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SENSITIVITY ANALYSIS ON HYDROGEN UTILIZATION FACTOR OF THE HÄFELE-MANNE MODEL

A. Suzuki and L. Schrattenholzer

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Summary

This paper is to report on the results of a sensitivity analysis on the hydrogen utilization factor η_U of the Häfele-Manne model. The model societies to be treated here are 1.60 and 1.80, and the values of η_U selected here are 1.0, 1.2, 1.5, and 2.0.

The calculation results indicate that qualitatively speaking, while the value of η_U has little effect on optimal solutions for model society 1.60 it has a significant effect on optimal solutions for model society 1.80. In other words, in model society 1.60 the qualitative interpretation of the optimal solutions does not significantly vary with the value of η_U; on the other hand in the case of model society 1.80 the optimal transition from petroleum-and-gas to HTGR hydrogen does significantly change with the value of η_U $(1.0 < \eta_U < 1.5)$.

The Häfele-Manne model assumes that the break-even value of η_U which yields no difference of energy costs between petroleum-and-gas and HTGR hydrogen is 1.4. Hence if the petroleum-and-gas resources are sufficient to prevent more expensive nonelectrical energy supply alternatives from being introduced into the energy market (model society 1.60 is not sufficient in this sense but model society 1.80 is sufficient), and if we take the value of η_U which is less than the break-even value of 1.4, instead of the $\eta_U = 1.5$ in the Häfele-Manne model, then the optimal strategy on a transition from petroleum-and-gas to HTGR hydrogen is significantly different from the solution in the Häfele-Manne model.

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1. The Häfele-Manne model [1] (what we call "model" here includes not only the mathematical framework but also the data used) introduces the parameter η_U which is called the hydrogen utilization factor. The definition of the parameter η_U is the value of BTU's of petroleum or natural gas replaced per BTU's of hydrogen utilized.[1] In other words each BTU of hydrogen is equivalent to η_U BTU's of petroleum-and-gas, being roughly estimated from the comparison of net thermal values in end uses between the two.

2. The parameter η_U has an important role in the model. It is explicitly included in the equation concerning the nonelectrical energy demand constraints,[1] and also is used in estimating the static comparison of annual costs per TW_{th}; the cost of hydrogen produced from the process heat of HTGR is a little lower than the cost of petroleum-and-gas. The difference is slight, and it obviously depends on the value of η_U assumed in the model.

3. It is almost impossible to assess the value of η_U definitely, because it is involved with some uncertainties relating to the technological assessment of the future of hydrogen technology. The model takes the value

$$\eta_U = 1.5$$

not from an exhaustive investigation but from a rough estimation,[1] and yet some other values are possible. Therefore this paper shows the results of sensitivity analysis on η_U of the Häfele-Manne model.

4. The Häfele-Manne model studies three different model societies with respect to energy demand projection,[2] and three levels of petroleum-and-gas availability,[3] nine logically possible cases. Here we have studied one of those three model societies, model society 1, and two of the three levels of petroleum-and-gas availability, i.e. 60 and 80 years of petroleum-and-gas resources in terms of the annual consumption rate corresponding to 35% of the world's entire 1970 consumption of petroleum-and-gas (1.875 TW = .056 Q). According to the identification expression of the Häfele-Manne model, the cases to be studied here are cases 1.60 and 1.80.

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[1] Häfele and Manne [1], p. A-6.

[2] Häfele and Manne [1], pp. 20-27.

[3] Häfele and Manne [1], p. 32.

5. For the sake of sensitivity analysis four values of η_U are chosen for each case: 1.0, 1.2, 1.5, and 2.0. Then possibly 2 x 4 = 8 cases are to be examined. To distinguish these, we shall employ the following expressions. Case 1.60/1.0 refers to model society 1 with sixty years of petroleum-and-gas resources and hydrogen utilization factor 1.0. Cases 1.60/1.5 and 1.80/1.5 correspond to the base cases which have been already examined in the Häfele-Manne model.

6. First let us show the interpretation of the optimal solution for the base case in order to make it easier to understand the results of sensitivity analysis. The two parts of Figure 3 illustrate the optimal transition from fossil to nuclear fuels over the planning horizon, 1970 to 2030, for C-1.60/1.5. Figure 3a shows the solution for nonelectric energy, and Figure 3b shows the solution for electricity.

7. In interpreting the results in Figure 3a, the following four facts presumed in the Häfele-Manne model should be noted here.

(1) There are three possible nonelectrical energy supply technologies: petroleum-and-gas, hydrogen made from the process heat of the HTGR, and hydrogen from electrolysis. Comparison of the static energy costs shows that hydrogen from HTGR is the cheapest, petroleum-and-gas is more expensive, and hydrogen from electrolysis is extremely expensive (see Table 1).[4]

(2) From the viewpoint of behavioral constraints on the rate of diffusion of new technologies, an upper bound is fixed for the HTGR construction rate (see Table 2)[5]; the introduction of the HTGR begins in 1991, and the construction rate can increase gradually up to 1997. From the year 2000 on there is no practical limit.

(3) The HTGR is coupled to the FBR. While U^{235} is used as the initial inventory of fissile materials for the HTGR, the annual refueling requirements of the HTGR is supplied with U^{233} converted from Th^{232} by the FBR as well as by the HTGR itself.[6] Therefore the availability of hydrogen from the HTGR depends endogenously upon the activity level of the FBR which is determined from electrical energy demand aspects.

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[4] Häfele and Manne [1], p. B-4.

[5] Häfele and Manne [1], p. 21.

[6] Häfele and Manne [1], p. 12.

(4) The existing level of petroleum-and-gas resources is definite and is assumed in this case to be below the amount 3.375Q, corresponding to sixty years of the 1970 annual consumption rate of the most-developed country.

8. From consideration of Fact (2) the planning horizon is to be divided into three stages:

N1) 1970 to 1988, when it is impossible to introduce the HTGR;

N2) 1991 to 1997, when it is possible to introduce the HTGR; however, an upper bound of the introduction rate is fixed exogenously;

N3) 2000 to 2030, when it is possible to introduce the HTGR without any exogenous limit.

9. Over the first stage, N1, the nonelectrical energy demand is met fully with petroleum-and-gas because of Fact (1). Since the length of this stage is about twenty years, Fact (4) has not become critical yet.

10. Over the second stage, N2, hydrogen from the HTGR is introduced to the utmost and yet it does not satisfy the total demand of nonelectrical energy. Hence petroleum-and-gas is additionally used. In 1997, however, Fact (4) is critical since the amount of petroleum-and-gas required for the thirty-year-life operation of the residual petroleum-and-gas supply plant should be taken into account. Therefore hydrogen from electrolysis is introduced in 1997 to make up for the shortage of nonelectrical energy demand.

11. In the third stage, N3, a remarkable transition from petroleum-and-gas to the HTGR hydrogen is observed. The transition results from the following. It is assumed in the Häfele-Manne model that plant lives are a fixed thirty years, and that therefore any plant must operate for thirty years. It implies that all the petroleum-and-gas and electrolytic hydrogen plants existing in 1997 must be used to get a thirty-year operation. Hence over this stage, the HTGR hydrogen meets the difference between the total nonelectrical demand and the energy supply from all the residual petroleum-and-gas and electrolytic hydrogen unless Fact (3) is critical. The criticality of Fact (3) is observed in the years 2024 to 2030 when petroleum-and-gas resources are completely exhausted. Therefore in the years 2024 to 2030 the HTGR hydrogen is used to the utmost due to Fact (3), and electrolytic hydrogen is introduced to make up for the shortage of nonelectrical energy supply.

12. Relating to the results for electricity in Figure 3b, the following three facts presumed in the Häfele-Manne model are to be noted here.

(1) There are three possible electrical energy supply technologies: coal, the LWR, and the FBR. Comparison of the static energy costs shows that the FBR is the cheapest, the LWR is more expensive and coal is the most expensive (see Table 1).

(2) From the viewpoint of behavioral constraints on the rate of diffusion of new technologies, an upper bound is fixed for the LWR and the FBR construction rates (see Table 2); the LWR technology can be used from the beginning of the planning horizon, and from 1988 on the upper bound is infinity. FBR technology can be introduced gradually from 1988, and from 1997 on it has no practical limit in this respect.

(3) The initial inventory of Pu for the FBR is mainly supplied from Pu produced by the LWR and therefore the avilability of FBR technology rests endogenously on the amount of Pu which has been produced by LWR.

13. From consideration of Fact (2) the planning horizon is again to be divided into three stages:

E1) 1970 to 1985, when it is impossible to introduce the FBR;

E2) 1988 to 1994, when it is possible to introduce the FBR; however, an upper bound of the introduction rate is fixed exogenously;

E3) 1997 to 2030, when it is possible to introduce the FBR without any exogenous limit.

14. Over the first stage, E1, the LWR technology is introduced to the utmost, due to Fact (2), and coal is used to make up for the shortage of the energy supply, i.e. the difference between the total electrical energy demand and the energy supply from the LWR.

15. Over the second stage, E2, the FBR technology is introduced to the utmost, due to Fact (2). There is also the energy supply from the residual coal plants because of the fixed service life. Hence the LWR technology is used as a buffer.

16. Over the third stage, E3, no introduction of the LWR is observed since there is no upper bound to the FBR construction rate. In other words, the difference between the total electrical energy demand, including the requirement for the electrolysis, and the energy supplies from the residual coal plants and the residual LWR plants is met by the FBR technology. Figure 3b indicates that Fact (3) is not binding in C-1.60/1.5.

17. Paragraphs 7 to 16 gave the qualitative interpretation of the optimal solution for one of the base cases, C-1.60/1.5. Next, let us show the results for other cases: C-1.60/1.0, C-1.60/1.2, and C-1.60/2.0.

18. Figure 1 represents the optimal solutions for nonelectrical energy and electricity of C-1.60/1.0. As for nonelectrical energy (Figure 1a), the value of η_U has no explicit effect on Facts (2), (3), and (4) in paragraph 7. Concerning Fact (1), however, the static cost ranking of the alternatives for producing nonelectrical energy is changed by the value of η_U. Namely, the value $\eta_U = 1.0$ brings about the following ranking: petroleum-and-gas is the cheapest (\$50/KW$_{th}$ year), HTGR hydrogen is more expensive (\$70/KW$_{th}$ year), and electrolytic hydrogen is the most expensive (\$126/KW$_{th}$ year). This means that there is no economic incentive for hydrogen to take the place of petroleum-and-gas. In the case of model society 1.60, however, the petroleum-and-gas availability is not enough to retard the phase of hydrogen introduction because even in C-1.60/1.5 the petroleum-and-gas resource is completely exhausted within the planning horizon. Hence the optimal solution for petroleum-and-gas in C-1.60/1.0 is almost completely the same as in C-1.60/1.5.

19. Comparing Figure 1a with Figure 3a, it is observed that electrolytic hydrogen in C-1.60/1.0 is used more than in C-1.60/1.5. This is to be understood from the following. On one hand, both HTGR hydrogen and electrolylytic hydrogen in Figures 1a and 3a are in terms of TW$_{th}$ petroleum-and-gas equivalent. That is to say, using $Q_h(t)$ to denote the amount of hydrogen energy generated by HTGR process heat or electrolysis at time t, the hydrogen energy represented in the figures corresponds to $\eta_U \cdot Q_h(t)$, and therefore, in order to compare the amount of $Q_h(t)$ in Figure 1a with that in Figure 3a, it is necessary to divide the hydrogen quantity represented in Figure 3a by $\eta_U = 1.5$. On the other hand, the U^{233} requirement of the HTGR for producing hydrogen is roughly proportional not to $\eta_U \cdot Q_h(t)$ but to $Q_h(t)$. Hence if $\eta_U \cdot Q_h(t) = \text{const}$, then the U^{233} requirement for C-1.60/1.0 is 1.5 times as much as for C-1.60/1.5. In other words, Fact (3) in paragraph 7 is more likely to become binding. According to Figure 1a, the bindingness of

Fact (3) is observed between 2009 and 2024, when electrolytic hydrogen is additionally used.

20. With respect to electricity (Figure 1b), the results for C-1.60/1.0 in the years of the first stage, E1, are the same as for C-1.60/1.5. In the years of the second stage, E2, and the third stage, E3, however, some differences resulting from the greater use of electrolytic hydrogen are observed. For C-1.60/1.0, electrolytic hydrogen is starting in 1994, and the electricity required for the electrolysis is supplied by the LWR because of Fact (2) in paragraph 12. This is the reason why we can observe the small difference in the second stage, E2. Also in 1997, some of the LWR electricity is used for electrolysis for producing hydrogen because the availability of the FBR in this year is restricted due to Fact (3) in paragraph 12. After 2000, however, there are neither exogenous (Fact (2)) nor endogenous (Fact (3)) constraints on the availability of the FBR and therefore no more LWR's are introduced. Hence, qualitatively, no essential change is observed in the third stage, E3, except for the LWR in 1997. The greater uses of FBR and LWR electricity are only due to the fact that the endogenous electrical demand for electrolysis of hydrogen production is greater for C-1.60/1.0 than for the base case C-1.60/1.5.

21. After all, in comparing the results for C-1.60/1.0 with those for C-1.60/1.5, there is no significant qualitative difference. Most of the discussions to interpret the results for C-1.60/1.5 are valid for C-1.60/1.0. Figure 2 illustrates the results for C-1.60/1.2 and confirms that qualitatively the optimal solutions for these three cases are very similar.

22. Figure 4 is used to show the optimal solution for C-1.60/2.0, where hydrogen technology is to be utilized most efficiently. In this case Facts (1) to (4) in paragraph 7 and Facts (1) to (3) in paragraph 12 are all valid, though for C-1.60/1.0 and C-1.60/1.2 the cost ranking of nonelectrical alternatives is changed. Therefore there are no factors bringing about significant differences of the optimal solutions between C-1.60/2.0 and C-1.60/1.5, and, in calculation results, the optimal solutions for C-1.60/2.0 are nearly the same as for C-1.60/1.5, not only qualitatively, but also quantitatively. Figure 4 indicates that, in the years 2027 to 2030, the total nonelectrical energy demand can be supplied only by HTGR hydrogen and that there is no use of electrolytic hydrogen. For this reason the FBR is used in the years 2027 to 2030 just to meet the exogenous electrical demand.

23. Next, let us show the results for the other cases where the petroleum-and-gas resources are presumed to be eighty years in terms of the 1970 annual consumption rate of the most-developed country. Figures 5,6, and 7 correspond to C-1.80/1.0, C-1.80/1.5, and C-1.80/2.0 respectively, showing that:

(a) the timing of the nonelectrical energy supply pattern depends strongly upon the value of η_U, and yet

(b) the value of η_U has no effect on the timing of the electrical energy supply pattern, aside from the endogenous electrical energy demand.

24. With regard to the cost ranking of nonelectrical energy supply alternatives, it is supposed in the Häfele-Manne model that

1) if $\eta_U < 1.4$, then petroleum-and-gas is the cheapest, HTGR hydrogen is more expensive and electrolytic hydrogen is the most expensive.

2) if $\eta_U > 1.4$ then, HTGR hydrogen is the cheapest, petroleum-and-gas is more expensive and electrolytic hydrogen is the most expensive.

25. Because of this supposition, in the case of C-1.80/1.0, petroleum-and-gas should be used to the limit of availability and then the difference between the nonelectrical energy demand and the petroleum-and-gas supply is met by HTGR hydrogen. The eighty-year life span of petroleum-and-gas resources can follow the total nonelectrical energy demand by itself up to the year 2000, and therefore Fact (2) in paragraph 7 is not observed in Figure 5a. Furthermore, when HTGR hydrogen cannot meet the difference because of Fact (3) in paragraph 7, electrolytic hydrogen is additionally used. As mentioned in paragraph 19, Fact (3) is the most liable to be binding in the case where $\eta_U = 1.0$. According to Figure 5a, the introduction of electrolytic hydrogen starts in the year 2015.

26. In the cases of C-1.80/1.5 and C-1.80/2.0, however, Fact (2) in paragraph 7 has an important role in determining optimal transitions from petroleum-and-gas to HTGR hydrogen since HTGR hydrogen is the cheapest technology. Therefore, qualitatively, the optimal solutions for these two cases in the first stage, N1, and the second stage, N2, are completely the same. In the third stage, N3, some significant difference can be observed, although electrolytic

hydrogen does not contribute in either case. Namely, in C-1.80/1.5, Fact (3) in paragraph 7 is sometimes at work because of the lower value of η_U, and then petroleum-and-gas is used in the third stage, N3, in order to supplement the shortage of supply due to Fact (3). This means that petroleum-and-gas will be exhausted in some year. On the other hand, in C-1.80/2.0, Fact (3) in paragraph 7 is not binding in any year because of the higher value of η_U and therefore petroleum-and-gas is not exhausted.

27. As concerns electricity, in Figures 5b,6b, and 7b, it can be seen that the value of η_U has no effect on the determination of the optimal transitions from coal to the LWR and the FBR except that for C-1.80/1.0 some FBR and LWR electricity is used for the endogenous energy demand associated with the use of electrolytic hydrogen. The optimal solution for C-1.80/2.0 is completely the same as that for base case C-1.80/1.5.

28. After all, the effect of the value η_U on optimal solutions is much more remarkable for the model society 1.80 than for the model society 1.60, especially in the aspects of the nonelectrical energy supply pattern. More specifically, the difference in optimal transitions from petroleum-and-gas to HTGR hydrogen between C-1.80/1.0 and C-1.80/1.5 is the most significant because the value η_U of C-1.80/1.0 is less than the break-even value $\eta_U = 1.4$ (which yields the equality between the energy cost of petroleum-and-gas and the energy cost of HTGR hydrogen) and because the value η_U of C-1.80/1.5 is greater than the break-even value $\eta_U = 1.4$. Figures 8 to 12 are attached to give a visual understanding of the conclusions.

Table 1. Static comparison of annual costs per TW_{th} [1]
(neglecting costs and credits for plutonium and U^{233})

	plant type i	cur_i	$.13(cap_i)^{(a)}$	factor for LWR or PETG equivalence$^{(b)}$	total annual costs ($\$10^9$/yr per TW_{th}) expressed in LWR or petroleum equivalents
ELEC	COAL	30.	25.	$\frac{\eta_L}{\eta_C} = .833$	46.
	LWR	5.8-10.5$^{(c)}$	26.	1.	32. - 36. (depending on uranium cost)
	FBR	3.5	34.	$\frac{\eta_L}{\eta_B} = .833$	31.
NELE	ELHY	31. (based upon FBR costs)	2.6	$\frac{1}{(\eta_L)(\eta_E)(\eta_U)} = 2.5$	84.
	PETG	50.	0	1.	50.
	HTRB	7.	28.	$\frac{1}{(\eta_T)(\eta_U)} = 1.333$	47.

Notes:

(a)
$$.13/\text{year} = \begin{pmatrix}\text{factor for in-}\\ \text{curring capital}\\ \text{costs 2 years}\\ \text{prior to full}\\ \text{power date}\end{pmatrix} \begin{pmatrix}\text{annual capital}\\ \text{recovery factor,}\\ \text{30 year life,}\\ \text{10\% discount}\\ \text{rate}\end{pmatrix}$$
$$= \quad (1.1)^2 \qquad\qquad (.106)$$

(b) efficiency factors (useful output/primary energy input):

$\eta_L = 1/3$

$\eta_B = \eta_C = \eta_H = .4$

$\eta_E = .8$ = electrolyzer efficiency

$\eta_T = .5$ = thermal efficiency for HTR plus thermochemical plant for water-splitting

$\eta_U = 1.5$ BTU of petroleum or natural gas replaced per BTU of hydrogen utilized for oil re-refining, petrochemical and air transport.

(c) $5.8 = (2.00)(\frac{1}{3})(8.76)$; for uranium at \$15/lb

$10.5 = (3.60)(\frac{1}{3})(8.76)$; for uranium at \$50/lb.

Table 2. Upper bounds on reactor construction rates [1]

(unit: GW thermal per year)

Calendar year	Nuclear plant type i / Period t	LWR	HTGR	FBR model society 1	FBR model societies 2,3
1970	0	0	0	0	0
1973	3	20	0	0	0
1976	6	40	0	0	0
1979	9	60	0	0	0
1982	12	80	0	0	0
1985	15	100	0	0	0
1988	18	∞	0	30	0
1991	21	∞	20	60	20
1994	24	∞	40	90	40
1997	27	∞	60	∞	60
2000 and thereafter	30	∞	∞	∞	∞

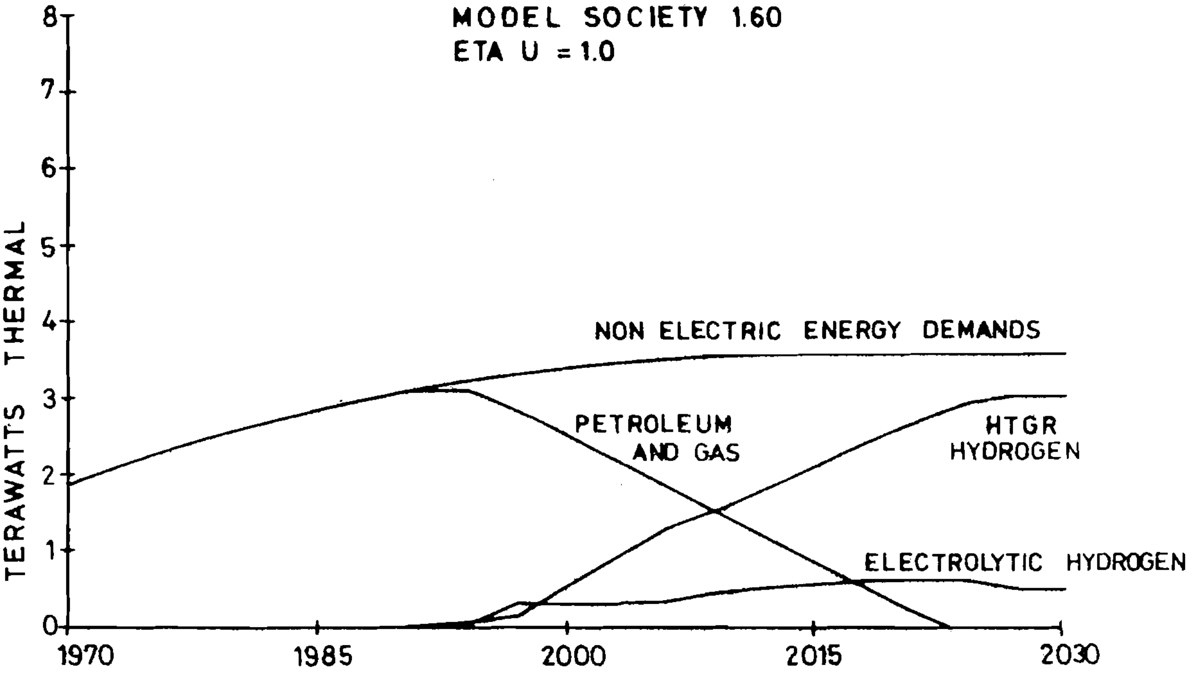

FIGURE 1a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

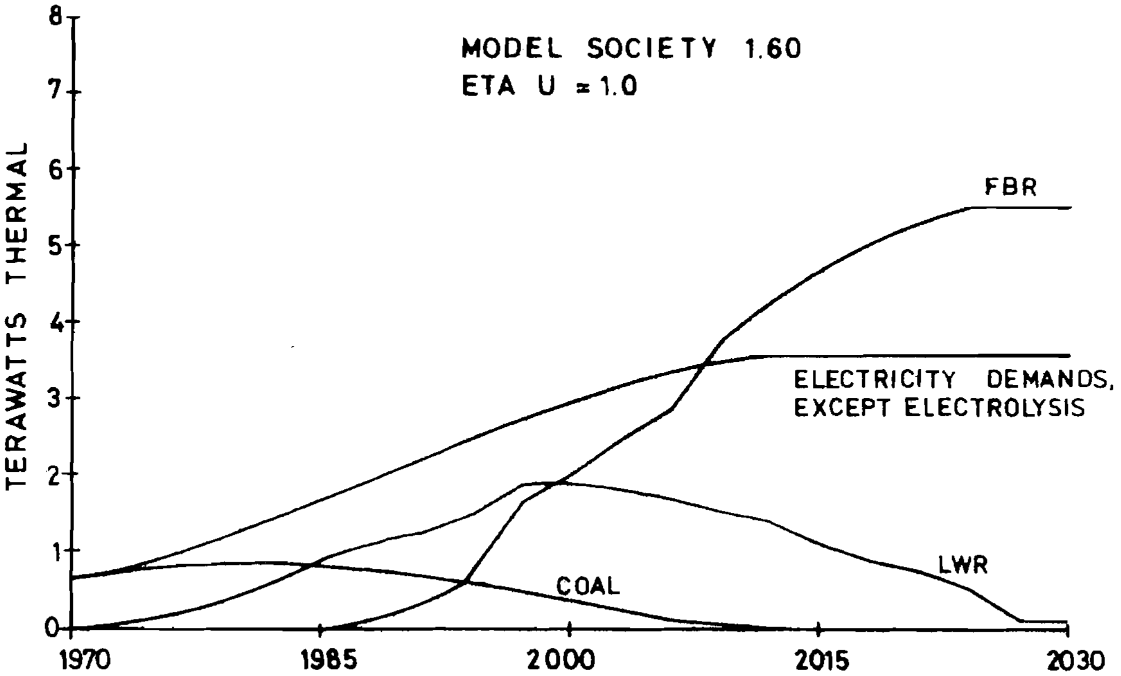

FIGURE 1b. ELECTRICITY DEMANDS AND SUPPLIES

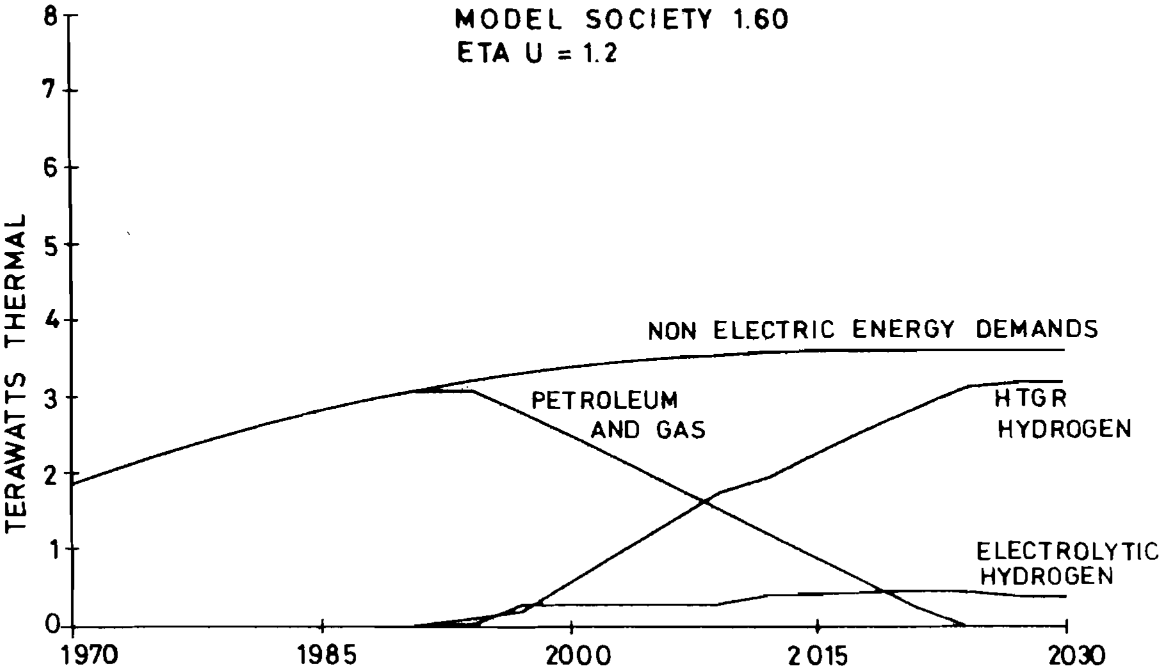

FIGURE 2a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

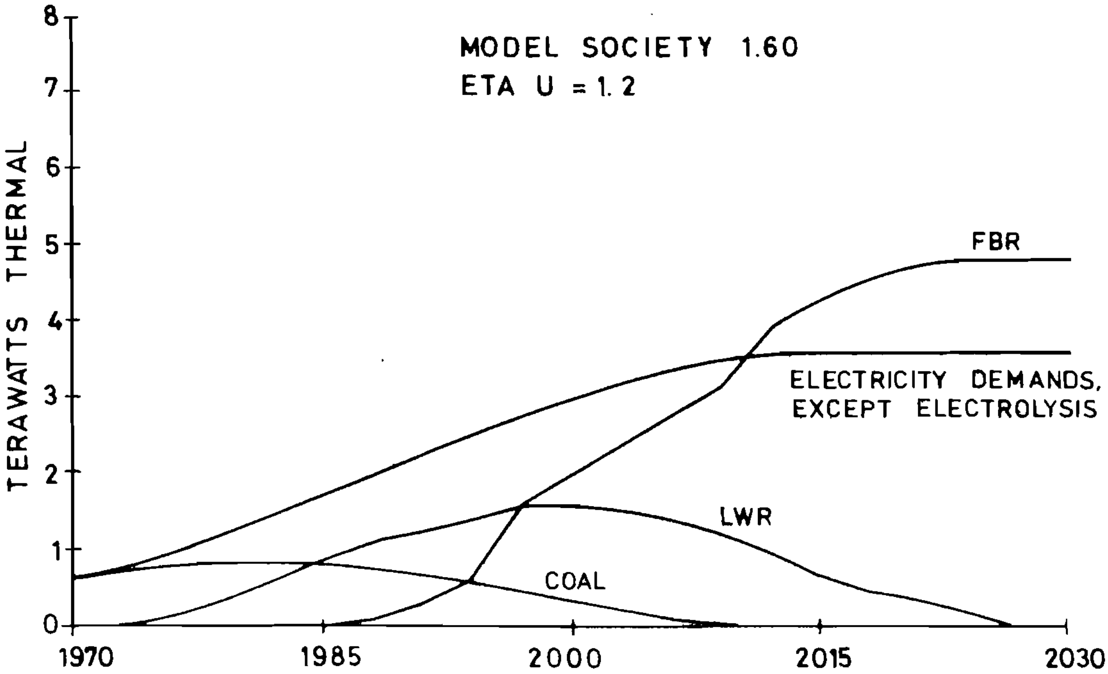

FIGURE 2b. ELECTRICITY DEMANDS AND SUPPLIES

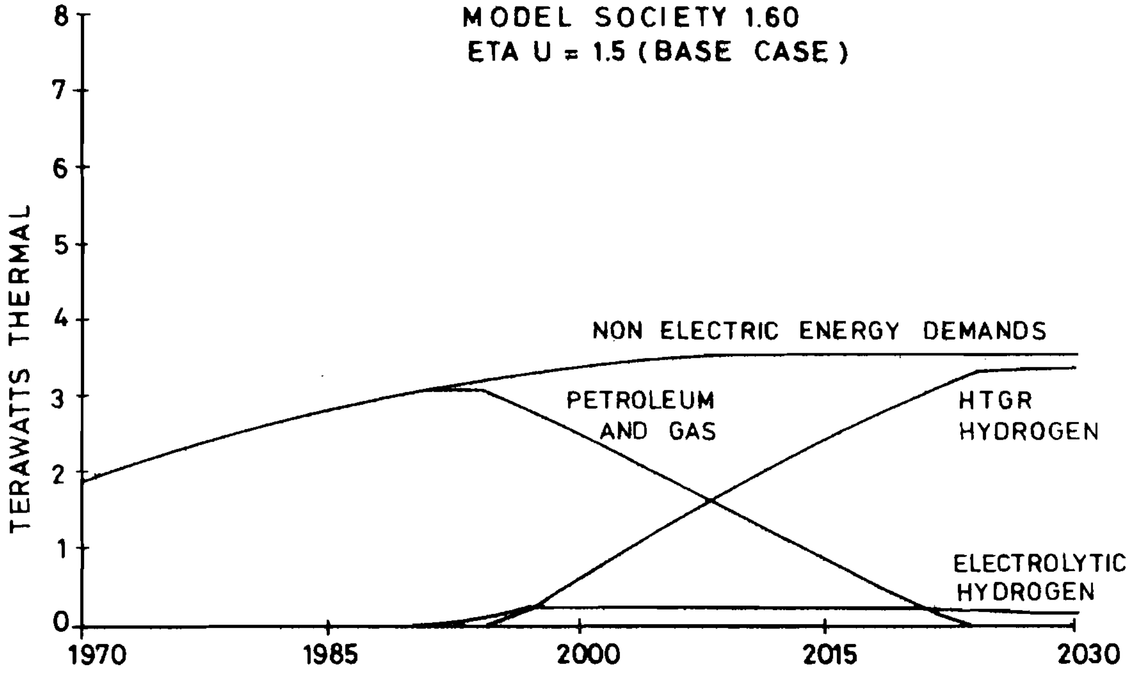

FIGURE 3a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

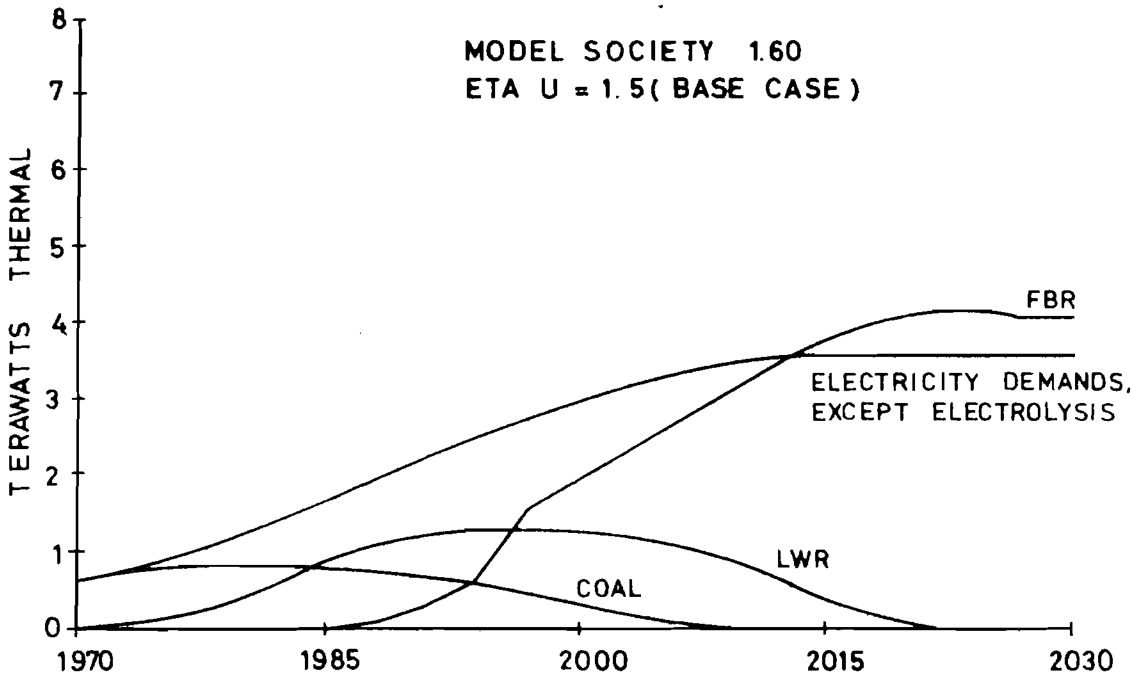

FIGURE 3b. ELECTRICITY DEMANDS AND SUPPLIES

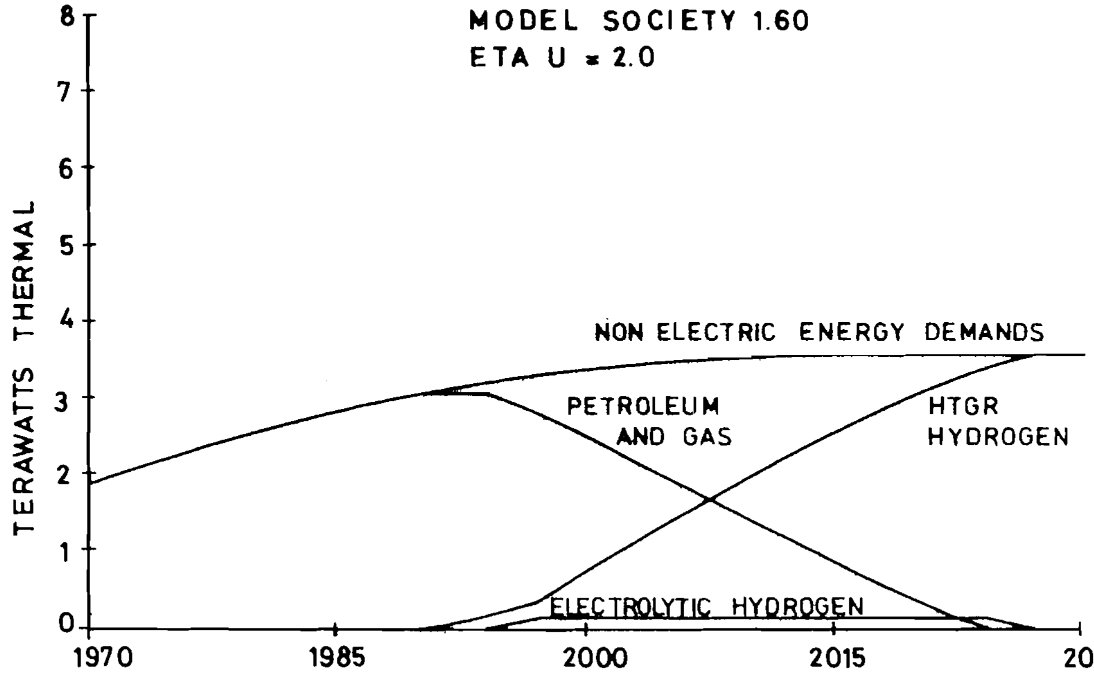

FIGURE 4a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

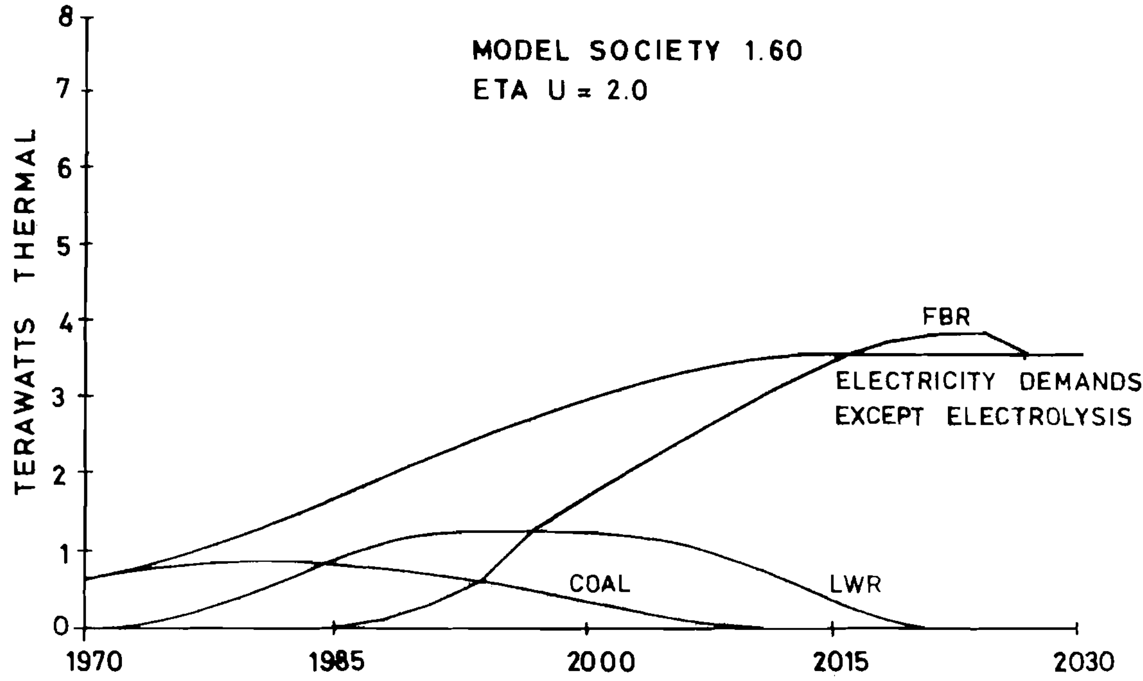

FIGURE 4b. ELECTRICITY DEMANDS AND SUPPLIES

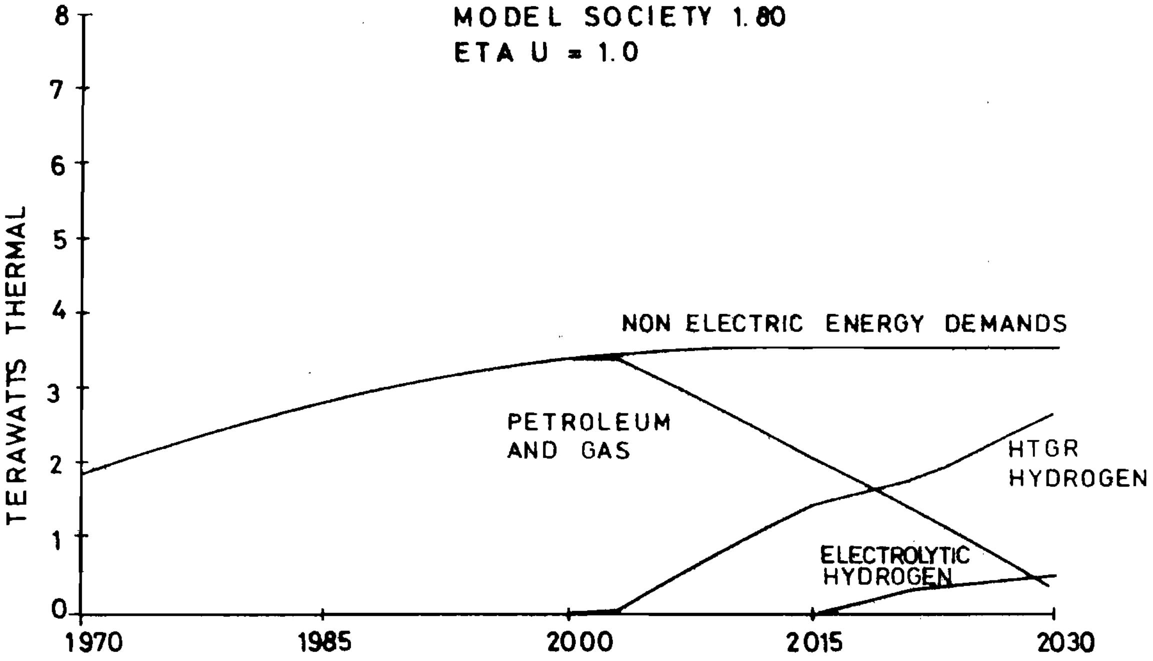

FIGURE 5a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

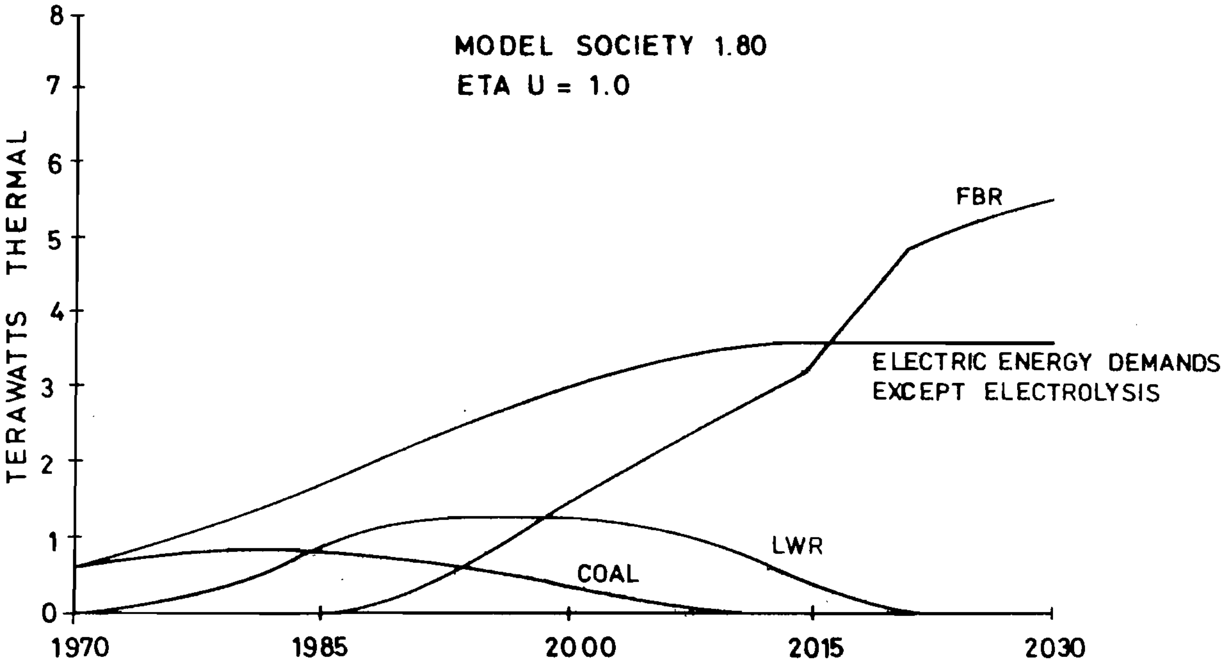

FIGURE 5b. ELECTRICITY DEMANDS AND SUPPLIES

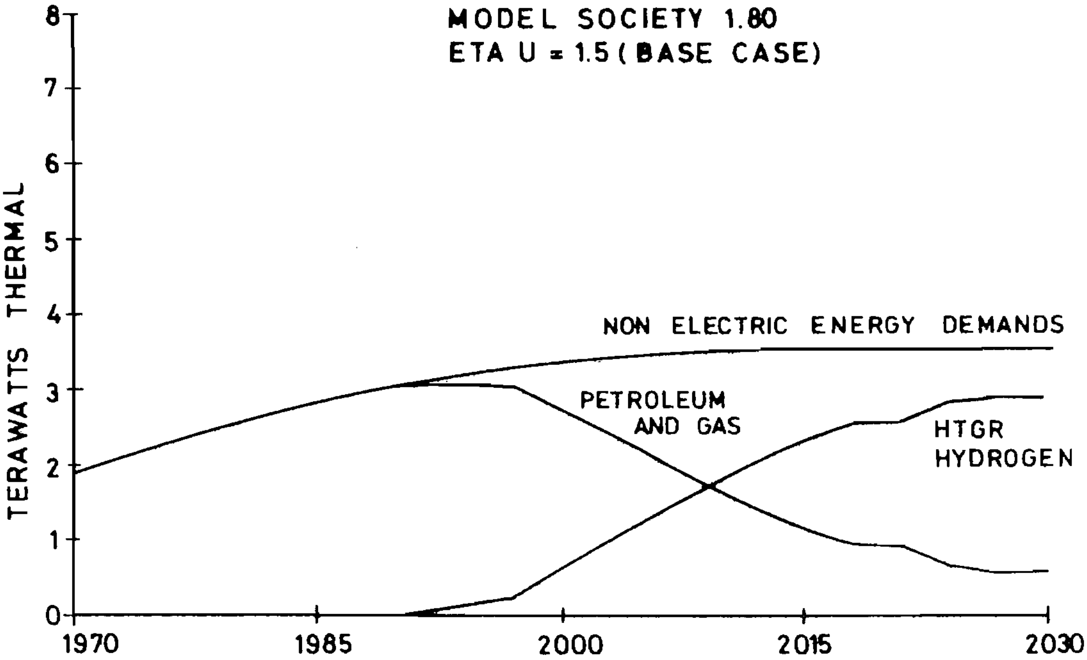

FIGURE 6a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

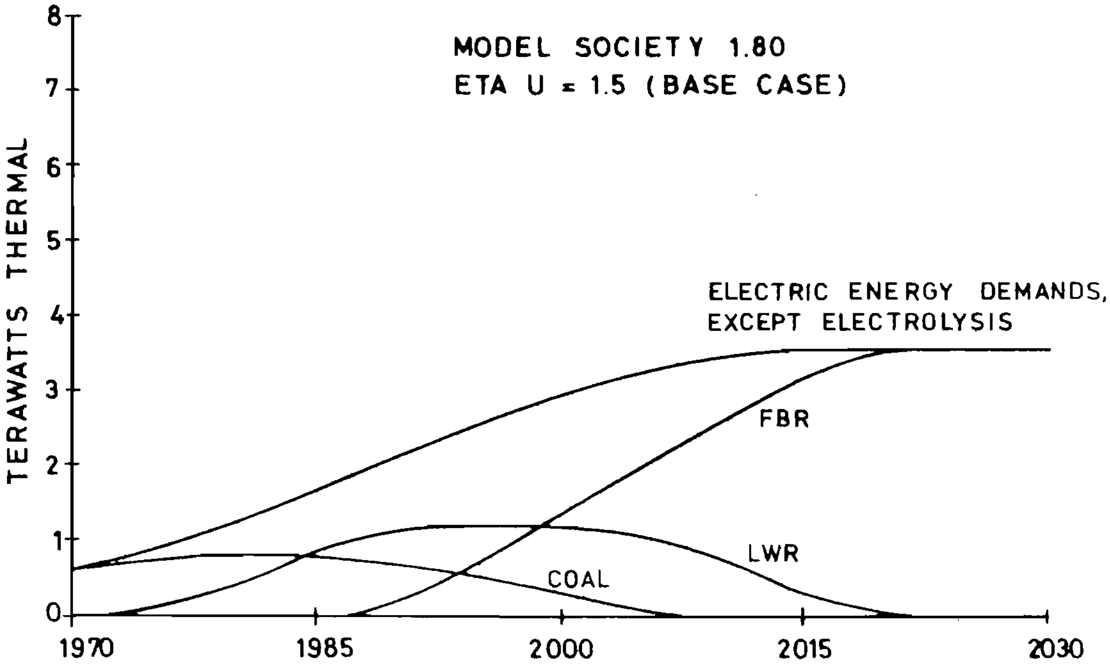

FIGURE 6b. ELECTRICITY DEMANDS AND SUPPLIES

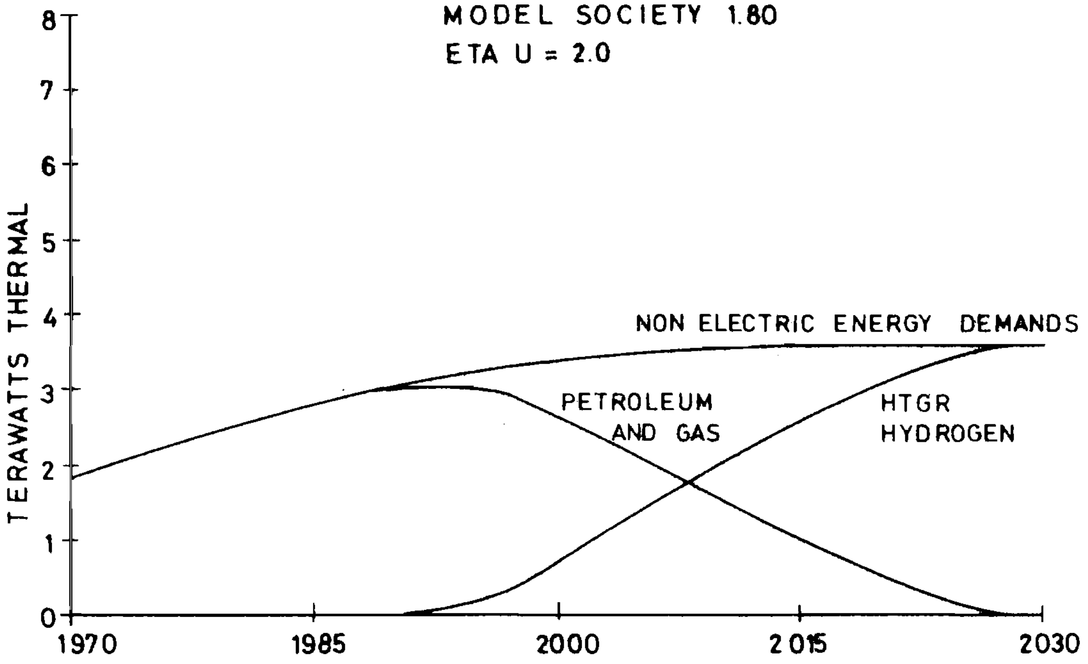

FIGURE 7a. NON ELECTRIC ENERGY DEMANDS AND SUPPLIES

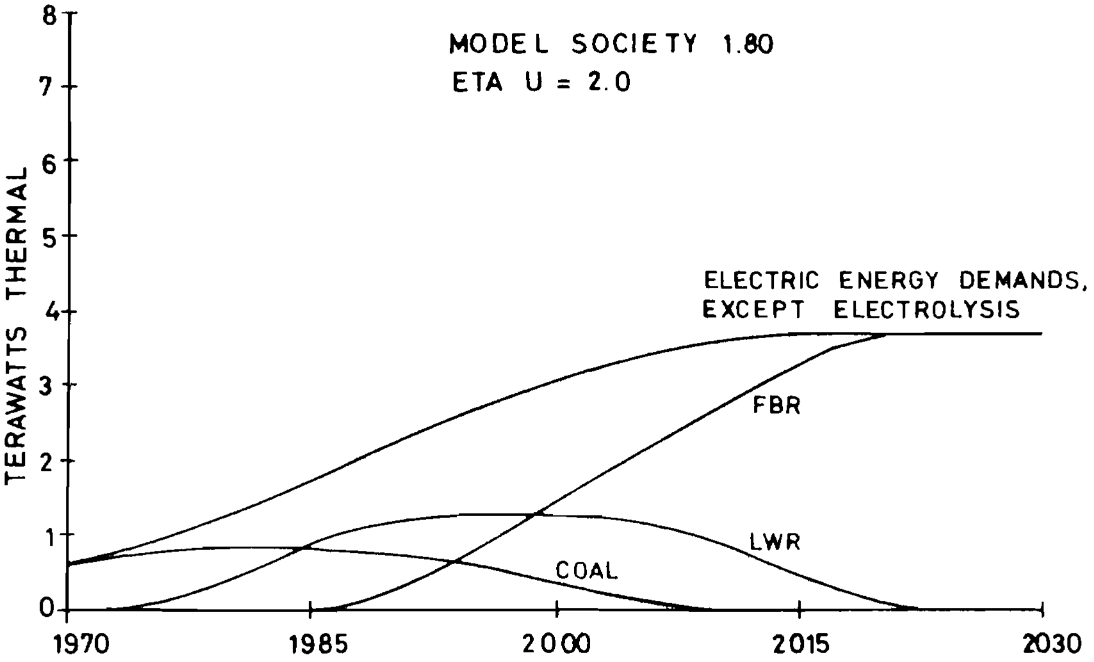

FIGURE 7b. ELECTRICITY DEMANDS AND SUPPLIES

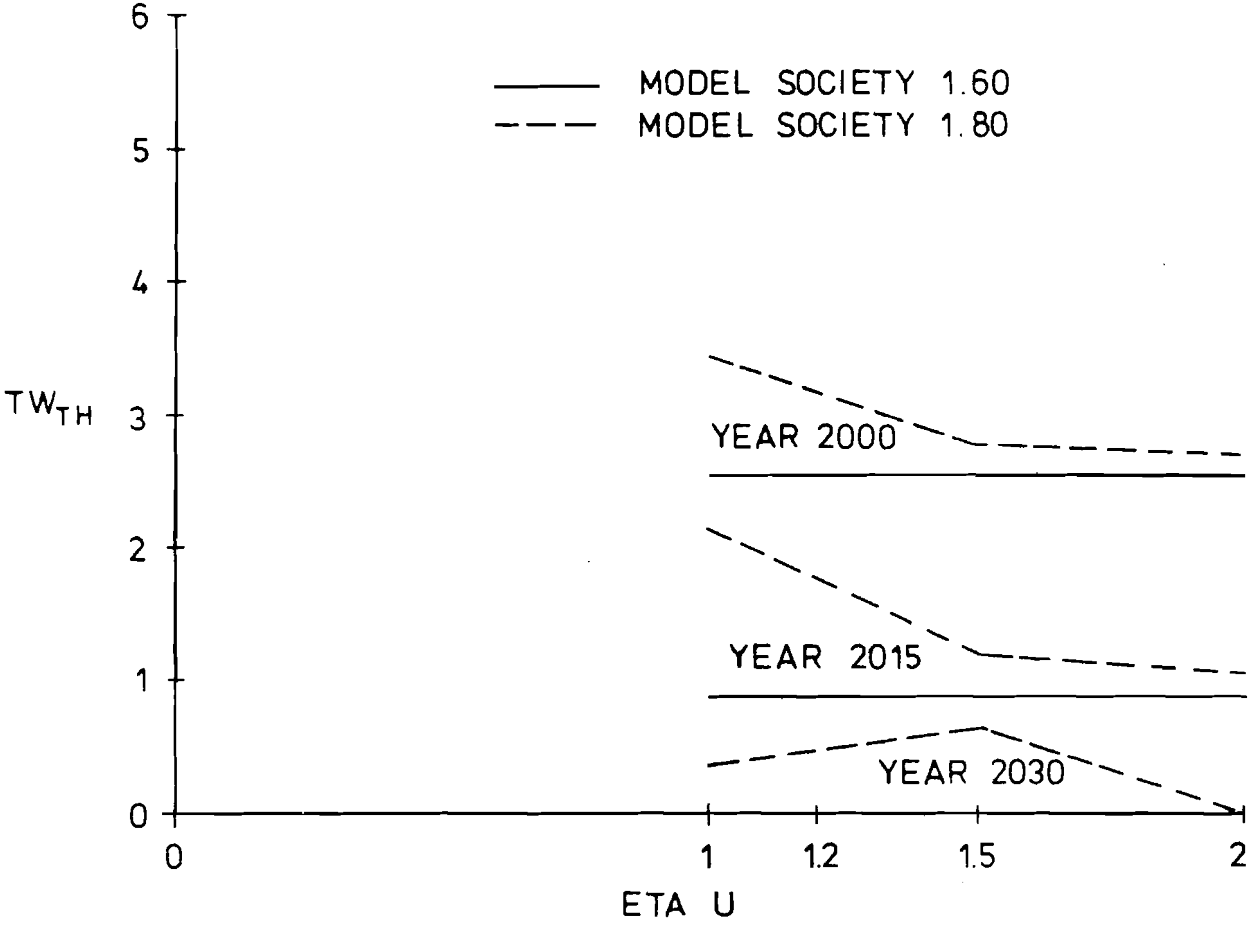

FIGURE 8. AMOUNT OF PETROLEUM AND GAS CAPACITY DEPENDENT ON ETA U

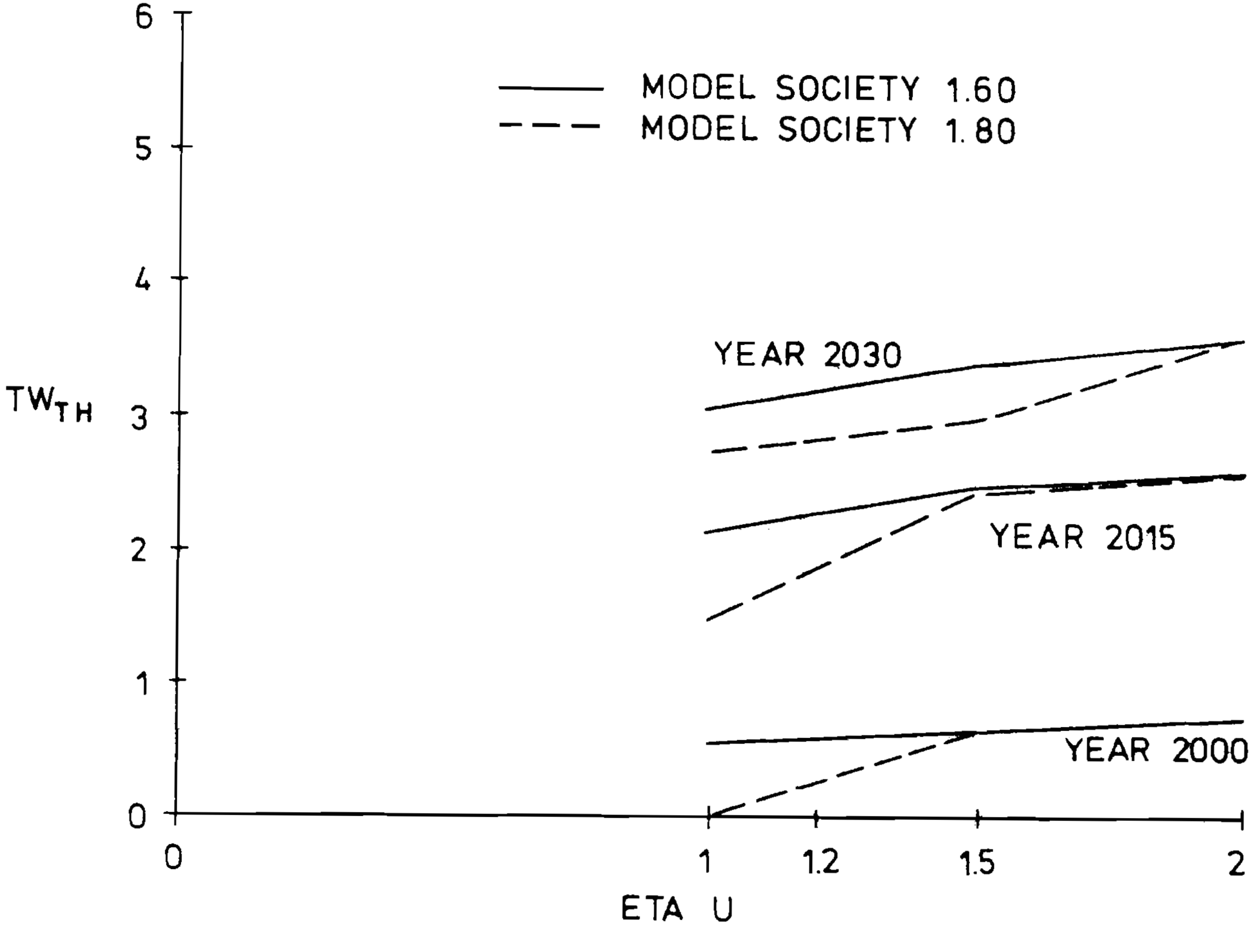

FIGURE 9. AMOUNT OF H T G R HYDROGEN DEPENDENT ON ETA U

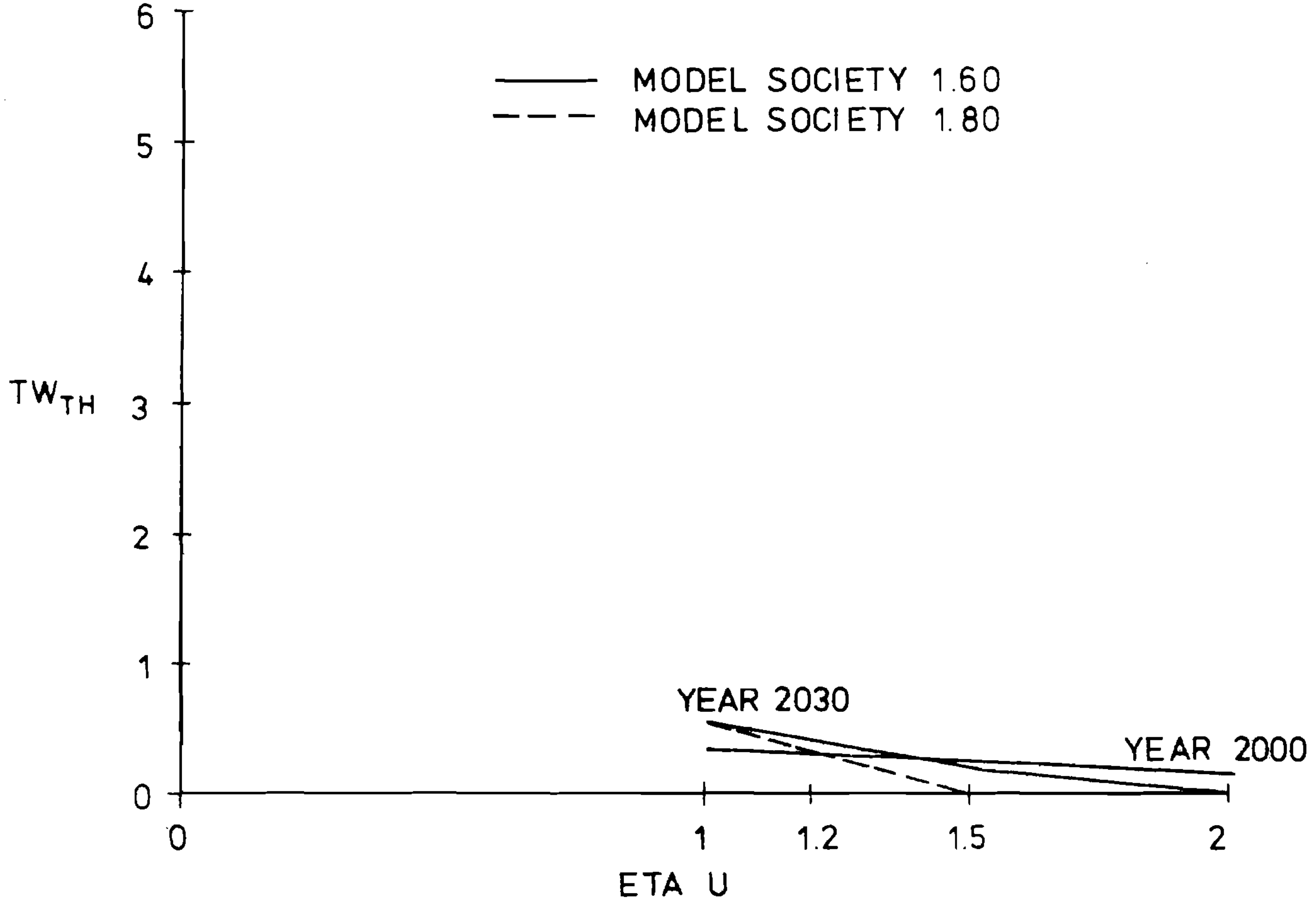

FIGURE 10. AMOUNT OF ELECTROLYTIC HYDROGEN DEPENDENT ON ETA U

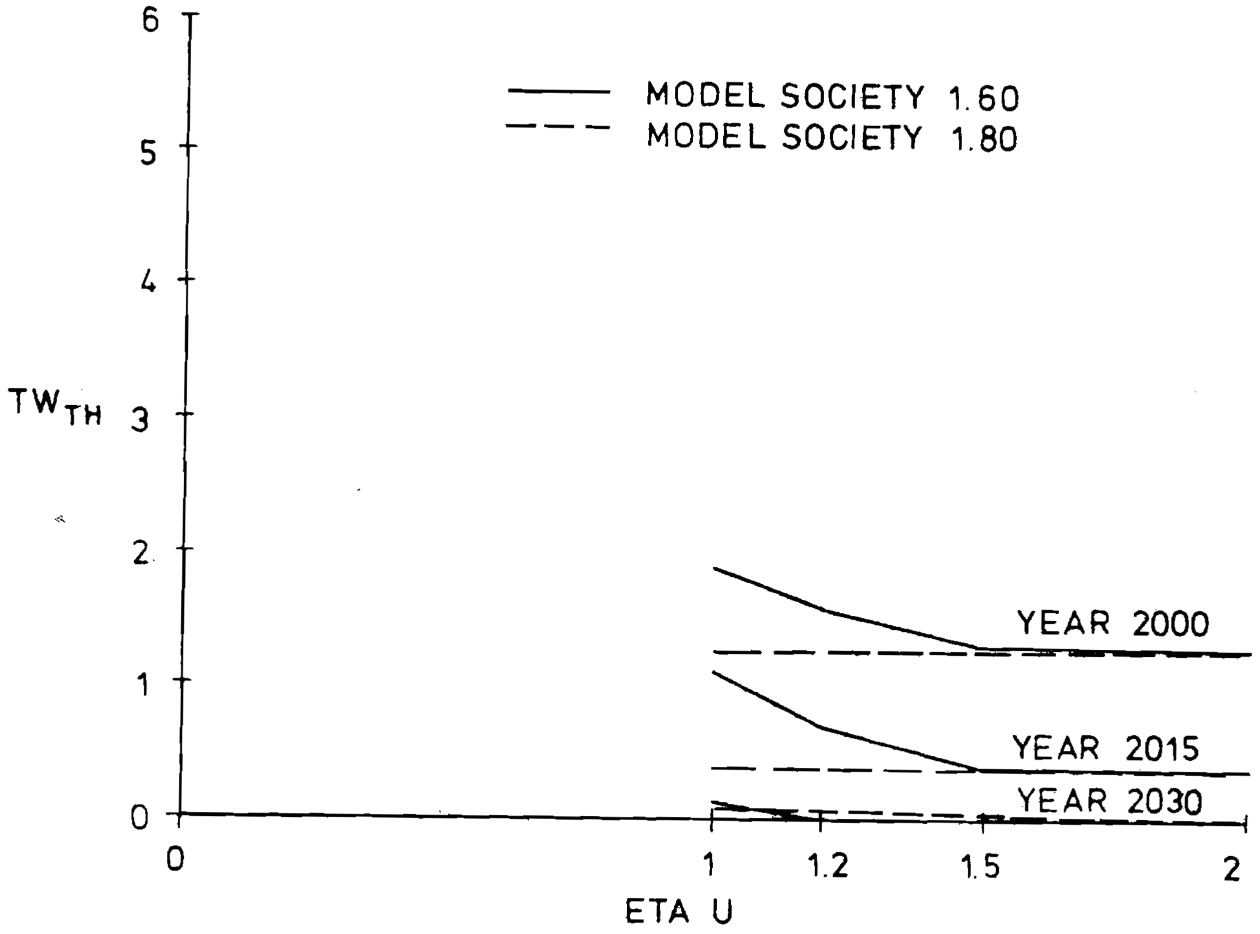

FIGURE 11. AMOUNT OF L W R CAPACITY DEPENDENT ON ETA U

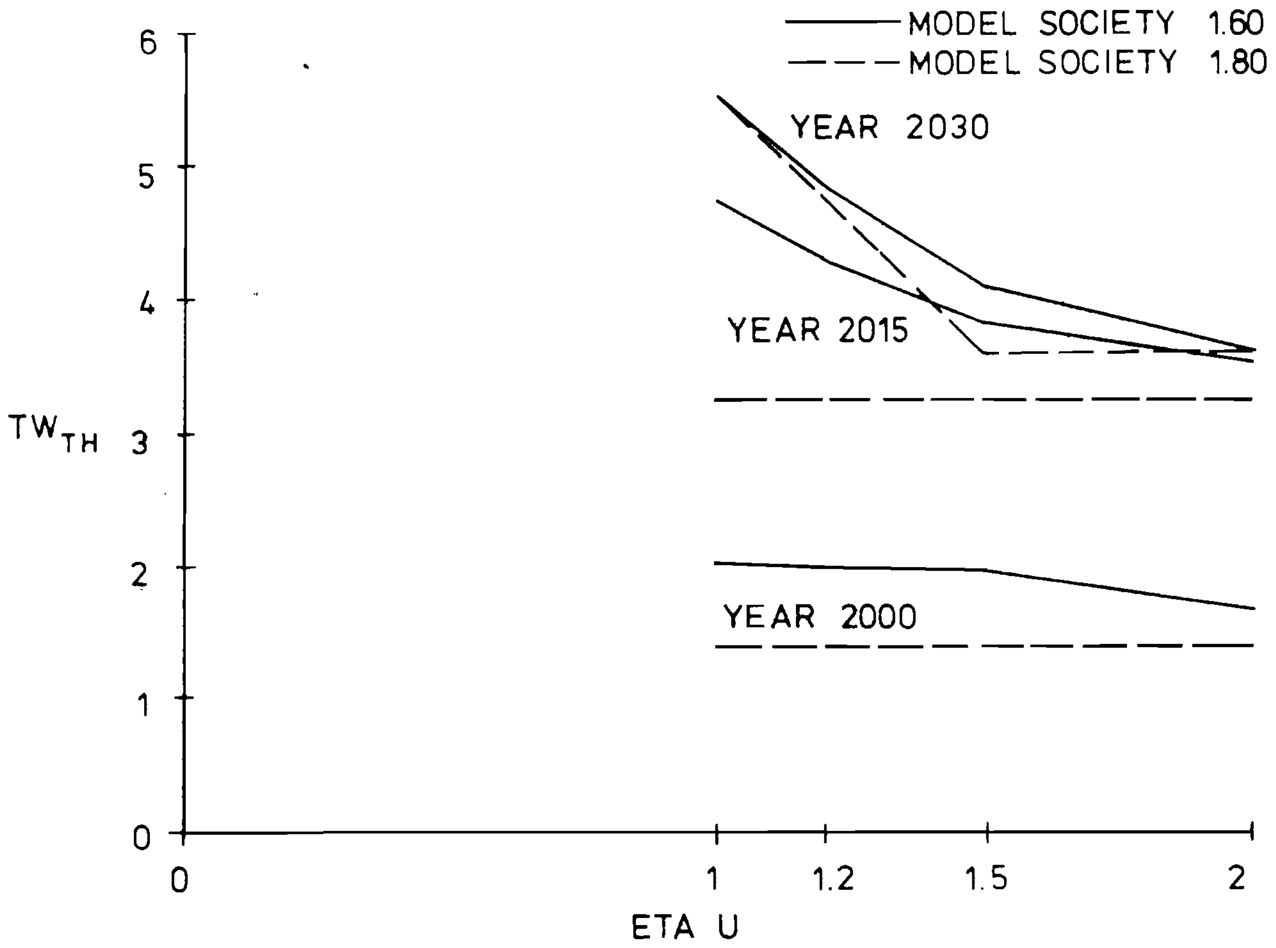

FIGURE 12. AMOUNT OF F B R CAPACITY DEPENDENT ON ETA U

References

[1] Häfele, W. and A.S. Manne. "Strategies for a Transition from Fossil to Nuclear Fuels." IIASA Report RR-74-7. Laxenburg, Austria, June 1974.