JOURNAL OF APPLIED ELECTROCHEMISTRY 12 (1982) 163–169

The approximate costing of electro-organic processes

R. E. W. JANSSON

Wolfson Centre for Electrochemical Science, Southampton University, Southampton, UK

Received 21 May 1981

Published cost data for four electro-organic syntheses at scales of 30 to 10^4 tonnes y^{-1} have been reviewed and cast into like form by making some simple assumptions. The patterns of spending revealed are remarkably similar despite the differences in chemistry and scale. From these data it is suggested that a first estimate of the total annual process cost of an industrial synthesis is given by 2.2 times the installed cell capital plus the cost of raw materials. Improved estimates for other financial strategies than the baseline case may be obtained from the tables. Selectivity of reaction is identified as a factor of paramount importance in improving the economics of electro-organic processes.

---

1. Introduction

At the early stages of assessing a process for possible industrialization it is relatively easy to determine the values of the main operating parameters, such as current efficiency and space–time yield, as a function of current density and other system variables. It is harder to estimate the capital cost and performance of real cells from these data, although well defined principles do exist [1–3], and hardest of all to estimate the overall cost, since this is heavily influenced by separation costs and often the physical chemistry of a partly reacted process stream is unknown. However, although few in number, enough detailed costings have now been published to suggest that there is a fairly uniform pattern of spending, regardless of chemical system or scale, so that approximate total capital and process costs can be estimated from laboratory data *via* the estimation of cell capital. This paper describes the process. The pattern of spending also suggests targets for research in electrochemical engineering to improve the profitability of electrochemical syntheses.

2. Chemical systems and analysis

The systems which have been reported in enough detail for general use are:

(a) the production of hydroquinone from benzene *via* quinone (URBK process [3, 4]);

(b) the production of benzaldehyde from toluene (ETH process [5]);

(c) the production of glyoxylic acid from oxalic acid (Newcastle process [6, 7]); and

(d) the production of calcium gluconate from glucose (CECRI process [8]).

The first is a direct oxidation followed by a direct reduction (in the same divided cell), the second a difficult indirect oxidation, using electrogenerated Ce(IV), the third a direct reduction, and the last a mild indirect oxidation, using electrogenerated HOBr. Conditions are shown in Table 1.

Since the published capital costs are all based on slightly different assumptions and with slightly different itemizations, they have been rationalized under four main headings to show the gross patterns of spending without confusing detail (Table 2). Despite differences in chemistry, scale and country of origin the patterns show surprising similarities. The largest irregularity is the apparently high cost of building in India; if this is reduced to 8% of the total to approximate Western practice then the pattern of the CECRI process becomes closer to those of the others. In any event the salient feature of Table 2 is the relatively high cost of process equipment (even for the simple operations listed in Table 1) which may be equivalent to or greater than that of the cells, including electrodes.

Table 3 shows the process costs extracted from the original sources [3, 5–8]; again there are similarities. The largest cost in each case is due to

0021–891X/82/020163–07$02.70/0

Table 1. The systems

Product	*Starting material*	*Medium*	*Cell*	*Separation*	*References*
1. Hydroquinone	Benzene	aq. H_2SO_4/benzene	Divided, planar electrodes. PbO_2 anode, Pb cathode	Crystallization from aqueous phase	[4]
2. Benzaldehyde	Toluene	5M $HClO_4$, Ce III/IV 1 : 15 toluene : *n*-hexane	Concentric cylinders Pt/Ti anode, smaller Cu cathode	Solvent extraction (*n*-hexane) and distillation	[5]
3. Glyoxylic acid	Oxalic acid	aq. sat. $(COOH)_2$	Divided, planar electrodes Pb/As anode, Pb cathode	Partial evaporation and crystallization of residual oxalic acid to give 50% w/w aq. solution	[6, 7]
4. Calcium gluconate	Glucose monohydrate	aq. $NaBr/CaCO_3$	Undivided tank, rotating cylindrical graphite anodes planar graphite cathodes	Crystallization	[8, 9]

Table 2. Capital costs

Installed capital	*(A) Hydroquinone [3]*		*(B) Benzaldehyde [5]* *,†		*(C) Glyoxylic acid [6, 7]*		*(D) Gluconate [9]*		*Gluconate if buildings 8% of total (%)*	*Average A, B & C*
	k$	%	*k$*	%	*k$*	%	*k$*	%		
1. Cell + electrodes	8 964	46	1287	37	182.5	31	10.31	17	21	38
2. Rectifiers etc.	2 775	14	358	10	66.3	11	6.38	10	12	12
3. Process equipment	7 220	37	1603	46	349.5	58	30.19	49	59	47
4. Buildings	660	3	248	7	–	–	15.00	24	8	5
Totals	16 619	100	3496	100	598.4	100	61.88	100	100	102
Capacity (tonne y^{-1})	10^4		10^3		300		30			
Installed capital/ capacity (\$/kg y^{-1})	1.96		3.50		1.99		2.08			
Year of assessment	1980‡		1980		1975		1981			
Country of origin	W. Germany/USA		Switzerland		UK		India			

* Installation costs split proportionately between installations 1, 2 and 3.

† Assumption: \$ = Sfr 1.67 = £0.455 = Rs 8.

‡ Danly's 1979 figures [3] adjusted by 10% for inflation [10].

Table 3. Unadjusted process costs

Process costs	*Hydroquinone*			*Benzaldehyde*			*Glyoxylic acid*			*Gluconate*		
	¢/kg	*%*		*¢/kg*	*%*		*¢/kg*	*%*		*¢/kg*	*%*	
1. Raw materials	61.3	19		21.8	19		65.6	37		113.1	40	
2. Utilities	70.8	22		35.2	20		39.2	22		13.9	8	
3. Maintenance	10.9	3		16.8	9		4.0	2		10.3	4	
4. Labour	12.3	4		21.5	12		7.3	4		15.4	6	
5. Overheads	26.1	8		6.5	4		9.0	5		3.3	1	
6. Administration, sales & Research	32.3	10		21.5	12		12.5	7		15.0	5	
7. Depreciation	31.4*	10	34	37.5†	21	31	20.0‡	11	23	10.3§	4	40
8. Other capital charges	78.2*	24		18.0†	10		22.0‡	12		100.3§	36	
Totals	323.3	100		178.8	100		179.6	100		281.6	100	

* Ten year depreciation period, return on investment is 25% on installed capital × 1.45 for off-site costs.
† Six year depreciation period, 8% interest on capital.
‡ Ten year depreciation period, 10% interest, insurance 1% of capital.
§ Ten year depreciation of plant and machinery, 12% interest, 25% return on investment, minor taxes and 2.5% royalty on sales.

financial charges, which depend heavily on financial policy. For example, for the ETH process [5] it is assumed that the interest rate is 8% and the depreciation period is six years, whereas for the CECRI process the cost of (uninstalled) plant and machinery is depreciated over 10 years, an interest rate of 12% is assumed, a return on investment of 25% on installed capital is suggested and a royalty of 2.5% is levied against sales [8]. Clearly it is hard to compare like with like, while for present purposes it is more interesting to consider incremental cost of the electrochemical step rather than total process cost, which includes the costs of materials as diverse as benzene and glucose. Accordingly in Table 4 the costs of raw materials have been excluded and uniform capital charge applied (40% on installed capital, which is slightly more stringent than the totals of items 7 and 8 in Table 3). In Table 4 it will be seen that by far the largest add-on cost comes from capital charges, with utilities (electricity, steam and water) only one-third to one-half that amount. The cost of utilities in the CECRI process is surprisingly small but another source [9] quotes a higher power consumption (12 kWh kg^{-1} cf. 4 kWh kg^{-1}) so this figure may in fact be higher and the percentage costs therefore slightly different.

Of course cell costs can be minimized by reiteration in design [10] but it is important to note that process equipment costs at least as much as cells, therefore it is necessary to optimize cell and separation steps together [2, 3, 11]. In fact it may be preferable to accept a slightly higher cell cost for the sake of greater selectivity of reaction, hence lower process equipment costs, such is the leverage that capital costs have on the overall process economics.

For interest's sake the overall performances using the adjusted process costs but now including raw materials are shown in Table 5. It is noteworthy that the ratio of the total investment to the annual sales value of product is less than unity for all except the benzaldehyde (ETH) process, which reflects the latter's high technological content (also shown by the high maintenance and labour costs in Table 4), while even with the imposition of a 40% capital charge three out of four processes show positive returns on investment. Since all of the processes probably have potential for further optimization [11] this is encouraging.

3. Projection

While admittedly there are large errors due to the paucity of information, which can only be reduced when a larger data base is available, the average percentages in Tables 2 and 3 can be used for making projections once the cell capital cost has been estimated by well known procedures [1–3] from laboratory data. From the average values in Table 2 the total installed capital is given approximately by 102/38 = 2.68 times the estimated installed cell capital. Under present economic conditions the annual capital related charges are about 40% of the total installed capital*, and from Table 4 it can be seen that on average these represent about 48/99 = 1/2.06 of the total process costs excluding raw materials. A first estimate of the total process cost of an undeveloped system, therefore, is given by:

$$\begin{aligned}\text{Annual process cost} &= \text{Installed cell capital} \times 2.68 \times 0.4 \times 2.06 + \text{Raw materials}\\ &= 2.2 \times \text{Installed cell capital} + \text{Raw materials}.\end{aligned}$$

For comparison the factors obtained from Tables 2 and 3 using the original data are 1.8, 1.9 and 1.8, respectively, for the hydroquinone, benzaldehyde and glyoxylic acid processes, or about 20% lower, however the capital changes originally assumed are rather low by current standards. Because of the different technological circumstances of the Indian process and uncertainties about the costs of building and utilities, it has not been included in the average; the factor obtained from the original data is 3.4.

In individual cases a closer estimate can be obtained from Tables 2 and 3 by using the closest model to the system of interest and the appropriate financial assumptions to get an improved overall factor.

4. Targets for research

Clearly capital costs have powerful leverage on the process economics. Of course cell capital can be reduced by reiteration in design [10] but Table 2

---

* In the hydroquinone case Danly [3] multiplies installed capital by a factor of 1.45 to account for off-site costs.

*Table 4. Adjusted process costs**

Process costs	*(A)* *Hydroquinone*		*(B)* *Benzaldehyde*		*(C)* *Glyoxylic acid*		*(D)* *Gluconate*		*Average* *A, B & C*
	¢/kg	*%*	*¢/kg*	*%*	*¢/kg*	*%*	*¢/kg*	*%*	
1. Utilities	70.8	26	35.2	18	39.2	26	13.9	10	23
2. Maintenance	10.9	4	16.8	9	4.0	3	10.3	7	5
3. Labour	12.3	4	21.5	11	7.3	5	15.4	11	7
4. Overheads	26.1	9	6.5	3	9.0	6	3.3	2	6
5. Administration, sales & research	32.3	12	21.5	11	12.5	8	15.0	11	10
6. Capital charges	125.1	45	89.9	47	79.9	53	82.5	59	48
Totals	277.5	100	191.4	99	151.9	101	140.4	100	99

* Excluding raw materials, capital charges 40% on installed capital.

*Table 5. Overal performance**

	Hydroquinone	*Benzaldehyde*	*Glyoxylic acid*	*Gluconate*
Process cost ($/kg)	3.39	2.13	2.17	2.53
Contemporary sale price ($/kg)	3.74†	2.64 [5]	2.16 [6]	2.88 [9]
Investment/Annual sales value	0.52	1.32	0.92	0.72
$\frac{\text{(Sales − Total product cost)}}{\text{Investment}}$	0.18	0.15	0	0.17

* Adjusted process costs: including raw materials, capital charges at 40% on installed capital.
† Danly's [3] figure adjusted 10% to conform with capital adjustment, Table 1.

suggests that this should never be done at the expense of selectivity of reaction, since process equipment accounts for such a large fraction of the total. Further, rectifier costs are relatively minor, so it may be preferable to accept some electrical inefficiency for the sake of greater selectivity; the total cost of utilities may even be unaltered since an increase in electrolysis power may be offset by a decrease in energy consumed in separation processes. Selectivity of reaction must therefore be a main driving force in design, and in many cases may be more important than high current efficiency or high current density.

5. Conclusion

From a simple analysis of published cost data for a number of processes it is suggested that a first estimate of the total annual process cost of a fairly conventional electrochemical process is given roughly by 2.2 times the installed cell capital plus the cost of raw materials, although in special circumstances and after considerable process development it may be very different [12]. The pattern of spending suggests that selectivity of reaction is of paramount importance in electro-organic syntheses.

References

[1] K. B. Keating and V. D. Sutlić, *Amer. Inst. Chem. Eng. Symp. Ser.* No. 185 (1979) 76.
[2] D. E. Danly, 'Kirk-Othmer Encyclopaedia of Chemical Technology', 3rd Ed. Vol. 8. Wiley, New York (1979) p. 696.
[3] D. E. Danly, 'Scale-up of electro-organic processes', presented at a Course on Electro-organic Synthesis (Organizer M. M. Baizer), University of California, Los Angeles, January (1980).
[4] M. Fremery, H. Höver and G. Schwartziose, *Chemie-Ing. Techn.* **46** (1974) 635.
[5] K. Kramer, P. Robertson and N. Ibl, *J. Appl. Electrochem.* **10** (1980) 29.
[6] R. J. Morton, PhD thesis, University of Newcastle-upon-Tyne (1975).
[7] F. Goodridge, K. Lister, R. E. Plimley and K. Scott, *J. Appl. Electrochem.* **10** (1980) 55.
[8] G. S. Subrumanian, CECRI (Madras Unit) private communication (1980).
[9] G. S. Subramanian, 'Electro-Organic Processes' unpublished work.
[10] R. E. W. Jansson, *Phil Trans. R. Soc. Lond. A* (1981) in the press.
[11] F. Goodridge, *Phil. Trans. R. Soc. Lond. A.* (1981) in the press.
[12] D. E. Danley, 'Hydrocarbon Processing', April (1981) p. 161.