FORECASTING INDUSTRIAL WATER UTILIZATION IN THE PETROLEUM REFINING SECTOR: AN OVERVIEW

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INTRODUCTION

Forecast growth rates in energy demand [DuPree and West, 1972] imply the future utilization of substantial quantities of water in the petroleum refining sector. Such a projection is based on the traditional extrapolation of past trends [Water Resources Council, 1968; Wollman and Bonem, 1971]. This approach, however, fails to recognize the relationships between public, as well as private, policy options and the amount of water demanded.

In this paper, various factors affecting the utilization of water in the petroleum refining industry are investigated. Refining was chosen for discussion for two reasons. First, it is a major water using industry, accounting for approximately 10 percent of the total national industrial intake of water. Second, at a time when the nation is evaluating energy policy alternatives, relatively little attention has been devoted to the relationships between these alternatives and water resources management issues. In the first section of the paper, several direct factors influencing the demand for water in petroleum refining will be discussed. Included among these are the price of water, environmental quality legislation, and technological factors. Throughout, each factor is related to relevant public policy issues in a descriptive manner. Although the primary purpose of this section is to provide a general overview of the principal water resources management policy issues which must be considered in any analysis of future water utilization, several empirical estimates of the potential impact of policy alternatives are presented. In the second section, the relationship of these factors to the degree of water recirculation is presented.

Alternative petroleum consumption forecasts and refinery location scenarios are developed in the third section. By way of illustration, a series of alternative water utilization forecasts for the domestic petroleum refining sector are, then, developed and compared to those presented by others in the concluding section.

WATER USE IN PETROLEUM REFINING

Approximately 1427 billion gallons of water were withdrawn in 1968 for use in United States petroleum refineries. Of this total, only 6 percent was utilized as process water while 74 percent was utilized for cooling and condensing, 12 percent for power generation and 8 percent for boiler feed [U.S. Department of Commerce, 1968]. Thus, cooling requirements constitute a major determinant of water usage. On the average, 378 gallons of intake water were required in 1968 to refine a barrel of crude oil. This compares with 470 gallons in 1958 and 468 gallons in 1954 [API, 1971; Otts, 1963; U.S. Department of Commerce, 1968]. There was, however, a wide variation about the mean value. For example, in 1968 the water intake per barrel of crude petroleum refined varied between 40 gallons and 693 gallons. This variation was a function of many interrelated parameters including the process technology utilized, the produce mix produced, the degree of process integration, water price, and environmental regulations.

In the following discussion, three major factors affecting the demand for water per unit of crude petroleum processed will be considered. These are: (1) the price of water; (2) environmental regulations and; (3) process technology.

Price: A principal factor influencing the intake demand for water is price. Theoretically, price and quantity demanded are inversely related. Increases in the cost or price of water may result through changes in public policy, or a situation of drought which forces a refinery to reduce withdrawals. In the latter case, the shadow price associated with a withdrawal constraint would approximately correspond to an increase in water price. In addition, increases in the cost or price of water result as water quality declines. In the petroleum refinery sector, as in other industrial sectors, the portion of water treated prior to use is increasing [Thompson, 1971]. This indicates a general increase to the industry in the cost of intake water.

In a study by Russell, estimates are derived of refinery response to increases in the cost of water withdrawals [Russell, 1973]. These costs, including the cost of pretreatment, are entered into a refinery simulation model and increased incrementally. Using this approach, Russell shows that the intake water demand curve for a simulated 150,000 bbl/day refinery may be represented by a step function. At a cost of $.039/1,000 gallons for cooling water, installation of a cooling tower became profitable, cutting water withdrawals by a factor of 10. It should be noted that installation of a cooling tower did not result in a substantial increase in consumptive use as there was an equivalent consumptive use through evaporation when heated water is discharged directly into a water course. Further price increases resulted in an increase in water recirculation. However, total intake water demands, including process water intake demands, were relatively inelastic above or below the $.039/1,000 price level.

On the surface, Russell's analysis would indicate that a water price increase to $.039/1,000 gallons would substantially reduce intake water withdrawals. However, only 17 refineries out of a total of 109 sampled in 1954 utilized a once-through cooling system [Otts, 1963] and in 1967 only 6 refineries out of 122 reporting did not recycle water [Crossley, 1968]. Thus, factors other than the price of water may well be more important in the determination of future intake water demands. As stated by Bower:

> The dominant factor influencing internal water utilization and thereby water demand, has been the imposition of various types of effluent controls, however expressed. Thus, even when the cost of intake water is low, extensive recirculation may be practiced, either or both because of effluent controls or the internal economies possible by recirculation [Bower, 1968].

<u>Effluent Controls</u>: Effluent controls and policy, such as those contained in the 1972 Ammendments to the Federal Water Pollution Control Act and the Clean Air Act Ammendments of 1970, are of particular importance in forecasting future water demands for intake use as well as for dilution. The Ammendments to the Water Pollution Control Act (PL 29-500) are predicted on two national goals: (1) the elimination of discharge of pollutents into navigable waters by 1985 and (2) interim attainment by July 1, 1983 of water quality which provides for protection of fish, wildlife and recreation values. Effluent limitations are the basic mechanism for carrying out the goals of this act. Point sources other than public treatment works must use the best practical control technology

available not later than July 1, 1977. Discharge of waste heat is to be separately regulated so as to protect fish and wildlife resources. In essence, this legislation provides a mandate to reduce the volume of effluent and hence intake as well as dilution flow demands. The effect upon intake demands could be substantial. For example, a recent study indicates a reduction in water intake for a hypothetical refinery of approximately two-thirds [Porter, 1973].

Another often discussed mechanism for achieving water quality goals is the imposition of effluent charges or taxes. Previous studies have shown that a 2 cent tax per pound of BOD may result in a reduction of BOD discharge by more than 50 percent thereby reducing the demand for dilution flow [Thompson, 1971]. However, such charges may affect the magnitude of residuals discharged to other media. For example, Russell has demonstrated that a BOD charge could result in an increase in particulate matter discharged to the atmosphere [Russell, 1973]. As pointed out by officials of the Environmental Protection Agency, installation of scrubbing systems to reduce particulate matter emissions may result in an increase in water demands. Thus, in forecasting future water utilization, the complex interrelationships between intake water utilization, dilution demand and all relevant environmental quality policies must be simultaneously considered. Although such an analysis is beyond the scope of this paper, it should be noted that alterations in air quality programs alone may result in significant changes in water utilization. To illustrate, regulatory pressures are mounting to: (1) reduce lead alkalis used for gasoline octane improvement; (2) desulfurize residual oils and; (3) remove sulfur from stack gases. There is also evidence that an emphasis upon no-lead gasoline could result in an increase of water requirements of between 8 and 11 percent depending upon the octane rating. In addition, given present environmental standards, an increase in the sulfur content of the crude (due to a higher portion of foreign imports) by 50 percent could result in an increase of water requirements of approximately 1.2 percent [Russell, 1973]. Thus, as desulfurization of sour foreign crude imports is increasingly required, an increase in water demands can be expected.

Process Technology: A third factor, closely related to effluent controls, affecting per unit water demands in refining is the pattern of change in process technology. Refineries may be classified into three broad categories by type of technology: (1) old; (2) new and; (3) typical. An older refinery utilizes relatively inefficient or obsolescent processes, a new refinery uses all or most of the advanced processes, while a typical refinery utilizes the processes and subprocesses most widely utilized today [U.S. Department of the Interior, 1967; Oil and Gas Journal, 1967].

The average waste water flow from an older refinery has been estimated at 250 gallons per barrel of crude, while that of a newer refinery at 50 gallons per barrel of crude [U.S. Department of the Interior, 1967]. A comparison of waste water flows under different process technologies does not allow a direct comparison of intake demands because of differences in consumptive loss. However, as consumptive loss is relatively small compared to intake requirements, it is clear that technological change can have a significant effect upon intake water demands. The extent to which process technology will be altered over the next several decades is a matter of conjecture. However, at the present time U.S. refineries are processing crude petroleum at a virtual full capacity rate [API, 1974]. Given the projected consumption forecasts for petroleum products and increasing environmental standards, it may be hypothesized that new domestic refinery capacity utilizing "advanced" process technology will be constructed to at least partially meet these increasing energy demands. This assumes that assured supply sources can be obtained [Johnson, 1974]. Thus, a technological shift may occur in the future which could result in a reduction in the average demand for water per barrel of crude refined.

A closely related technological factor which must be considered is the degree of refinery complexity which is defined as the <u>combination</u> of processes utilized as opposed to the <u>type</u> or age of process technology discussed above. Over the past several decades, there has been a general increase in refinery complexity [Bower, 1968]. This is due, in part, to changes in the finished product mix. Higher proportions of middle distillates and gasoline, as opposed to residual fuel oils, are being produced today because of their greater profitability [API, 1971; Johnson, 1974]. As refinery complexity increases, there is an increase in residual heat and hence water utilization per unit of product.

It should be noted, however, that the product mix output, which is a principal factor affecting complexity, has remained quite stable over the past 10 years [API, 1971]. Moreover, recent short-term forecasts indicate only minor shifts in the product mix [Adams and Griffin, 1972]. On the other hand, energy shortages could lead to changes in the product mix that were not anticipated until very recently. For example, the petroleum shortfall during the winter of 1974 led to a pronounced shift from the production of gasoline to the production of fuel oil. Based upon Russell's coefficients, such a change if prolonged could result in a decrease in water utilization of approximately 16 percent [Russell, 1973].

From the above discussion, we see that alterations in per unit intake water demands may be induced by environmental legislation, technological change, and to a lesser extent, water resource pricing policies. The principal response to the factors discussed will be to change the amount of water recirculated. Thus, for the purpose of forecasting future water demands, the degree of recirculation, which is defined as the ratio of recirculated water to gross water applied, becomes a key parameter and a logical proxy for the effects discussed above.

THE DEGREE OF RECIRCULATION

Based upon data from the <u>1968 Census of Manufacturers</u> and from the American Petroleum Institute, the following relationship between intake water consumption and the degree of recirculation in the refinery production process was derived.

$$I = 1524.1 - 1511.1\ R/G$$
$$(T = -7.922)$$
$$R^2 = .83$$

where: I = intake water in gallons per barrel of crude

R = recirculated water in gallons per barrel of crude

G = gross water flow in gallons per barrel of crude

As would be expected, intake water is substantially reduced as the degree of recirculation increases. The relationship between recirculation and the demand factors, then, is the important consideration.

In areas of the country with less than 20 inches of annual precipitation, the degree of recirculation tends to be higher than in areas in which the annual precipitation exceeds 20 inches. This relationship holds true not only for the petroleum refining sector but also for the electric power generation sector [Lob and Ward, 1971; U.S. Department of Commerce, 1968]. Thus, it may be inferred that if water is limited or if a withdrawal constraint is imposed, the degree of recirculation tends to increase.

Little evidence is available on the relationship between the degree of recirculation and environmental standards. However, data from the 1967 American Petroleum Institute survey indicates that the average degree of recirculation is 38 percent for those refineries utilizing only primary waste treatment. This compares to 73 percent for those utilizing intermediate and biological waste water treatment [Crossley, 1968]. This data may indicate that the degree of recirculation increases as environmental restrictions increase. Since Russell's data indicates a decrease in most residuals as recirculation increases [Russell, 1973], there is reason to believe that one response to increased environmental standards will be to increase the degree of recirculation.

The 1967 API survey indicated little, if any, relationship between refinery capacity or complexity and the degree of recirculation. An empirical examination of the data, however, shows that there is a statistically significant difference (at the 0.95 percent confidence level) between total intake consumption and refining complexity. In general, as complexity increases, intake water utilization per unit increases.

In general, it may be anticipated that a high degree of recirculation will be associated with stringent effluent limitations, and a relatively high cost of input water; while a low degree of recirculation may be associated with less stringent effluent regulations and lower water intake or treatment costs. In addition, total intake utilization tends to increase as refining complexity increases. If these factors are held constant, the quantity of water utilized in the petroleum refining sector will depend upon the future domestic consumption of petroleum and that portion refined in the United States.

THE DEMAND FOR PETROLEUM

Although numerous forecasts of energy and petroleum consumption are available, few if any explicitly attempt to estimate both supply and demand and hence consumption as a function of market variables such as price, prices of other fuels, supply constraints or alternative public policies. Changes in market forces or public policy can significantly affect the future demand for petroleum and hence water utilization in the petroleum refining sector. Thus, the approach utilized in this paper is to develop several alternative scenarios of petroleum demand. For this purpose, a parametric model of fossil fuel markets is utilized [Kalter, 1973].

The model is a market simulation framework which is utilized to forecast the demand and supply of oil, natural gas and coal. Variations in the size and speed of consumer and producer response to price, income and population changes may be tested. In addition, alternative forecasts may be developed for various policy actions such as the deregulation of natural gas prices at the wellhead.

The petroleum component of the model assumes that any shortfall between domestic demand and production will be closed by imports. Imports, as well as price, consumption and reserve additions, are the product of the solution. The natural gas component of the model can assume wellhead prices which are deregulated to various degrees or conditions of continued regulation. The coal component of the model is similar in principle to the natural gas component under unregulated conditions. For both of these components, price changes and consumption are the products of the solution.

Interfuel competition is taken into account in the model by the addition of post production costs to the wellhead or mine-mouth prices resulting from the basic parametric model in order to obtain burner tip prices on a BTU basis. When the burner tip cost or price per BTU for the respective fuels differs by an exogenously predetermined percentage, demand shifts are modified within the model context. Environmental constraints can be entered so that the market solution is modified to maintain environmental standards.

<u>Model Assumptions</u>: For purposes of this analysis, two alternative petroleum forecasts were prepared. These forecasts differ with respect to the assumptions concerning long-run demand elasticities. The model assumptions and variables utilized for each forecast are presented in Table 1.

Both forecasts assume deregulation of natural gas prices at the wellhead. The long-run natural gas demand elasticity is assumed to be -0.7, while the long-run supply elasticity is assumed to be 0.7 [MacAvoy and Breyer, 1973]. For the coal sector, a long-run demand elasticity of -0.7 is also assumed; the long-run supply elasticity is set at 3.0. A high burner tip price differential between coal and other fossil fuels (50 percent) is maintained in both projections. This approximates the situation where relaxation of air quality standards does not take place. The model results for petroleum are presented in Table 2.

In general, the results obtained from the parametric model fall in the low end of the range of the results from other forecasts [DuPree and West, 1972]. Case 1 forecasts, especially, are lower than most recent forecasts. Given price interdependencies and a high petroleum demand elasticity, fuel switching occurs with coal and gas picking up a large share of the growth in consumption. The difference in petroleum consumption estimates due to different assumptions regarding demand price elasticity and the prices of other fuels thus appears potentially substantial. If water use policy variables are held constant, a substantial variation in water utilization is possible due solely to alterations in the fossil fuel market structure and policy. In addition, it is important to recognize that recently there has been a virtual stagnation in the growth of domestic refining capacity in relation to the consumption of petroleum products. Thus, a substantial variation in future water use is possible depending upon whether new refinery capacity is located in the United States or abroad.

Future Domestic Refining Capacity: Over the 1963-1973 period, domestic refinery capacity increased by approximately one-third to a total of 13,248 million barrels per calendar day [U.S. Department of the Interior, 1972]. However, the refined product shortfall has increased rapidly over the past five years and in 1973 imports of refined products totaled 4 million barrels per day. Moreover at present, there is a lack of significant planned domestic refinery expansion from 1974 onward [U.S. Department of the Interior, 1972].

Three principal factors account for the recent stagnation of domestic refining capacity growth in relation to demand: (1) environmental constraints; (2) uncertainty with regard to foreign crude supplies, and; (3) domestic product prices were not considered high enough to justify capital expenditures in new capacity [Wall Street Journal, 1973]. As domestic crude petroleum production peaked in 1972, the only source of additional crude for the near future lies abroad. Thus, the principal factors which will influence the expansion of domestic refining capacity in the future include: (1) actions by foreign countries; (2) transportation costs, and; (3) environmental considerations. Obviously a great deal of uncertainty is associated with the future impact of these factors. However, given the lead time necessary to develop new domestic capacity, the Office of Oil and Gas states that, "nothing significant in terms of new domestic capacity could be realized before 1976." In addition, there are indications that unless public policy is drastically altered, domestic refining capacity will be maintained at present levels through at least 1980 [U.S. Department of the Interior, 1972].

For the purpose of this analysis, domestic capacity projections developed by the National Petroleum Council will be utilized as one forecast. For 1975 the shortfall of refining capacity is projected to be 25.9 percent of domestic consumption. This shortfall rises to 26.7 percent by 1980 and 30.7 percent by 1985 [NPC, 1973]. As an alternative forecast, it will be assumed that a concerted effort is begun immediately to expand domestic capacity, and that imports of refined products will be eliminated by 1980. This forecast is commensurate with the President's recently announced program of energy self-sufficiency by 1980. These two forecasts are intended to represent polar cases for this analysis. At this point, the variables considered can be integrated to form alternative water utilization forecasts.

ALTERNATIVE WATER UTILIZATION FORECASTS

The following combinations of variables were chosen to illustrate two possible forecasts of future water utilization in the petroleum refining sector. The variables combined to form the first forecast include continuation of current water pricing policies, liberal enforcement of environmental regulations, a minimum of technological change in the U.S. refining industry, a shortfall in domestic refining capacity of 26.7 percent in 1980 increasing to 30.7 percent in 1985, a 6.7 billion barrel per year consumption of petroleum in 1980, and a 7.5 billion barrel consumption in 1985. Under these conditions, it is anticipated that the average water withdrawals per barrel of crude will remain at the current level of approximately 378 gallons per barrel.

The second forecast assumes a water pricing policy such that cooling towers are utilized by all petroleum refineries. In addition it is assumed that technological change in the refining sector will be such that virtually all refineries will be utilizing the newest process technology and that self-sufficiency in refining capacity will be achieved by 1980. Under these conditions, it is assumed that the average degree of recirculation will increase to .95 and that withdrawals per barrel of crude will average approximately 88 gallons. Commensurate with the low forecast variables, petroleum consumption of 5.0 billion barrels per year in 1980 and 5.2 billion barrels in 1985 is used.

The projected withdrawals for the nation under each combination of variables is presented in Table 3. Also included in Table 3 are the withdrawals projected by Wollman and Bonem.

SUMMARY AND CONCLUSIONS

A range of alternative futures is possible depending upon energy consumption, environmental quality standards, technological change, and a host of other variables. Given emerging energy as well as water resource policy options, a consideration of their combined effect is a critical element in future water resource management decisions. For example, the magnitude of potential localized water shortages or use conflicts depends largely upon the policies adopted with regard to energy as well as water resources. Since water resource demands associated with energy demands may require adjustments in regional as well as national policies and programs, a consideration of alternative futures associated with both factors is a necessary element in all planning and resource management programs.

Table 1. Model Variables and Assumptions
(Petroleum Sector)

Variables and Assumptions	Case 1	Case 2
Long-run demand elasticity	-.7	-.1
Long-run supply elasticity	.9	.9
Demand elasticity response rate	50% in 3 years, 100% in 8 years	
Supply elasticity response rate	50% in 3 years, 100% in 8 years	
Exports	Endogenous in both cases	
Price	Endogenous in both cases	

Table 2. Projections of Petroleum Consumption
(billion barrels/year)

Case	1980	1985
1	5.0	5.2
2	6.7	7.5

Table 3. Projection Demands for Water in Petroleum Refining, 1980

Alternative	Withdrawals in Barrels (billions) 1980	1985
1	1856	1,966
2	440	458
Bonem and Wollman	1,071 - 1,993[a]	---

[a]Derived from Wollman and Bonem [1971]. Their results were derived for self-supplied fresh water only. Thus, a factor based upon the 1968 Census of Manufacturers was applied to adjust their totals to include all water intake from self-supplied, brackish and public waters.

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