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A STUDY ON THE DEMAND ASPECTS OF THE HÄFELE-MANNE MODEL - AN APPLICATION OF THE MATHEMATICAL TECHNIQUE OF THE HOFFMAN MODEL

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A Study on the Demand Aspects of the Häfele-Manne Model - An Application of the Mathematical Technique of the Hoffman Model

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1. Introduction

Wolf Häfele and Alan Manne [1] present a dynamic model to find an optimal strategy on a transition from fossil to nuclear fuels such that the following five constraints hold in the planning horizon, 1970 to 2045, for a model society:

a) supply aspects:

1) the limited reserves of petroleum-and-gas,
2) the limited reserves of low-cost uranium,
3) the limited industrial capacity for construction of nuclear reactors,
4) the limited financial resources available to the energy supplying sector, and

b) demand aspects:

5) the minimum requirement of exogenous energy demands of the two macroscopic sectors, electrical energy and nonelectrical energy.

The energy supply alternatives considered in the model are:

a) for electrical energy:

1) coal steam generating plant,
2) light water moderated reactor (LWR), and
3) liquid metal fast breeder reactor (FBR), and

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b) for nonelectrical energy:

   1) petroleum-and-gas,
   2) hydrogen from thermochemical water splitting by process heat of high-temperature gas cooled reactor (HTGR), and
   3) hydrogen produced from electrolysis.

Almost all of the optimal solutions of the Häfele-Manne model indicate that the limited reserves of petroleum-and-gas necessitate the rapid change of the nonelectrical energy supply pattern from a petroleum-and-gas basis to a hydrogen basis. From the standpoint of individual energy consumers, however, for one consumer such an abrupt change is beyond acceptability due to the consumer's high inertia, while for another consumer it is acceptable owing to the consumer's flexibility. Therefore it is worthwhile considering the question of how rapidly the changes required by the optimal solution of the Häfele-Manne model must occur for the individually more disaggregated energy demand sectors. The analysis of this question with the help of the Hoffman model [2] is the general subject of this paper.

Kenneth Hoffman built a static model to determine an optimal energy resource allocation to the following fifteen demand sectors:

1) space heat,
2) air conditioning,
3) intermediate load electricity,
4) base load electricity,
5) peak load electricity,
6) water desalination,
7) pumped storage and synthetic fuel,
8) water heating,
9) miscellaneous thermal uses,
10) air transport,
11) ground transport, public and commercial,
12) ground transport, private,
13) iron production,
14) cement production, and
15) petrochemistry and synthetic materials.

While Hoffman's numerical results were shown in the year 2000 for the USA, the mathematical framework of this model is useful for any year in the future. If one can find conditions for compatibility between the Hoffman model and the Häfele-Manne model then one will be able to obtain an answer for the question mentioned above by making sequential use of the Hoffman model. The compatibility is concerned chiefly with the input data used in the two models. The Häfele-Manne model treats the society (model society 1) in which the energy demands are projected under the assumption that the primary energy consumption per capita doubles from 10 to 20 KW_{th} between the years 1970 and 2015, and the population size increases from 250×10^6 to 350×10^6. On the other hand the energy society treated in the Hoffman model is based on roughly 20 KW_{th}/cap with 300×10^6 people. Hence as far as the macroscopic specifications relevant to energy demand projections are concerned, it is possible to find a modelling condition which yields compatibility between the two models.

Now the purpose of this paper is to show the timing of an energy allocation pattern to Hoffman's fifteen demand sectors satisfying an optimal strategy of the Häfele-Manne model. More specifically, a linear programming optimization problem will be solved year by year by using the mathematical technique of the Hoffman model. The problem is characterized by:

a) the upper bound of energy supply of the individual supply alternatives fixed by an optimal solution of the Häfele-Manne model. For an illustration, the model society 1.60 is chosen; and

b) the lower bound of energy demand of the individual demand sectors fixed for each year, 1997, 2000, 2003, 2006, and 2009 in accordance with the demand projection of the Hoffman model.

2. Analytical Method[1]

The Hoffman model formulates a national energy system in a transportation network format. The network is quantified with the energy flows from alternate resources through the various conversion and delivery activities to specific end uses. The problem to be treated here has six exogenous (coal, LWR, FBR, petroleum-and-gas, HTGR-hydrogen, and electrolytic hydrogen) and one endogenous (pumped

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[1] See [2], pp. 60-70.

storage[2]) supply sectors, and fifteen demand sectors. The schematic description of the problem is shown in Figure 1 according to the Hoffman network.

In the Hoffman model the intermediate energy form on the individual possible paths from each supply sector to each demand sector is chosen as an independent variable to be optimized, and therefore the number of variables in our problem is 7 x 15 = 105 including all the possibilities.

Figure 2 illustrates the analytical method of the Hoffman model. For a given path j, a resource S_u is converted to intermediate energy form X_j at an efficiency e_{uj}. In turn the intermediate energy form is used to satisfy demand D_v at an efficiency D_{vj}. A cost c_j and set of coefficients f_{wj} describing other additional constraints are also defined per unit of intermediate energy form.

The mathematical formulation of the model is as follows:

minimize the total cost:[3] $C = \sum_j c_j x_j$,

subject to

1) supply constraint: $\sum_j \frac{1}{e_{uj}} x_j \leq S_u$,

2) demand constraint: $\sum_j d_{vj} x_j \geq D_v$,

3) other constraints: $\sum_j f_{wj} x_j \leq B_w$, and

4) nonnegativity condition: $x_j \geq 0$.

Supply constraint equations are defined for each supply sector, and demand constraint equations are defined for each demand sector except for peak electricity because the amount of peak electrical demand is given not exogenously but endogenously. Other constraints to be considered here are:

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[2] In the Hoffman model the supply sector of pumped storage has an important role in describing the mathematical constraints on energy load fluctuation, and the energy amount required for this sector is determined endogenously.

[3] In his original work, Hoffman used various objective functions. We here used his first one which he classified as "technological" strategy.

1) off-peak constraints that specify the maximum amount of energy available from each central station electrical source to serve off-peak electrical or thermal demands,

2) pumped storage and synthetic fuel balance equations that ensure equality between the amount of energy supplied to pumped storage and/or synthetic fuel and that delivered from pumped storage and/or synthetic fuel including losses, and

3) endogenous demand constraints by which portions of central station electrical demands can be reassigned internally to categories with different load factors.

3. Input Data Preparation

Now our problem has one objective function and three sorts of constraint equations: hence four sets of coefficients c_j, e_{uj}, d_{vj}, and f_{wj} and three sets of right-hand side values, S_u, D_v, and B_w are to be assigned for each year. For the purpose of this examination it is necessary in preparing these input data to use as much data of the Häfele-Manne model as possible.

While the Hoffman model considers the whole of the network shown in Figure 1, the Häfele-Manne model focuses on one-half, i.e. the energy supplying subsystem from each energy resource to each intermediate energy form (electrical and non-electrical energy). Therefore the Häfele-Manne model gives the input data for supply constraint equations and cost coefficients excluding delivery costs, and the Hoffman model is utilized to make up the input data for all the other constraint equations.

Table 1 shows the cost coefficients for our problem which are obtained from adding the Hoffman energy delivery costs to the Häfele-Manne energy costs. Further, Appendix A makes a comparison of the energy costs for each of the supply alternatives between the two models.

Table 2 gives the coefficients for supply constraint equations which correspond to the inverse of thermal efficiencies for coal, LWR, and FBR technologies and correspond to the production efficiencies of oil products and hydrogen for petroleum-and-gas and hydrogen technologies respectively.

In preparing the right-hand side values of supply constraint equations the compatibility study was done; it was found at the first computing trial that the equilibrium activity level 20 KW_{th}/cap of the model society 1.60 is not enough to satisfy the Hoffman demand constraints. Then a kind of trial-and-error computation was done in such a way that the equilibrium activity level was increased gradually up to the level which satisfies the Hoffman demand constraints.

As a result it turned out that the revised activity level of the Häfele-Manne model society 1.60 should be between 24 KW_{th}/cap and 25 KW_{th}/cap depending on the year, and finally the level 25 KW_{th}/cap was selected to yield the right-hand side values of supply constraint equations for each year, as shown in Table 3.

The coefficients of demand constraint equations were made up generally in accordance with the energy utilization efficiencies used in the Hoffman model. It is to be noted here that not only the Hoffman model but also the Häfele-Manne model defines the hydrogen utilization factor which implies BTU of petroleum-and-gas replaceable for one BTU of hydrogen utilized in end uses, and yet the values of that factor assessed in the two models are quite different (see Table 4). One of the authors did a sensitivity analysis on that factor of the Häfele-Manne model and demonstrated that the hydrogen utilization factor, the value of which was distributed from unity to two in the analysis, has a significant effect on the solution of the Häfele-Manne model [3]. In our problem treated here, however, the value is fixed as 1.5 for each demand sector according to the Häfele-Manne estimation.

The right-hand side values of demand constraint equations were assigned under the assumptions that the minimum requirement of energy, D_v, for each demand constraint, which the Hoffman model assesses for the year 2000, is kept relatively constant during the years 1997 to 2009, although total energy demand does vary with time in accordance with the Häfele-Manne demand projection. The values are shown in Table 5.

With respect to the other constraints, the input data used in the Hoffman model were also employed for our problem. Appendix B is attached to exhibit a complete set of the input data.

4. Calculation Result

Figures 3.1 to 3.15 are the representation of the time sequential changes of energy supply pattern for individual demand sectors which were obtained from our calculation.

The result indicates that:

1) For the demand sectors of space heat and air conditioning the rapid changes from petroleum-and-gas to hydrogen are observed (Figures 3.1 and 3.2).
2) Concerning the electrical demand sectors it is to be noted that the FBR supplies 100% of the requirements for both intermediate and base load electricities, and that, for peak electricity as well, it replaces the 1997 LWR energy supply role by 2009 (Figures 3.3 to 3.5).
3) For water desalination, petroleum-and-gas and LWR electricity are used almost equally for each year, and the energy supply pattern is at a steady state (Figure 3.6).
4) With respect to the pumped storage and synthetic fuel demand sector, all the energy is used for synthetic fuel (hydrogen) production and it is given in the form of electricity (Figure 3.7).
5) The water heating demand sector uses only hydrogen for each year. There is no change of energy supply pattern (Figure 3.8).
6) As for the demand sector of miscellaneous thermal uses, while LWR electricity meets about 40% of the total demand for each year, the remarkable change from petroleum-and-gas to hydrogen is required to meet the remaining 60% (Figure 3.9).
7) The energy supply pattern for the air transport is hardly realistic since the solution indicates that the revival use of petroleum-and-gas comes to pass in 2009 after the rapid change from petroleum-and-gas basis in 1997 to hydrogen basis in 2003 (Figure 3.10).
8) The optimal solution for the demand sectors of ground transports suggests that electric motor propulsion units which use electricity directly from central power stations and electric vehicles whose batteries are charged by off-peak electric energy should be employed for public-and-commercial uses and for private use respectively in place of internal combustion engines (Figures 3.11 and 3.12).

9) For all the remaining demand sectors of industrial uses, iron production, cement production, and petrochemistry-and-synthetic materials, the solution implies that nothing but petroleum-and-gas is used (Figures 3.13 to 3.15).

After all, the calculation result says that:

a) Ground transports must be based on electric propulsion systems instead of internal combustion engines before the year 2000. The energy requirement for these demands is about 25% of the total electrical demand in terms of primary energy form.

b) The energy demand for water heating must be met by hydrogen energy before the year 2000. The energy requirement for this demand is about 10% of the total hydrogen use in terms of primary energy form.

c) The technological renovation in the field of energy utilization on space heat, air conditioning, miscellaneous thermal uses and air transport must be done so as to accept the rapid change from petroleum-and-gas basis to hydrogen basis about the year 2000. The sum of these energy requirements is about 65% of the total petroleum-and-gas use in the year 2000.

Appendix C is attached for the complementary purpose of giving a complete set of the solutions.

5. Concluding Remarks

This study is just to observe the acceptability of the Häfele-Manne model strategy from the standpoint of the energy consumer's society, and it is not the aim of this paper to draw general conclusions on the acceptability. As far as the calculation result illustrated here is concerned, the optimal strategy of the Häfele-Manne model society 1.60 necessitates the rapid transformation of the manner of energy utilization in some demand sectors, such as space heat, water heating, miscellaneous thermal uses, air transport and ground transports.

If this transformation is beyond the acceptability of the individual demand sector, the Häfele-Manne model should be improved in this sense: one of the possible methods is to additionally take into consideration the constraint on the acceptability being described by an upper bound of increasing or decreasing rate of individual energy supply technology uses.

While both the Häfele-Manne and the Hoffman models presume that per capita primary energy consumption will be approximately 20 KW_{th}/cap in the year 2000, the illustrated example indicates that there is 20% to 25% difference between the two presumptions. This difference is due mainly to the fact that the Häfele-Manne model projects the energy demands in terms of primary energy form while the Hoffman model does so in terms of final energy form. There are two types of energy efficiency in the process from the primary energy form to the final energy form, and the energy requirements for individual end uses described in terms of primary energy form are significantly dependent on the two efficiencies lying in the corresponding process.

The demand sector where the efficiency dependency is the most remarkable is water desalination; it is presumed in the Hoffman model that the utilization efficiency of solar energy for water desalination is 100% while the efficiency of every other supply alternative is only 10%. Hence the optimal solution of the Hoffman model indicates that solar energy is the best for that sector because of this high efficiency, and yet, in our calculation result, more than 10% of the total primary energy requirement must be used for this sector because of the exclusion of the solar energy alternative. The inclusion of a solar option will be considered in subsequent work.

Table 1. Cost coefficients.

(\$/10^6 BTU of intermediate energy form, 100% Load factor)

	Current	Capital	Total
Coal Electricity1)	2.80	2.82	5.62
LWR Electricity1)	.58	3.25	3.83
FBR Electricity1)	.29	3.47	3.76
Pumped Storage2)	.17	1.52	1.69
Petroleum-&-Gas3)	2.26/1.75/1.36		2.26/1.75/1.36
HTGR Hydrogen	.67	1.73	2.40
Electrolytic Hydrogen2)	.20	.33	.55

[1] Corresponding intermediate energy form is electricity except for water desalination.

[2] Excluding the cost for used electricity.

[3] Corresponding intermediate energy forms are classified into three forms: gasoline/fuel oil/residual oil.

Table 2. Supply coefficients.

Supply Efficiency	Hoffman	Häfele-Manne
Coal Electricity	42%	40%
LWR Electricity	30%	33%
FBR Electricity	42%	40%
Pumped Storage	71%	2)
P-and-G Nonelectric	91%	3)
HTGR Hydrogen	2)	50%
Electrolytic Hydrogen	83%	80%

Note: 1) The values underlined are taken as input data.

2) The corresponding supply sector is not considered.

3) The value is not written explicitly.

Table 3. Supply constraints.

(Unit: mQ = 10^{15} BTU of primary energy form)

Year	1997	2000	2003	2006	2009
Coal Electricity	15.00	15.00	11.40	8.10	4.80
LWR Electricity	88.50	88.50	83.70	80.10	74.70
FBR Electricity	47.10	58.50	70.50	82.80	94.80
Pumped Storage	1.00	1.00	1.00	1.00	1.00
Petroleum-and-Gas	76.20	76.20	65.40	54.30	42.90
HTGR Hydrogen	10.80	29.40	49.20	68.70	87.30
Electrolytic Hydrogen	20.26	20.26	20.26	20.26	20.26

Table 4. Hydrogen utilization factor η_u estimated in the Hoffman model and the Häfele-Manne model.

Demand Sector (v)	$\eta_u(v)$	
	Hoffman	Häfele-Manne
Space Heat	1.26	av. 1.5
Air Conditioning	1.10	
Intermed. Elec. L.F. 0.5	1.47	
Base Load Elec. L.F. 1.0	1.47	
Peak Elec. L.F. 0.1	1.47	
Water Desalination	1.10	
Pumped Storage & Synth. Fuel	1.10	
Water Heating	1.10	
Misc. Thermal Uses	1.26	
Air Transport	1.10	
Ground Trans. Pub. & Coml.	1.10	
Ground Trans. Private	1.10	
Iron Production	1.10	
Cement Production	1.26	
Petrochem. & Synth. Matl.	1.10	

Supply Sectors — I.E.F. — Demand Sectors

a) $\text{P \& G} \xrightarrow[1/1.1]{} \text{oil products} \xrightarrow[d_v,\ \text{oil}]{} v$

b) $\text{HTGR or Electricity} \xrightarrow{} \text{Hydrogen} \xrightarrow[d_v,\ \text{hyd}]{} v$

$$\eta_u\ (v) = 1.1 \times \frac{d_v,\ \text{hyd}}{d_v,\ \text{oil}}$$

Table 5. Demand constraints.

(Unit: mQ = 10^{15} BTU of final energy form)

	1997	2000	2003	2006	2009
Space Heat	11.46	12.20	12.85	13.39	13.80
Air Conditioning	3.66	3.90	4.11	4.28	4.41
Intermed. Elec.	2.54	2.70	2.84	2.96	3.05
Base Load Elec.	12.21	13.00	13.69	14.27	14.71
Peak Elec.	-	-	-	-	-
Water Desalination	2.44	2.60	2.74	2.85	2.94
Pump. Storage & Synth. Fuel	5.92	6.30	6.64	6.92	7.13
Water Heating	2.54	2.70	2.84	2.96	3.05
Misc. Thml. Uses	35.50	37.80	39.82	41.50	42.77
Air Transport	1.60	1.70	1.79	1.87	1.92
Ground Trans. Pub. & Coml	2.82	3.00	3.16	3.29	3.39
Ground Trans. Private	5.73	6.10	6.43	6.70	6.90
Iron Production	1.88	2.00	2.11	2.20	2.26
Cement Production	1.31	1.40	1.47	1.54	1.58
Petrochem. & Synth. Matl.	9.86	10.50	11.06	11.53	11.88

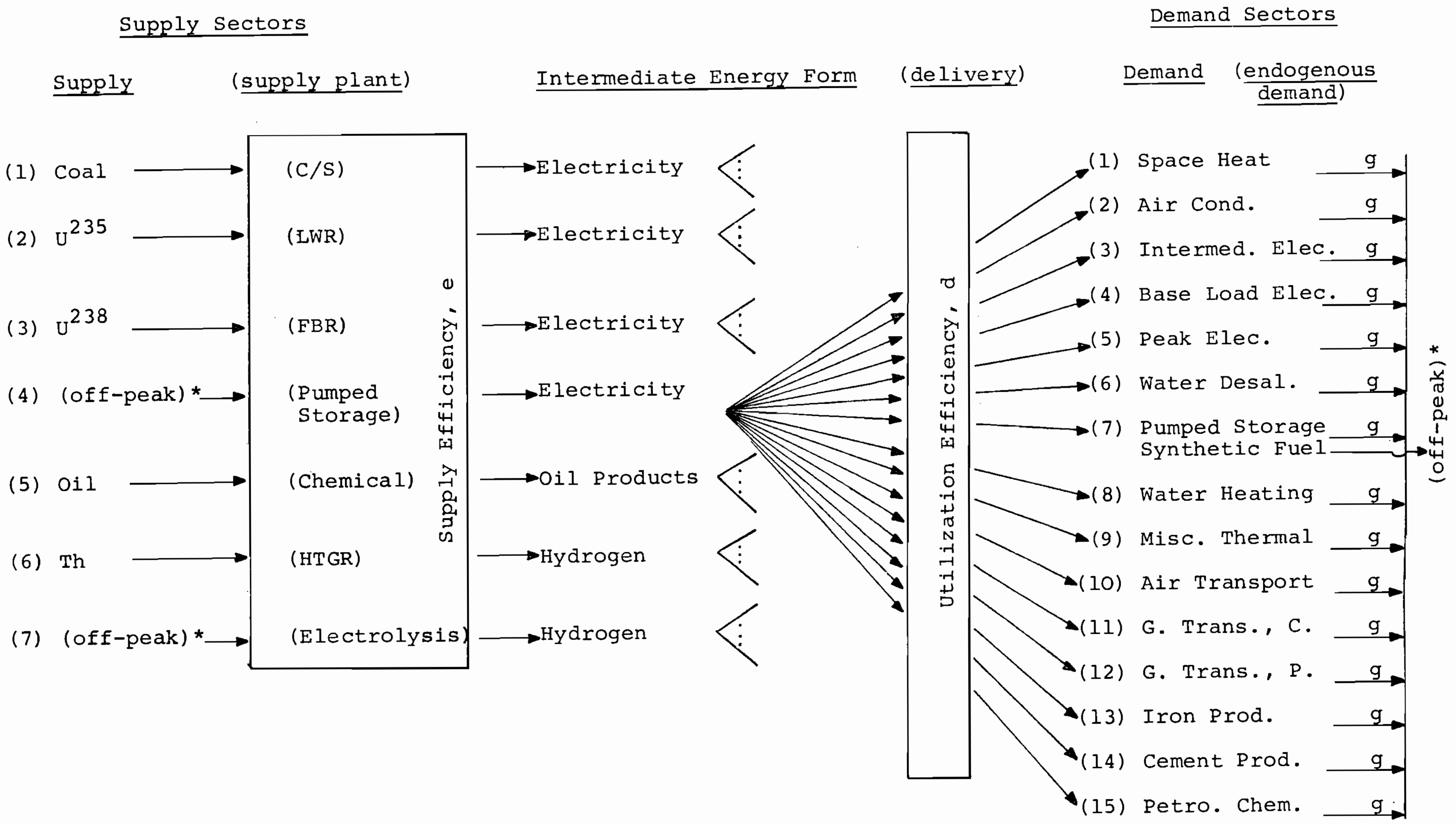
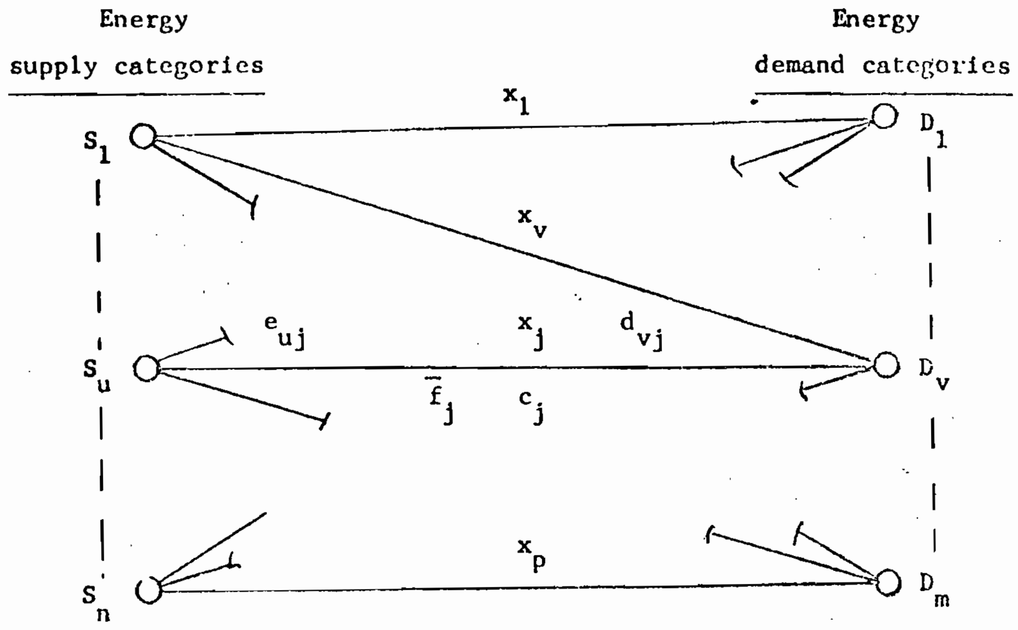


Figure 1. Schematic description of the problem in the format of the Hoffman model.



Definition of terms:

S_u	Supply constraints, u = 1,n
D_v	Demand constraints, v = 1,m
x_j	Quantity of intermediate energy form j delivered from S_u to D_v ; j=1,p where p=n·m
e_{uj}	Supply efficiency for energy x_j
d_{vj}	Utilization efficiency for energy x_j
$\bar{f}_j$	Other constraint equation coefficients for variables x_j, constrained by $\bar{B}$. Both $\bar{f}_j$ and $\bar{B}$ are column vectors of dimension ℓ
c_j	Cost per unit quantity of energy x_j

Figure 2. Graphical representation of linear programming model (after K.C. Hoffman [2], p. 61).

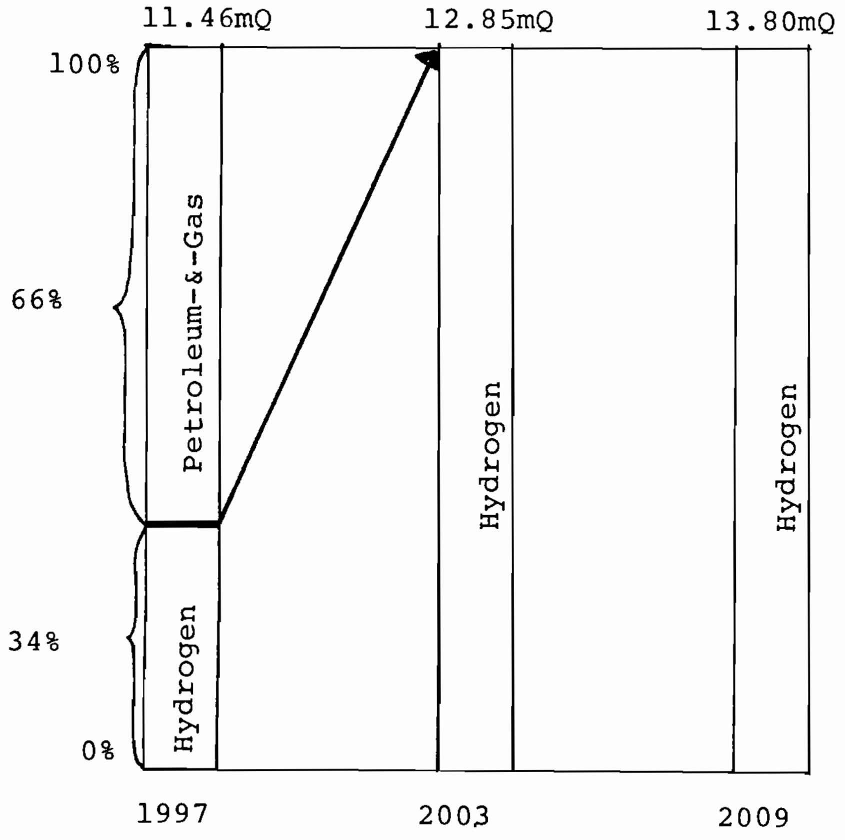


Figure 3.1. Time sequential change of energy supply pattern for space heat.

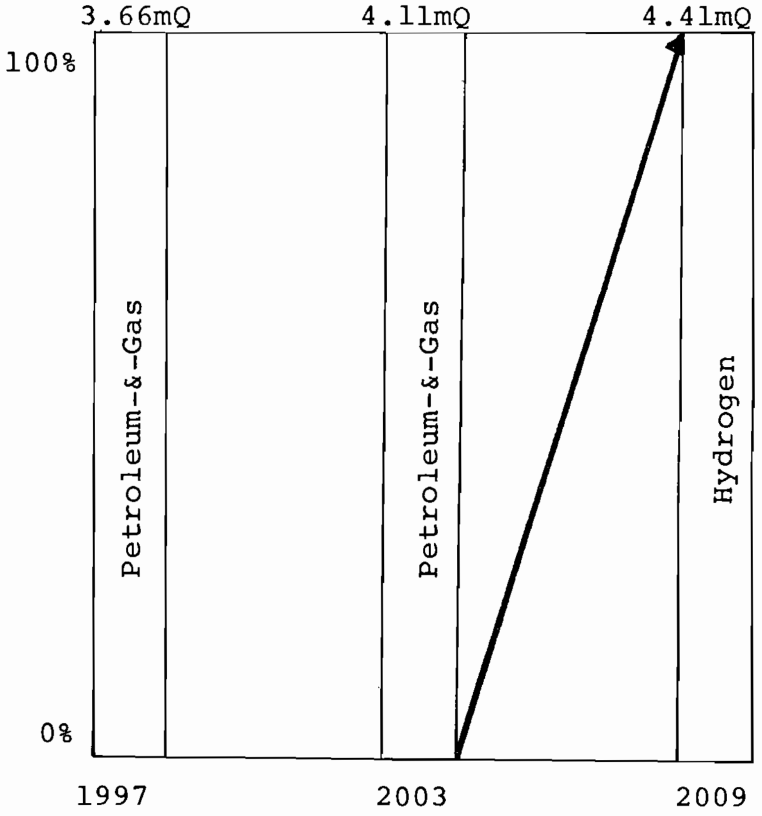


Figure 3.2. Time sequential change of energy supply pattern for air conditioning.

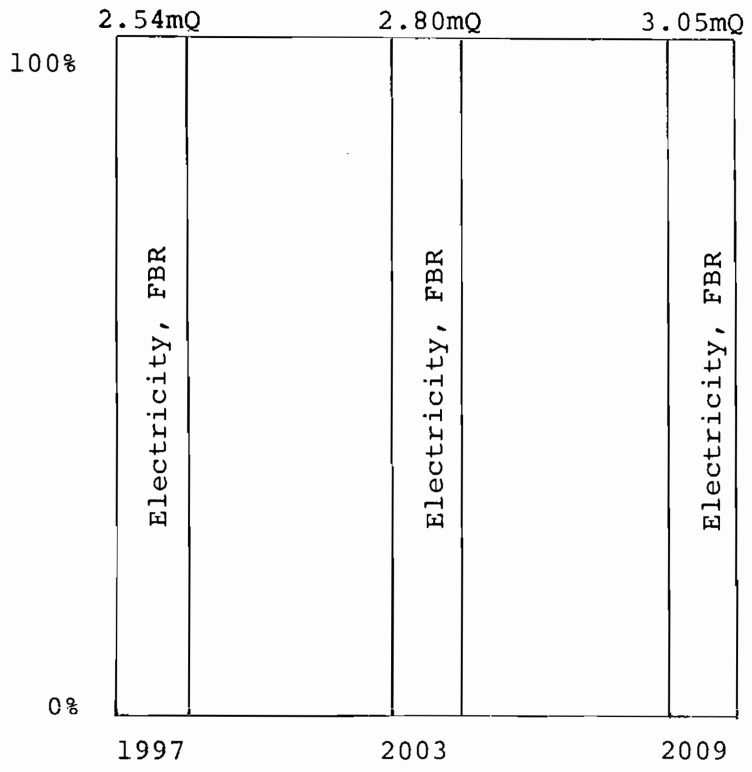


Figure 3.3. Time sequential change of energy supply pattern for intermediate load electricity.

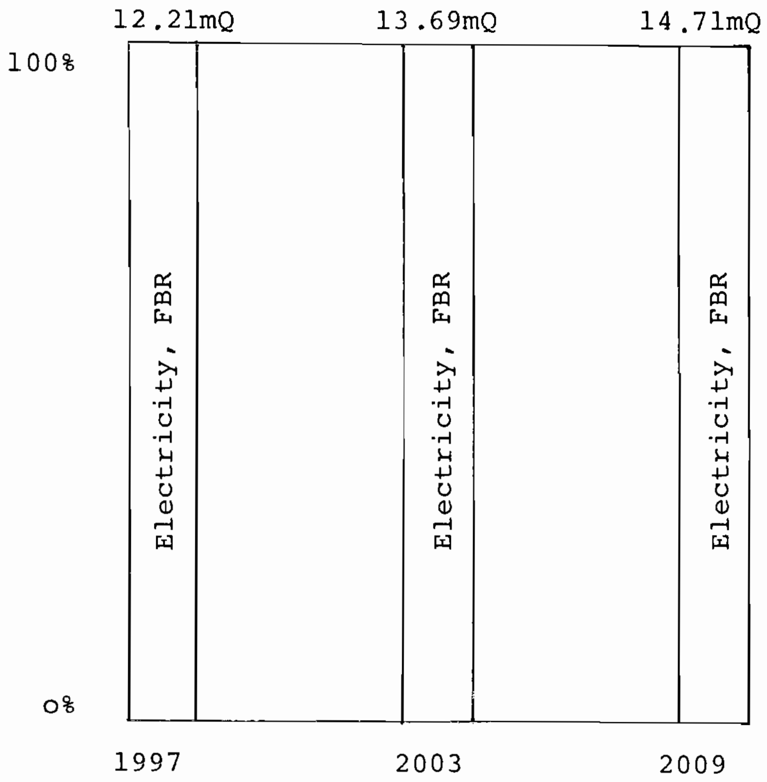


Figure 3.4. Time sequential change of energy supply pattern for base load electricity.

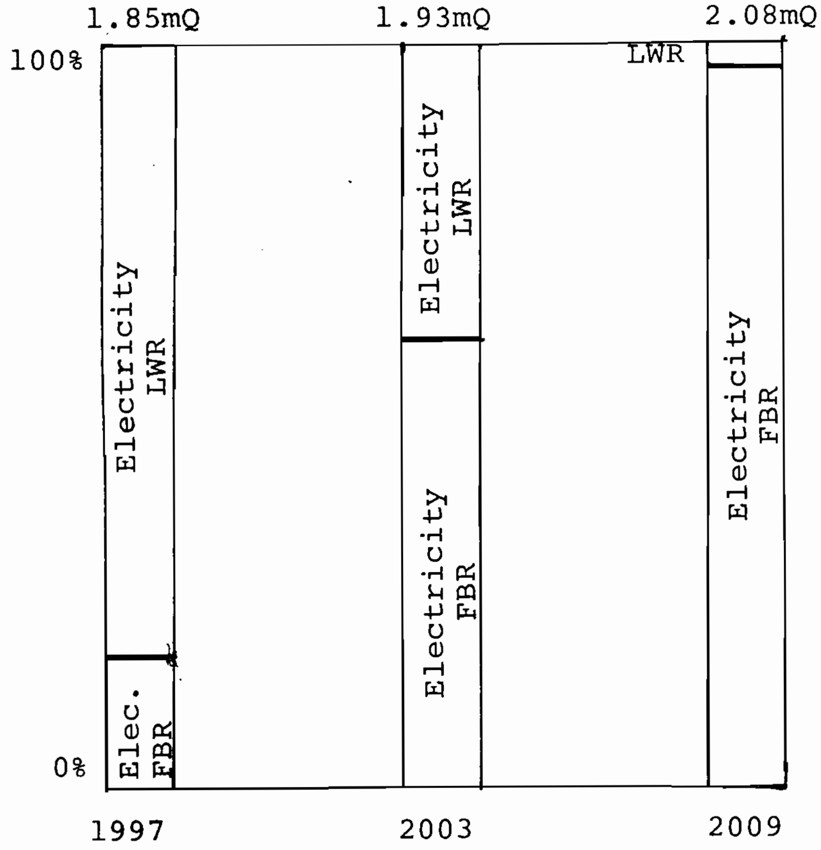


Figure 3.5. Time sequential change of energy supply pattern for peak electricity.

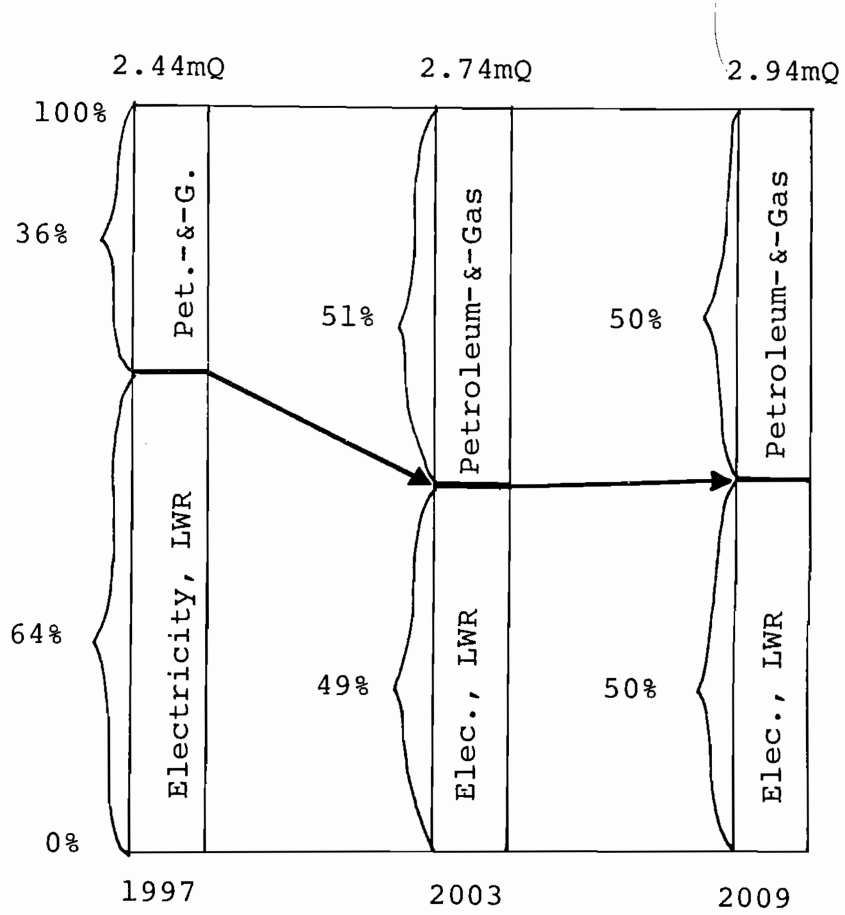


Figure 3.6. Time sequential change of energy supply pattern for water desalination.

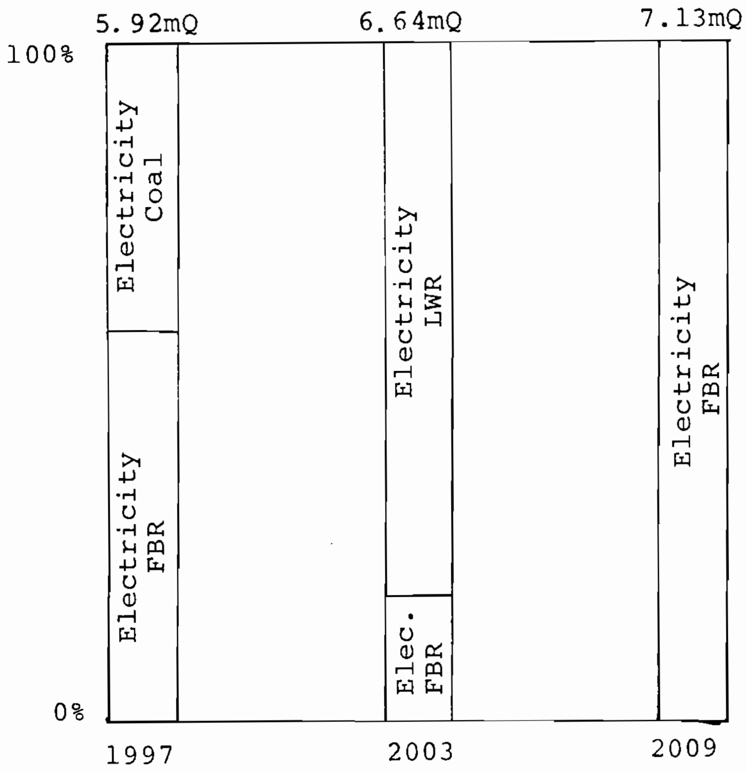


Figure 3.7. Time sequential change of energy supply pattern for pumped storage and synthetic fuel.

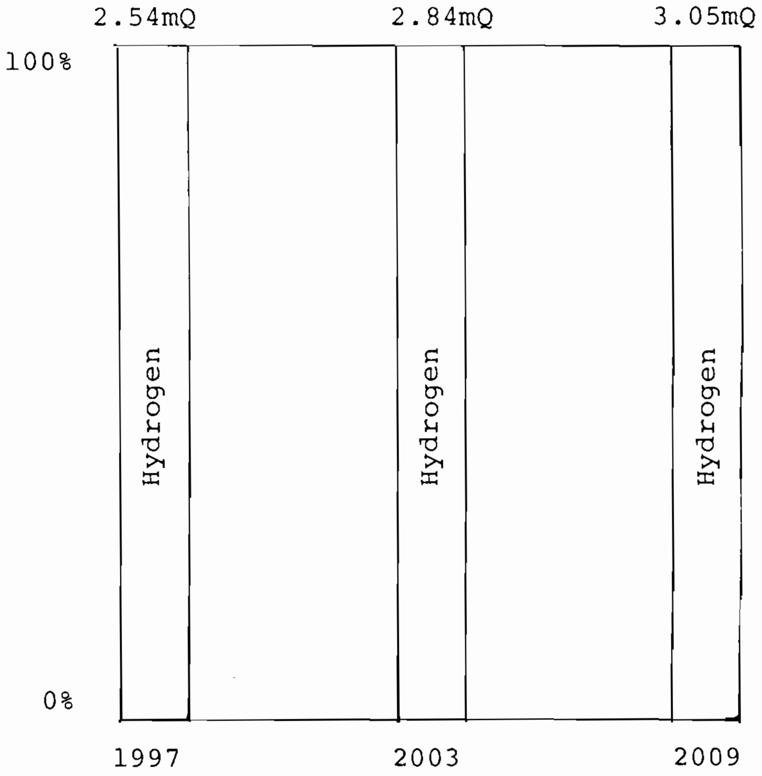


Figure 3.8. Time sequential change of energy supply pattern for water heating.

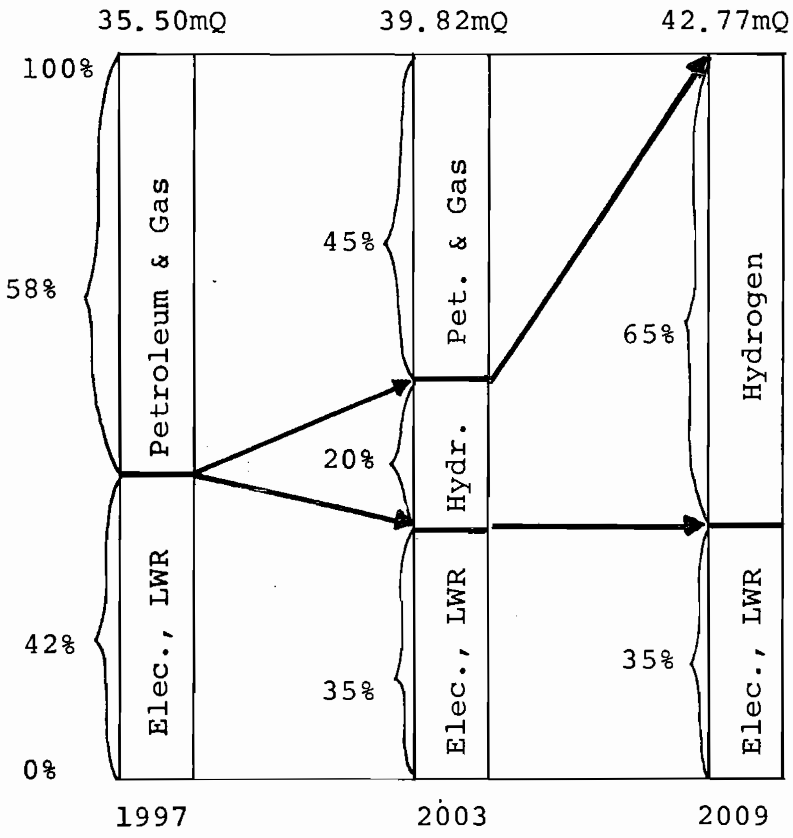


Figure 3.9. Time sequential change of energy supply pattern for miscellaneous thermal uses.

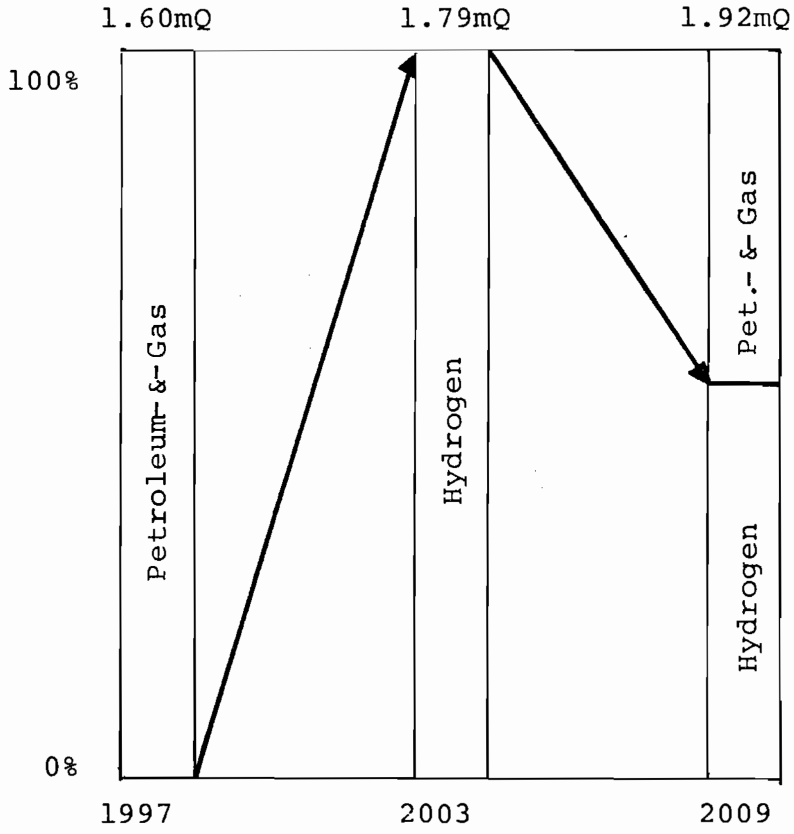


Figure 3.10. Time sequential change of energy supply pattern for air transport.

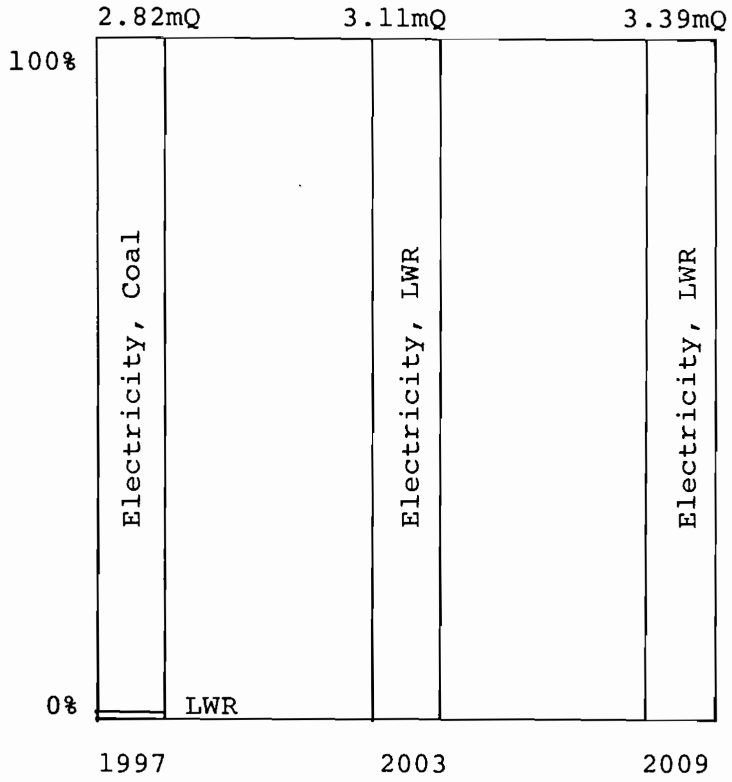


Figure 3.11. Time sequential change of energy supply pattern for ground transportation, public and commercial.

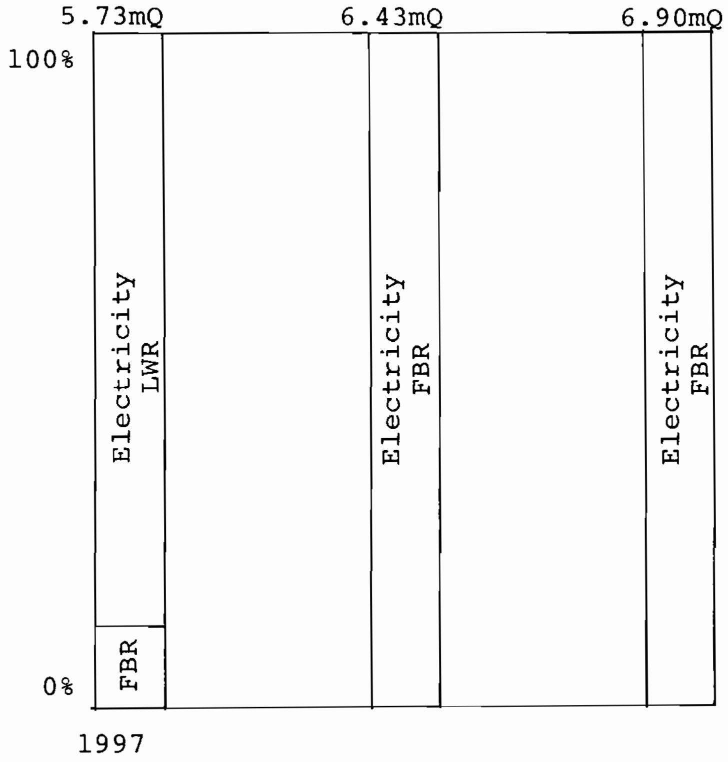


Figure 3.12. Time sequential change of energy supply pattern for ground transportation, private.

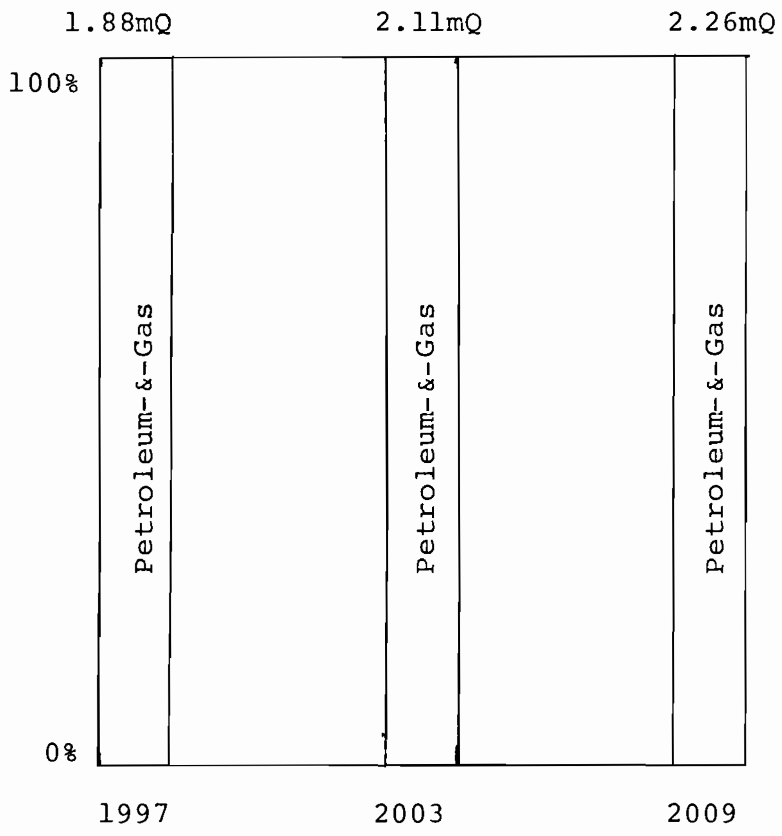


Figure 3.13. Time sequential change of energy supply pattern for iron production.

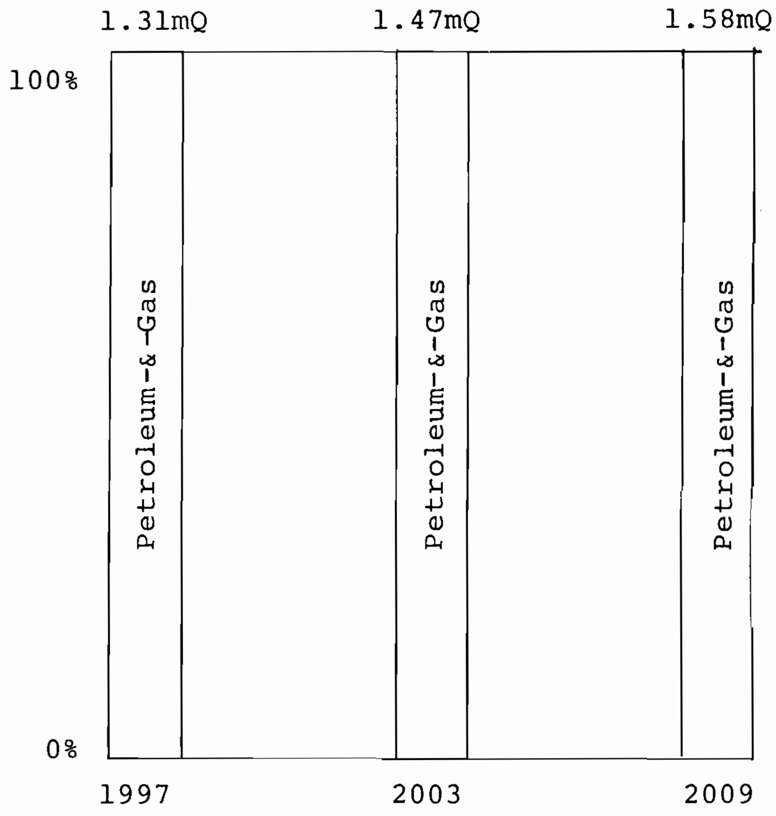


Figure 3.14. Time sequential change of energy supply pattern for cement production.

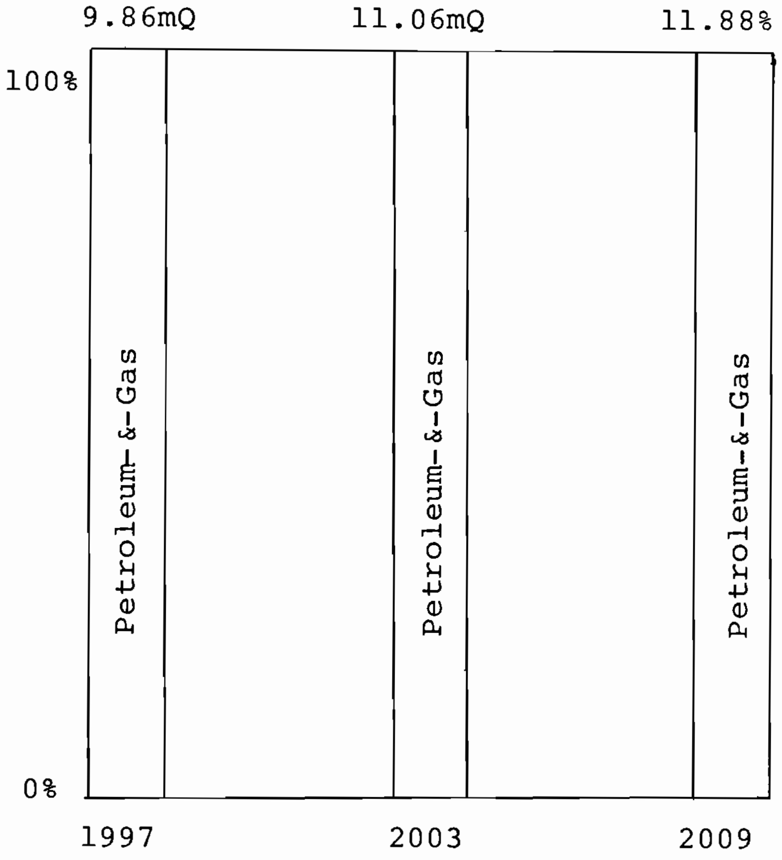


Figure 3.15. Time sequential change of energy supply pattern for petrochemistry and synthetic materials.

APPENDIX A

Comparison of Cost Estimations

The Hoffman estimation:

in terms of 1970 US dollars;

capital recovery factor is estimated by the conditions: annual interest rate 9.3%; plant life thirty years.

The Häfele-Manne estimation:

in terms of 1974 US dollars;

capital recovery factor is estimated by the conditions: annual interest rate 10%; plant life thirty years.

Table A.1. For coal electricity.

Coal Electricity		Hoffman	Häfele-Manne	Our problem
a) Current				
base[1)]	$\$/10^6BTU_{th}$	0.25	1.00	1.00
delivery	$\$/10^6BTU_{th}$	0.12		0.12
subtotal	$\$/10^6BTU_{th}$	0.37	1.00	1.12
thermal efficiency		0.42	0.40	0.40
for IEF[2)]	$\$/10^6BTU_e$	0.88	2.50	2.80
b) Capital (100% LF[3)])				
base	$/KWe	278	400	400
transmission	$/KWe	250		250
subtotal	$/KWe	528	400	650
CRF[4)]	/year	0.1	0.13	.13
for IEF[2)]	$\$/10^6BTU_e$	1.76	1.73	2.82
c) Total				
for IEF[2)]	$\$/10^6BTU_e$	2.64	4.23	5.62

[1] Including operating and maintenance cost.

[2] IEF = Intermediate Energy Form.

[3] LF = Load Factor.

[4] CRF = Capital Recovery Factor.

Table A.2. For LWR electricity.

	LWR Electricity		Hoffman	Häfele-Manne	Our problem
a)	Current				
	base	$\$/10^6\mathrm{BTU}_{th}$	0.16	0.19 1)	0.19 1)
	thermal efficiency		0.30	0.33	0.33
	for IEF	$\$/10^6\mathrm{BTU}_e$	0.53	0.58	0.58
b)	Capital (100% LF)				
	base	\$/KWe	337	500	500
	transmission	\$/KWe	250		250
	subtotal	\$/KWe	587	500	750
	CRF	/year	0.1	0.13	0.13
	for IEF	$\$/10^6\mathrm{BTU}_e$	1.96	2.17	3.25
c)	Total				
	for IEF	$\$/10^6\mathrm{BTU}_e$	2.49	2.75	3.83

[1] Including enrichment costs.

Table A.3. FBR electricity.

FBR Electricity			Hoffman	Häfele-Manne	Our problem
a)	Current				
	base	$/10^{6}BTU$_{th}$	0.11	0.12	0.12
	thermal efficiency		0.42	0.40	0.40
	for IEF	$/10^{6}BTU$_e$	0.26	0.29	0.29
b)	Capital (100% LF)				
	base	$/KWe	384	550	550
	transmission	$/KWe	250		250
	subtotal	$/KWe	634	550	800
	CRF	/year	0.1	0.13	0.13
	for IEF	$/10^{6}BTU$_e$	2.11	2.38	3.47
c)	Total				
	for IEF	$/10^{6}BTU$_e$	2.37	2.67	3.76

Table A.4. For pumped storage.

Pumped Storage		Hoffman	Häfele-Manne	Our problem
a) Current				
for IEF	$\$/10^6 BTU_e$	0.17	0.17	0.17
b) Capital (100% LF)				
base	$/KWe	100		
transmission	$/KWe	250		
subtotal	$/KWe	350		
CRF	/year	0.1	0.13	0.13
for IEF	$\$/10^6 BTU_e$	1.17	1.52	1.52
c) Total				
for IEF	$\$/10^6 BTU_e$	1.34	1.69	1.69

Table A.5. For petroleum-and-gas.

Petroleum-and-Gas Nonele.		Hoffman	Häfele-Manne	Our problem
a) Current				
crude oil	\$/barrel	shale oil1)	10	10
base	$\$/10^6$BTU			
gasoline		1.06	2.152)	2.152)
fuel oil		0.82	1.673)	1.673)
residual oil		0.64	1.304)	1.304)
delivery5)	$\$/10^6$BTU			
gasoline		0.11		0.11
fuel oil		0.08		0.08
residual oil		0.06		0.06
b) Capital		nil	nil	nil
c) Total				
for IEF	$\$/10^6$BTU			
gasoline		1.17	2.15	2.26
fuel oil		0.90	1.67	1.75
residual oil		0.70	1.30	1.36

[1] It is assumed that price of crude oil will escalate to but not exceed price of shale oil.

[2] $$\frac{\$10}{\text{barrel}} \times \frac{\text{barrel}}{6\text{x}10^6\text{BTU}} \times \frac{1.06}{0.82} = \$2.15/10^6\text{BTU}$$

[3] $$\frac{\$10}{\text{barrel}} \times \frac{\text{barrel}}{6\text{x}10^6\text{BTU}} \times \frac{0.82}{0.82} = \$1.67/10^6\text{BTU}$$

[4] $$\frac{\$10}{\text{barrel}} \times \frac{\text{barrel}}{6\text{x}10^6\text{BTU}} \times \frac{0.64}{0.82} = \$1.30/10^6\text{BTU}$$

[5] Cost of delivery in large quantities for utility and industrial uses.

Table A.6. For HTGR hydrogen.

HTGR Hydrogen		Hoffman	Häfele-Manne	Our Problem
a) Current				
base	$/10^{6}BTU$_{th}$		0.23	0.23
production efficiency			0.5	0.5
base	$/10^{6}BTU$_{Hyd}$		0.47	0.47
delivery	$/10^{6}BTU$_{Hyd}$	0.20		0.20
subtotal for IEF	$/10^{6}BTU$_{Hyd}$		0.47	0.67
b) Capital (100% LF)				
base	$/KWe		500	500
subtotal	$/KWe		500	500
CRF		0.1	0.13	0.13
for IEF	$/10^{6}BTU$_{Hyd}$		1.73	1.73
c) Total				
for IEF	$/10^{6}BTU$_{Hyd}$		2.20	2.40

Table A.7. For electrolytic hydrogen.

Electrolytic Hydrogen		Hoffman	Häfele-Manne	Our problem
a) Current				
base				
delivery	$/$10^6BTU_{Hyd}$	0.20		0.20
subtotal	$/$10^6BTU_{Hyd}$	0.20		0.20
b) Capital (100% LF)				
base	$/KWe		60	60
CRF	/year	0.1	0.13	0.13
production efficiency		0.83	0.80	0.80
for IEF	$/$10^6BTU_{Hyd}$	0.50	0.33	0.33
c) Total				
for IEF	$/$10^6BTU_{Hyd}$	0.70	0.33	0.55

APPENDIX B

A Complete Set of Input Data

Number of Variables	72
Number of Constraints	29
(1) Supply Constraints	7
(2) Demand Constraints	14
(3) Off-Peak Constraints	6
(4) Pumped Storage and Synthetic Fuel Balance Equation	1
(5) Endogenous Demand Constraint	1

Table B.1. Specification of indices j of variables representing intermediate energy form.

Supply \ Demand	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans. Private	Iron Production	Cement Production	Petrochem and Synth Matl.
Coal Electricity	1	2	3	4	5	6	7	8	9	*	10	11	12	13	*
LWR Electricity	14	15	16	17	18	19	20	21	22	*	23	24	25	26	*
FBR Electricity	27	28	29	30	31	32	33	34	35	*	36	37	38	39	*
Pumped Storage	*	*	40	*	41	*	*	*	*	*	*	*	*	*	*
P-and-G Nonelectric	42	43	**	**	**	44	*	45	46	47	48	49	50	51	52
HTGR Hydrogen	53	54	**	**	**	55	*	56	57	58	59	60	61	62	*
Electrolytic Hydrogen	63	64	**	**	**	65	*	66	67	68	69	70	71	72	*

Note: * The corresponding possible paths are omitted in Hoffman's model.

** The corresponding possible paths are omitted in our problem because the supply sectors for nonelectrical demand should not be used for electrical demand according to Häfele-Manne's model.

Table B.2. Cost coefficients ($\$/10^6$BTU of intermediate energy form).

Supply \ Demand	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Lead Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans Private	Iron Production	Cement Production	Petrochem and Synth Matl.
Coal Electricity	2.80	11.25	8.43	5.93	30.97	1.12	2.80	2.80	6.56		8.43	2.80	5.93	5.93	
LWR Electricity	0.58	10.33	7.08	4.19	33.08	0.19	0.58	0.58	4.91		7.08	0.58	4.19	4.19	
FBR Electricity	0.29	10.80	7.22	3.41	34.96	0.12	0.29	0.29	4.91		7.23	0.29	3.41		
Pumped Storage			3.20		15.34										
P-and-G Nonelectric	2.36	2.36				1.36		2.36	1.75	2.26	2.91	2.91	1.36	1.36	1.36
HTGR Hydrogen	3.27	3.27				2.57		3.27	2.57	3.57	4.77	4.77	2.57	2.57	
Electrolytic Hydrogen	1.23	1.23				0.53		1.23	0.53	1.53	2.73	2.73	0.53	0.53	

Table B.3. Coefficients $1/e_{ui}$ and right-hand side values S_u (mQ) of supply constraint equations.

Demand / Supply	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stye and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans. Private	Iron Production	Cement Production	Petrochem and Synth Matl.		Supply Constraint[1]
Coal Electricity	2.5	2.5	2.5	2.5	2.5	1.0	2.5	2.5	2.5		2.5	2.5	2.5	2.5			15.00
LWR Electricity	3.0	3.0	3.0	3.0	3.0	1.0	3.0	3.0	3.0		3.0	3.0	3.0	3.0			88.50
FBR Electricity	2.5	2.5	2.5	2.5	2.5	1.0	2.5	2.5	2.5		2.5	2.5	2.5	2.5			58.50
Pumped Storage			1.4		1.4												1.0
P-and-G Nonelectric	1.1	1.1				1.1		1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1		76.20
HTGR Hydrogen	2.0	2.0				2.0		2.0	2.0	2.0	2.0	2.0	2.0	2.0			29.40
Electrolytic Hydrogen	1.25	1.25				1.25		1.25	1.25	1.25	1.25	1.25	1.25	1.25			20.26

[1] For the year 2000, for example.

Table B. 4. Coefficients d_{vi} and right-hand side values D_v(mQ) of demand constraint equations.

Supply \ Demand	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth. Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans Private	Iron Production	Cement Production	Petrochem and Synth Matl.
Coal Electricity	1.0	3.0	1.0	1.0		0.1	1.0	1.0	1.0		0.8	0.6	0.6	1.0	
LWR Electricity	1.0	3.0	1.0	1.0		0.1	1.0	1.0	1.0		0.8	0.6	0.6	1.0	
FBR Electricity	1.0	3.0	1.0	1.0		0.1	1.0	1.0	1.0		0.8	0.6	0.6	1.0	
Pumped Storage			1.0												
P-and-G Nonelectric	0.7	2.5				0.1		0.7	0.7	0.2	0.2	0.2	0.4	0.7	1.0
HTGR Hydrogen	1.0	3.4				0.1		1.0	1.0	0.3	0.3	0.3	0.5	1.0	
Electrolytic Hydrogen	1.0	3.4				0.1		1.0	1.0	0.3	0.3	0.3	0.5	1.0	
Demand Constraint[1]	12.2	3.9	2.7	13.0		2.6	6.3	2.7	37.8	1.7	3.0	6.1	2.0	1.4	10.5

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[1] For the year 2000, for example.

Table B.5. Coefficients of weekly off-peak constraint equations.

Demand / Supply	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans. Private	Iron Production	Cement Production	Petrochem and Synth Matl.		Right-Hand Side Value
Coal Electricity			-0.8		-8.0	0.42	1.0	1.0	-0.2		-0.8	1.0				≤	0.0
LWR Electricity			-0.8		-8.0	0.42	1.0	1.0	-0.2		-0.8	1.0				≤	0.0
FBR Electricity			-0.8		-8.0	0.42	1.0	1.0	-0.2		-0.8	1.0				≤	0.0
Pumped Storage																	
P-and-G Nonelectric																	
HTGR Hydrogen																	
Electrolytic Hydrogen																	
Demand Constraint																	

Table B.6. Coefficients of seasonal off-peak constraint equations.

Demand Supply	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans. Private	Iron Production	Cement Production	Petrochem and Synth Matl.		Right-Hand Side Values
Coal Electricity	1.00	-1.25														≤	0.0
LWR Electricity	1.00	-1.25														≤	0.0
FBR Electricity	1.00	-1.25														≤	0.0
Pumped Storage																	
P-and-G Nonelectric																	
HTGR Hydrogen																	
Electrolytic Hydrogen																	
Demand Constraint																	

Table B.7. Coefficients of pumped storage and synthetic fuel balance equations.

Demand / Supply	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans. Private	Iron Production	Cement Production	Petrochem and Synth Matl.		Right-Hand Side Value
Coal Electricity							-1.0										
LWR Electricity							-1.0										
FBR Electricity							-1.0										
Pumped Storage			1.4		1.4										}	=	0.0
P-and-G Nonelectric																	
HTGR Hydrogen																	
Electrolytic Hydrogen	1.25	1.25				1.25		1.25	1.25	1.25	1.25	1.25	1.25	1.25			
Demand Constraint																	

Table B.8. Coefficients of endogenous demand constraint equations.

Demand Supply	Space Heat	Air Conditioning	Intermed. Elec. L.F. 0.5	Base Load Elec. L.F. 1.0	Peak Elec. L.F. 0.1	Water Desalination	Pump Stge and Synth Fuel	Water Heating	Misc. Thermal Uses	Air Transport	Ground Trans. Pub. and Coml.	Ground Trans. Private	Iron Production	Cement Production	Petrochem and Synth Matl.		Right-Hand Side Value
Coal Electricity		0.2	0.1	0.05	-1.0				0.05		0.1						
LWR Electricity		0.2	0.1	0.05	-1.0				0.05		0.1						
FBR Electricity		0.2	0.1	0.05	-1.0				0.05		0.1						
Pumped Storage			0.1		-1.0											=	0.0
P-and-G Nonelectric																	
HTGR Hydrogen																	
Electrolytic Hydrogen																	
Demand Constraint																	

APPENDIX C

Time Sequential Change of Energy Allocation Pattern of Individual Supply Alternatives

(Unit: mQ = 10^{15} BTU of primary energy form)

Table C.1. Coal electric energy.

	1997	2000	2003	2006	2009
Space Heat					
Air Conditioning					
Intermed. Elec.					
Based Load Elec.					
Peak Elec.					
Water Desalination					
Pump. Stge. and Synth. Fuel	6.35		.01		
Water Heating					
Misc. Thml. Uses					
Air Transport					
Ground Trans., Pub. and Coml.	7.93	.20	.01		
Ground Trans., Private		.15			
Iron Production					
Cement Production					
Petrochem. and Synth. Matl.					
Total	14.28	.35	.02	.00	.00
Supply Constraint	15.00	15.00	11.40	8.10	4.80
Slack	.72	14.65	11.38	8.10	4.80

Table C.2. LWR electric energy.

	1997	2000	2003	2006	2009
Space Heat					
Air Conditioning					
Intermed. Elec.					
Base Load Elec.					
Peak Elec.	4.53	3.27	2.28	1.17	.12
Water Desalination	15.74	12.53	13.39	14.24	14.63
Pump. Stge. and Synth. Fuel		18.90	17.82	8.64	
Water Heating					
Misc. Thml. Uses	43.05	36.96	39.45	41.70	41.46
Air Transport					
Ground Trans., Pub. and Coml.	.09	9.99	10.77	11.22	11.55
Ground Trans., Private	25.11	6.81			
Iron Production					
Cement Production					
Petrochem. and Synth. Matl.					
Total	88.50	88.50	83.70	76.96	67.75
Supply Constraint	88.50	88.50	83.70	80.10	74.70
Slack	.00	.00	.00	3.14	6.95

Table C.3. FBR electric energy.

	1997	2000	2003	2006	2009
Space Heat					
Air Conditioning					
Intermed. Elec.	5.78	6.13	6.45	6.73	6.93
Base Load Elec.	29.08	30.95	32.60	33.98	35.03
Peak Elec.	.85	1.83	2.93	4.08	5.10
Water Desalination					
Pump. Stge. and Synth. Fuel	8.45		1.75	10.10	17.83
Water Heating					
Misc. Thml. Uses					1.18
Air Transport					
Ground Trans., Pub. and Coml.					
Ground Trans., Private	2.95	19.58	26.80	27.93	28.75
Iron Production					
Cement Production					
Petrochem. and Synth. Matl.					
Total	47.10	58.50	70.50	82.80	94.80
Supply Constraint	47.10	58.50	70.50	82.80	94.80
Slack	.00	.00	.00	.00	.00

Table C.4. Pumped storage.

	1997	2000	2003	2006	2009
Space Heat					
Air Conditioning					
Intermed. Elec.					
Base Load Elec.					
Peak Elec.					
Water Desalination					
Pump. Stge. and Synth. Fuel					
Water Heating					
Misc. Thml. Uses					
Air Transport					
Ground Trans. Pub. and Coml.					
Ground Trans., Private					
Iron Production					
Cement Production					
Petrochem. and Synth. Matl.					
Total	.00	.00	.00	.00	.00
Supply Constraint	1.00	1.00	1.00	1.00	1.00
Slack	1.00	1.00	1.00	1.00	1.00

Table C.5. Petroleum-and-gas.

	1997	2000	2003	2006	2009
Space Heat	6.07				
Air Conditioning	1.61	1.72	1.80	1.88	
Intermed. Elec.					
Base Load Elec.					
Peak Elec.					
Water Desalination	9.53	15.21	15.41	15.69	16.25
Pump. Stge. and Synth. Fuel					
Water Heating					
Misc. Thml. Uses	32.12	39.06	27.91	5.29	
Air Transport	8.80	1.36		10.29	4.88
Ground Trans., Pub. and Coml.					
Ground Trans., Private					
Iron Production	5.17	5.50	5.81	6.05	6.22
Cement Production	2.06	2.20	2.31	2.42	2.49
Petrochem. and Synth. Matl.	10.85	11.55	12.17	12.68	13.07
Total	76.20	76.20	65.40	54.30	42.90
Supply Constraint	76.20	76.20	65.40	54.30	42.90
Slack	.00	.00	.00	.00	.00

Table C.6. HTGR hydrogen.

	1997	2000	2003	2006	2009
Space Heat	10.80	14.32	15.08	26.78	22.30
Air Conditioning					2.60
Intermed. Elec.					
Base Load Elec.					
Peak Elec.					
Water Desalination					
Pump. Stge. and Synth. Fuel					
Water Heating		5.40	5.68		
Misc. Thml. Uses			16.52	41.92	55.54
Air Transport		9.68	11.94		6.88
Ground Trans., Pub. and Coml.					
Ground Trans., Private					
Iron Production					
Cement Production					
Petrochem. and Synth. Matl.					
Total	10.80	29.40	49.20	68.70	87.30
Supply Constraint	10.80	29.40	49.20	68.70	87.30
Slack	.00	.00	.00	.00	.00

Table C.7. Electrolytic hydrogen.

	1997	2000	2003	2006	2009
Space Heat	2.75	6.30	6.64		3.31
Air Conditioning					
Intermed. Elec.					
Base Load Elec.					
Peak Elec.					
Water Desalination					
Pump. Stge. and Synth. Fuel					
Water Heating	3.18			3.70	3.81
Misc. Thml. Uses				3.23	
Air Transport					
Ground Trans., Pub. and Coml.					
Ground Trans., Private					
Iron Production					
Cement Production					
Petrochem. and Synth. Matl.					
Total	5.92	6.30	6.64	6.92	7.13
Supply Constraint	20.26	20.26	20.26	20.26	20.26
Slack	14.34	13.96	13.62	13.34	13.13

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