction catalyst and separation systems such as PSA.

System integration: Integration of several steps, Techno-economics of process alternatives to match the optimum technology with the available feed stocks.

Modular systems approach: There is an opportunity for biomass systems to address small scale and remote applications. These systems will require novel conversion and gas conditioning technologies, designed for the resources available in a particular region.

Value Co-product integration: Appropriate systems for conversion of by-product streams from chemical and biological conversion of biomass, are the best prospects for near-term development.

Larger-scale demonstration: Most promising technologies will need to be selected at larger scale with successful utilization of H₂ (i.e. fuel cells, IC engines, turbine etc.)

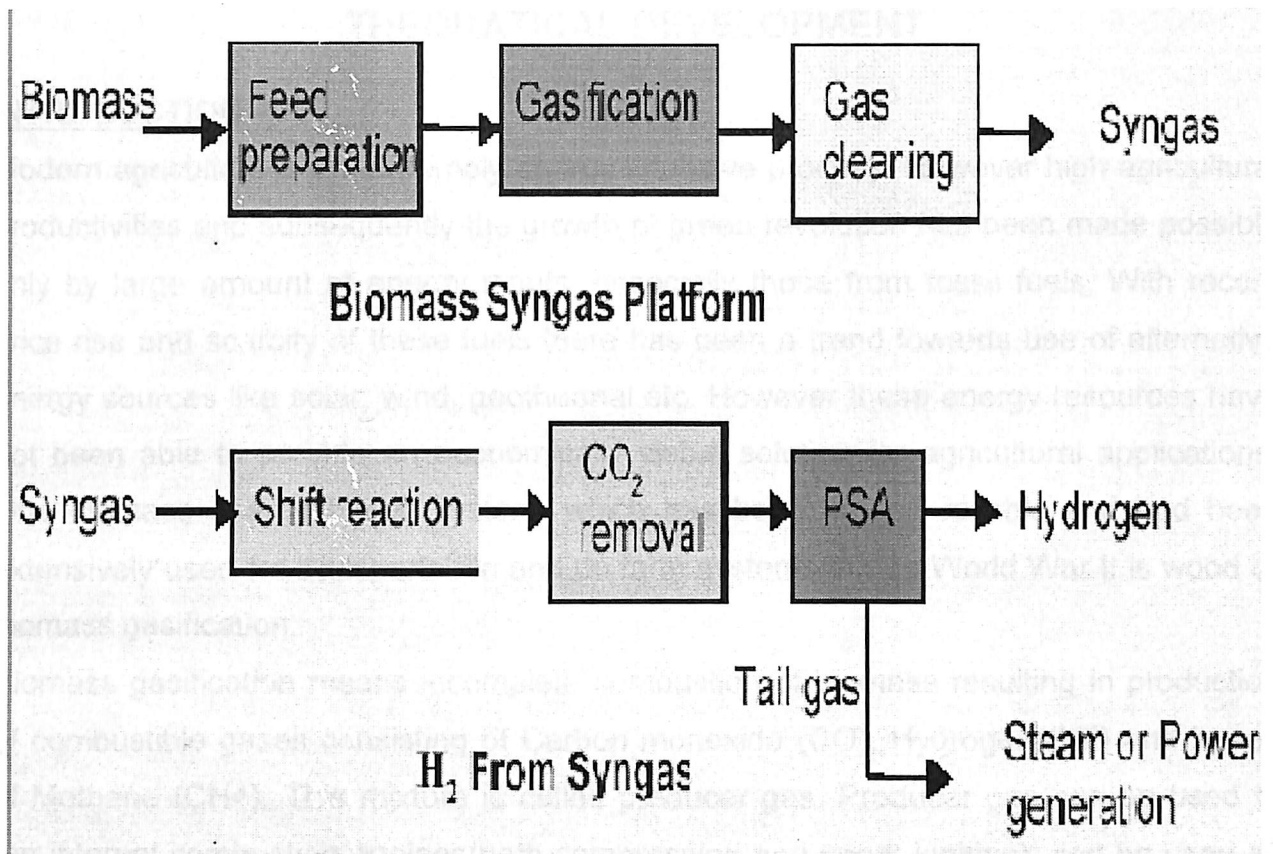


Fig.2.2 KEY PROCESS STEPS IN BIOMASS TO HYDROGEN PRODUCTION

CHAPTER 3 THEORITICAL DEVELOPMENT

INTRODUCTION

Modern agriculture is an extremely energy intensive process. However high agricultural productivities and subsequently the growth of green revolution has been made possible only by large amount of energy inputs, especially those from fossil fuels. With recent price rise and scarcity of these fuels there has been a trend towards use of alternative energy sources like solar, wind, geothermal etc. However these energy resources have not been able to provide an economically viable solution for agricultural applications. One biomass energy based system, which has been proven reliable and had been extensively used for transportation and on farm systems during World War II is wood or biomass gasification.

Biomass gasification means incomplete combustion of biomass resulting in production of combustible gases consisting of Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane (CH₄). This mixture is called producer gas. Producer gas can be used to run internal combustion engines(both compression and spark ignition), can be used as substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol – an extremely attractive chemical which is useful both as fuel for heat engines as well as chemical feedstock for industries. Since any biomass material can undergo gasification, this process is much more attractive than ethanol production or biogas where only selected biomass materials can produce the fuel. Besides, there is a problem that solid wastes (available on the farm) are seldom in a form that can be readily utilized economically e.g. Wood wastes can be used in hog fuel boiler but the equipment is expensive and energy recovery is low. As a result it is often advantageous to convert this waste into more readily usable fuel from like producer gas. Hence the attractiveness of gasification. However under present conditions, economic factors seem to provide the strongest argument of considering gasification. In many situations where the price of petroleum fuels is high or where supplies are unreliable the biomass gasification can provide an economically viable system – provided the suitable biomass feedstock is easily available (as is indeed the case in agricultural systems).

HISTORICAL BACKGROUND

The process of gasification to produce combustible from organic feeds was used in blast furnaces over 180 years ago. The possibility of using this gas for heating and power generation was soon realized and there emerged in Europe producer gas systems, which used charcoal and peat as feed material. At the turn of the century petroleum gained wider use as a fuel, but during both world wars and particularly World War II, shortage in petroleum supplies led to widespread re-introduction of gasification. By 1945 the gas was being used to power trucks, buses and agricultural and industrial machines. It is estimated that there were close to 9000,000. Vehicles running on producer gas all over the world. After World War II the lack of strategic impetus and the availability of cheap fossil fuels led to general decline in the producer gas industry. However Sweden continued to work on producer gas technology and the work was accelerated after 1956 Suez Canal crisis. A decision was then made to include gasifiers in Swedish strategic emergency plans. Research into suitable designs of wood gasifiers, essentially for transport use, was carried out at the National Swedish Institute for Agricultural Machinery Testing and is still in progress . The contemporary interest in small scale gasifier R&D, for most part dates from 1973 oil crisis. The U.S. research in this area is reviewed by Goss. The manufacturing also took off with increased interest shown in gasification technology. At present there are about 64 gasification equipment manufacturers all over the world.

THEORY OF GASIFICATION

The production of generator gas (producer gas) called gasification, is partial combustion of solid fuel (biomass) and takes place at temperatures of about 1000⁰C. The reactor is called a gasifier. The combustion products from complete combustion of biomass generally contain nitrogen, water vapor, carbon dioxide and surplus of oxygen. However in gasification where there is a surplus of solid fuel (incomplete combustion) the products of combustion are combustible gases like Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane and nonuseful products like tar and dust. The production of these gases is by reaction of water vapor and carbon dioxide through a glowing layer of charcoal. Thus the key to gasifier design is to create conditions such that

- a) Biomass is reduced to charcoal and,
- b) Charcoal is converted at suitable temperature to produce CO and H₂.

Principles of Biomass Gasification

Biomass fuels such as firewood and agriculture-generated residues and wastes are generally organic. They contain carbon, hydrogen, and oxygen along with some moisture. Under controlled conditions, characterized by low oxygen supply and high temperatures, most biomass materials can be converted into a gaseous fuel known as producer gas, which consists of carbon monoxide, hydrogen, carbon dioxide, methane and nitrogen. This thermo-chemical conversion of solid biomass into gaseous fuel is called biomass gasification. The producer gas so produced has low a calorific value (1000-1200 Kcal/Nm³), but can be burned with a high efficiency and a good degree of control without emitting smoke. Each kilogram of air-dry biomass (10% moisture content) yields about 2.5 Nm³ of producer gas. In energy terms, the conversion efficiency of the gasification process is in the range of 60%-70%.

Gasification Processes

Four types of gasifier are currently available for commercial use:

- >counter-current fixed bed
- >co-current fixed bed
- >fluidized bed
- >entrained flow.

- The **counter-current fixed bed ("up draft") gasifier** consists of a fixed bed of carbonaceous fuel (e.g. coal or biomass) through which the "gasification agent" (steam, oxygen and/or air) flows in counter-current configuration. The ash is either removed dry or as a slag. The slagging gasifiers require a higher ratio of steam and oxygen to carbon in order to reach temperatures higher than the ash fusion temperature. The nature of the gasifier means that the fuel must have high mechanical strength and must be non-caking so that it will form a permeable bed, although recent developments have reduced these restrictions to some extent. The throughput for this type of gasifier is relatively low. Thermal efficiency is high as the gas exit temperatures are relatively low. However,

this means that tar and methane production is significant at typical operation temperatures, so product gas must be extensively cleaned before use or recycled to the reactor.

- The **co-current fixed bed ("down draft") gasifier** is similar to the counter-current type, but the gasification agent gas flows in co-current configuration with the fuel (downwards, hence the name "down draft gasifier"). Heat needs to be added to the upper part of the bed, either by combusting small amounts of the fuel or from external heat sources. The produced gas leaves the gasifier at a high temperature, and most of this heat is often transferred to the gasification agent added in the top of the bed, resulting in an energy efficiency on level with the counter-current type. Since all tars must pass through a hot bed of char in this configuration, tar levels are much lower than the counter-current type.

- In the **fluidized bed reactor**, the fuel is fluidized in oxygen and steam or air. The ash is removed dry or as heavy agglomerates that defluidize. The temperatures are relatively low in dry ash gasifiers, so the fuel must be highly reactive; low-grade coals are particularly suitable. The agglomerating gasifiers have slightly higher temperatures, and are suitable for higher rank coals. Fuel throughput is higher than for the fixed bed, but not as high as for the entrained flow gasifier. The conversion efficiency can be rather low due to elutriation of carbonaceous material. Recycle or subsequent combustion of solids can be used to increase conversion. Fluidized bed gasifiers are most useful for fuels that form highly corrosive ash that would damage the walls of slagging gasifiers. Biomass fuels generally contain high levels of corrosive ash.

- In the **entrained flow gasifier** a dry pulverized solid, an atomized liquid fuel or a fuel slurry is gasified with oxygen (much less frequent: air) in co-current flow. The gasification reactions take place in a dense cloud of very fine particles. Most coals are suitable for this type of gasifier because of the high operating temperatures and because the coal particles are well separated from one another. The high temperatures and pressures also mean that a higher throughput can be achieved; however thermal efficiency is somewhat lower as the gas must be cooled before it can be cleaned with existing technology. The high temperatures also mean that tar and methane are not present in the product gas; however the oxygen requirement is higher than for the other

types of gasifiers. All entrained flow gasifiers remove the major part of the ash as a slag as the operating temperature is well above the ash fusion temperature. A smaller fraction of the ash is produced either as a very fine dry fly ash or as a black colored fly ash slurry. Some fuels, in particular certain types of biomasses, can form slag that is corrosive for ceramic inner walls that serve to protect the gasifier outer wall. However some entrained bed type of gasifiers do not possess a ceramic inner wall but have an inner water or steam cooled wall covered with partially solidified slag. These types of gasifiers do not suffer from corrosive slags. Some fuels have ashes with very high ash fusion temperatures. In this case mostly limestone is mixed with the fuel prior to gasification. Addition of a little limestone will usually suffice for the lowering the fusion temperatures. The fuel particles must be much smaller than for other types of gasifiers. This means the fuel must be pulverized, which requires somewhat more energy than for the other types of gasifiers. By far the most energy consumption related to entrained bed gasification is not the milling of the fuel but the production of oxygen used for the gasification.

GASIFIER FUEL CHARACTERISTICS

Almost any carbonaceous or biomass fuel can be gasified under experimental or laboratory conditions. However the real test for a good gasifier is not whether a combustible gas can be generated by burning a biomass fuel with 20-40% stoichiometric air but that a reliable gas producer can be made which can also be economically attractive to the customer. Towards this goal the fuel characteristics have to be evaluated and fuel processing done.

Many a gasifier manufacturers' claim that a gasifier is available which can gasify any fuel. There is no such thing as a universal gasifier. A gasifier is very fuel specific and it is tailored around a fuel rather than the other way round. Thus a gasifier fuel can be classified as good or bad according to the following parameters:

- 1) Energy content of the fuel
- 2) Bulk density
- 3) Moisture content
- 4) Dust content

- 5) Tar content
- 6) Ash and slagging characteristic

A. Energy content and Bulk Density of fuel

The higher the energy content and bulk density of fuel, the similar is the gasifier volume since for one charge one can get power for longer time.

B. Moisture content

In most fuels there is very little choice in moisture content since it is determined by the type of fuel, its origin and treatment. It is desirable to use fuel with low moisture content because heat loss due to its evaporation before gasification is considerable and the heat budget of the gasification reaction is impaired. For example, for fuel at 25⁰C and raw gas exit temperature from gasifier at 300⁰C, 2875 KJ/kg moisture must be supplied by fuel to heat and evaporate moisture. Besides impairing the gasifier heat budget, high moisture content also puts load on cooling and filtering equipment by increasing the pressure drop across these units because of condensing liquid. Thus in order to reduce the moisture content of fuel some pretreatment of fuel is required. Generally a desirable moisture content for fuel should be less than 20%.

C. Dust content

All gasifier fuels produce dust. This dust is a nuisance since it can clog the internal combustion engine and hence has to be removed. The gasifier design should be such that it should not produce more than 2-6 g/m³ of dust. Dust produced as a function of gas production for wood generators used during World War II. The higher the dust produced, more load is put on filters necessitating their frequent flushing and increased maintenance.

D. Tar content

Tar is one of the most unpleasant constituents of the gas as it tends to deposit in the carburetor and intake valves causing sticking and troublesome operations. It is a product of highly irreversible process taking place in the pyrolysis zone. The physical property of tar depends upon temperature and heat rate and the appearance ranges from brown and watery (60% water) to black and highly viscous (7% water). There are approximately 200 chemical constituents that have been identified in tar so far. Very

little research work has been done in the area of removing or burning tar in the gasifier so that relatively tar free gas comes out. Thus the major effort has been devoted to cleaning this tar by filters and coolers. A well-designed gasifier should put out less than 1 g/m³ of tar. Usually it is assumed that a downdraft gasifier produces less tar than other gasifiers. However because of localized inefficient processes taking place in the throat of the downdraft gasifier it does not allow the complete dissociation of tar. More research effort is therefore needed in exploring the mechanism of tar breakdown in downdraft gasifiers.

E. Ash and Slagging Characteristics

The mineral content in the fuel that remains in oxidized form after complete combustion is usually called ash. The ash content of a fuel and the ash composition has a major impact on trouble free operation of gasifier.

Ash basically interferes with gasification process in two ways:

- a) It fuses together to form slag and this clinker stops or inhibits the downward flow of biomass feed.
- b) Even if it does not fuse together it shelters the points in fuel where ignition is initiated and thus lowers the fuel's reaction response.

Ash and tar removal are the two most important processes in gasification system for its smooth running. Various systems have been devised for ash removal. In fact some fuels with high ash content can be easily gasified if elaborate ash removal system is installed in the gasifier.

Slagging, however, can be overcome by two types of operation of gasifier:

- 1) Low temperature operation that keeps the temperature well below the flow temperature of the ash.
- 2) High temperature operation that keeps the temperature above the melting point of ash.

The first method is usually accomplished by steam or water injection while the latter method requires provisions for tapping the molten slag out of the oxidation zone. Each method has its advantages and disadvantages and depends on specific fuel and gasifier design. Keeping in mind the above characteristics of fuel, only two fuels have been thoroughly tested and proven to be reliable. They are charcoal and wood. They

were the principal fuels during World War II and the European countries had developed elaborate mechanisms of ensuring strict quality control on them. Charcoal, specifically, because of being tar free and having relatively low ash content property was the preferred fuel during World War II and still remains so. However there is a major disadvantage of charcoal in terms of energy. Charcoal is mostly produced from wood and in conversion of wood to charcoal about 50% of original energy is lost. When made by pit method (as is normally made in most developing countries) the losses can be as high as 80%. Besides with the present energy crisis where most countries do not have enough supply of wood it is advantageous and attractive to use agricultural residues. For the agricultural sector this is an extremely attractive alternative.

TECHNICAL DETAILS OF A BIOMASS GASIFIER

THE PROCESS

Gasification is a process by which solid biomass is converted by a thermo-chemical process into clean gaseous form in a solid Bio residue gasifier. The process involves subjecting the solid biomass to partial pyrolysis in sub-stoichiometric quantities of oxygen, resulting in the formation of producer gas, which is composed of 18% H₂, 20% CO, 2% CH₄, 12 % CO₂ and rest N₂ and has a mean calorific value of 4.7 MJ/Kg.

SYSTEMS:-

- A. Gasification Plant.
- B. Power Package.
- C. Auxiliaries.

A) GASIFICATION PLANT

The Gasification Plant is engineered incorporating all the necessary safety features for long term reliable performance, with minimum down time for maintenance. The system consists of gasification reactor of 1000 kg/hr capacity, a scrubbing system for cooling the producer gas, a high efficiency cleaning system to clean the gas to extremely high quality for rendering it suitable for engine operation and necessary ducting to the engine. The gasifier system is rated at a feed consumption of 1000 Kg/hour at 100% capacity and generation of one MW. This system is also designed to accept a wide variety of properly sized solid bio-residues such as chopped coconut fronds, coconut

husk, corn cobs, mulberry stalks, cotton stalks, weeds like Prosopis Juliflora, Ipomoea with a moisture content around 15% or briquettes from agro residue such as rice husk, de-oiled rice bran, coir pith etc. of known composition. Typical consumption of biomass would be 1.0 kg/kWh generated, depending on the ash and moisture content of the biomass. The Gasification Plant incorporates the following sub systems.

B) GASIFIER REACTOR

The reactor is a cylindrical vessel made of mild steel, with an inner lining of cold face insulation bricks and ceramic tiles composed largely of alumina. Air nozzles, provided around the combustion zone, are kept open during the running of the system. To allow for uniform air availability across the reacting bed, an additional air nozzle called the central nozzle is directed to the reactor core. A water seal with a removable cover forms the top of the reactor, which is kept open during the entire operation of the system, to facilitate primary air induction and loading of feedstock. A grate is provided at the reactor bottom to hold the char or ash as the case may be, with a mechanism for intermittent extraction of char/ash.

GAS COOLING SYSTEM

It consists of a direct water impingement cooler, which is meant for cooling the hot gases from the gasifier reactor to ambient for engine applications and scrubbing the gas to remove the entrained tar and particulate matter. When the gasifier system is operated at the rated load, the system requires 80 M³/Hr on a continuous basis for a one MW rating. The coolers perform the twin functions of cooling and cleaning the producer gas.

GAS FILTERING SYSTEM

This sub system consists of a series of a quartz based gas filter, a bag filter, a catalytic converter and a fine quality paper filter. The purpose of the filtering system is to reduce the quantity of tar, particulate matter and moisture in the gas.

BURNER

This is provided to check the initial quality of the combustible gas as also for emergency flaring.

INSTRUMENTATION & CONTROL AUTOMATION

The Instrumentation consists of automatic gas flow meter and pressure indicators

located on-line to monitor the quantity and rate of gas production. Instrumentation is also provided for monitoring temperatures in the reactor, automatic retraction of top cover, automatic start/stop of the bucket elevator, automatic control of gas feed into the engine and automatic char/ash extraction. Relevant parameters such as system pressures along the gas flow path, gas consumed by the engine and operating parameters such as pressure, temperature, etc are also displayed for operational convenience.

CONTROLS & SAFETY FEATURES

The system shall be provided with the following safety elements

- 1) Oxygen monitoring system - to indicate if there is any leakage of air into the system, forewarning the operator to take necessary preventive action.
- 2) Water seals - most of the system elements are provided with water seals to release pressure in the event of the system getting pressurized. The water seals, with their low-level bubbling noise, also act as adjunct annunciators of system pressure build-up.
- 3) Automatic reactor shut off - to shut off the reactor automatically in the event of power failure.
- 4) The automation for start-up consists of a plc based control system, which controls the following actions:
 - 5) Automatic retraction of top cover with pneumatic arms.
 - 6) Automatic positioning of two-way chute.
 - 7) Automatic cut-on and cut-off of biomass loading in the reactor using ultrasonic sensors.
 - 8) Automatic control of blower operation providing secondary air to the reactor.
 - 9) Automatic extraction of ash from the grate bottom.
 - 10) Automatic control of air blower speed to suit engine requirements.
 - 11) Automatic emergency flaring of gas.

CHAPTER 4

ANALYSIS OF COST ESTIMATION

An acceptable plant design must represent a plant that can produce a product which will sell at a profit. Initially, sufficient capital must be committed to construct all aspects of the facility necessary for the plant.

Since net profit equals total income minus all expenses, it is essential that the chemical engineer be aware of the various type of the costs associated with each manufacturing step. Funds must be available for direct plant expenses, such as those for raw materials, labor, and utilities, and for direct expenses, such as administrative salaries, product sales, and distribution costs. In this chapter, investment and plant operation costs are reviewed as well as cash flow and gross and net profits.

FACTORS AFFECTING INVESTMENT & PRODUCTION COSTS

When an engineer determines costs for any type of industrial process, these cost should be of sufficient accuracy to provide reliable decision. To accomplish this, the engineer must have a complete understanding of the many factors that can affect costs. For example, some companies have reciprocal arrangements with other companies whereby certain raw materials or type of equipment may be purchase at prices lower than the prevailing market prices. Therefore, if the engineer bases the cost of raw material for the process on regular market prices, the result may be that the process could appear to be unprofitable rather than profitable. Accordingly, the engineer must be aware of actual prices for raw materials and equipments, company policies government regulation, and other factors affecting costs.

Sources of equipment:

One of the major costs involved in any chemical process is for equipment. In many cases, standard types of tanks, reactors, or other equipment are used, and a substantial reduction in cost can be realized by employing idle equipment or by purchasing second-hand equipment. If new equipment must be bought, several independent quotations should be obtained from different manufacturers, when specification are given to the manufacturers, the chances for a low cost estimate are increased if overly strict limitations on the design are kept to a minimum.

Price fluctuations:

In today's economic market, prices may vary widely from one period to another. For example, plant operators or supervisors can not be hired today at the same wage rate as in 1985. The same statement applies to comparing prices of equipment purchased at different times. The engineer, therefore, must keep up to date on price and wage fluctuation. One of the most complete sources of information on existing price conditions is the monthly labor review, published by the U.S bureau of labor statistics. The publication gives up to date information on present prices and wages for different types of industries.

Company Policies:

Policies of individual companies have a direct affect on costs. For example, some companies have particularly strict safety regulations, and these must be met in every detail. Accounting procedures and method for allocating corporate costs vary among companies. Company policies with reference to labor unions must be considered, because these can affect overtime labor charges and the type of work that operators or other employees can perform. Labor union policies may, for example, even dictate the amount of wiring and piping that can be done on a piece of equipment before it is brought into the and thus have a direct affect on total cost of installed equipment.

Operating time and rate of production:

One of the factors that has a major affect on the profits is the fraction of time a process is in operation. If equipment stands idle for an extended period, raw materials and labor costs are usually low; however, many other costs, designated as fixed costs, for example, maintenance, protection, and depreciation, continue even though the equipment is not in active use. More importantly, any time that a plant is not producing a product, it is not producing revenue. Some time must be allowed periodically to perform scheduled routine maintenance; however, downtime should be kept to a necessary minimum, as it is one of the chief sources of poor profitability in process plants.

Sales demand, rate of production, and operating time are closely interrelated. The ideal plant should operate under a time schedule that gives the maximum production rate consistent with market demand, safety, maintainability, and economics operating conditions. In this way, the total cost per unit of production is minimized because the

variable costs averaged over time are low. If the production capacity of the process is greater than the sales demand, the operation can be operated continuously at reduced capacity or periodically at full capacity.

Government policies:

The national government has many laws and regulations that have direct affect on industrial costs. Some examples of these are important and export tariff regulations depreciation rates, income tax rules, and environmental and safety regulations. Of these, income tax regulations and depreciations have the largest impact on most businesses.

As of the writing of this text, modifications of federal corporate tax laws were under consideration in the U.S. congress. However, the last major change in federal corporate income tax rates was in 1993 and in depreciations was in 1988. The important point to remember is that law is subject to change at any time, and the design engineer must consult with tax expert to be sure that the most current tax codes are used in economic analyses.

CAPITAL INVESTMENT

A traditional economic definition of capital is "a stock of accumulated wealth". In an applied sense, capital is saving that may be used as the owner decides. One use of the savings is investment; that is, to use the savings"...to promote the production of the goods, instead of being available solely for purposes immediate enjoyment with"... the view of obtaining an income or profit".

Before an industrial plant can be put into operation, large sum of money must be available to purchase and install the required machinery and equipment. Land must be obtained, service facilities must be made available, and the plant must be erected complete with all piping, controls, and services. In addition, funds are required with which to pay the expenses involved in the plant operation before sales revenue becomes available.

The capital needed to supply the required manufacturing and plant facilities is called the *fixed capital investment (FCI)*, while the necessary for the operation of the plant is termed the *working capital (WC)*. The sum of fixed capital investment and the working capital is known as *total capital investment (TCI)*. The fixed capital portion may be

further subdivided into *manufacturing fixed capital investment*, also known as *direct cost*, and *non manufacturing fixed capital investment*, also known as *indirect cost*.

Fixed-capital investment:

Manufacturing fixed capital investment represents the capital necessary for the installed process equipment with all components that are needed for complete process operation. Expenses for site preparation, piping instruments, insulations, foundations and auxiliary facilities are typical examples of costs included in the manufacturing fixed capital investment.

The capital required for construction overhead and for all plant components that are not directly to the process operation is designated the non manufacturing fixed capital investment. These plant components include the land; processing buildings, administrative and other offices, warehouses, laboratories, transportation, shipping, and receiving facilities, utility and waste disposal facilities, shops and other permanent parts of the plant. The construction overhead cost includes field office and supervision expenses, home office expenses, engineering expenses, miscellaneous construction costs, contractors' fees, and contingencies. In some cases, construction overhead is proportional between manufacturing and non manufacturing fixed capital investment.

Working capital:

The working capital for an industrial plant consist of the total amount of money invested in

- (1) Raw materials and supplies carried in stock.
- (2) Finished products in stock and semi finished products in the process of being manufactured.
- (3) Accounts receivable.
- (4) Cash kept on hand for monthly payment of operating expenses, such as salaries, wages, and raw material purchases.
- (5) Accounts payable.
- (6) Taxes payable

The raw material inventory included in working capital is usually amounts to a one month supply of the raw materials valued at delivered prices. Finished products in stock and semi finished products have a value approximately equal to the total manufacturing

cost for one month's production. Because credit terms extended to customers are usually based on an allowable 30 days payment period, the working capital required because of accounts receivable ordinarily amounts to the production cost for one month of operation.

The ratio of working capital to total capital investment varies with different companies, but most chemical plants use an initial working capital amounting to 10 to 20 percent of the total capital investment. This percentage may increase to as much as 50 percent or more for companies producing products of seasonal demand, because of the large inventories which must be maintained for appreciable periods.

COST INDEXES

Most cost data that are available for making a preliminary or predesign estimate are only valid at the time they were developed. Because prices may have changed considerably with time due to changes in economic conditions, some method must be used for updating cost data applicable at a past date to costs that are representative of conditions at a later time. This can be done by the use of cost indexes.

A cost index is an index value for a given time showing the cost at that time relative to a certain base time. If the cost at some time in the past is known, the equivalent cost at present can be determined by multiplying the original cost by the ratio of the present index value to the index value applicable when the original cost was obtained, namely,
Present Cost=Original Cost {Index value at present/index value at time original cost was obtained}

Cost indexes can be used to give a general estimate, but no index can take into account all factors, such as special technological advancements or local conditions. The common indexes permit fairly accurate estimates if the period involved is less than 10 years. Indexes are frequently used to extrapolate costs into the near future. The cost estimator may project costs forward from the time a study is being done until the expected start-up time of a plant. Such projections are done by using extrapolated values of an index, or an expected inflation rate.

Table 3.1: Cost index data for chemical and allied products

YEAR	INDEX
1994	383.1
1995	385.1
1996	386.5
1997	387.3
1998	388.4
1999	389.5
2000	390.6
2001	394.1
2002	394.3
2003	395.6
2004	402.0
2005	444.2
2006	468.2
2007	495.0

COST COMPONENT IN CAPITAL INVESTMENT

Capital investment is the total amount of money needed to supply the necessary plant and manufacturing facilities plus the amount of money required as working capital for operation of the facilities.

Purchased equipments:

The cost of purchased equipment is the basis of several predesign methods for estimating capital investment. Sources of equipment prices, methods of adjusting equipment prices for capacity, and methods of estimating auxiliary process equipment are therefore essential to the estimator in making reliable cost estimates. The various type of equipment can often be divided into:-

- (1) Processing equipment
- (2) Raw material handling and storage equipment, and
- (3) Finished products handling and storage equipment.

The sizes and specification of the equipment needed for a process are determined from the equipment parameters fixed or calculated along with the material and energy balances. The most accurate method for determining process equipment costs is to obtain firm bids from fabricators or suppliers. Often, fabricators can supply quick estimates that will be close to the bid price but will not take too much time. Second best in the reliability are cost values from the file of past purchase orders. When used for

pricing new equipment, purchase order prices must be corrected with the appropriate cost index ratio. Limited information on process equipment costs has also been published in various engineering journals.

Purchased equipment delivery:

Purchased equipment prices are usually quoted as f.o.b (free on board, meaning that the purchaser pays the freight). Clearly freight costs depend upon many factors, such as the weight and size of the equipment, distance from source to plant, and method of transport. For predesign estimates, a delivery allowance of 10 percent of the purchased equipment cost is recommended.

Purchased equipment installation:

Installation of process equipment involves costs for labor, foundations, supports, platform, construction expenses, and other factors directly related to erection of purchased equipment. An analysis of a number of typical chemical plants indicates that the cost of the purchased equipment varies from 65 to 80 percent of the total installed cost depending upon the complexity of the equipment and the type of plant in which the equipment is installed. Installation costs for equipment, therefore, are estimated to vary from 25 to 55 percent of the delivered purchased – equipment costs. Expenses for equipment insulation and piping insulation are often included under the respective headings of equipments installation cost and piping costs. The total costs for labor and materials required for insulating equipment and piping in ordinary chemical plants is approximately 8 to 9 percent of the delivered purchased equipment cost. This is equivalent to approximately 2 percent of the total capital investment.

Instrumentation and control:

Instrument costs, installation labor costs, and expenses for auxiliary equipment and materials constitute the major portion of the capital investment required for instrumentation. Total instrumentation and control cost depends on the amount of control required and may amount to 8 to 50 percent of the total delivered equipment cost.

For the normal solid fluid chemical processing plant, a value of 26 percent of the delivered purchased equipment cost is recommended as an estimate for the total

instrumentation and control cost. The cost represents approximately 5 percent of the total capital investment.

Piping:

The cost for piping covers labor, valves, fittings, pipe, support, and other items involved in the complete erection of all piping used directly in the process. This includes raw material, intermediate product, finished product, steam, water, air, sewer, and other process piping. Since process plant piping can run as high as 80 percent of delivered purchased equipment cost or 20 percent of the fixed capital investment, the importance of this item in capital cost equipment is clear.

Electrical system:

The electrical system consists of four major components, namely, power wiring, lighting, transformation and service, and instrument and control wiring. In most chemical plants the installed cost of electrical system is estimated to be 15 to 30 percent of the delivered purchased equipment cost or between 4 to 8 percent of the fixed capital investment.

Buildings:

The cost of buildings, including services, consists of expenses for labor, materials, and supplies involved in the erection of all buildings connected with the plant. Costs for the plumbing, heating, lighting, ventilation and similar building services are included. The cost of buildings, including services, for different types of process plants as a percentage of purchased equipment cost and fixed capital investment.

Land:

The cost for land and accompanying surveys and fees depends on the location of the property and may vary by the cost factor per acre as high as 30 to 50 between rural district and a highly industrialized area. As a rough average, land cost for industrial plants amounts to 4 to 8 percent of the purchased equipment cost or 1 to 2 percent of the total capital investment. By law, the cost of land cannot be depreciated; therefore it is usually not included in the fixed capital investment. Rather, it is shown as a one time investment at the beginning of plant construction.

Engineering and supervision:

The cost for construction design and engineering, including internal or licensed software, computer based drawings, purchasing, accounting, construction and cost

engineering, travel, communications, and home office expense plus overhead, constitute the capital investment for engineering and supervision. This cost, since it cannot be directly charged to equipment, materials or labor, is normally considered an indirect cost in fixed capital investment for the process plant.

Construction Expenses:

Another indirect plant cost is the item of construction or field expense and includes temporary construction and operation, construction tools and rentals, home office personnel located at the construction site, construction payroll, travel and living, taxes and insurance, and other construction overhead. This expense item is occasionally included under equipment installation, or more often engineering, supervision, and construction. For ordinary chemical process plants, the construction expenses average roughly 8 to 10 percent of the fixed capital investment of the plant.

Contractor's fee:

The contractor's fees varies for different situations, but it can be estimated to be about 2 to 8 percent of the direct plant cost or 1.5 to 6 percent of the fixed capital investment.

Contingencies:

A contingency amount is included in all but the smallest estimates of capital investment in recognition of the fact that the experience shows there will be unexpected events changes that inevitably increase the cost of project. Events, such as storms, floods, transportation accidents, strikes, price changes, small design changes, errors in estimation, and other unforeseen expenses, will occur even though they cannot be predicted. Contingency factors ranging from 5 to 15 percent of the fixed capital investment are commonly used, with 8 percent being considered a reasonable average value.

ESTIMATION OF TOTAL PRODUCTION COST

The third major component of economic analysis is the total of all costs of operating the plant, selling the products, recovering the capital investment, and contributing to corporate functions such as management and research and development. These costs usually are combined under the general heading of *total product cost*. The latter, in turn, is generally divided into two categories: *manufacturing costs* and *general expenses*. Manufacturing costs are also referred to as *operating* or *production costs*. Further

subdivision of the manufacturing costs is somewhat dependent upon the interpretation of variable, fixed, and overhead costs.

Manufacturing costs:

All expenses directly connected with the manufacturing operation or the physical equipment of a process plant itself are included in the manufacturing costs. These expenses, as considered here, are divided into three classifications:

(1) Variable production costs.

(2) Fixed charges.

(3) Plant overhead costs.

Variable production costs include expenses directly associated with the manufacturing operation. This type of cost involves expenditures for raw materials, direct operating labor, supervisory and clerical labor directly applied to the manufacturing operation, utilities, plant maintenance and repairs, operating supplies, laboratory supplies, royalties, catalysts, and solvents. These costs are incurred for the most part only when the plant operates, hence the term *variable costs*. It should be recognized that some of the variable costs listed here as part of the direct production cost have an element of fixed cost in them. For instance, maintenance and repair costs decrease with reduced production level, but some maintenance and repair still occurs when the process plant is shut down.

Fixed charges are expenses which are practically independent of production rate expenditures for depreciation, property taxes, insurance, financing and rent are usually classified as fixed charges. These charges, except for depreciation, tend to change due to inflation. Because depreciation is on a schedule established by tax regulations, it may differ from year to year, but it is not affected by inflation.

Plant overhead cost are for hospital and services; general plant maintenance and overhead, safety services, payroll overhead including social security and other retirement plans, medical and life insurance, and vacation allowances, packaging, restaurant and recreation facilities, salvage services, control laboratories, property protection, plant superintendence, warehouse and storage facilities, and special employee benefits. These costs are similar to the fixed charges since they do not vary widely with changes in production rate.

Variable production costs

Raw materials In any industry, one of the major costs in production operation is for the raw materials used in the process. The category *raw material* refers in general to those materials that are directly consumed in making the final products; this includes chemical reactants and constituents and additives included in the product. Materials necessary to carry out process operation but which do not become part of the final product, such as catalysts and solvents, are listed separately.

Operating Labor In general, operating labor may be divided into skilled and unskilled labor. Hourly wage rates for operating labor in different industries at various locations can be obtained from the U.S. Bureau of labor publications entitled *monthly labor review*. For chemical process, operating labor usually amounts to about 10 to 20 percent of the total product cost.

Operating supervision and clerical assistance A certain amount of direct supervisory and clerical assistance is always required for a manufacturing operation. The necessary amount of this type of labor is closely related to total amount of operating labor, complexity of the operation, and product quality standards. The cost for direct supervisory and clerical labor averages about 15 percent of the cost for operating labor. For reduced capacities, supervision usually remains fixed at the 100 percent capacity rate.

Utilities The cost for utilities, such as, steam, electricity, process and cooling water, compressed air, natural gas, fuel oil, refrigeration, and waste treatment and disposal, varies widely depending on the amount needed, plant location and source

Maintenance and Repairs Annual cost for maintenance and repairs may range from 2 to 20 percent of the equipment cost. Charges for plant buildings average 3 to 4 percent of the building cost. In the process industries, the total plant cost per year for maintenance and repairs ranges from 2 to 10 percent of the fixed capital investment, with 7 percent being a reasonable value.

For operating rates less than plant capacity, the maintenance and repair cost is generally estimated as 85 percent of that at 100 percent capacity for a 75 percent operating rate, and 75 percent of that 100 percent capacity for a 50 percent operating rate.

Operating Supplies Consumable items such as charts, lubricants, test chemicals, custodial supplies, and similar supplies cannot be considered as raw materials or maintenance and repair materials, and these are classified as operating supplies. The annual cost for these types of supplies is about 15 percent of the total cost for maintenance and repairs.

Laboratory Charges The cost of laboratory test for control of operations and for product quality control is covered in this manufacturing cost. This expense is generally calculated by estimating the employee- hours involved and multiplying this by the appropriate rate. For quick estimates, this cost may be taken as 10 to 20 percent of the operating labor.

Patents and Royalties Patents cover many product and manufacturing processes. To use patents owned by others, it is necessary to pay for patent rights or a royalty based on the amount of material produced. Even when the company involved in the operation obtained the original patent, a certain amount of total expenses involved in the development and procurement of the patent rights should be borne by the plant as an operating expense. In case of this type, these costs are usually amortized over the legally protected life of the patent. Although a rough approximation of patent and royalty costs for patented processes is 0 to 6 percent of the total product cost, cost specific to the patent position in question are always preferred.

Fixed Charges

Costs that change little or not at all with amount of production are designated as fixed cost or charges. These include costs for depreciation, local property taxes, insurance, and loan interest. Expenses of this type are a direct function of the capital investment and financing arrangement. They should be estimated from the fixed capital investment. Rent is usually taken as zero in preliminary estimates. As a rough approximation, these charges amount to about 10 to 20 percent of the total product cost.

Depreciation The equipment, buildings, and other material objects comprising a manufacturing plant require an initial investment that must be paid back, and this is done by charging depreciation as a manufacturing expense. Since depreciation rates are very important in determining the amount of income tax, the Internal Revenue

Service, under U.S tax law, determines the rate at which depreciation may be charged for various types of industrial facilities.

Financing Interest is considered to be the compensation paid for the use of borrowed capital. A fixed rate of interest is established at the time the capital is borrowed; therefore, interest is a definite cost if it is necessary to borrow the capital used to make the investment for a plant. Although the interest on borrowed capital is a fixed charge, there are many persons who claim that interest should not be considered as a manufacturing cost, but that it should be listed as a separate expense under the general heading of management or financing cost. Annual interest rate amount to 5 to 10 percent of the total value of the borrowed capital.

Local Taxes The magnitude of local property taxes depends on the particular locality of the plant and the regional laws. Annual property taxes for plants in highly populated areas are ordinarily in the range of 2 to 4 percent of the fixed capital investment. In less populated areas, local property taxes are about 1 to 2 percent of the fixed capital investment.

Property Insurance Insurance rates on the type of process being carried out in the manufacturing operation and on the extent of available protection facilities. These rates amount to be 1 percent of the fixed capital investment per year.

Rent Annual costs for rented land and building amount to about 8 to 12 percent of the value of rented property. In preliminary estimates, rent is usually not included.

Plant Overhead Costs

The costs considered in the preceding sections are directly related to the production operation. In addition, however, many other expenses are always involved if the complete plant is to function as an efficient unit. The expenditures required for routine plant services are included in *plant overhead costs*. Non manufacturing machinery, equipment, and buildings are necessary for many of the general plant services, and fixed charges and direct costs for these items are part of the plant overhead costs. The plant overhead cost for any plant is about 50 to 70 percent of the total expenses for operating labor, supervision, and maintenance.

COST CALCULATIONS OF HYDROGEN PRODUCTION FROM BIOMASS (GASIFICATION PROCESS)

ASSUMPTIONS:

1	Biomass Cost	Rs 1/Kg
2	Capacity of plant	150000 Kg/day of H ₂
3	1 KWhr = 1Unit	3.5 Rs
4	Investment conversion factor	0.7 for U.S.A & 0.9 for U.K
5	Biomass Handling & Drying equipment cost	Rs 1000/Kg/per day of H ₂
6	Gasifier cost	Rs 800/Kg/per day of H ₂
7	Air Separation Unit (ASU) cost	Rs 1080/Kg/per day of H ₂
8	(Shift+Cooling+Cleanup) equipment cost	Rs 1000/Kg/per day of H ₂
9	H ₂ Liquefaction equipment cost	Rs 1000/Kg/per day of H ₂

$$\text{Cost of B} = \text{Cost of A} (\text{Capacity of B} / \text{Capacity of A})^{0.7}$$

$$\text{Capital cost as per 2007} = \text{Capital cost as per 2007} (\text{PPI of 2007} / \text{PPI of 2002})$$

GIVEN DATA:

S.NO	Process	Kg/hr	kg/day	KWhr/day	Rs/day
A	Hydrogen Prod.	6250	150000	,-	,-
B	Feed Stock Required	70416.6666	1689999.998	,-	1690000
C	Oxygen Required	56214.9999	1349159.998	,-	,-
D	CO ₂ Emission	109500.9999	2628023.998	,-	,-
E	POWER:				
E1	Hydrogen Liquefaction	,-	,-	1650000	5775000
E2	ASU Unit	,-	,-	55500	194250

Table 4.1: Operating Labors

S.NO.	PROCESS	PER SHIFT	TOTAL
1	Gasification	2	8
2	O2 plant	1	4
3	biomass handling	1	4
4	gas clean	1	4
5	shift	1	4
6	PSA	1	4
7	GTL	2	8
8	Boilers	1	4
9	Instrumentation	1	4
10	Electrical	1	4
11	maintenance	1	4
12	TOTAL OPERATORS	12	52

Table 4.2: Employees cost

Table

S.NO.	COSTS	Rs/Yr	Rs/day
F	Total operators= 52		
	Avg= Rs 5000/operator		
	Avg salary of 52 operator	3120000	8548
G	Supervisor cost(15% of G)	468000	1283
H	QA/QC Lab(15% of G)	468000	1283
I	Payroll employee(60% of (G+H))	2152800	5899

Table 4.3: Equipment Cost (EC)

S.NO	EQUIPMENTS	\$	Rs	TOTAL COST(Rs, Crore)
1	Biomass handling and Drying (\$ or Rs/Kg/day of biomass)	25	1000	87
2	Gasifier (\$ or Rs/Kg/day of biomass)	20	800	70
3	ASU (\$ or Rs/Kg/day of oxygen)	27	1080	75
4	shift reaction + cooling + cleanup (\$ or Rs/Kg/day of CO2)	15	600	81
5	Hydrogen liquefaction (\$ or Rs/Kg/day of H2)	700	28000	216

Table 4.4: Component of Equipment cost

EQUIPMENTS→	% of equipment costs	Biomass Handling & Drying	Gasifier	ASU	Shift reaction	Hydrogen liquefaction
COSTS(Rs, Crore)						
Equipment cost	-	87	69	75	80	21
Installation & Erection	12	10.4	8	9	10	25
Piping & Insulation	20	17.3	14	15	16	43
Instrumentation	6	5.2	4	5	5	12
Miscellaneous	4	3.4	3	3	3	86
Building	35	30	24	26	28	75
Administration Cost	10	9	7	7	8	21
Electrical Cost	8	7	5.5	6	6	17
Total		169	200	200	157	420

Table 4.5: Equipment Cost Conversion

	Rs	MM\$
Total Equipments Cost(as per 2002)	10275907201	257
Total Equipments Cost(as per 2007)	12900263922	323

Table 4.6: Component of Capital Cost

S.NO.	COSTS	Rs	MM\$
1	Total Equipments Cost(as per 2007)	12900263922	323
2	Taxes(4% of equipment cost)		
<i>a</i>	<i>Biomass & Handling</i>	34666667	1
<i>b</i>	<i>Gasifier</i>	277333334	1
<i>c</i>	<i>ASU</i>	29889084	1
<i>d</i>	<i>Shift reaction+Cooling+cleanup</i>	32344911	1
<i>e</i>	<i>Hydrogen Liquefaction</i>	86153847	3
3	Total Direct cost(1+2(a to e))	13111051762	327
4	Overhead field cons.(20% of 1)	2580052784	65
5	Engg. Cost (10% of 1)	1290026392	33
6	Contingencies(10% of 1)	1290026392	33
7	Working capital(20%of 1)	2580052784	65
8	Total indirect cost(add 4 to 7)	7740158353	193
9	Total Capital Investment(3+8)	20905043058	522

Table 4.7: Component of Manufacturing Cost

S.NO.	DIRECT COST	Rs/Yr(Crore)	MM\$/Yr	Rs/Kg H2
1	Feed Stock cost	56	13.9	11
2	Operators cost	0.3	0.07	0.06
3	supervisor cost	0.04	0.01	0.01
4	QA/QC lab cost	0.04	0.01	0.01
5	ELECTRICAL:			
F1	Hydrogen Liquefaction	190	48	38.5
F2	ASU Unit	6.4	2	1.3
6	Total direct mfg. cost(1 to 5)	253	63	51
7	Payroll employees cost	0.2	0.05	0.04
8	Local Taxes(1.5% of total direct cost of capital table)	20	5	4
9	Insurance(0.5% of total direct cost of capital table)	6.5	2	1
10	Admin cost(25% of working capital of capital cost table)	64.5	16	13
11	Plant maintenance(6% of total capital investment of capital table)	125	31	25
12	Patent (3% of total direct cost of capital table)	39	10	8
13	Depreciation(6% of total direct cost of capital table)	109	27	22
14	Interest on WC(11% of working capital of capital table)	28	7	6
15	Total indirect mfg.cost(7 to 14)	394	98.5	80
16	Total mfg.cost(6 + 15)	647	162	131

COST CALCULATIONS OF HYDROGEN PRODUCTION FROM NATURAL GAS

ASSUMPTIONS:

- | | | |
|---|--|--------------------------------------|
| 1 | Natural Gas Cost | Rs 1/Kg |
| 2 | Capacity of plant | 150000 Kg/day of H ₂ |
| 3 | 1 KWhr = 1Unit | 3.5 Rs |
| 4 | Investment conversion factor | 0.7 for U.S.A & 0.9 for U.K |
| 5 | H ₂ Liquefaction equipment cost | Rs 1000/Kg/per day of H ₂ |

$$\text{Cost of B} = \text{Cost of A} \left(\frac{\text{Capacity of B}}{\text{Capacity of A}} \right)^{0.7}$$

$$\text{Capital cost as per 2007} = \text{Capital cost as per 2007} \left(\frac{\text{PPI of 2007}}{\text{PPI of 2002}} \right)$$

GIVEN DATA:

S.NO	Process	Kg/hr	kg/day	KWhr/day	Rs/day
A	Hydrogen Prod.	6250	150000	,-	,-
B	Natural Gas required	490440	11770560	,-	3480960
C	CO ₂ Emission	1420728	34097472	,-	,-
D	POWER:				
D1	Hydrogen Liquefaction	,-	,-	1650000	5775000
D2	SMR Unit	,-	,-	31080	108780

Table 4.8: Operating Labors

S.NO.	PROCESS	PER SHIFT	TOTAL
1	Reformer	6	24
2	GTL	2	8
3	Boilers	1	4
4	Instrumentation	1	4
5	Electrical	1	4
6	maintenance	1	4
7	TOTAL OPERATORS	12	48

Table 4.9: Employees cost table

S.NO.	COSTS	Rs/Yr	Rs/day
E	Total operators= 48		
	Avg=Rs 5000/operator		
	Avg salary of 48 operator	2880000	7891
F	Supervisor cost(15% of E)	432000	1184
G	QA/QC Lab(15% of E)	432000	1184
H	Payroll employee(60% of (E+F))	1987200	5445

Table 4.10 Equipment Cost (EC)

S.NO	EQUIPMENTS	\$	Rs	TOTAL COST(Rs,Crore)
1	SMR UNIT (\$ or Rs/scf/day of H2)	0.66	26.4	85
2	Hydrogen liquefaction (\$ or Rs/Kg/day of H2)	633	25320	195

Table 4.11: Component of Equipment Cost

EQUIPMENTS	% of equipment	SMR UNIT	Hydrogen liquefaction
COSTS(Rs, Crore)	Costs		
Equipment cost	-	85	195
Installation & Erection	12	10	23
Piping & Insulation	20	17	39
Instrumentation	6	50.5	11
Miscellaneous	4	3	8
Building	35	29	68
Administration Cost	10	8	19
Electrical Cost	8	7	15.5
Total		164	380

Table 4.12: Equipment Cost Conversion

	Rs (Crore)	MM\$
Total Equipments Cost(as per 2002)	544	136
Total Equipments Cost(as per 2007)	682	171

Table 4.13: Component of Capital Cost

S.NO.	COSTS	Rs	MM\$
1	Total Equipments Cost(as per 2007)	6828589653	171
2	Taxes(4% of equipment cost):		
a	<i>SMR UNIT</i>	33670154	1
b	<i>Hydrogen Liquefaction</i>	77907693	2
3	Total Direct cost(1+2(a to b))	6968663286	174
4	Overhead field cons.(20% of 1)	1365717931	35
5	Engineering Cost (10% of 1)	682858966	18
6	Contingencies(10% of 1)	682858966	18
7	Working capital(20%of 1)	1365717931	35
8	Total indirect cost(add 4 to 7)	4097153792	102
9	Total Capital Investment(3+8)	110365817078	276

Table 4.14: Component of Manufacturing Cost

S.NO.	DIFFERENT COSTS	Rs/Yr(Crore)	MM\$/Yr	Rs/Kg H2
1	Natural Gas cost	115	29	23
2	Operators cost	0.2	0.07	1
3	supervisor cost	0.04	0.01	1
4	QA/QC lab cost	0.04	0.01	1
5	ELECTRICAL:			
F1	Hydrogen Liquefaction	191	48	38
F2	SMR UNIT	3.5	1	1
6	Total direct mfg. cost(1 to 5)	309	77	62
7	Payroll employees cost	0.2	0.05	1
8	Local Taxes(1.5% of total direct cost of capital table)	10	3	2
9	Insurance(0.5% of total direct cost of capital table)	3.5	1	1
10	Admin cost(25% of working capital of capital cost table)	34	8.6	6
11	Plant maintenance(6% of total capital investment of capital table)	66	16.6	13
12	Patent (3% of total direct cost of capital table)	21	5	4
13	Depreciation(6% of total direct cost of capital table)	58	14.5	11
14	Interest on WC(11% of working capital of capital table)	15	4	3
15	Total indirect mfg.cost(7 to 14)	209	52	42
16	Total mfg.cost(6 + 15)	518	129.5	104

CHAPTER 5

RESULTS AND DISCUSSION

1. Components of Capital Cost:

The capital investment for base capacity 150000 Kg H₂/day was estimated for both biomass as well as natural gas feed stocks. The total equipment cost for the year 2007 for biomass gasification and for SMR for natural gas was found by using equation

$$\text{Cost at 2007} = \text{cost at 2002} (495/394.3)$$

The estimated total capital cost using biomass gasification was Rs 210 crore in which the total equipment cost was Rs 129 crore, Taxes are around Rs 16 crore, overhead field construction cost was Rs 26 crore, the engineering cost and contingencies cost were same i.e. Rs 13 crore and the working capital was Rs 26 crore. The 62% of the total capital investment is of the equipment cost for biomass gasification

The estimated capital cost using SMR for natural gas was Rs 111 crore in which the total equipment cost was Rs 68 crore, Taxes are around Rs 13 crore, overhead field construction cost was Rs 14 crore, the engineering cost and contingencies cost were same i.e. Rs 6 crore and the working capital was Rs 11 crore. The 61% of the total capital investment is of the equipment cost for SMR for natural gas.

The capital cost distribution for both biomass gasification and SMR for natural gas for the plant capacity of 150000 Kg H₂/day is shown in figure 5.1 and figure 5.2.

Therefore in future improve in equipment design and improvement in technology can reduce the total capital cost.

Table 5.1: Capital cost component

COSTS	SMR(crore RS)	GASIFICATION(crore Rs)
Total Equipments Cost(as per 2007)	129	68
Taxes	16	13
Overhead field cons	26	14
Engg. Cost	13	6
Contingencies	13	6
Working capital	26	11

CAPITAL COST DISTRIBUTION FOR 150000

Kg/Day

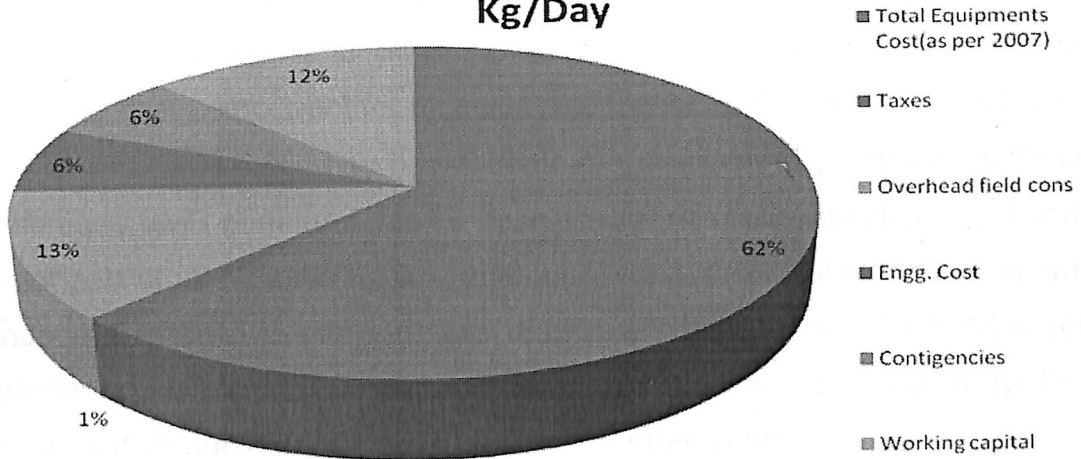


Figure 5.1: Capital cost component for Gasification Process

CAPITAL COST DISTRIBUTION FOR 150000

Kg/Day

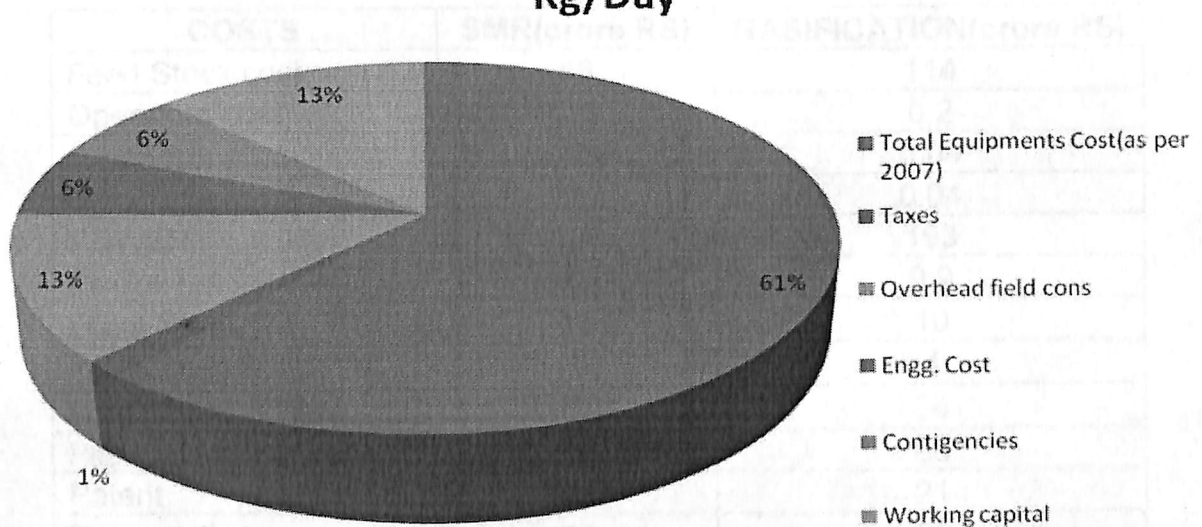


Figure 5.2: Capital cost Distribution Chart for SMR Process

2. Components of Manufacturing Cost:

The manufacturing investment for base capacity 150,000 Kg H₂/day was estimated for both biomass gasification and SMR for natural gas feed stocks. The calculation of manufacturing cost component for biomass gasification and SMR for natural gas shown in table 4.8 and table 4.16. The components of manufacturing costs for both biomass gasification and SMR of natural gas for base capacity are shown in figure 5.3 and 5.4..

The major part of manufacturing cost component is of power of Rs 196 crore and plant maintenance is of Rs 125 crore in case of biomass gasification. For SMR process Rs 193 crore for power i.e. 38% of total manufacturing cost and Rs 114 crore for feedstock i.e. 22% of total manufacturing cost, rest 50% are other costs.

Therefore in future new technologies should come up which can take up the power more efficiently and further research is to be done to reduce the maintenance cost.

Table 5.2: Manufacturing cost component

COSTS	SMR(crore RS)	GASIFICATION(crore RS)
Feed Stock cost	55	114
Operators cost	0.3	0.2
supervisor cost	0.04	0.04
QA/QC lab cost	0.04	0.04
POWER	196	193
Payroll employees cost	0.2	0.9
Local Taxes	19	10
Insurance	6	4
Admin cost	64	34
Plant maintenance	125	66
Patent	40	21
Depreciation	11	58
Interest on WC	28	16

**MANUFACTURING COST DISTRIBUTION FOR
150000 Kg/Day of HYDROGEN**

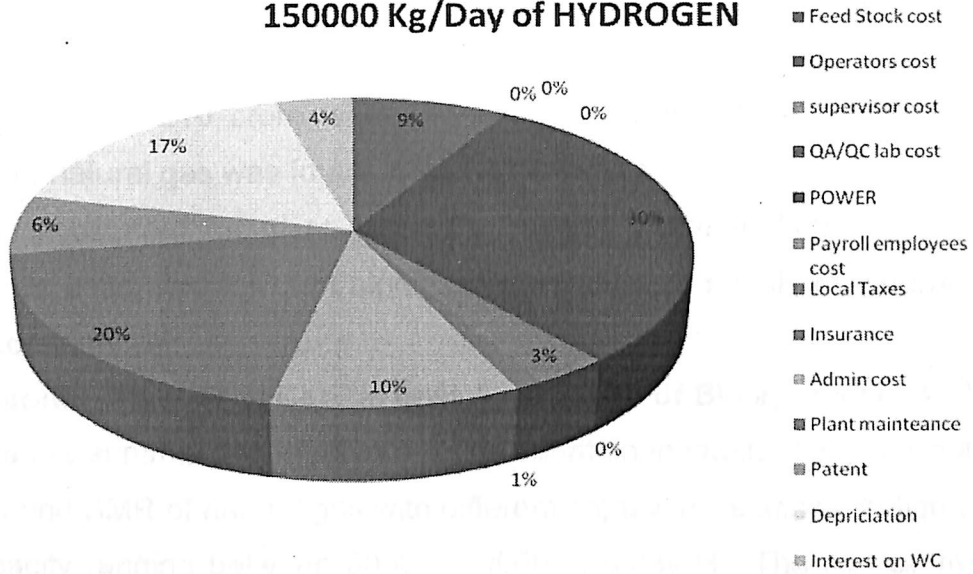


Figure 5.3 : Capital cost Distribution for gasification Process

**MANUFACTURING COST DISTRIBUTION FOR
150000 Kg/Day**

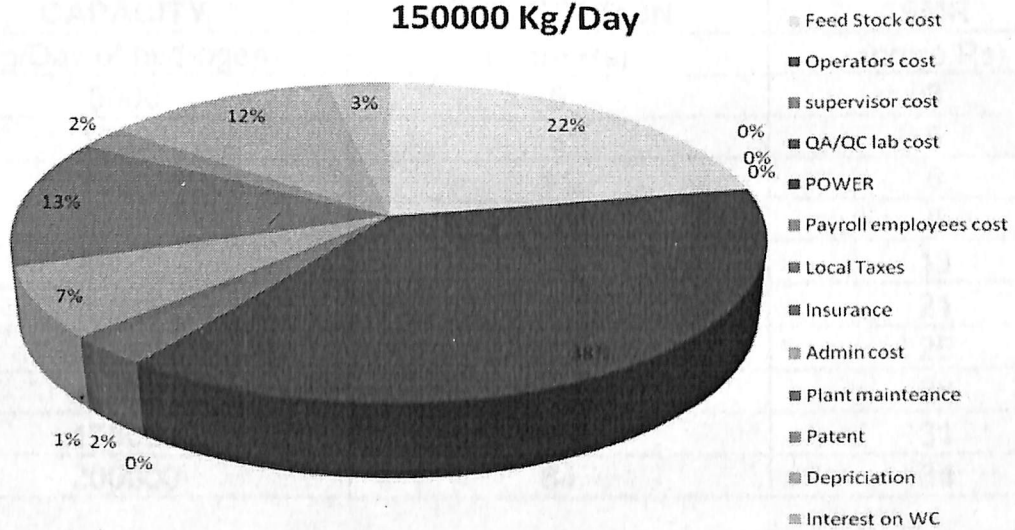


Figure 5.4: Capital cost Distribution Chart for SMR Process

3. Effect of variation in capacity on annual capital cost of hydrogen production:

The capital investment for base capacity 150,000 Kg H₂/day was estimated for both biomass as well as natural gas feed stocks. The estimated capital cost using biomass gasification was Rs 210 crore while the capital investment on hydrogen production using SMR of natural gas was found to be Rs 111 crore.

The capital investment for plant capacities ranging between 5000 – 200000 kg/day hydrogen was estimated for both biomass gasification and SMR of natural gas routes using the equation:

$$\text{Capital costs (B)} = \text{Capital cost A (capacity of B) / capacity of A}^{0.7}$$

The results are summarized in table 5.3. The variation in capital costs for both biomass gasification and SMR of natural gas with different capacities is shown in figure 5.5.

In the capacity ranging between 5000 – 200000 Kg/day H₂. The capital investment in SMR was found to be much lower than the biomass gasification.

Table 5.3: Effect of variation in capacity on capital cost

CAPACITY (Kg/Day of hydrogen)	GASIFICATION (crore Rs)	SMR (crore Rs)
5000	5	3
10000	8	5
15000	11	6
25000	15	8
50000	25	13
100000	40	21
125000	46	25
150000	53	28
175000	59	31
200000	64	34

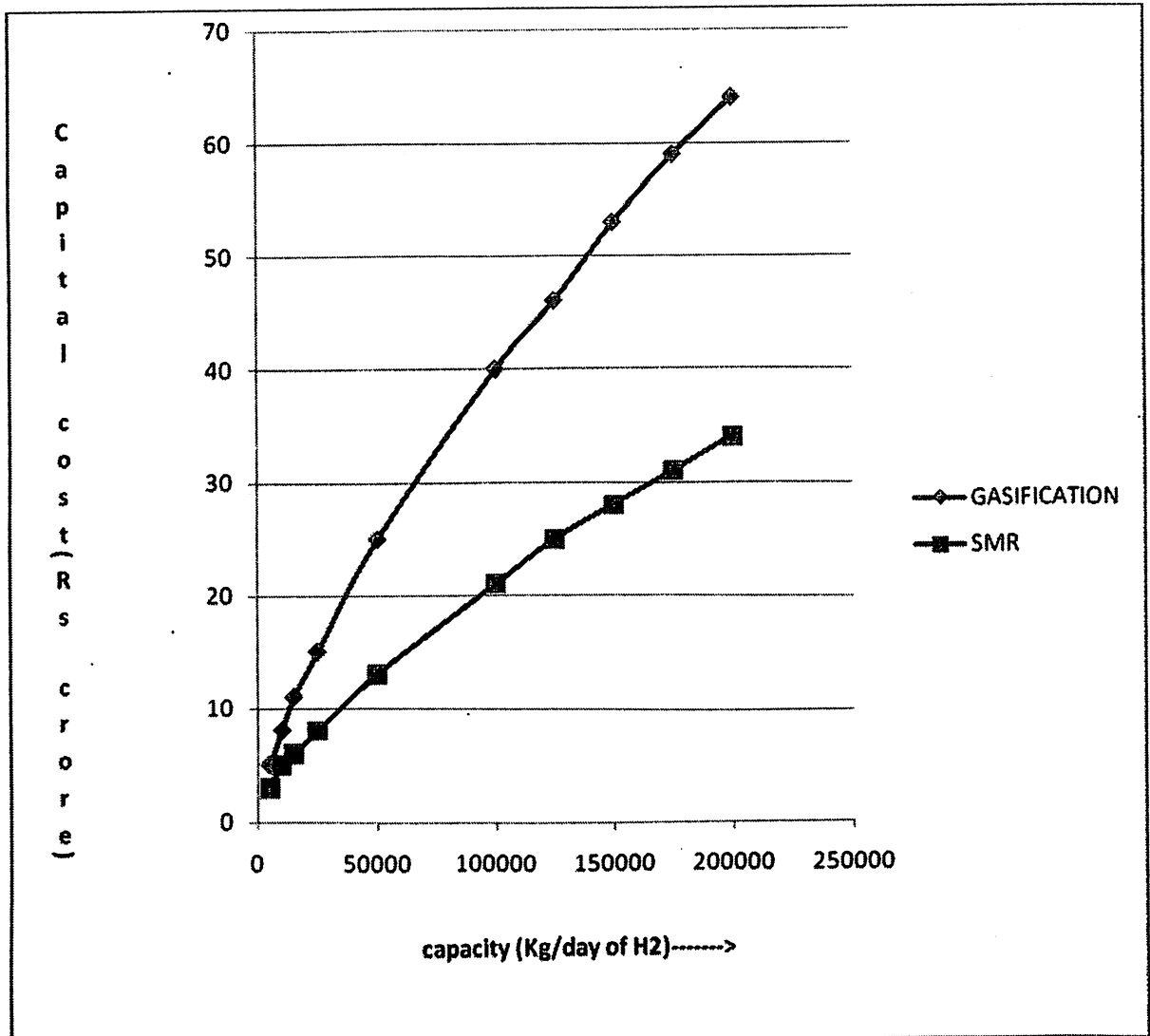


Figure 5.5: Effect of variation in capacity on Capital Cost

4. Effect of variation in capacity on annual manufacturing cost of hydrogen production:

The total manufacturing investment for base capacity, 150000 Kg H₂/day was estimated for both biomass and natural gas feed stocks. The estimated annual manufacturing cost using biomass gasification was Rs 647 crore while the manufacturing investment on hydrogen production using SMR for natural gas was found to be Rs 519 crore given in table no. 4.8 and table no. 4.16 for the base capacity of 150000 Kg/day of hydrogen.

The manufacturing investment for plant capacities ranging between 5000-200000 Kg H₂/day was estimated for both biomass gasification and for SMR for natural gas and is summarized in table 5.4. The variation in manufacturing cost of hydrogen production for both biomass gasification and SMR for natural gas with different capacities is shown in figure 5.6. In the capacity ranging between 5000 – 200000 Kg H₂/day the total manufacturing investment is less in biomass gasification and for the capacity of 50000 Kg H₂/day the manufacturing amount is equal for both the processes but for capacities 100000 – 200000 Kg H₂/day the manufacturing investment is less for SMR for natural gas.

Table 5.4: Effect of variation in capacity on manufacturing cost

CAPACITY (Kg/Day of H ₂)	MANUFACTURING COST OF H ₂ PROD.FROM BIOMASS(crore Rs)	MANUFACTURING COST OF H ₂ PROD.FROM NATURALGAS(crore Rs)
5000	0.6	2
10000	1	2.4
15000	2	3
25000	3	4
50000	6	6
100000	13	12
125000	14	12.5
150000	17	13
175000	19	15
200000	22	17

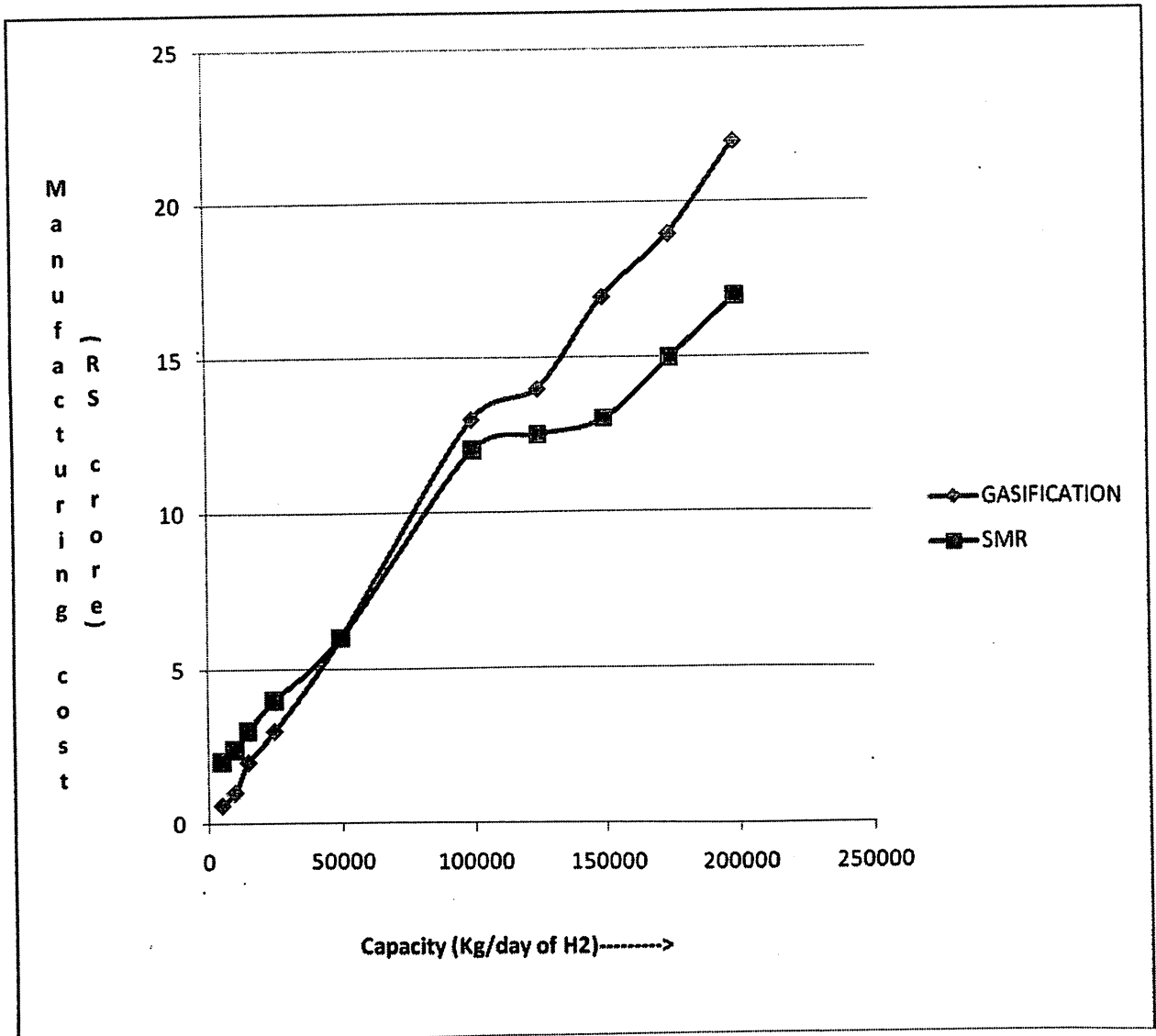


Figure 5.6: Effect of variation in capacity on manufacturing Cost

5. Effect of variation in capacity on per Kg cost of hydrogen production:

The effect of variation in capacity on manufacturing cost per Kg of Hydrogen production is shown in figure 5.7. The estimated cost for different capacities is given in table 5.5. For the lower capacities range between 5000 to 25000 Kg/day of hydrogen production the price is less in case of biomass gasification but for capacities range between 50000 to 200000 Kg/day of hydrogen the cost of hydrogen production is less in SMR for natural gas. From this we can also say that the gasification process is insensitive to capacities.

Table 5.5 : Effect of variation in capacity on Operating Cost per Kg of H₂ Production

CAPACITY (Kg/Day)	OPERATING COST/ KG OF H₂ PROD.FROM BIOMASS (Rs/Kg of H₂)	OPERATING COST/ KG OF H₂ PROD.FROM NATURALGAS(Rs/Kg of H₂)
5000	134.43	476.84
10000	132.55	284.34
15000	131.92	220.18
25000	131.42	168.85
50000	131.05	130.35
100000	130.67	110.99
125000	130.64	107.15
150000	130.61	104.59
175000	130.59	102.76
200000	130.58	101.39

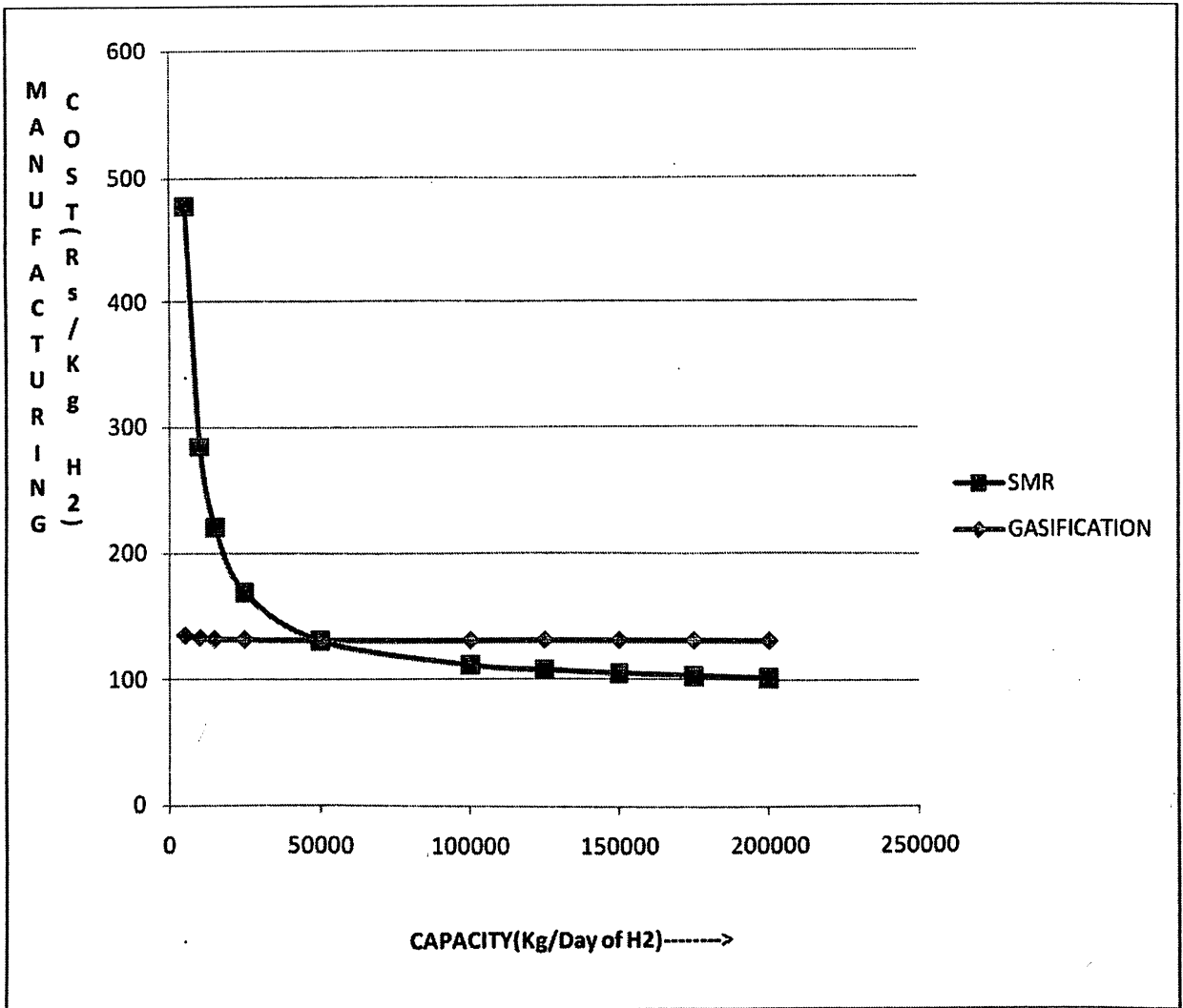


Figure 5.7 : Effect of variation in capacity on Operating Cost per Kg of H₂ Production

6. Effect of increase in price of feed stocks:

Effect of increase in price of feed stocks for base capacity 150,000 kg hydrogen/day, was estimated for both biomass gasification and SMR for natural gas. For Rs 1000/ton biomass the cost of hydrogen production from gasification was Rs 131/ kg of hydrogen and for the Rs 900/kg of natural gas the cost of hydrogen production was Rs 100/kg of hydrogen for SMR process. For the biomass price range between 400-1600 Rs/ ton the cost of hydrogen production vary between Rs 124 to 138/kg of hydrogen and for SMR process the natural gas price range between Rs 200 to 2450/kg the hydrogen production cost is vary between Rs 87-133/kg of hydrogen. The results are summarized in table 5.6 and the increase in price of feed stocks for both biomass gasification and natural gas SMR process is shown in figure 5.8. In future after 10 yrs when the price of natural gas increases too much at that time the production of hydrogen from biomass is economically viable from biomass gasification process.

Table 5.6: Effect of increase in price of feed stock

BIOMASS PRICE(Rs/Ton) X 100	H2 PROD. by Gasification(Rs/Kg)	NG PRICE(Rs/Kg) X 50	H2 PROD. By SMR(Rs/Kg)
400	124	200	87
600	127	450	91
800	129	650	96
1000	131	900	100
1200	133	1150	105
1400	136	1350	110
1600	138	1600	114
		1850	119
		2050	124
		2300	128
		2450	133

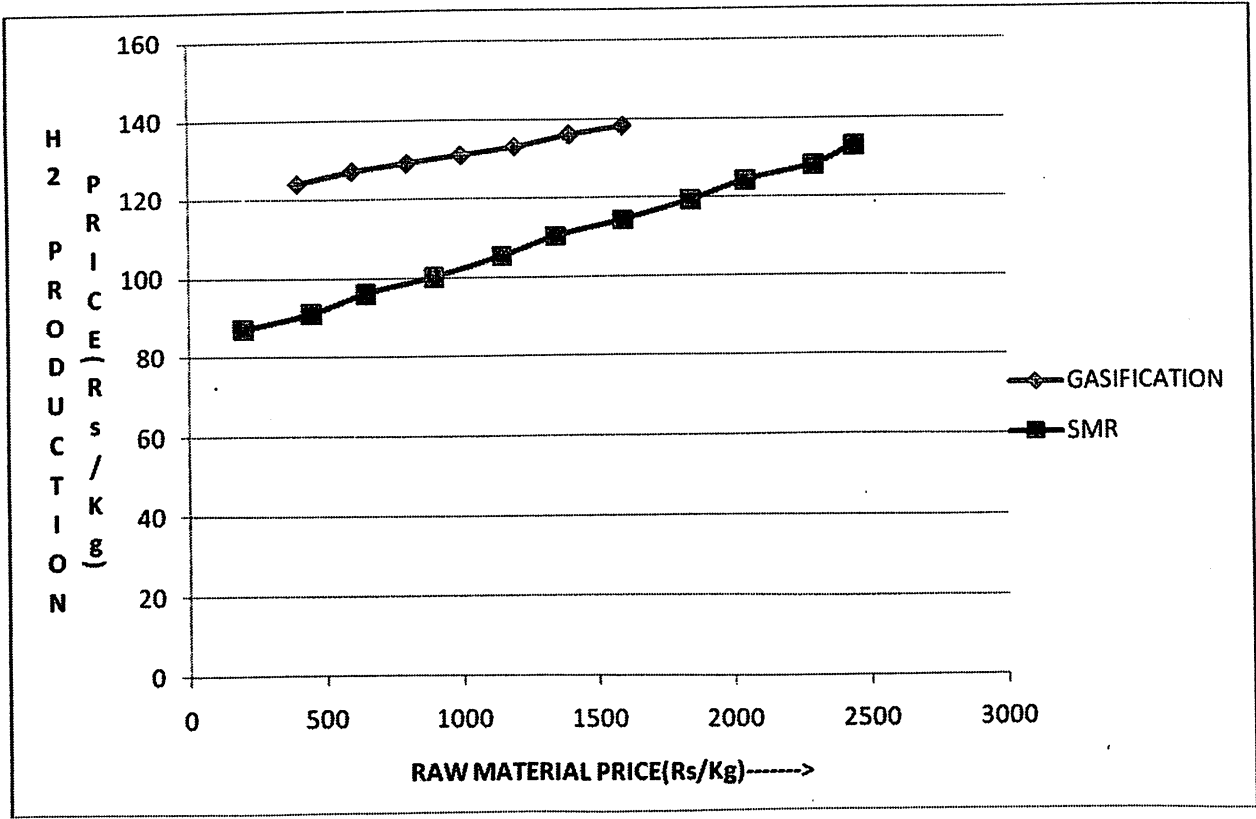


Figure 5.8 Effect of increase in price of feed stock

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The thesis brings out the following conclusions:

1. For the base capacity of 150,000kg hydrogen/day we did the economic analysis of hydrogen production from biomass gasification and SMR for natural gas .The estimated capital cost for the base capacity for biomass gasification was Rs 210 crore and in SMR for natural gas was Rs 111crore.

These estimated capital costs were further subdivided into more parts. For biomass gasification the estimated cost component of capital cost are as follows:

- Total equipment cost = Rs 129 crore
- Taxes = Rs 16 crore
- Overhead field construction = Rs 26 crore
- Engineering cost = Rs 13 crore
- Contingencies = Rs 13 crore
- Working capital = Rs 26 crore

For SMR process the estimated cost component of capital cost are as follows:

- Total equipment cost = Rs 68 crore
- Taxes = Rs 13 crore
- Overhead field construction = Rs 14 crore
- Engineering cost = Rs 6 crore
- Contingencies = Rs 6 crore
- Working capital = Rs 13 crore

2. The estimated total manufacturing cost for the base capacity for biomass gasification was Rs 647 crore and in SMR for natural gas was Rs 518 crore. This manufacturing cost was further subdivided in the different costs for the base capacity of 150,000 kg hydrogen/day. The major part of manufacturing cost for biomass gasification of Rs 196 crore for power i.e. 30% of manufacturing cost and Rs125 crore for maintenance cost i.e. 20% of the manufacturing cost.

In the same way the major part of manufacturing cost component for SMR process is of Rs 193 crore for power i.e. 38% of the manufacturing cost and Rs 114 crore for feed stock cost i.e. 20% of the total manufacturing cost.

3. The capital investment for base capacity 150,000 Kg H₂/day was estimated for both biomass as well as natural gas feed stocks. The estimated capital cost using biomass gasification was Rs 210 crore while the capital investment on hydrogen production using SMR of natural gas was found to be Rs 111 crore. The capital investment for plant capacities ranging between 5000 – 200000 kg/day hydrogen was estimated for both biomass gasification and SMR of natural gas routes using the equation:

$$\text{Capital costs (B)} = \text{Capital cost A (capacity of B} \backslash \text{capacity of A)}^{0.7}$$

In the capacity ranging between 5000 – 200000 Kg/day H₂ the capital investment in SMR was found to be much lower than the biomass gasification.

4. Effect of variation in plant capacity on manufacturing investment for the base capacity of 150,000 Kg hydrogen/day was estimated for both biomass as well as natural gas feed stocks. The estimated annual manufacturing cost using biomass gasification was Rs 647 crore while the manufacturing investment on hydrogen production using SMR for natural gas was found to be Rs 519 crore. In the capacity ranging between 5000 – 200000 Kg H₂/day the total manufacturing investment is less in biomass gasification and for the capacity of 50000 Kg H₂/day the manufacturing amount is equal for both the processes but for capacities 100000 – 200000 Kg H₂/day the manufacturing investment is less for SMR for natural gas.

5. The effect of variation in capacity on manufacturing cost per Kg of Hydrogen for the lower capacities range between 5000 to 25000 Kg/day of hydrogen production the price is less in case of biomass gasification but for capacities range between 50000 to 200000 Kg/day of hydrogen the cost of hydrogen production is less in SMR for natural gas. From this we can also say that the gasification process is insensitive to capacities.

1: Effect of increase in price of feed stocks for base capacity 150,000 kg hydrogen/day, was estimated for both biomass gasification and SMR for natural gas. For Rs 1000/ton biomass the cost of hydrogen production from gasification was Rs 131/ kg of hydrogen and for the Rs 900/kg of natural gas the cost of hydrogen production was Rs 100/kg of

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