INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 33 (2008) 6006–6020

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Cost analysis of a thermochemical Cu–Cl pilot plant for nuclear-based hydrogen production

M.F. Orhan , I. Dincer* , G.F. Naterer

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, ON, Canada L1H 7K4

ARTICLE INFO

Article history:
Received 19 January 2008
Received in revised form
13 May 2008
Accepted 13 May 2008
Available online 30 September 2008

Keywords:
Hydrogen
Energy
Resource
Thermochemical cycle
Process heat
Nuclear
Economic analysis

ABSTRACT

This article presents an economic analysis of a Cu–Cl pilot plant with an associated parametric study. The analysis takes into account the different types of cost components such as the energy costs, operation, maintenance, fixed charges on capital investment, etc. The cost items with their percentage ranges and factors that affect accuracy and scaling are examined. Through this scaling method, the total capital investment and total cost of a Cu–Cl pilot plant are estimated by scaling against the corresponding costs of an S–I plant as presented by Brown et al. Using a six-tenths-factor rule (scaling method) with a capacity factor of 0.6, the fixed-capital investment and product cost of a Cu–Cl pilot plant are roughly estimated at about US$27.5 M and US$4.6 M for a plant capacity of 5 tons of hydrogen per day, which could be higher due to yet unforeseen factors and costs, not currently available with existing information about the Cu–Cl cycle. The fixed-capital investment and total product cost correspond to the operating and maintenance costs of the plant, respectively. The sensitivity studies show that the costs vary significantly with the size of pilot plant capacity, percentages of cost components and the capacity factor. The parametric studies with variable plant capacities, approximations and capacity factors are performed and results are illustrated in this article. Numerous assumptions and approximations have been used in this paper, in absence of actual equipment cost data for the Cu–Cl cycle. Therefore, the results of this paper cannot be generalized for other specific cases and scenarios.

1. Introduction

Hydrogen is widely believed to be world's next-generation fuel, since it is a clean energy carrier that is environmentally benign and sustainable, compared to fossil fuels. Hydrogen demand is expected to increase rapidly over the next decade. Many researchers worldwide are trying to develop new technologies for producing hydrogen that are more cost effective, without greenhouse gas emissions. Thermochemical cycles are one of the most promising methods in these regards. Reducing the cost and environmental impact of hydrogen production is a key challenge facing the future transition to a hydrogen economy. A promising method of hydrogen production is thermochemical water decomposition with a copper–chlorine (Cu–Cl) cycle to split water into hydrogen and oxygen through intermediate copper and chlorine compounds. These chemical reactions would form a closed internal loop that recycles all chemicals on a continuous basis, without emitting any greenhouse gases externally to the atmosphere.

Nuclear heat could be harnessed for large-scale hydrogen production with a thermochemical cycle. The Cu–Cl cycle could be potentially coupled with nuclear reactors to achieve higher

* Corresponding author.
E-mail addresses: mehmet.orhan@uoit.ca (M.F. Orhan), ibrahim.dincer@uoit.ca (I. Dincer), greg.naterer@uoit.ca (G.F. Naterer).
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2008.05.038

efficiencies and lower costs of hydrogen production than any other conventional technology. However, scaling up from small test tube and lab-scale experiments to larger pilot or commercial scales of hydrogen production requires an economic analysis to determine the overall viability of a thermochemical pilot plant. This article performs an economic analysis of a Cu–Cl pilot plant, including capital costs, administrative salaries, product-distribution costs and so forth.

Determination of the necessary investment and capital costs is an important step before construction of a pilot plant for any industrial process. The total investment for any process consists of the fixed-capital investment for the physical equipment and facilities in the plant, plus the working capital for cash flow that must be available to pay salaries, maintain inventory, and handle other special items requiring a direct cash outlay. Therefore, detailed consideration should be given to the analysis of costs in an industrial design process, as it involves capital costs, manufacturing costs, and general expenses such as income taxes. It is important to have capital cost estimates that are as accurate as possible to have a good understanding of the economic feasibility of the project. Also, it is important to use consistent estimation techniques so that different alternatives can be compared on the same basis, and comparisons can be made between projects. This article has these two objectives; reasonable accuracy (despite limited actual data available for a Cu–Cl pilot plant) and consistency of comparisons. Thus, in order to obtain as accurate as possible the overall cost, we must take into consideration the factors of price fluctuations, company policies, governmental regulations, etc., as they affect the investment and production costs.

The total equipment cost is one of the major costs involved in any chemical plant. Generally, standard types of tanks, reactors, or other equipment are used, and a substantial reduction in cost can be made by utilizing idle equipment, or by purchasing used equipment. If new equipment is required, several independent quotations are normally obtained from different manufacturers. Prices may vary widely from one vendor to another and over time. This fluctuation factor must be considered when the capital cost is determined. Up-to-date prices and fluctuations are important factors in the cost analysis.

Different policies of individual companies have a direct impact on costs. For example, there may be strict safety regulations and these must be met in every aspect. Accounting procedures and methods for determining the depreciation costs vary among different companies. The company policies with respect to labor unions should also be considered, because these will affect overtime labor charges and the type of work the operators or other employees can perform. Labor-union policies may even affect the amount of wiring and piping that can be used on a piece of equipment, before it is brought into the plant. Thus, they may have a direct effect on the total cost of installed equipment. Another important factor in costs is the fraction of total available time, during which a process is in operation. When equipment stands idle for an extended period of time, the labor costs are generally low. However, other costs such as those for maintenance, protection and depreciation continue even though the equipment is not in active use.

The operating time, rate of production and sales demand are closely inter-related. An ideal plant should operate under a time schedule that gives the maximum production rate, while maintaining the highest profitability. In this manner, the total cost per unit of production is kept near a minimum because the fixed costs are utilized to the fullest extent. This ideal method of operation is based on the assumption that the sales demand is sufficient to absorb all of the material produced. If the production capacity of the process is greater than the sales demand, the operation can be carried out at a reduced capacity, or periodically at full capacity.

Federal or local governments may have regulations and restrictions that have a direct effect on industrial costs. Some examples are import and export tariff regulations, restrictions on permissible depreciation rates and income-tax regulations. Therefore, governmental policies with respect to capital gains, effects of governmental regulations on cost and gross earnings tax should be included when costs are determined. Each company has its own method for meeting these regulations, but changes in the laws or economic conditions of the company require constant surveillance, if minimal costs are to be maintained.

A detailed presentation of data and techniques for preliminary capital cost estimation and a cost estimating technique (called the 'module technique') have been presented by Guthrie [2]. This technique was used by Brown et al. [4] to estimate the capital and operation costs of a commercial plant for thermochemical hydrogen production based on the sulfur–iodine (S–I) cycle. Atikol and Aybar [8] developed a method that utilized local conditions for estimating the unit production cost of fresh water for new RO systems to be constructed. Some of the most important cost components were the capital cost, electricity cost and the costs related to maintenance, membrane replacement and chemicals [8].

The feasibility of using biomass to provide electricity was investigated and evaluated over a capacity ranging from 5 to 50 MW, taking into account the total capital investments, revenues from energy sales, total operating costs and logistical costs (Caputo et al. [9]). A cost analysis based on the methods of thermoeconomics was applied to a 300 MW pulverized coal-fired power plant, located in Yiyang (Hunan Province, China) by Zhang et al. [10]. This method, as derived from the second law of thermodynamics, can provide a detailed analysis for costs of the power plant, as well as the effects of different operating conditions and parameters on the performance of each individual component [10].

An economic analysis of a modified dry grind ethanol process, with recycling of pretreated and enzymatically hydrolyzed distillers' grains, was studied by Perkis et al. [13]. An exergoeconomic analysis of a novel process to generate electricity and hydrogen was presented by Tsatsaronis et al. [14]. Coal and high-temperature heat were used as input energy sources to the process [14].

A thermoeconomic optimization method that systematically generates the best configurations of an integrated system was presented by Palazzi et al. [15]. In their methodology, the energy flows are computed by conventional process simulation software. The system is integrated using pinch-based methods that rely on optimization techniques. This defines the minimum amount of energy required and it sets the basis to design an ideal heat exchanger network. A thermoeconomic method is then used to compute the integrated system performances, sizes and costs [15].

The monthly averaged global solar radiation and sunshine duration data were utilized by Rehman et al. [16] to calculate the cost of solar energy generated with PV panels. The analysis also includes renewable energy production and economical assessment of a 5 MW installed capacity photovoltaic-based plant for electricity generation. The study utilizes RetScreen software to compute the energy production and economical assessment [16]. A generalized modeling tool was used by Rubin et al. [17] to estimate and compare the emissions, efficiency, resource requirements and current costs of fossil fuel power plants with CCS on a systematic basis [17].

The capital and operating costs associated with a small package plant, MBR, for small-scale domestic usage has been appraised by Fletcher et al. [19]. The analysis proceeded through consideration of the estimated amortized capital costs of the plant's individual components and their installation, coupled with the operating costs, largely based on energy demand and residuals management. Energy demand was calculated from the aeration and pumping costs, with aeration based on a combination of empirical relationships for membrane aeration and mass balances. Also, a modified Activated Sludge Model, Version 2, was used for estimating the tank size and sludge generation [19].

Historical experience curves were used by Rubin et al. [21] as the basis for estimating future cost trends for four types of electric power plants, equipped with CO_2 capture systems: pulverized coal (PC) and natural gas combined cycle (NGCC) plants with post-combustion CO_2 capture; coal-based integrated gasification combined cycle (IGCC) plants with pre-combustion capture; and coal-fired oxyfuel combustion for new PC plants [21].

The objectives of this study are to present a detailed analysis of the general methodology of cost estimation for a thermochemical pilot plant, including all cost items with their percentages, the factors that affect accuracy, and a scaling method. It also evaluates the total capital investment and the total overall cost of a Cu–Cl pilot plant with the scaling method and it compares the results for varying plant capacities and assumptions.

2. Overview of copper–chlorine cycle

Thermochemical cycles consist of a series of reactions in which water is thermally decomposed and all other chemicals are recycled. Only heat and water are consumed. Unfortunately, most thermochemical cycles require process heat at very high temperatures of at least 850–900 °C. Recently, Atomic Energy of Canada Limited and the U.S. Argonne

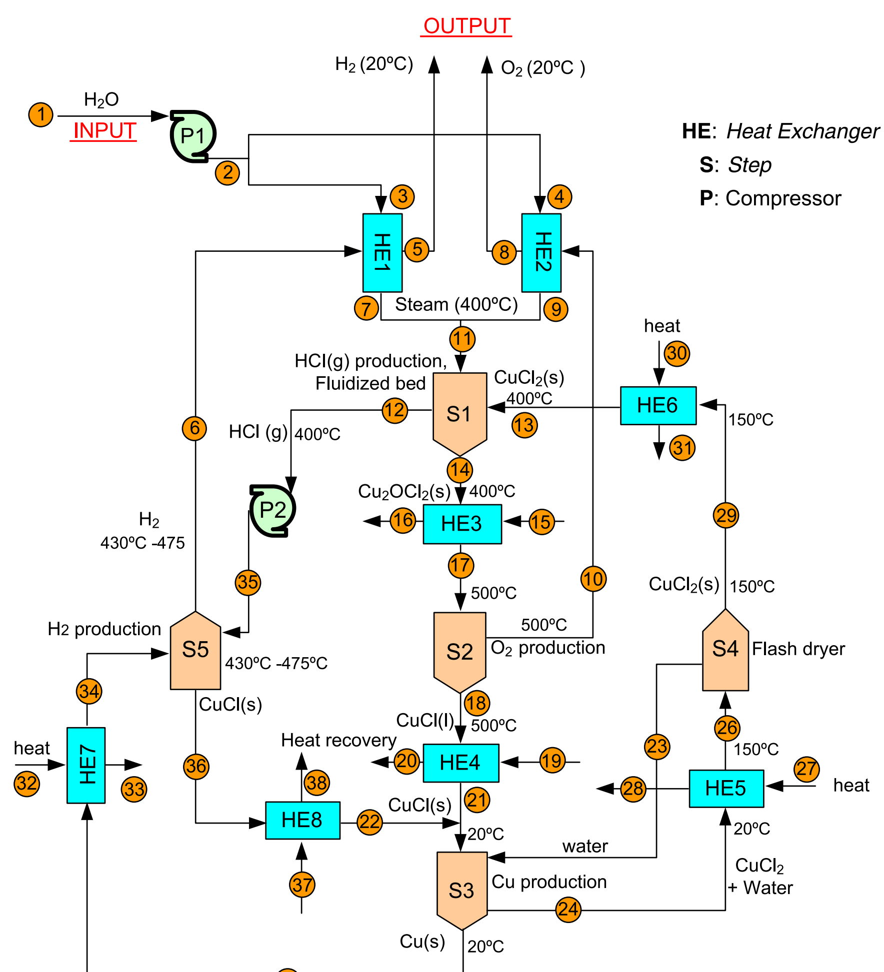

Fig. 1 – Conceptual layout of a thermochemical Cu–Cl pilot plant.

National Laboratory have been developing low temperature cycles, designed for lower temperature heat, 500–550 °C, which can be more readily integrated with nuclear reactors. For this temperature range, the copper–chlorine (Cu–Cl) cycle is the most promising cycle. Several Cu–Cl cycles have been examined in the laboratory and various alternative configurations have been identified, as well as proof-of-principle experiments that demonstrate the scientific feasibility of the processes. A preliminary assessment of the cycle efficiency demonstrates its promising potential [6].

A conceptual layout of a Cu–Cl pilot plant is illustrated in Fig. 1. The thermochemical water decomposition, potentially driven by nuclear heat with a copper–chlorine cycle, would split water into hydrogen and oxygen through intermediate copper and chlorine compounds [5]. The cycle involves five steps: (1) HCl (g) production step with equipment like a fluidized bed, (2) oxygen production step, (3) copper (Cu) production step, (4) drying step, and finally (5) hydrogen production step. A chemical reaction takes place in each step, except the drying step. These chemical reactions form a closed internal loop that recycles all of the copper–chlorine compounds on a continuous basis, without emitting any greenhouse gases externally to the atmosphere [5]. The Cu–Cl cycle is one of the most promising ways to produce hydrogen efficiently, without emitting any greenhouse gases to the atmosphere.

3. Cost analysis of a Cu–Cl pilot plant

3.1. *Analysis of the total capital investment*

Before an industrial plant can be certified into operation, investments are needed to purchase and install the necessary machinery and equipment. Land and service facilities must be obtained, and the plant must be erected complete with all piping, controls and services. In addition, it is necessary to have cash available for payment of expenses involved in the plant operation.

The capital needed for manufacturing and plant facilities is called the fixed-capital investment, whereas that necessary for the ongoing operation of the plant is termed the working capital. The sum of the fixed-capital investment and the working capital is the total capital investment. The fixed-capital portion may be further subdivided into the manufacturing fixed-capital investment and the non-manufacturing fixed-capital investment [1]. The manufacturing fixed-capital investment is the capital necessary for the installed process equipment with all auxiliaries that are needed for complete process operation. Expenses for piping, instruments, insulation, foundations and site preparation are typical examples of costs included in the manufacturing fixed-capital investment.

Fixed capital required for construction overhead, and chemical plant components that are not directly related to the process, is designated as the non-manufacturing fixed-capital investment. These plant components may include the land, building(s), administrative and other offices, warehouse(s), laboratory, transportation, shipping and receiving facilities, utility and waste-disposal facilities, machine shop(s) and other permanent parts of the plant. The construction overhead cost consists of field-office and supervision expenses, engineering expenses, miscellaneous construction costs, contractor's fees and contingencies. In some cases, construction overhead is subdivided between manufacturing and non-manufacturing fixed-capital investments [1].

The working capital for an industrial plant consists of the total cash invested in:

- raw materials and supplies carried in stock;
- finished products in stock and semifinished products in the process of being manufactured;
- accounts receivable;
- cash kept on hand for monthly payment of operating expenses such as salaries, wages, and raw material purchases;
- accounts payable; and
- taxes payable.

The ratio of the working capital to total capital investment varies with different companies, but most chemical plants use an initial working capital of between 10% and 20% of the total capital investment. This percentage may increase up to 50% or more for companies producing products of seasonal demand, because of the large inventories that must be maintained for

Table 1 – List of fixed-capital investment items for a chemical plant

Chemical processing	Site development	Industrial buildings	Off-site facilities	Project indirect costs
-Equipment Cost	-Land, surveys and fees	-Administration office	-Steam generation and distribution system	-Construction overhead
-Installation	-Dewatering and drainage	-Laboratory	-Power generation and distribution system	-Freight, insurance, taxes
-Piping	-Site clearing	-Medical	-Pollution control facilities	-Engineering and supervision costs
-Concrete	-Excavation	-Warehouses	-Yard lighting and communication	-Contingencies
-Instrumentation	-Grading	-Maintenance shops	-Receiving, storage and shipping	-Contract fee
-Controls	-Underground sewers	-Garages		
-Electrical equipment	-Piling	-Cafeterias		
-Other materials	-Roads, walkways and paving	-Steel structures		
	-Parking lots			
	-Landscaping			
	-Fencing			
	-Fire protection facilities			

appreciable periods of time. Table 1 summarizes the main items needed in a new facility, in order to provide a complete assessment of the total fixed-capital investment.

An estimate of the capital investment for a process may vary from a rough design estimate, based on little information except the size of the proposed project, to a detailed estimate prepared from complete drawings and specifications. Between these two extremes of capital investment estimates, there can be numerous other estimates that vary in accuracy, depending on the stage of development of the project. These estimates are called by various names. The American Association of Cost Engineers has proposed the following names:

1. Ratio estimate: based on similar previous cost data; accuracy of the estimate is about ±30%.
2. Factored estimate: based on knowledge of major items of equipment; accuracy of the estimate is about ±30%.
3. Scope estimate: based on sufficient data to permit an estimate to be budgeted; accuracy of the estimate is about ±20%.
4. Project control estimate: based on almost complete data, but still before the completion of drawings and specifications; accuracy of the estimate within ±10%.
5. Contractor's estimates: based on complete engineering drawings, specifications and site surveys; accuracy of the estimate is about ±5%.

In this study, for a thermochemical Cu–Cl pilot plant the following information is not currently available: complete engineering drawings, specifications, site surveys that are required for contractor's estimates, complete data that are required for a project control estimate and certain detailed data for a scope estimate. Therefore, this article will use a ratio estimate and approximate the equipment cost by scaling down the cost that was previously reported by Brown et al. [4] for a commercial S–I plant. The equipment cost for an S–I plant with 790 tons/day of hydrogen production capacity was $125 million. A rough Cu–Cl estimate is based on a logarithmic relationship known as the six-tenths-factor rule, which yields a result if the new piece of equipment is similar to one of another capacity for which cost data are available [1]. According to this rule, if the cost of a given unit at one capacity is known, the cost of a similar unit with "X" times the capacity of the first unit is approximately $(X)^{0.6}$ times the cost of the initial unit, i.e.

$$\text{Cost of equipment.a} = \text{cost of equipment.b} \times \left(\frac{\text{capacity of equipment.a}}{\text{capacity of equipment.b}}\right)^{0.6}$$

The application of the 0.6 rule of thumb for new purchased equipment is an over-simplification of a key cost estimate, since the actual values of the cost capacity factor may vary from less than 0.2 to greater than 1 [1]. The 0.6 factor is used in this article as a preliminary initial estimate, from which parametric studies will be performed to determine the sensitivity to different

Table 2 – Typical variation in percentages of fixed capital investments

Component	Range (%)	Median (%)
Direct costs		
Purchased equipment	20–40	32.5
Purchased equipment installation	7.3-26	12.5
Instrumentation and controls	2.5–7	4.3
Piping (installed)	3.5–15	9.3
Electrical (installed)	2.5–9	5.8
Buildings (including services)	6–20	11.5
Yard improvements	1.5–5	3.2
Service facilities (installed)	8.1–35	18.3
Land	1–2	1.5
Indirect costs		
Engineering and supervision	4–21	13
Construction expenses	4.8–22	14.5
Contractor's fee	1.5–5	3
Contingency	6–18	12.3

Source: adapted from Ref. [1].

Table 3 – Cost comparison of fixed-capital investment components, as an average percentage of the fixed capital investment from three independent sources

Component	1	2	3
Direct costs (%)	70	70	70
Purchased equipment	23	23	23
Purchased equipment installation	9	10	9
Instrumentation and controls	3	3	3
Piping (installed)	7	9	9
Electrical (installed)	4	2	2
Buildings (including services)	8	6	7
Yard improvements	2	3	5
Service facilities (installed)	13	13	11
Land	1	1	1
Indirect costs (%)	30	30	30
Engineering and supervision	9	8	10
Construction expenses	10	9	8
Contractor's fee	2	4	3
Contingency	9	9	9
Fixed-capital investment (%)	100	100	100

Source: adapted from Ref. [1].

Table 4 – Percentages of cost components for a thermochemical CuCl pilot plant

Component	Percentage
Purchased equipment	23
Purchased equipment installation	9
Instrumentation and controls	3
Piping	9
Electrical	2
Buildings	7
Yard improvements	5
Service facilities	11
Land	1
Total direct costs	70
Engineering and supervision	8
Construction expenses	9
Contractor's fee	4
Contingency	9
Total indirect costs	30
Fixed-capital investment	100

factors. After estimating the equipment cost, the total capital investment, total product cost and the cost of other components will be determined accordingly.

Table 2 summarizes the typical variations in component costs, as percentages of a fixed-capital investment for multi-process grass-roots plants or large battery-limit additions. A grass-roots plant is defined as a complete plant erected on a new site. The total investment includes all costs of land, site development, battery-limit facilities and auxiliary facilities. A geographical boundary defining the coverage of a specific project is a battery limit. Usually this encompasses the manufacturing area of a proposed plant or new addition, including all process equipment, but excluding the provision of storage, utilities, administrative buildings or auxiliary facilities, unless otherwise specified. Normally, this excludes the site preparation so that it may be applied to the extension of an existing plant. Table 3 shows a cost comparison of fixed-capital investment components, as an average percentage of the fixed-capital investment from three independent sources [1]. Based on this information, the component cost percentages are obtained as follows (see Table 4).

3.2. Cost analysis of the total product cost

In addition to the capital investment, other important costs are related to operating the plant and selling the products. These costs can be grouped under a general category of the total product cost. This total product cost generally involves the manufacturing costs and general expenses. Manufacturing costs are also known as the operating or production costs. Fig. 2 shows a detailed checklist with typical costs involved in chemical processing operations. The total

Fig. 2 – Individual and total product costs for a typical chemical plant [1].

Table 5 – Estimation of total product cost

Component	Basis
I Manufacturing cost	Production cost + fixed charges + plant overhead costs
A. Direct production costs	About 60% of total product cost
1. Raw materials	10–50% of total product cost
2. Operating labor	10–20% of total product cost
3. Direct supervisory and clerical labor	10–25% of operating labor
4. Utilities	10–20% of total product cost
5. Maintenance and repairs	2–10% of fixed capital investment
6. Operating supplies	0.5–1% of fixed capital investment
7. Laboratory charges	10–20% of operating labor
8. Patents and royalties	0–6% of total product cost
B Fixed charges	10–20% of total product cost
1. Depreciation	10% of fixed capital investment + 2–3% of building
2. Local taxes	1–4% of fixed capital investment
3. Insurance	0.4–1% of fixed capital investment
4. Rent	8–10% of value of rented land and buildings
C Plant overhead costs	5–15% of total product cost
II General expenses	Administrative costs + distribution and selling costs + research and development costs
A. Administrative costs	2–5% of total product cost
B. Distribution and selling costs	2–20% of total product cost
C. Research and development costs	5% of total product cost
D. Financing (interest)	0–7% of total capital investment
III Total product cost	Manufacturing cost + general expenses

Source: Adapted from Ref. [1].

product costs are commonly calculated by one of following three ways: daily basis, unit-of-product basis or annual basis. The annual cost basis is often advantageous for the following reasons:

1. The effect of seasonal variations is smoothed out.
2. Plant on stream time and the equipment operating factor are considered.
3. It permits a more rapid calculation of operating costs at less than full capacity.
4. It provides a convenient way of including infrequent but large expenses, such as the annual turnaround costs in a refinery.

Table 5 shows a summary of the approximated total product cost, with individual components and their percentages. The

Table 6 – Cost item percentages for the Cu–Cl pilot plant

Component	Basis
Raw materials	10% of total product cost
Operating labor	10% of total product cost
Direct supervisory and clerical labor	10% of operating labor
Utilities	10% of total product cost
Maintenance and repairs	3% of fixed capital investment
Operating supplies	0.7% of fixed capital investment
Laboratory charges	10% of operating labor
Patents and royalties	0% of total product cost
Depreciation	2% of fixed capital investment + 2% of building
Local taxes	1% of fixed capital investment
Insurance	0.4% of fixed capital investment
Rent	8% of value of rented land and buildings
Plant overhead costs	5% of total product cost
Administrative costs	2% of total product cost
Distribution and selling costs	2% of total product cost
Research and development costs	5% of total product cost
Financing (interest)	1% of total capital investment
Total product cost	100%

Table 7 – Fixed-capital investment for a Cu–Cl pilot plant with different production capacities

Component	Hydrogen production capacity		
	3 tons/day	5 tons/day	7 tons/day
Purchased equipment (23%)	4,652,900	6,322,700	7,737,200
Purchased equipment installation (9%)	1,820,700	2,474,100	3,027,600
Instrumentation and controls (3%)	606,900	824,700	1,009,200
Piping (9%)	1,820,700	2,474,100	3,027,600
Electrical (2%)	404,600	549,800	672,800
Buildings (7%)	1,416,100	1,924,300	2,354,800
Yard improvements (5%)	1,011,500	1,374,500	1,682,000
Service facilities (11%)	2,225,300	3,023,900	3,700,400
Land (1%)	202,300	274,900	336,400
Total direct cost (70%)	$14,161,000	$19,243,000	$23,548,000
Engineering and supervision (8%)	1,618,400	2,199,200	2,691,200
Construction expense (9%)	1,820,700	2,474,100	3,027,600
Contractor's fee (4%)	809,200	1,099,600	1,345,600
Contingency (9%)	1,820,700	2,474,100	3,027,600
Total indirect cost (30%)	$6,069,000	$8,247,000	$10,092,000
Fixed-capital investment (100%)	$20,230,000	$27,490,000	$33,640,000

total product costs can be categorized into two sub-groups: manufacturing costs and general expenses. In manufacturing costs, all expenses directly connected with the manufacturing operation or the physical equipment in the plant itself are included in the manufacturing costs. These expenses are divided into three classifications as follows:

1. Direct production costs include expenses directly connected with the manufacturing operation. This type of cost involves expenditures for raw materials, direct operating labor, supervisory and clerical labor directly connected with the manufacturing operation, plant maintenance and repairs, operating supplies, power, utilities, royalties and catalysts.
2. Fixed charges are expenses that remain nearly constant from year to year and do not vary widely with changes in the production rate. Depreciation, taxes, insurance and rent require expenditures that can be classified as fixed charges.
3. Plant overhead costs include the various services; general plant maintenance and overhead; payroll overhead including pensions, vacation allowances, social security and life insurance; packaging, property protection, plant superintendence, warehouse and storage facilities and special employee benefits.

General expenses are also involved in a plant's operations, in addition to the manufacturing costs. These general expenses may be classified as: (1) administrative expenses, (2) distribution and marketing expenses, (3) research and development expenses and (4) financing expenses.

1. Administrative expenses include costs for executive and clerical wages, office supplies, engineering and legal expenses, upkeep on office buildings and general communications.
2. Distribution and marketing expenses are costs incurred in the process of selling and distributing the various products. These costs include expenditures for materials handling, containers, shipping, sales offices and advertising.
3. Research and development expenses are incurred for technological advancement with facilities in the pilot plant. These costs refer to salaries, wages, special equipment, research facilities and consultant fees related to developing new processes and technologies.
4. Financing expenses include the extra costs involved in procuring the funds needed for capital investment. Financing expenses include the interest on borrowed money, which is sometimes listed as a fixed charge.

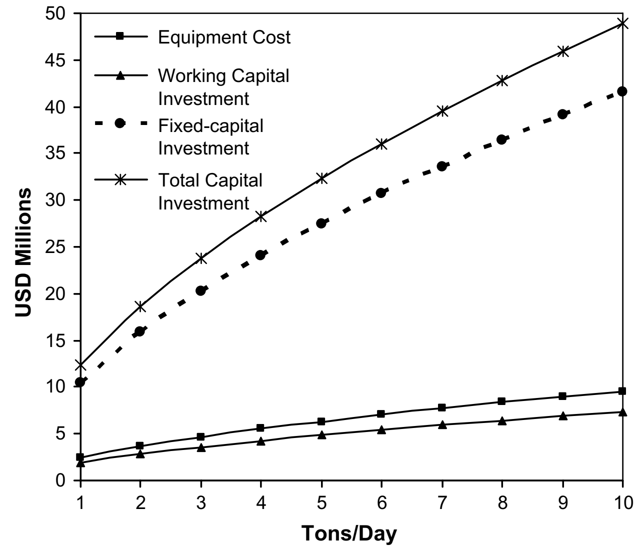

Fig. 3 – Cost items of a Cu–Cl pilot plant with a 0.6 cost capacity factor.

Table 6 shows the component cost percentages that are approximated for the thermochemical Cu–Cl pilot plant, based on the ranges given in Table 5.

4. Results and discussion

The results for the fixed-capital investment and its components are given in Table 7. This table shows the purchased equipment, installation, instrumentation and controls, piping, electrical, buildings, yard improvements, service facilities and land. These give the total direct cost of about 70% of the fixed-capital investment. The remaining 30% of the fixed-capital investment is indirect costs, engineering and supervision, construction expenses, contractor's fees and contingencies.

Using a scaling method to estimate the purchased equipment cost by using the six-tenths-factor rule and scaling down the equivalent equipment cost of a commercial S–I plant [4], the fixed-capital investment and other items are estimated from the purchased equipment cost by assuming the typical percentages that were given in Table 4. As mentioned earlier, the working capital investment is about 15% of the total capital investment and the fixed-capital investment is 85%. By using these percentages and results for the fixed-capital investment from Table 7, the resulting total capital investment and working capital investment are calculated and

Table 8 – Total capital investment for a Cu–Cl pilot plant with different production capacities

Component	Basis	Hydrogen production capacity		
		3 tons/day	5 tons/day	7 tons/day
Fixed-capital investment	85% of total capital investment [1]	20,230,000	27,490,000	33,640,000
Working capital investment	15% of total capital investment [1]	3,570,000	4,851,176	5,936,470
Total capital investment (100%)		$23,800,000	$32,341,176	$39,576,470

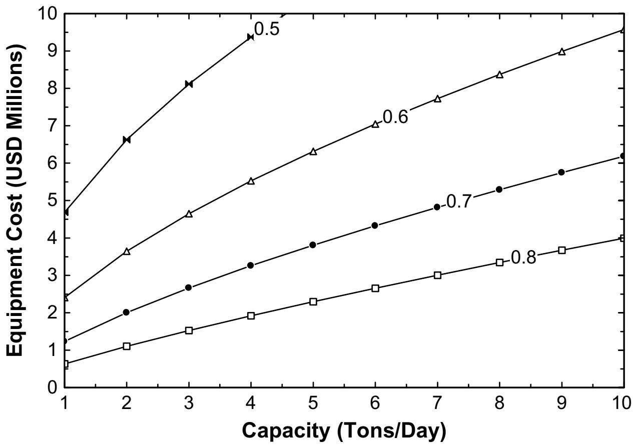

Fig. 4 – Variation of equipment cost with plant capacity and capacity factor.

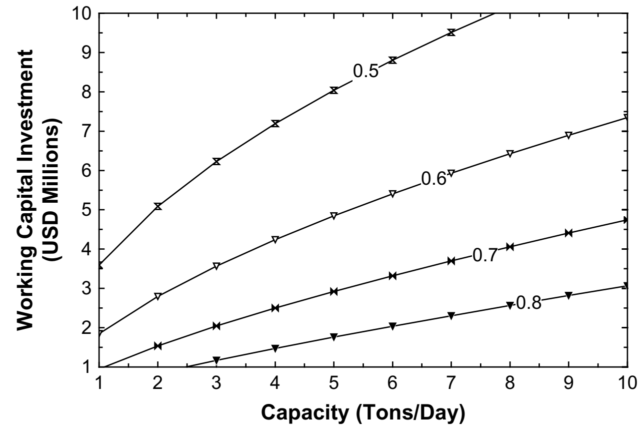

Fig. 6 – Variation of working capital investment with plant capacity and capacity factor.

presented in Table 8. The results in Tables 7 and 8 are determined from equipment costs that are calculated based on a capacity factor of 0.6.

Fig. 3 shows the variations of equipment cost, working capital investment, fixed-capital investment and the total capital investment, with a capacity factor of 0.6. The equipment cost and working capital investment curves are very similar. They change in the range of \$2–9 million, while the plant capacity varies from 1 to 10 tons of hydrogen per day. The fixed-capital investment, which is 70% of the total capital investment, varies in the range of \$10–40 million, while the total capital investment lies in the range of \$12–49 million, when changing the plant capacity from 1 to 10 tons of hydrogen per day. From the results in Fig. 3, the cost per unit of capacity decreases with capacity until some maximum capacity is reached. Thus, most of the chemical plant operates at the maximum size, suggested by the costing algorithms. If the maximum capacity is reached, multiple parallel units are required.

All costs vary with the capacity factor, as well as the plant capacity. Fig. 4 shows that equipment cost changes considerably when altering the capacity factor. For example, the equipment cost for a plant capacity of 3 tons/day is about \$1 million at a capacity factor of 0.8, but it is about \$8 million at a capacity factor of 0.5 for the same plant capacity. This variation is even higher at the higher plant capacity. The increasing rates of curves in Fig. 4 are not equal to each other. The economic projections are more realistic at large plant capacities above 5–10 tons per day, since the overall economics of thermochemical plants becomes increasingly unfavourable at smaller scales, where electrolysis or other methods become more cost competitive to produce small quantities of hydrogen.

The variation of fixed, working and total capital investments with plant capacity and capacity factor are illustrated in Figs. 5–7, respectively. In these three figures, the variation of costs increases, when decreasing the capacity factor. In other words, the rate of increasing costs is reduced with a higher capacity factor. For example in Fig. 6, at a capacity factor of 0.7, the range of working capital investment varies from \$1 to 4.5 million, but for the capacity factor of 0.6, it lies between \$2 and 7 million.

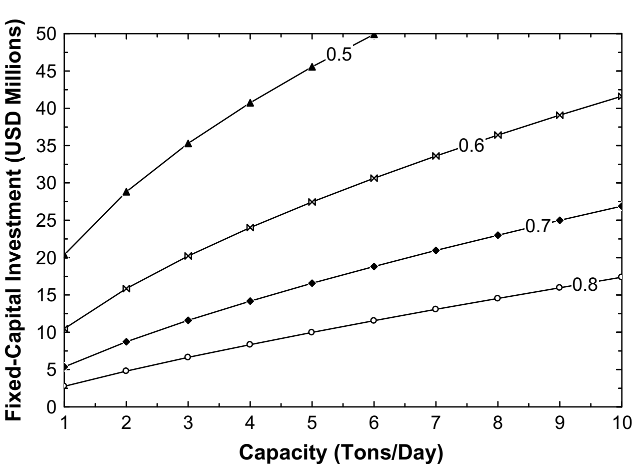

Fig. 5 – Variation of fixed-capital investment with plant capacity and capacity factor.

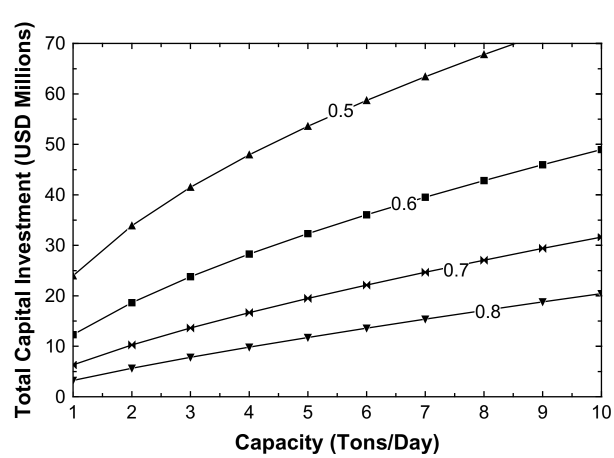

Fig. 7 – Variation of total capital investment with plant capacity and capacity factor.

Table 9 – Estimated annual total product cost for the Cu–Cl pilot plant

Component	Basis	Annual cost		
		3 tons/day	5 tons/day	7 tons/say
Raw materials	10% of total product cost	349,500	460,600	554,800
Operating labor	10% of total product cost	349,500	460,600	554,800
Direct supervisory and clerical labor	10% of operating labor	34,950	46,060	55,480
Utilities	10% of total product cost	349,500	460,600	554,800
Maintenance and repairs	3% of fixed capital investment	606,400	823,900	1,008,000
Operating supplies	0.7% of fixed capital investment	141,500	192,200	235,200
Laboratory charges	10% of operating labor	34,950	46,060	55,480
Patents and royalties	0% of total product cost	0	0	0
Depreciation	2% of fixed capital investment + 2% of building	442,700	587,700	710,600
Local taxes	1% of fixed capital investment	202,100	274,600	336,100
Insurance	0.4% of fixed capital investment	80,850	109,900	134,400
Rent	8% of value of rented land and buildings	175,900	175,900	175,900
Plant overhead costs	5% of total product cost	174,800	230,300	277,400
Administrative costs	2% of total product cost	69,900	92,120	111,000
Distribution and selling costs	2% of total product cost	69,900	92,120	111,000
Research and development costs	5% of total product cost	174,800	230,300	277,400
Financing (interest)	1% of total capital investment	237,800	323,100	395,400
Total product cost		$3,495,000	$4,606,000	$5,548,000

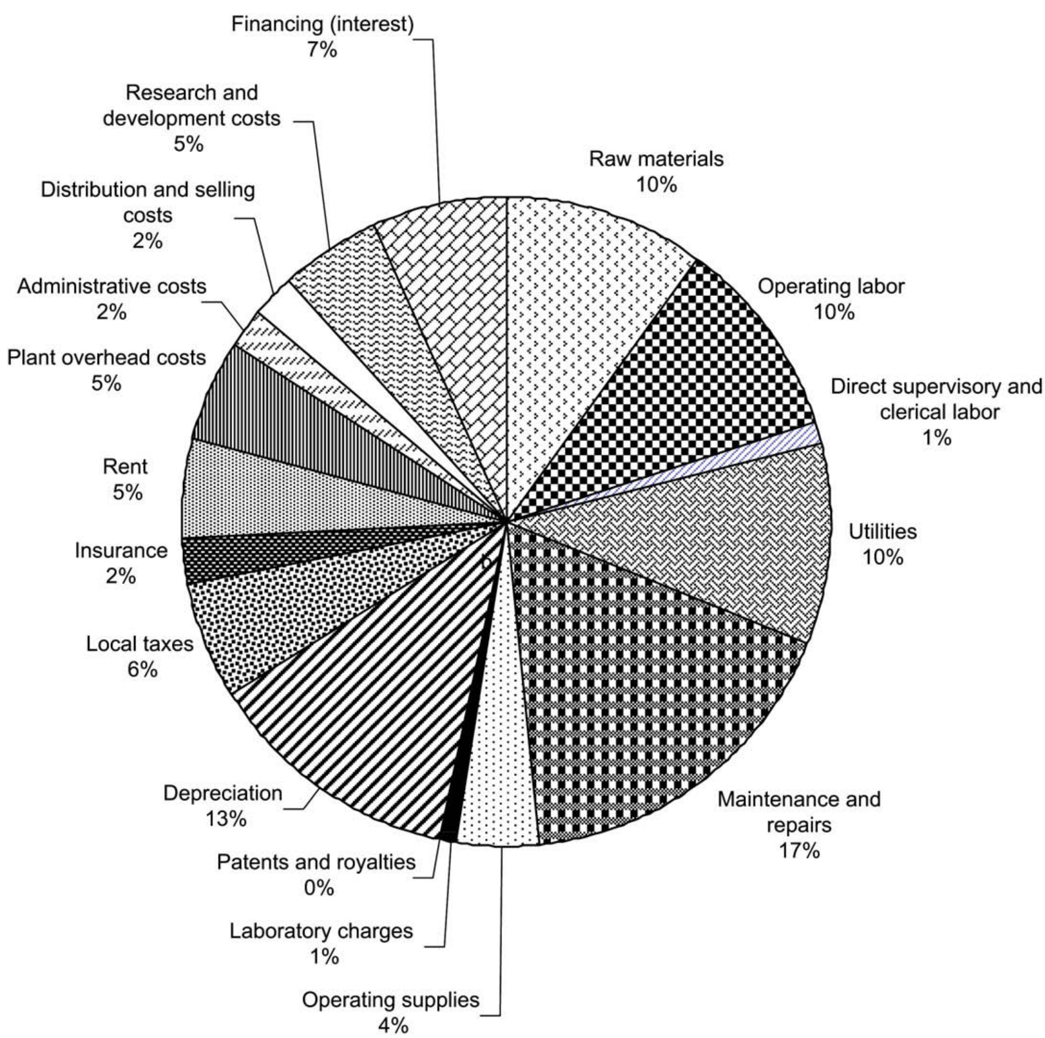

Fig. 8 – Total production cost components by percentage of total product cost.

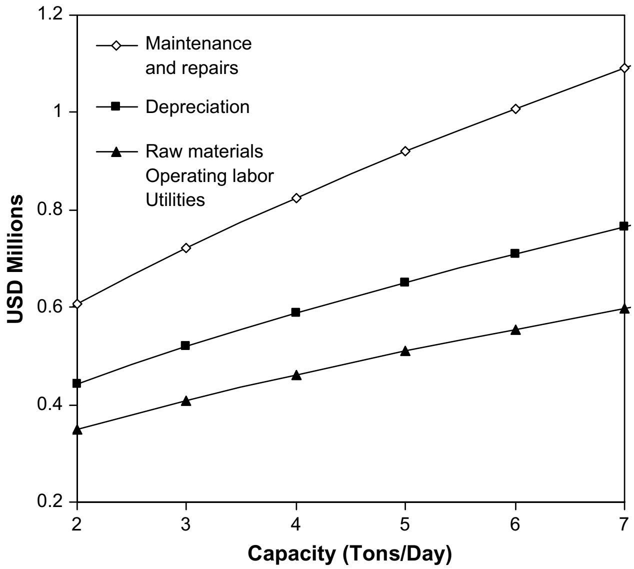

Fig. 9 – Deviation of main cost items with a plant capacity factor of 0.6.

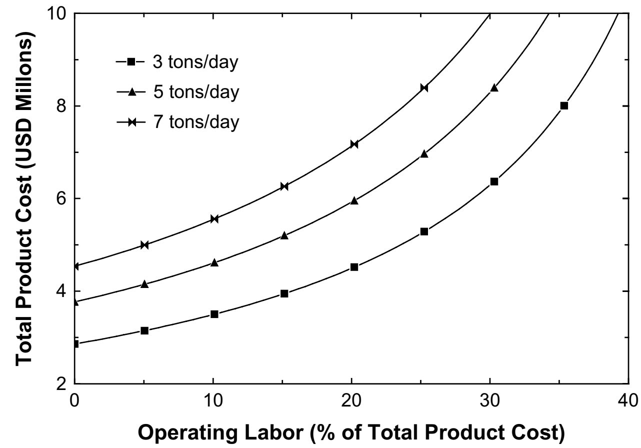

Fig. 11 – Total product cost with varying operating labor cost and plant capacity.

From Table 9, the percentages of maintenance and repairs, operating supplies, depreciation, local taxes, insurance, rent and financing are given based on the fixed-capital investment, building, land and total capital investment, which were already calculated. These cost items, with percentages that are given in terms of the total capital investment, cover 54% of the total product cost. From this relation, the total product cost and the other cost items are calculated. Table 9 shows the results for the total product cost and its components based on a 0.6 capacity factor.

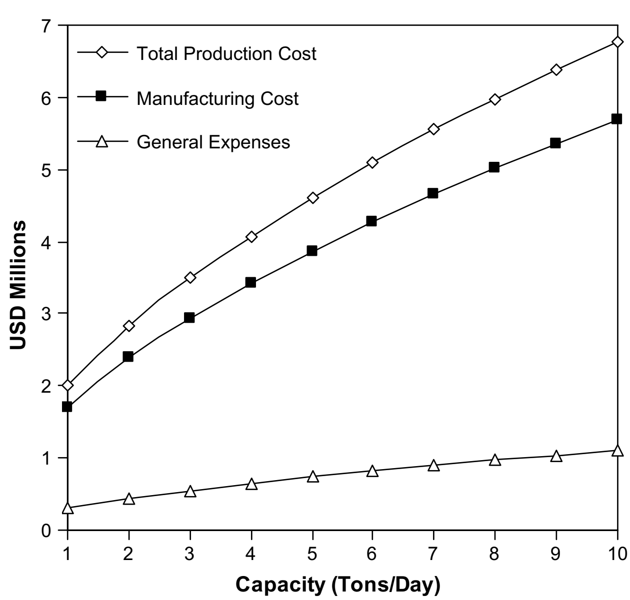

Fig. 10 – Deviation of total production cost and its components with a capacity factor of 0.6.

Fig. 8 shows the cost components by percentage of total product cost. Maintenance and repair costs cover the main portion, 17% of the product cost. Depreciation corresponds to 13%, while operations, labor, utilities and raw materials are 10% of the production cost individually. As with capital investments, the total product cost and its components vary significantly with pilot plant capacity. Fig. 9 shows the variation of the main cost items of the total production cost, such as maintenance and repairs, depreciation, raw materials, labor and utilities, assuming a capacity factor of 0.6. The variations of total production cost, manufacturing cost and general expenses are illustrated in Fig. 10. In Fig. 9, raw materials, operating labor and utilities follow the same curve and change between $0.35 and 0.5 million. The same percentage, 10% of the total product cost, is assumed for these three items. Depreciation varies from $0.45 to 0.7 million, while maintenance and repairs vary from $0.6 to 1.1 million. In Fig. 10, the curves for the total production cost and manufacturing cost are close to each other and higher than the general expenses curve. In this case, 85% of the total product

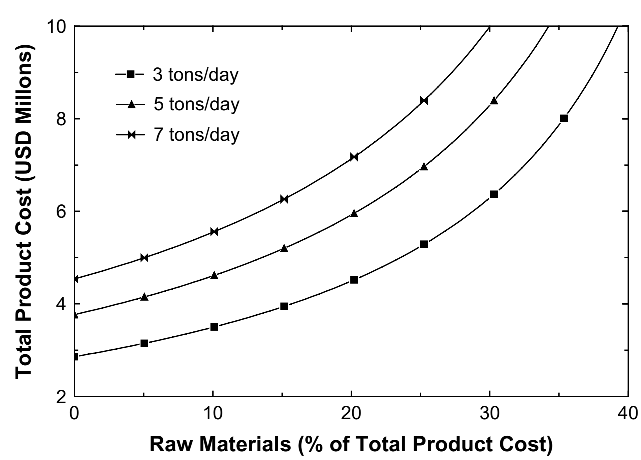

Fig. 12 – Total product cost with varying material cost and plant capacity.

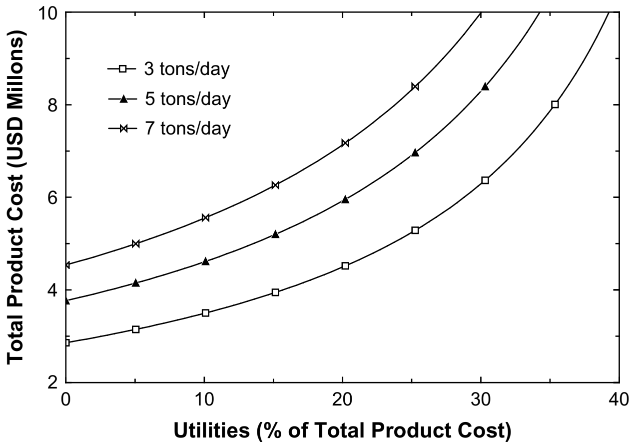

Fig. 13 – Total product cost with varying utilities cost percentage and plant capacity.

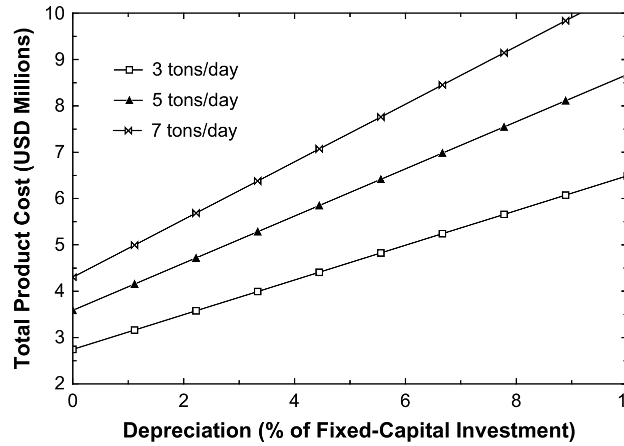

Fig. 15 – Total product cost with varying depreciation percentage and plant capacity.

cost lies in manufacturing costs and only 15% of the total product cost arises from general expenses.

One of the major factors that affect the total production cost is the percentage of each cost item. Figs. 11–13 present the variation of total product cost with different percentages of operating labor, raw materials and utilities, respectively. These three graphs follow the same trends, because the same percentage is used for operating labor, raw materials and utilities, based on 10% of the total product cost in Table 9. In these three figures, the increasing rate of total product cost rises sharply with the component percentage. The same basis of operating labor, raw materials and utilities was used as a fixed percentage of total product cost, so they are directly proportional to the total product cost.

Figs. 14 and 15 show the total product cost with different percentages of maintenance, repairs and depreciation, respectively. These two graphs follow the same trends, but different from Figs. 11–13, because their basis is a fixed percentage of the fixed-capital investment, not the total

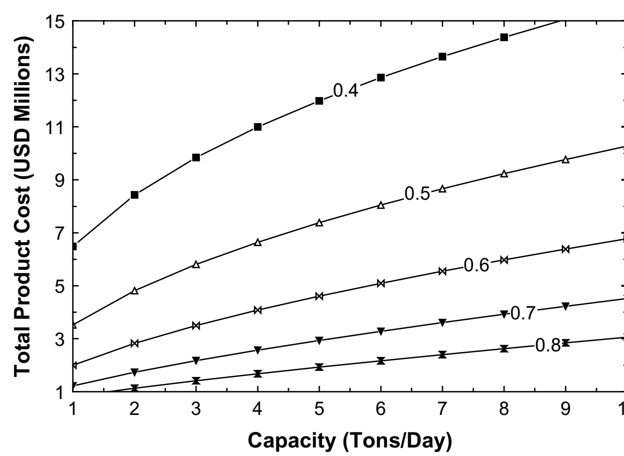

Fig. 16 – Variation of total product cost with plant capacity and capacity factor.

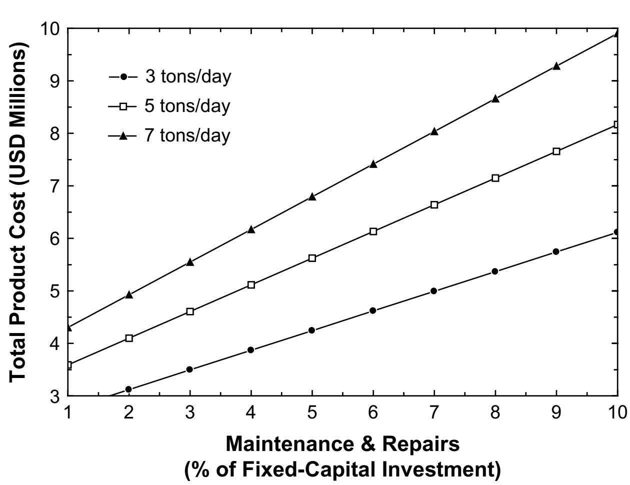

Fig. 14 – Total product cost for varying maintenance/repair cost percentage and plant capacity.

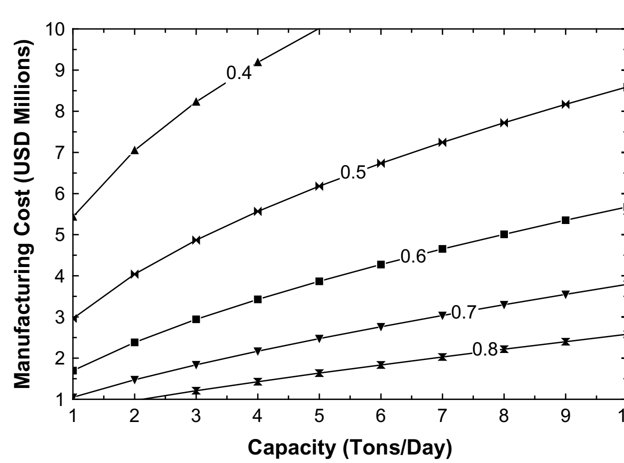

Fig. 17 – Variation of manufacturing cost with plant capacity and capacity factor.

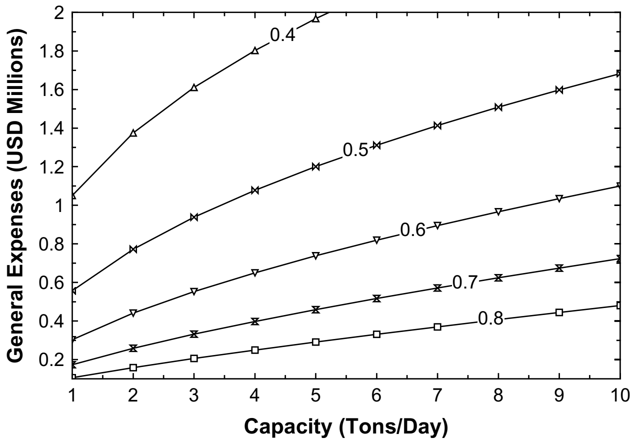

Fig. 18 – Variation of general expenses with varying plant capacity and capacity factor.

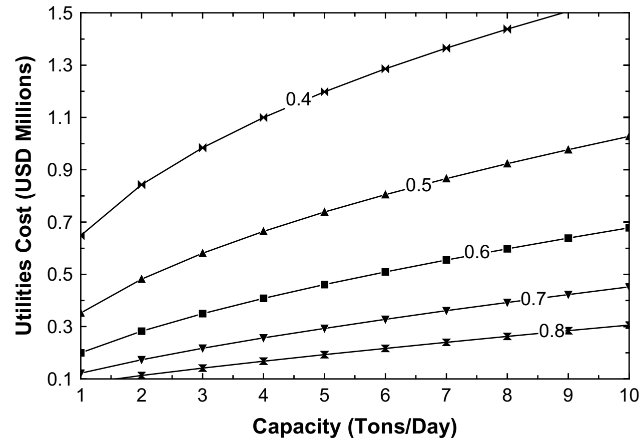

Fig. 21 – Variation of utilities cost with varying plant capacity and capacity factor.

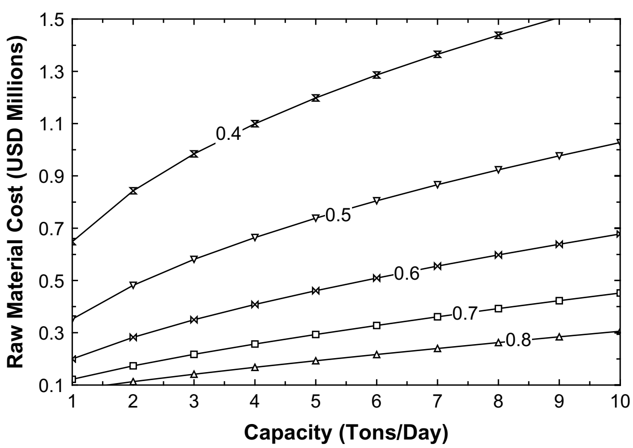

Fig. 19 – Variation of raw material cost with varying plant capacity and capacity factor.

product cost. Thus, Figs. 14 and 15 follow linear curves, while Figs. 11–13 follow logarithmic curves.

As mentioned earlier for the capital investment, the total product cost and its components also vary with the capacity factor, as well as the plant capacity. Figs. 16–23 illustrate the variation of the total product cost and its main components with varying production capacities and capacity factors. All of the figures follow a similar trend with different cost ranges. For example in Fig. 16, the cost range of the total product cost varies from $1 to 15 million, whereas in Fig. 23, the depreciation varies from $1 to 2 million. In Figs. 16–23, the costs increase with plant capacity, according to a concave down logarithmic trend. This shows that the cost of unit capacity decreases with production capacity. With an increasing capacity factor, the costs decrease. The curves for capacity factors of 0.6, 0.7 and 0.8 have close similarity, while greater variation exist for capacity factors of 0.5 and 0.4. This suggests that the capacity factor will lie between 0.6 and 0.8.

These results have illustrated the expected trends of pilot plant costs, particularly the sensitivity to various parameters

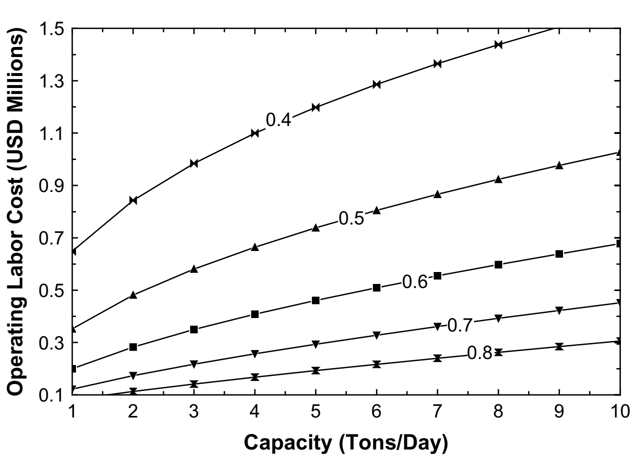

Fig. 20 – Variation of operating labor cost with varying plant capacity and capacity factor.

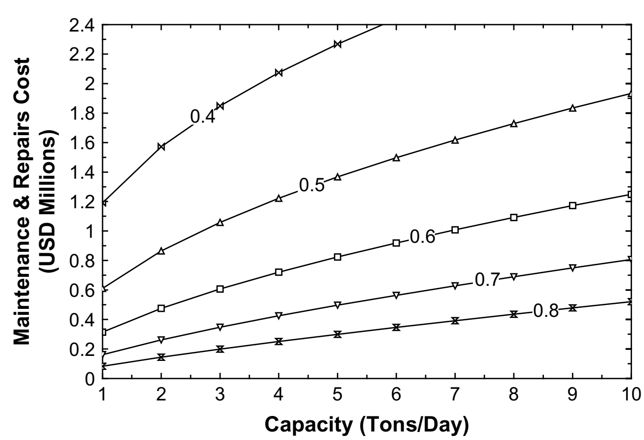

Fig. 22 – Variation of maintenance and repairs cost with plant capacity and capacity factor.

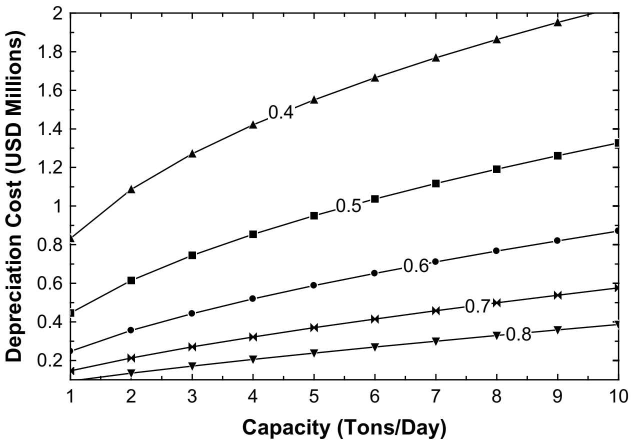

Fig. 23 – Variation of depreciation with plant capacity and capacity factor.

like the capacity factor, depreciation, maintenance and so forth. Several recent studies in the *International Journal of Hydrogen Energy* [25–29] have shown that nuclear energy is a promising source for hydrogen production by high-temperature thermochemical cycles, such as the Cu–Cl to S–I cycles. This article has presented sensitivity studies with an economic cost analysis of a Cu–Cl pilot plant, which can serve a useful basis for scaling up the technology to future pilot scale and commercial capacities of hydrogen production.

5. Conclusions

This article has investigated a cost analysis of a Cu–Cl pilot plant for hydrogen production. Determining the investment and production costs is an important step, before implementation of a plant design. Consistent estimation techniques should be used, so that alternatives can be compared on the same basis. This article has estimated the pilot plants costs, with respect to the following two objectives: accuracy and consistency. In order to be able to obtain as accurately as possible the cost estimate, various factors such as updated price fluctuations, governmental regulations, etc., should be considered, as they affect the investment and production costs. In the case of a design estimate, based on limited current information except the size of the proposed project, a logarithmic relationship known as the six-tenths-factor rule gives a preliminary approximation, for a new piece of equipment that is similar to one of another capacity, for which cost data are available. According to this rule, if the cost of a given unit at one capacity is known, the cost of a similar unit with "*X*" times the capacity of the first unit is approximately $(X)^{0.6}$ times the cost of the initial unit. By using this six-tenths-factor rule (called a scaling method), the total capital investment of a Cu–Cl pilot plant was estimated under a variety of assumptions. The sensitivity of costs with plant capacity, capacity factor and percentages of each cost component were assessed in this article. A detailed parametric study showed the variation of different costs with these three factors, as well as the relation between these factors. It was found that the costs per unit of capacity decrease with production capacity, until a maximum capacity is reached. If the maximum capacity is reached, multiple parallel units are recommended for production of hydrogen. The rising rate of costs increases with lower capacity factors.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Ontario Research Excellence Fund and Atomic Energy of Canada Limited (particularly Dr. S. Suppiah and Dr. A. Miller).

REFERENCES

[1] Peters MS, Timmerhaus KD. Plant design and economics for chemical engineers. New York,: McGraw Hill; 1968.
[2] Guthrie KM. Data and techniques for preliminary capital cost estimating. Chem Eng Prog 1969;76(6):114–42.
[4] Brown LC, Besenbruch GE, Lentsch RD, Schultz KR, Funk JF, Pickark PS, et al. High efficiency generation of hydrogen fuels using nuclear power. Technical report GA-A24285 General Atomics San Diego, CA 2003.
[5] Naterer GF. Economics of a thermochemical pilot plant for nuclear-produced hydrogen in Ontario, Technical Report. Oshawa, Ontario, Canada,: University of Ontario Institute of Technology; 2007.
[6] Lewis MA, Serban M, Basco JK. Hydrogen production at <550 °C using a low temperature thermochemical cycle Argonne National Laboratory.
[8] Atikol U, Aybar HS. Estimation of water production cost in the feasibility analysis of RO Systems. Desalination 2005; 184(1–3):253–8.
[9] Caputo AC, Palumbo M, Pelagagge PM, Scacchia F. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. Biomass Bioenergy 2005; 28(1):35–51.
[10] Zhang C, Wang Y, Zheng C, Lou X. Exergy cost analysis of a coal fired power plant based on structural theory of thermoeconomics. Energy Conversion Manage 2006;47(7–8): 817–43.
[13] Perkis D, Tyner W, Dale R. Economic analysis of a modified dry grind ethanol process with recycle of pretreated and enzymatically hydrolyzed distillers' grains. Bioresour Technol 2008;99(12):5243–9.
[14] Tsatsaronis G, Kapanke K, Marigorta AMB. Exergoeconomic estimates for a novel zero-emission process generating hydrogen and electric power. Energy 2008;33(2):321–30.
[15] Palazzi F, Autissier N, Marechal FMA, Favrat D. A methodology for thermo-economic modeling and optimization of solid oxide fuel cell systems. Appl Thermal Eng 2007;27(16):2703–12.
[16] Rehman S, Bader MA, Al-Moallem SA. Cost of solar energy generated using pv panels. Renewable Sustainable Energy Rev 2007;11(8):1843–57.
[17] Rubin ES, Chao Chen C, Rao AB. Cost and performance of fossil fuel power plants with co_2 capture and storage. Energy Policy 2007;35(9):4444–54.
[19] Fletcher H, Mackley T, Judd S. The cost of a package plant membrane bioreactor. Water Res 2007;41(12):2627–35.
[21] Rubin ES, Yeh S, Antes M, Berkenpas M, Davison J. Use of experience curves to estimate the future cost of power

plants with CO_2 capture. Int J Greenhouse Gas Control 2007; 1(2):188–97.
[25] Haseli Y, Naterer GF, Dincer I. Comparative assessment of greenhouse gas mitigation of hydrogen passenger trains. Int J Hydrogen Energy 2008;33(7):1788–96.
[26] Sakaba N, Kasahara S, Onuki K, Kunitomi K. Conceptual design of hydrogen production system with thermochemical water-splitting iodine–sulphur process utilizing heat from the high-temperature gas-cooled reactor HTTR. Int J Hydrogen Energy 2007;32(17):4160–9.
[27] Yamawaki M, Nishihara T, Inagaki Y, Minato K, Oigawa H, Onuki K, Hino R, Ogawa M. Application of nuclear energy for environmentally friendly hydrogen generation. Int J Hydrogen Energy 2007;32(14):2719–25.
[28] Sakurai M, Ueno S. Preliminary analysis of transportation cost of nuclear off-peak power for hydrogen production based on water electrolysis. Int J Hydrogen Energy 2006;31(15):2378–85.
[29] Utgikar V, Thiesen T. Life cycle assessment of high temperature electrolysis for hydrogen production via nuclear energy. Int J Hydrogen Energy 2006;31(7):939–44.