APPENDICES

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APPENDIX 1. CLINE'S GROWTH RATE PROJECTIONS: CLOSING THE INCOME GAP IN 650 YEARS

In 1992 William Cline prepared an influential study on the economics of global warming. In order to estimate benefits and costs of global warming, and of efforts to reduce it, some base-line projections of economic growth over the period of concern are necessary. Cline's base-line projections for the more developed countries (MDC's) and the less developed countries (LDC's) are shown in **A1-1.** In the case of global warming the period of concern is two or three centuries.

Equity considerations were not a major focus of Cline's study, but that makes a look at the equity implications of his assumed growth trajectories all the more telling. We see that Cline projects that the ratio between the per capita incomes of the more and less developed countries will decline from about 4.3:1 to about 3:1 over the next 275 years. If the growth rates projected for 2275 remain unchanged after that date, the LDC's will "catch up" with the MDC's after an additional 365 years.[1] Per capita incomes in 2650 would be about $390,000, and average income for a family of four would be about $1,600,000.

[1] Given 185,397e^(.002t) = 61,376e^(.005t), then t = 365.

BOX A1-1. CLINE'S GROWTH RATE PROJECTIONS: CLOSING THE INCOME GAP IN 650 YEARS

Source: Cline (1992)

per capita income (1990 US $)	2000	2025	2050	2075	2100	2125	2150	2175	2200	2225	2250	2275
MDC's	17,020	22,934	30,902	41,639	56,106	71,953	92,274	112,614	137,438	155,689	176,364	185,397
growth rate (%/y	1.2	1.2	1.2	1.2	1.2	1.0	1.0	0.8	0.8	0.5	0.5	0.2
LDC's	3,985	5,782	8,389	12,172	15,610	20,019	25,673	32,924	42,222	47,829	54,181	61,376
growth rate (%/y	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5
MDC's/LDC's	4.27	3.97	3.68	3.42	3.59	3.59	3.59	3.42	3.26	3.26	3.26	3.02

FIGURE 1.

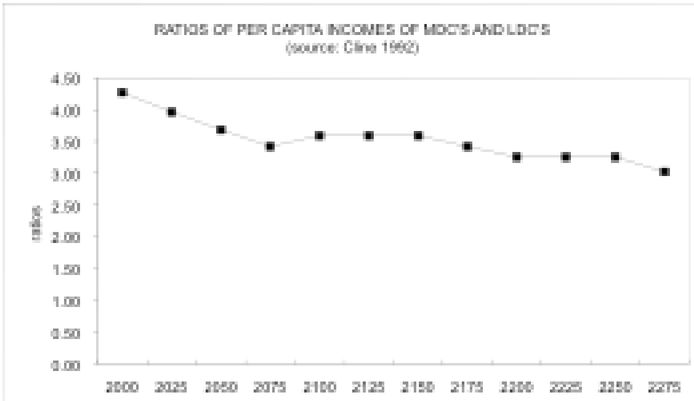


TABLE 1. COMPARISONS OF PER CAPITA INCOMES PROJECTED BY CLINE

Per Capita Income (1990 US $)

	World	family of 4	output growth rate
1995	6,319	25,276	
2100	21,000	84,000	
2275	77,700	310,000	
	"More developed countries"		
2275	185,400	742,000	.002/year
	"Less developed countries"		
2275	61,400	246,000	.005/year

APPENDIX 2. MODEL A: ESTIMATION OF INITIAL VALUES AND RATES OF CHANGE

For the Reference Scenario (Scenario I) I needed to specify initial values for population, per capita GDP, distribution of income by quintile, and energy intensity for each of the four world income/geographic sectors, i.e., high income, middle income, China and low income. For each of these variables and sectors I also needed to estimate an initial value for the rates at which each are changing. I also needed to specify rates of change during successive periods over the 150 years covered in the reference scenario of this model.

The general procedure I used was to review several to many existing studies and use these to choose sets of values that appeared to have broad support and that I believed to be reasonable otherwise. Rates of change for population, per capita GDP and income distribution used in the five policy scenarios (Scenarios 2 through 6) are motivated in the main text. The process used to estimate rates of change of energy intensity used in the five policy scenarios is described in this appendix. Sources for all estimates are shown in **Box A2-1,** and the values projected by these sources are shown in the additional boxes.

I. <u>INITIAL VALUES</u>

For initial values I relied on those shown in the 1996 *World Development Report.* The only modification was to separate China from the *Report*'s low income category and show it as a separate sector. Calculations for population and per capita GDP are shown in **A2-2.** Estimates of energy intensity are shown in **A2-3**.

The most accurate way to compute the share of output received by income quintiles in a sector is to calculate mean incomes for each quintile of each country in that sector and then aggregate these, from lowest to highest, into new quintiles. I did this for the high income sector but the difference between using this technique and simply taking the mean of the values given

BOX A2-1. Sources Consulted for Population, GDP and Energy Growth Rate Projections

1. Energy Modeling Forum-14. 1996. John Weyant, co-ordinator. Stanford University.

2. Holdren, John. 1995. World Energy Futures, class handout for ER 100/200, University of California, Berkeley.

3. Intergovernmental Panel on Climate Change. 1994. Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios.

4. Lazarus, Michael., and Lisa Greber, Jeff Hall, Carlton Bartels, Steve Bernow, Evan Hansen, Paul Raskin, and David Von Hippel (1993). Towards a Fossil Free Energy Future: The Next Energy Transition. A Technical Analysis for Greenpeace International. Boston, Stockholm Environment Institute - Boston Center; Tellus institute.

5. Londono, Juan Luis. 1996. Poverty, Inequality, and Human Capital Development in Latin America, 1950-2025. Washington, D.C.: The World Bank.

6. Manne, Alan S., Robert Mendelsohn and Richard Richels. 1993. MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Stanford University, Yale University and Electric Power Research Institute.

7. Sachs, Jeffrey, "Growth in Africa: It Can Be Done." The Economist, June 29, 1996.

8. Tol, Richard S. 1993. The Climate FUND. Vrije Universiteit. Amsterdam, Holland.

9. World Bank. 1996. World Development Report.

10. World Energy Council/IIASA. 1995. Global Energy Perspectives to 2050 and Beyond. Laxemburg, Austria.

BOX A2-2. INITIAL VALUES FOR POPULATION, GDP, AND AVERAGE ANNUAL GROWTH RATES, 1990-94

source: World Development Report, 1996. The World Bank

Calculated values that depend on growth rates use the exponential formula, r = ln(Q1/Q2)/n.

A. SEPARATION OF CHINA from LOW INCOME figures

GDP:	GDP '94 x10^12 (tbl 12, p210)	growth rate, 90-94 (%/yr) (tbl 11, p208)	GDP '90 x10^12 (calculated)
LOW INCOME COUNTRIES (including China)	1.21	6.20	0.94
CHINA	0.52	12.90	0.31

POPULATION:	POP 94 x10^6 (tbl 4, p 194-5) ==>	growth rate, 90-94 (%/yr)	POP 90 x10^6 (calculated)
LOW INCOME (including China)	3182.00	1.80	2960.95
CHINA	1191.00	1.20	1135.18

Per Capita GDP:	GDP/pop 94 (calculated) ==>	growth rate, 90-94	GDP/pop 90
LOW INCOME (including China)	379.76	4.40	318.47
CHINA	438.43	11.70	274.57

LOW INCOME COUNTRIES (WITHOUT CHINA):

		1994 (calculated)	growth rate, 90-94	1990
GDP	(x10^12)	0.69	2.09	0.63
POPULATION	(x10^6)	1991.00	2.17	1825.77
GDP/POP	($)	344.66	-0.08	345.77

B. MIDDLE INCOME COUNTRIES:

		1994	growth rate, 90-94 (average, %/yr)	1990
GDP	(x10^12)	4070.00	0.20	4037.57
POPULATION	(x10^6)	1570.00	1.50	1478.57
GDP/POP	($)	2592.36	-1.30	2730.73

C. HIGH INCOME COUNTRIES:

GDP	(x10^12)	20120.00	1.70	18797.32
POPULATION	(x10^6)	850.00	0.70	826.53
GDP/POP	($)	23670.59	1.00	22742.45

sources for middle and high income countries:
population '94 and population growth rate, '90-'94: Table 4 p194
GDP growth rate, '90-'94: Table 11 p 208
GDP '94: Table 12 p 210
all other values are derived

BOX A2-3. INITIAL VALUES FOR ENERGY INTENSITY

source: World Development Report, 1996. Tables 8 and 12

(kg = kg of oil equivalent)
(1 kg oil/year = 1.42 W)

	total commercial energy use, 1994 (x 10^6 kg)	(TW)	GDP, 1994 (x10^6) ('87 US $)	GDP/kg ('87 US $)	Watts/$GDP ('87 US $)
all low income	1222928	1.737	1208422		
China	770000	1.093	522172	0.678	2.094
low income, minus China	452928	0.643	686250	1.515	0.937
middle income	2501145	3.552	4069532	1.627	0.873
high income	4392058	6.237	20120240	4.581	0.310
TOTAL	8116131	11.525	25398194	3.129	0.454
in WDR:	8035058	11.410	25223462	3.139	0.452

for each country was small. For the remaining three sectors I simply used the mean of the quintile shares for each country in a sector, as shown in **A2-4**. The values shown for each quintile incorporate the simplifying assumption that the entire GDP is received by households. I don't believe that adjustment for this tendency would greatly affect the overall results of the scenario exercises, but extended treatments of the topics addressed in this exercise might test this assumption.

II. GROWTH RATE PROJECTIONS

I used the studies listed in Box A2-1 to develop assumptions concerning the rates of change of population, per capita GDP and energy intensity.

A. Population

I used the population growth rate assumptions used by the IPCC and Tellus, adjusted to account for the different aggregation of countries and regions.

B. Per Capita GDP

Summaries of the assumptions concerning growth of per capita GDP used in the source studies are shown in **A2-5.**

1. Near-term per capita GDP growth rates (1990-2000)

A. low income countries

The 1996 *World Development Report* shows negative growth for 1990-94 among the low income countries. However, the greatest part of this reflects the difficulties of 3 newly independent states (Tajikistan, Azerbaijan and Armenia), and Rwanda. The largest economies saw positive growth (India-2.9%; Pakistan-1.3%, Bangladesh-2%, Nigeria-1.2%). It's reasonable to assume that the aggregate negative growth results are temporary. Thus I chose 1% for the sector for the period 1994-2000. This is not inconsistent with the figures shown by other studies.

B. China

BOX A2-4. INITIAL VALUES FOR INCOME BY POPULATION QUINTILES

source: World Development Report, 1996. The World Bank.

A. LOW INCOME COUNTRIES

		Q1	Q2	Q3	Q4	Q5
1	Rwanda	9.7	13.2	16.5	21.6	39.1
2	Mozabique					
3	Ethiopia					
4	Tanzania	6.9	10.9	15.3	21.5	45.4
5	Burundi					
6	Sierra leone					
7	Malawi					
8	Chad					
9	Uganda	6.8	10.3	14.4	20.4	48.1
10	Madagascar	5.8	9.9	14	20.3	50
11	Nepal	9.1	12.9	16.7	21.8	39.5
12	Vietnam	7.8	11.4	15.4	21.4	44
13	Bangladesh	9.4	13.5	17.2	22	37.9
14	Haiti					
15	Niger	7.5	11.8	15.5	21.1	44.1
16	Guinea-Bissau	2.1	6.5	12	20.6	58.9
17	Kenya	3.4	6.7	10.7	17	62.1
18	Mali					
19	Nigeria	4	8.9	14.4	23.4	49.3
20	Yemen,Rep.					
21	Burkina Faso					
22	Mongolia					
23	India	8.5	12.1	15.8	21.1	42.6
24	Lao PDR	9.6	12.9	16.3	21	40.2
25	Togo					
26	Gambia, The					
27	Nicaragua	4.2	8	12.6	20	55.2
28	Zambia	3.9	8	13.8	23.8	50.4
29	Tajikistan					
30	Benin					
31	Cent. Af. Rep					
32	Albania					
33	Ghana	7.9	12	16.1	21.8	42.2
34	Pakistan	8.4	12.9	16.9	22.2	39.7
35	Mauritania	3.6	10.6	16.2	23	46.5
36	Azerbaijan					
37	Zimbabwe	4	6.3	10	17.4	62.3
38	Guinea	3	8.3	14.6	23.9	50.2
39	China (see below)					
40	Honduras	3.8	7.4	12	19.4	57.4
41	Senegal	3.5	7	11.6	19.3	58.6
42	Cote d'Ivoire	6.8	11.2	15.8	22.2	44.1
43	Congo					
44	Kyrgyz Rep					
45	Sri Lanka	8.9	13.1	16.9	21.7	39.3
46	Armenia					
47	Cameroon					
48	Egypt	8.7	12.5	16.3	21.4	41.1
49	Lesotho	2.8	6.5	11.2	19.4	60.1
50	Georgia					
51	Myanmar					

	Population (10^6)	GDP (10^6)
totals:	1991	686270

	Q1	Q2	Q3	Q4	Q5	
Mean share of income for the Quintile (%)	6.16	10.18	14.55	21.10	48.01	= 100
Mean Income for the Quintile ($):	106.12	175.52	250.69	363.71	827.45	

B. CHINA

	Population (10^6)	GDP (10^6)
totals:	1191	522172

	Q1	Q2	Q3	Q4	Q5	
Mean share of income for the Quintile (%)	6.20	10.50	15.80	23.60	43.90	= 100
Mean Income for the Quintile ($):	135.91	230.18	346.36	517.35	962.36	

[more...]

BOX A2-4. Initial Values (cont.)

C. MIDDLE INCOME COUNTRIES

			Q1	Q2	Q3	Q4	Q5
52	Bolivia		5.6	9.7	14.5	22	48.2
53	Macedonia						
54	Moldova		6.9	11.9	16.7	23.1	41.5
55	Indonesia		8.7	12.3	16.3	22.1	40.7
56	Philippines		6.5	10.1	14.4	21.2	47.8
57	Uzbekistan						
58	Morocco		6.6	10.5	15	21.7	46.3
59	Kazakstan		7.5	12.3	16.9	22.9	40.4
60	Guatemala		2.1	5.8	10.5	18.6	63
61	Papua New Guinea						
62	Bulgaria		8.3	13	17	22.3	39.3
63	Romania		9.2	14.4	18.4	23.2	34.8
64	Ecuador		5.4	8.9	13.2	19.9	52.6
65	Dominican Rep		4.2	7.9	12.5	19.7	55.7
66	Lithuania		8.1	12.3	16.2	21.3	42.1
67	El Salvador						
68	Jordan		5.9	9.8	13.9	20.3	50.1
69	Jamaica		5.8	10.2	14.9	21.6	47.5
70	Paraguay						
71	Algeria		6.9	11	15.1	20.9	46.1
72	Colombia		3.6	7.6	12.6	20.4	55.8
73	Tunisia		5.9	10.4	15.3	22.1	46.3
74	Ukraine		9.5	14.1	18.1	22.9	35.4
75	Namibia						
76	Peru		4.9	9.2	14.1	21.4	50.4
77	Belarus		11.1	15.3	18.5	22.2	32.9
78	Slovak Rep		11.9	15.8	18.8	22.2	31.4
79	Latvia		9.6	13.6	17.5	22.6	36.7
80	Costa Rica		4	9.1	14.3	21.9	50.7
81	Poland		9.3	13.8	17.7	22.6	36.6
82	Thailand		5.6	8.7	13	20	52.7
83	Turkey						
84	Croatia						
85	Panama		2	6.3	11.6	20.3	59.8
86	Russian Fed		3.7	8.5	13.5	20.4	53.8
87	Venezuela		3.6	7.1	11.7	19.3	58.4
88	Botswana						
89	Estonai		6.6	10.7	15.1	21.4	46.3
90	Iran						
91	Turkemistan		6.7	11.4	16.3	22.8	42.8
92	Brazil		2.1	4.9	8.9	16.8	67.5
93	South Africa		3.3	5.8	9.8	17.7	63.3
94	Maruitius						
95	Czech Rep		10.5	13.9	16.9	21.3	37.4
96	Malaysia		4.6	8.3	13	20.4	53.7
97	Chile		3.5	6.6	10.9	18.1	61
98	Trin & Tob						
99	Hungary		9.5	14	17.6	22.3	36.6
100	Gabon						
101	Mexico		4.1	7.8	12.5	20.2	55.3
102	Uruguay						
103	Oman						
104	sloveria		9.5	13.5	17.1	21.9	37.9
105	Saudi Arabia						
106	Greece						
107	Argentina						
108	Korea, Rep.						

	Population (10^6)	GDP (10^6)
totals:	1570	4069532

	Q1	Q2	Q3	Q4	Q5	
Mean share of income for the Quintile (%)	6.39	10.43	14.74	21.11	47.34	= 100
Mean Income for the Quintile ($):	828.09	1352.30	1910.96	2735.30	6134.99	

[more...]

BOX A2-4. Initial Values (cont.)

D. HIGH INCOME COUNTRIES

		population (10^6)	GDP (10^6)	20% of pop (10^6)	Q1	Q2	Q3	Q4	Q5
109	Portugal	10	87257	2					
110	New Zealan	3	50777	0.6	5.1	10.8	16.2	23.2	44.7
111	Spain	39	482841	7.8	8.3	13.7	18.1	23.4	36.6
112	Ireland	4	52060	0.8					
113	Israel	5	77777	1	6	12.1	17.8	24.5	39.6
114	Australia	18	331990	3.6	4.4	11.1	17.5	24.8	42.2
115	UK	58	1017306	11.6	4.6	10	16.8	24.3	44.3
116	Finland	5	97961	1	6.3	12.1	18.4	25.5	37.6
117	Italy	57	1024634	11.4	6.8	12	16.7	23.5	41
118	Kuwait	2	24289	0.4					
119	Canada	29	542954	5.8	5.7	11.8	17.7	24.6	40.2
120	Hong Kong	6	131881	1.2	5.4	10.8	15.2	21.6	47
121	Netherlands	15	329768	3	8.2	13.1	18.1	23.7	36.9
122	Singapore	3	68949	0.6	5.1	9.9	14.6	21.4	48.9
123	Belgium	10	227550	2	7.9	13.7	18.6	23.8	36
124	France	58	1330381	11.6	5.6	11.8	17.2	23.5	41.9
125	Sweden	9	196441	1.8	8	13.2	17.4	24.5	36.9
126	Austria	8	196546	1.6					
127	Germany	82	2045991	16.4	7	11.8	17.1	23.9	40.3
128	USA	261	6648013	52.2	4.7	11	17.4	25	41.9
129	Norway	4	109568	0.8	6.2	12.8	18.9	25.3	36.7
130	Denmark	5	146076	1	5.4	12	18.4	25.6	38.6
131	Japan	125	4590971	25	8.7	13.2	17.5	23.1	37.5
132	Switzerland	7	260352	1.4	5.2	11.7	16.4	22.1	44.6
133	UAE	2	35405	0.4					

totals:	850	20120240

	Q1	Q2	Q3	Q4	Q5	
Mean share of income for the Quintile (%)	6.23	11.93	17.30	23.87	40.67	= 100
Mean Income for the Quintile ($):	7373.48	14119.67	20475.30	28245.27	48134.72	

BOX A2-5. PER CAPITA GDP GROWTH RATE ASSUMPTIONS

This box displays the values that were used in a variety of studies as estimates of the rate at which per capita GDP would grow over the course of several to many decades in various parts of the world. These values were used to set per capita GDP growth rates used in the Model A reference scenario. As described in the Appendix 2 text, I chose values that appeared to have broad support, and that otherwise seemed reasonable.

A. LOW INCOME COUNTRIES

[All values shown are percent per year]

1. Tellus (based on IPCC 92)

Africa:	1990-2030:	.90
	2030-2100:	2.48
Southeast Asia:	1990-2030:	2.50
	2030-2100:	2.90
Middle East:	1990-2030:	.90
	2030-2100:	1.90

2. World Energy Council/IIASA (total growth rate, not per capita growth rate)

Africa:	1990-20:	hi = 3.3; mid = 3.0
	2020-50:	hi = 4.7; mid = 3.5
South Asia:	1990-20:	hi = 3.9; mid = 3.6
	2020-50:	hi = 4.6; mid = 3.5

3. Energy Modeling Forum

"other non-OECD": 1990-2000: 1.44
2000-2025: 2.55

4. Tol (based on Manne-Mendelsohn-Richels)

Africa: 1990-00: .0
2000-10: .25
2010-20: .75
2020-30: 1.35

5. IPPC (survey of 21 studies)

Africa, 1990-2020:

minimum:	.01
median:	1.50
average:	1.56
max:	2.98

6. Sachs, The Economist, 6/29/96

a. Africa: between 87-94, output per capita fell at a rate of 0.6% per year. The IMF and World Bank project 1-2 percent annual growth rates for the coming decade or so. Sachs calculates that the realistic goal should be 4.4%, which is only slightly (.5%) below the rate for other developing countries.

b. Asia: output grew by 7% in 1995.

[more…]

BOX A2-5. Per Capita GDP Growth Rate Assumptions (cont.)

B. CHINA

1. Tellus (following IPCC 92)
Centrally Planned Asia [CPA]: 1990-2030: 3.1
2030-2100: 3.1

2. World Energy Council/IIASA (total growth rate, not per capita growth rate)
CPA: 1990-2020: hi = 7.2; mid = 5.0
2020-2050: hi = 4.4; mid = 4.0

3. Energy Modeling Forum
China: 1990-2000: 2.71
2000-2025: 2.66

4. Tol (after Manne-Mendelsohn-Richels)
China: 1990-2000: 6.5
2000-2010: 5.0
2010-2020: 3.25

5. IPPC SURVEY (21 studies)
CPA, 1990-2020:

minimum:	2.01
median:	3.91
mean:	3.73
max:	5.07

[more…]

BOX A2-5. Per Capita GDP Growth Rate Assumptions (cont.)

C. MIDDLE INCOME COUNTRIES

1. Tellus (following IPCC 90)
Latin America: 1990-2030: 1.9
2030-2100: 2.2
Eastern Europe: 1990-2030: 2.9
2030-2100: 2.0

2. World Energy Council/IIASA (total growth rate, not per capita growth rate)
Eastern Europe: 1990-2020: hi = 2.3; mid = 0.9
2020-2050: hi = 4.6; mid = 3.6

3. Energy Modeling Forum
Former Soviet Union: 1990-2000: -2.0
2000-2025: 3.9

4. Tol (after Manne-Mendelsohn-Richels)
Soviet Union &Eastern Europe: 1990-2000: 2.0
2000-2010: 1.75
2010-2020: 1.9

Tol (cont.)
Latin America: 1990-2000: 1.0
2000-2010: 1.0
2010-2020: 1.25
2020-2030: 1.25

5. IPCC SURVEY (21 studies):
Eastern Europe & FSU, 1990-2020:
minimum: 0.77
median: 1.73
mean: 1.85
max: 3.8

6. Londono
Latin America per capita GDP grew at 1.9% in first part of 90's, and could maintain this growth for the next 10 years.

[more…]

BOX A2-5. Per Capita GDP Growth Rate Assumptions (cont.)

D. HIGH INCOME COUNTRIES

1. Tellus (following 1PCC 92)

USA	1990-2030:	1.6
	2030-2100:	1.3
Western Europe	1990-2030:	1.9
	2030-2100:	1.3

2. World Energy Council/IIASA (total growth rate, not per capita growth rate)

North America:	1990-2020:	hi = 2.3; mod = 2.0
	2020-2050:	hi = 1.6; mod = 1.4
Western Europe:	1990-2020:	hi = 2.2; mod = 1.9
	2020-2050:	hi = 1.6; mod = 1.3

3. Energy Modeling Forum

USA:	1990-2000:	2.18
	2000-2025:	1.97
EEC:	1990-2000:	2.15
	2000-2025:	2.09

4. Tol (Based on Manne-Mendelsohn-Richels)

OECD-America:	1990-2010:	1.5
	2010-2020:	1.75

5. IPCC SURVEY (21 studies)

USA, 1990-2020:

minimum:	.90
median:	1.96
mean:	1.91
max:	2.91

6. Londono:

per capita growth rate projected for industrialized countries is 2.4% for next decade.

E. TOTAL WORLD:

1. Greenpeace, following IPCC 90

total: 1990-2030: 1.3%; 1985-2100: 1.6%

2. Londono:

world, 1991-1994: 1.9%

The studies listed differ greatly in the assumptions they make about China's near-term economic growth. The *World Development Report* shows 11.7% for 1990-94. The Energy Modeling Forum estimates, which use an average of PPP and exchange rates, shows 2.71% for 1990-2000. The other studies show estimates of 3, 4, 5, and 6.5%. For the time being I chose the middle-range value of 5% as the growth of per capita income in China over the period 1994-2000.

C. Middle Income Countries

The recent negative growth rates shown by the World Bank for the middle income countries again largely reflect the experience of the newly independent states. The other countries in this sector are growing. In the other studies Latin America is projected to grow at about 1-2 %. I chose a figure of 1% as a reasonable expected growth rate of middle income countries between 1994 and the end of the decade.

D. High Income Countries

All the studies showed per capita GDP growth rates of 1.5-2% for the high income countries for 1990-2000. Since the historical rate is 1% for 1990-94, I chose 2% for 1994-2000.

II .Reference Scenario - Long Term Per Capita GDP Growth Rates (2000 - 2150)

I used the IPCC figures as reported by Tellus and IPCC as the basis for my per capita GDP growth rate estimates for 2000-2100. I used the values given in EMF-14 to help estimate these rates for 2100-2150.

The ten IPCC regions can be assigned to my four sectors roughly as follows:

Low Income: African + Southeast Asia
China: Centrally Planned Asia
Middle Income: Latin America + Middle East + USSR + Eastern Europe
High Income: JANZ + US + Western Europe

The Tellus per capita GDP growth rate assumptions give these results when recalculated using the 4-sector aggregation:

	2000-2030	2030-2100	2100-2150	2150-2200
1. Low	1.9	2.7	2.0	1.0
2. China	3.1	3.1	2.0	1.0
3. Middle	1.9	1.9	1.2	1.0
4. High	1.8	1.3	.8	.6

I adjusted these rates to show smoother transitions between decades, without changing the final output levels in a large way.

C. Energy Intensity

I used five studies listed in Box A2-1 to choose projected values for changes in energy intensity over time. Summaries of the values used in each of these studies are shown in **A2-6.** I based the estimate for the reference scenario, Scenario 1, on those used by Manne-Mendelsohn-Richels, and by Tol. The rates used in Scenario 2 are based on Holdren's estimates, but with an imposed upper limit of 2% on the annual rate of energy intensity improvement in the low and middle income sectors, and China. For Scenarios 3 to 6 I used Holdren's full estimates, including the very high rates of efficiency improvement he shows for the non-industrial world in the middle part of the coming century. I slowed the rates down in the final three decades before 2150 to offset these very high, continuing rates of improvement just a bit. The three scenarios are displayed in **A2-7.** All values shown are annual percentage declines in the ratio of energy use to GDP.

BOX A2-6. ENERGY INTENSITY CHANGE ASSUMPTIONS

Assumptions concerning the rate of change in energy intensity over coming decades are shown for five studies. These assumptions were used to help specify rates of change used in the Model A reference scenario and the several policy scenarios, as shown in Box A2-7. Citations are shown in Box A2-1. Energy intensity is the ratio of energy use to GDP. It is the inverse of energy efficiency, the ratio of GDP to energy use. A decline in energy intensity is an increase in energy efficiency.

1. Intergovernmental Panel on Climate Change (IPCC)

Values chosen for the IPCC scenarios, based on a review of 21 studies covering 1990-2020.

	World	CHINA & CPA	AFRICA	USA
1. NO INTERVENTION (= business-as-usual)				
max	1.84	2.85	.67	2.17
med	.94	1.59	.17	1.29
mean	.99	1.52	.30	1.35
min	.53	.22	.53	0.20
2. "POLICY"				
max	2.4	4.32	2.19	2.88
med	1.78	1.89	1.46	1.91
mean	1.74	2.24	1.31	1.87
min	1.08	.53	.30	.66

Calculation of overall energy intensity decline, 1900-2100:

USA	.904
CPA	1.46
EU & FSU	1.17
AFRICA	.543

2. Energy Modeling Forum 14 (1996)

			date				
Region	1990-2000	2000-2025	2025-2050	2050-2075	2075-2100	2100-2150	2150-2200
USA	.70	.63	.52	.37	.36	.26	.19
EEC	.70	.67	.51	.37	.36	.26	.19
other OECD	.72	.67	.51	.36	.36	.26	.19
CHINA	.87	.85	.94	.92	.91	.64	.32
FSU	-.66	1.25	1.07	.60	.62	.32	.26
other non-OECD	.46	.81	.77	.76	.83	.64	.32

EMF calculations are based on a formula by Arnulf Grubler of IIASA. Aggregate Energy Efficiency Improvements (AEEI) are a constant fraction, .32, of GDP/capita growth rates. Thus, if USA per capita growth rate for 1990-2000 is 2.18, short run AEEI is .32 x 2.18 = .70, as shown.

[more….]

Box A2-6. Energy Intensity Change Assumptions (cont.)

3. Mann-Mendlesohn-Richels (1993); also used by Tol (1993)

	90-00	00-10	10-20	20-30	30-40	40-50	2050-2100
OECD	.50	.50	.50	.50	.50	.50	.50
ME, LA, AFR, SA, SEA	0	0	.10	.20	.30	.40	.50
CHINA	1.00	1.00	.90	.80	.70	.60	.50
FSU & EE	.25	.25	.30	.35	.40	.45	.50

4. HOLDREN (1996)

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090
Reference case:											
Industrialized	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0	.90	.90	.80
Developing	0	.5	1.0	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0
Maximum feasible improvements:											
Industrialized	1.5	2.5	3.0	3.0	2.7	2.4	2.0	1.5	1.0	1.0	1.0
Developing	.5	1.0	2.0	2.3	2.5	2.7	2.8	2.7	2.4	1.8	1.0

5. World Energy Council/IIASA (1995)

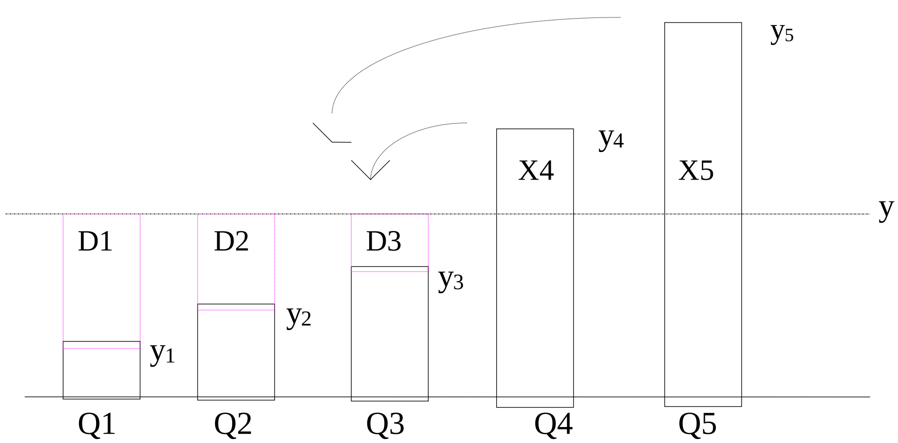
	High Growth	Middle Course	Ecologically Driven
World			
1990-2050	1.0	0.7	1.4
1990-2100	1.0	0.8	0.5
Regions (1990-2050)			
OECD	1.2	1.1	2.0
Reforming Economies	2.1	1.7	2.2
Developing Countries	1.6	1.2	1.9

BOX A2-7 t/k

APPENDIX 3. MODEL A INCOME DISTRIBUTION EQUATIONS

The equations shown in Boxes IA-10 and IA-11 of the text allow us to model changes in the distribution of income among quintiles over time. **Box A3-1,** below, illustrates how this works.

Box A3-1. Model A Income Distribution Procedure



At the end of each period proportion "r" of the total income above the mean income y [r (X4 + X5)] is redistributed to the three quintiles below the mean in the same proportion "s" that each of them is below the mean. For example, for the bottom quintile, Q1, this proportion is: s_1 = D1/(D1 + D2 + D3). We call "s" the redistributive proportionality factor.

This value can be expressed in terms of the mean income of the quintile (y_j) and the mean income of the sector as a whole (y), as:

$$s_1 = (y - y_1) / [(y - y_1)+(y - y_2)+(y - y_3)]$$

$$= (y - y_1) / [3y - (y_1 + y_2 + y_3)]$$

Which is equivalent to equation (6) shown in IIA-11 of the text (without the income sector subscript i). The values of s for the three quintiles to which it applies – Q1, Q2 and Q3 – are shown for all four income sectors in **A3-2.**

BOX A3-2. MODEL A REDISTRIBUTIVE PROPORTIONALITY FACTOR ("s")

1	2	3		4		5		6
Income Sector	Quintile	Mean Income		Sector Mean		Total Gap		Value of "s"
low income				344.8		501.4		
	Q1	106						0.4763
	Q2	176						0.3367
	Q3	251						0.1871
	Q4	364						
	Q5	827						
China				438.2		602.6		
	Q1	136						0.5015
	Q2	230						0.3455
	Q3	346						0.1530
	Q4	517						
	Q5	962						
middle income				2592.2		3685.6		
	Q1	828						0.4787
	Q2	1352						0.3365
	Q3	1911						0.1848
	Q4	2735						
	Q5	6135						
high income				23669.6		29040.8		
	Q1	7373						0.5612
	Q2	14120						0.3288
	Q3	20475						0.1100
	Q4	28245						
	Q5	48135						

Notes:

Columns 1, 2 and 3 identify the four income sectors, the five quintiles for each sector, and the per capita income of those each of those quintiles.

Column 4 shows the mean (or per capita) income for each income sector as a whole

Column 5 shows the "total gap" for each income sector, i.e., the sum of the amounts by which each of the first three quintiles are below the mean.

Column 6 shows the percent of the "total gap" represented by the "gap" of each quintile in a sector. This is the value of the redistributive proportionality factor, "s".

If a positive "r" is maintained over time the incomes for all quintiles will converge. A negative "r" will redistribute income from the three quintiles below the mean to the two above the mean.

The model allows a growth rate "g" to be exogenously specified for the economy as a whole. Thus the model can show how the per capita incomes of any quintile, and of the income sector as a whole, will change given assumptions about the aggregate growth rates of income and rates of change in the distribution of income.

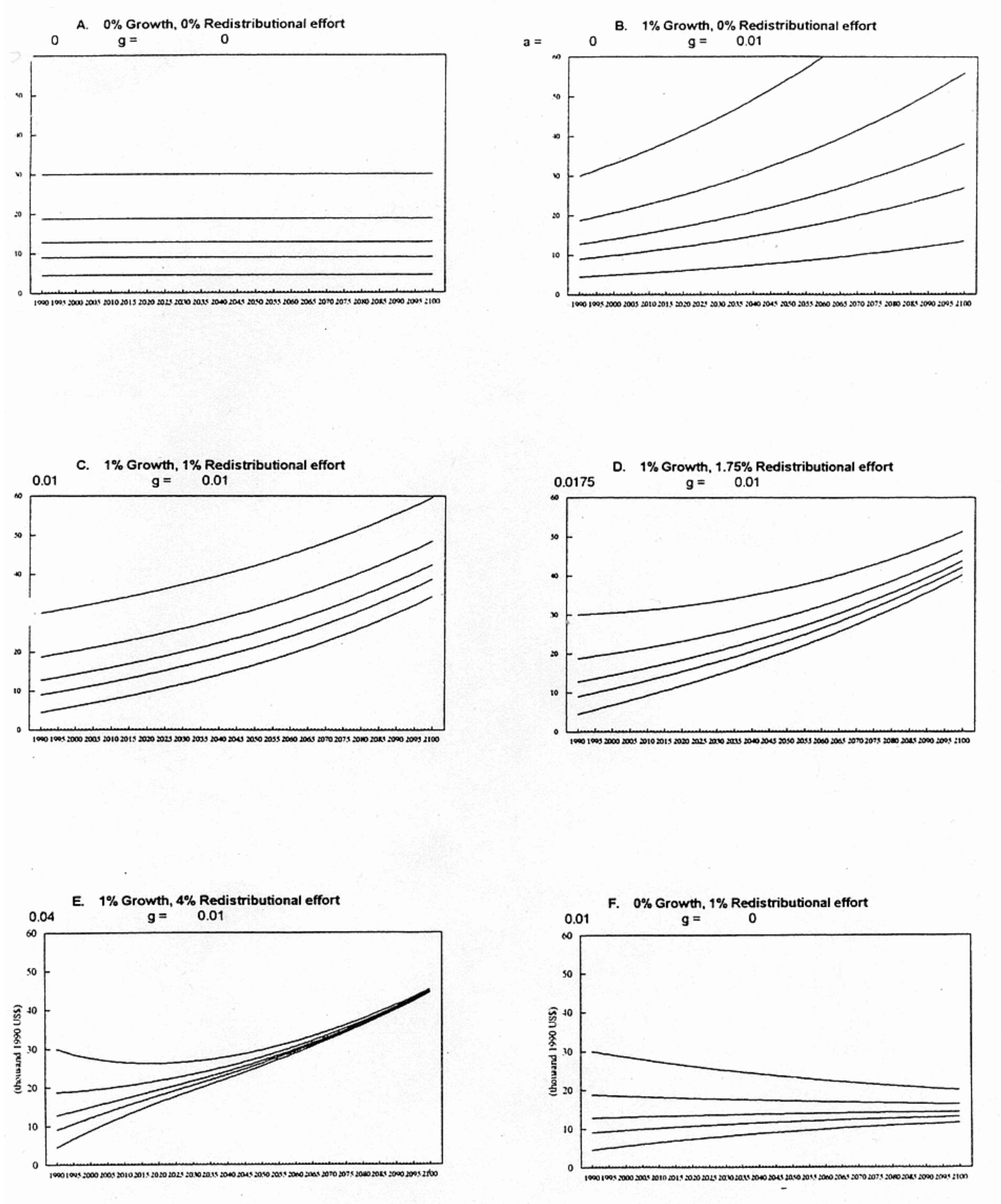
The figures in **A3-3** illustrate Model A's income distribution dynamics. Figure A shows the quintile distribution of income for the United States in 1990, in 1990 dollars, and illustrates the trivial scenario in which there is no change in the level of total income (g = 0) , and no change in the distribution of income (r = 0) , over the period between 1990 and 2100.

Figure B illustrates a scenario in which the economy grows at a constant rate of 1% per year (g = .01) but the distribution of income is unchanged (r = 0). Both the 80/20 ratio and the Gini Coefficient remain constant over time. However, the absolute difference between the incomes received by each quintile becomes greater.

Figure C shows total income growing at the same rate of 1% as in Figure 1b, but now shows redistributive pressure of 1% (r = .01). This means that 1% of the income of the top two quintiles that is above the mean of all five quintiles is redistributed to the bottom three quintiles, at the end of each period. Now the 80/20 ratio and Gini Coefficients decline over time, while the absolute difference among quintiles remains constant.

Figures D and E show the results of progressively stronger redistributive efforts, r = .0175 and r = .04, respectively. For any given rate of aggregate growth (in this example, 1%) there is a threshold level of redistributive effort above which the top quintile will be forced to undergo an absolute reduction in its income, rather than simply a reduction in its relative income share. In Figure D (r = .0175) incomes converge rapidly but at no point need the top income quintile forsake further income growth entirely. In Figure E however (r = .04), the incomes of the

BOX A3-3. Model A Income Distribution Dynamics



top quintile must decline until 2025, at which time they can begin to grow once more. Note that as the average incomes of the quintiles converge, their rates of growth do so as well.

Figure F illustrates a scenario in which there is no aggregate economic growth (g = 0) but the distribution of income becomes more equal. In this situation there is no choice but that the top quintiles undergo an absolute decline in their average incomes. It is instructive to compare Figure F with Figure C. Both show a redistributive pressure of 1% (r = .01) and thus show the same 80/20 ratios and Gini coefficients at every point in time. But in C this takes place while aggregate income is growing at 1%, while in F there is no growth of aggregate income.

Interpretation of "r"

As noted in the text, the term "redistributive pressure" is used here in a very general sense. It might refer to policies that take from the rich and give directly to the poor. It might refer to policies that tax the rich to provide educational services that increase the earnings abilities of the poor. Or it might refer to market mechanisms that are thought to generate greater income equality.

If we think of "r" as a tax, how heavy a tax does a value of r of say, 1%, imply? Suppose per capita income growth in the United States is expected to average 1% over the coming decades, and that in the absence of redistributive policy this growth would be shared equally by all income quintiles. This is the scenario of Figure B. Now suppose we wished to effect a more equal distribution of incomes, say along the lines shown in Figure C. What proportion of their total incomes would the upper quintiles have to forego, and how big a transfer would this represent for the lower quintiles?

We see in Table 1 of **A3-4** that a value of r of .01 implies a tax on the top quintile (Q5) of .495%, or $450 on a total household income of $90,900. The 4th quintile (Q4) is taxed at .211%, or $120 on a total household income of $56,820.

BOX A3-4. MODEL A GROWTH AND REDISTRIBUTION DYNAMICS

Table 1 shows that for a single period, an "r" value of .01 represents transfers of $450, or less than 1/2 of 1%, of the income of the fifth quintile to the bottom three quintiles.

Table 1. Growth and Redistribution over one period (g = .01, r = .01)

	mean household income			
	before	after	dollars	tax rate/
	redistribution	redistribution	transferred	grant rate
quintile				(%)
Q5	90900	90450	-450	-0.495
Q4	56820	56700	-120	-0.211
Q3	38640	38700	60	0.155
Q2	27270	27450	180	0.660
Q1	13650	13950	300	2.198

Table 2 shows that over 60 periods an "r" value of .01 represents a much larger transfer of income. By the final period over 22% of the income of the fifth quintile is being transferred to those in the bottom three quintiles.

Table 2. Growth and Redistribution over 60 periods (g = .01, r = .01)

Q5	mean household income				
	before	after	dollars	tax rate	80/20
year	redistribution	redistribution	transferred	(%)	ratio
1990	90900		-450	-0.495	6.67
2010	109830	100470	-9360	-8.522	4.29
2030	134010	111990	-22020	-16.432	3.16
2050	163500	126750	-36750	-22.477	2.52

Q1	mean household income				
	before	after	dollars	grant rate	80/20
year	redistribution	redistribution	transferred	(%)	ratio
1990	13650		300	2.198	6.67
2010	16470	23400	6930	42.077	4.29
2030	20100	35490	15390	76.567	3.16
2050	24540	50250	25710	104.768	2.52

Whether these are considered to be heavy taxes or not depends on the story that the model is interpreted to be telling. If the tax dollars are thought to be used for purposes that will increase the earnings of the lower three quintiles in the subsequent period by the amount of the transfer, then the effective tax rate can stay near the low levels shown in the first period.

However, if the model is thought to describe a system of direct income subsidies, then the amounts taxed and transferred become much larger. In this case we assume that the earned incomes of the lower quintiles increase by no more than 1% a year. In order to effect a meaningful redistribution the amounts transferred from the upper quintiles (the incomes of which are also increasing at 1% annually) must increase each year. This is shown in Table 2 in Box A3-4. A redistributive pressure of 1%, applied continuously, requires the effective tax rate on household incomes in Q5 in the years 2010, 2030 and 2050 to grow to 8.5%, 16%, and 22%, respectively. Similarly, by 2050 the level of income supplement being received by the bottom quintile ($25,710) is greater than the income received through earnings ($24,540).

APPENDIX A4. ECONOMIC INEQUALITY

1. Definitions and Measures

Measures of economic inequality used in this exercise include:

a) ***frequency distributions and histograms.*** A frequency distribution shows the number of income units (individuals, families, nations, etc.) that fall within a set of income ranges. The graphical display of this data is a histogram. Box IIB-9 in the text shows a simple frequency distribution and histogram of household income in 1992.

b) ***percentile ratios***. A simple measure of the inequality of a frequency distribution is the ratio between two percentiles from opposite ends of the distribution. The 80/20 and the 90/10 ratios are commonly used. The 80/20 ratio is calculated by taking the ratio of the total income (or mean income) of all income units in the fifth quintile of a population to that of the first, or bottom, quintile. The 80/20 ratio of the frequency distribution of household income shown in Table 1 of Box IIB-10 is 91.5 / 7.3, or 12.4 to 1.

c) ***Lorenz curves.*** The Lorenz curve is a graph of cumulative share of a variable, such as income or wealth, against the cumulative population share. The greater the convexity of the Lorenz curve with respect to the bottom right corner of the display, the greater the inequality of the distribution. The diagonal line represents a distribution of perfect equality. The Lorenz curve of the frequency distribution shown in Table 1 of Box IIB-10 is shown in Figure 1 of that box.

d) ***Gini coefficient.*** This is the most commonly used single statistic of inequality. It is the ratio of the area enclosed by the Lorenz curve and the diagonal, and the total area under the diagonal line. A Gini coefficient of 0.0 indicates perfect equality, and a ratio of 1.0 indicates perfect inequality. Some authors multiply the fractional Gini coefficient by 100, so that 0 indicates perfect equality and 100 indicates perfect inequality, as a convenience. The Gini coefficient can be calculated directly from a frequency distribution by using the formula[2]:

$$G = 1 + \left(\frac{1}{N}\right) - \left(\frac{2}{N^2 \bar{y}}\right) \sum_{i=1} (N - i + 1) y_i$$

where:

N = the number of percentiles
y = the relative shares of income of each percentile
y bar = the mean income share of the percentiles
i = the index number of the percentiles (1, 2, …N)

2. Interpreting the Gini coefficient

In general, one or two Gini points are not very significant, but ten Gini points is very significant.

Box A4-1 shows quintile distributions that typify groups of countries situated at different points along the gradient of inequality as measured by the Gini coefficient. We see that the 20 countries with the greatest income equality have an average Gini of about 28, while the 28 with the least income equality have a Gini of about 54.

Box A4-2 shows the amount of redistribution that would be required to change the Gini coefficient of the United States by one Gini point, from its current .37 to .36. This could be done by a tax of 5.7% on the incomes of the top quintile (Q5) of households, with the proceeds transferred to the next lowest quintile (Q4). Or it could be done if a tax of 1.5% was levied on Q5 but transferred to the bottom quintile (Q1).

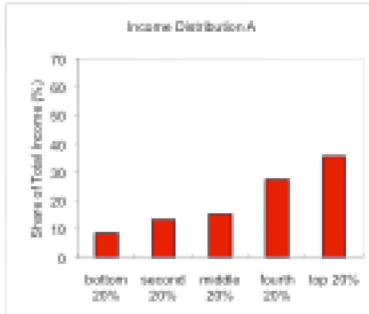
[2] See Cowell (1995) and Lambert (1993) for a review the technical tools for measuring economic inequality.

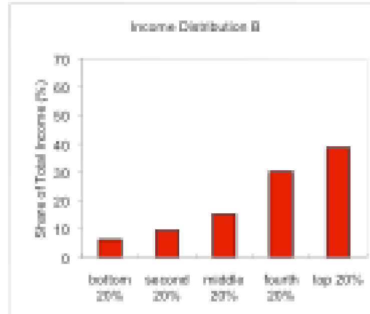
BOX A4-1. COMPARISON OF INCOME DISTRIBUTIONS

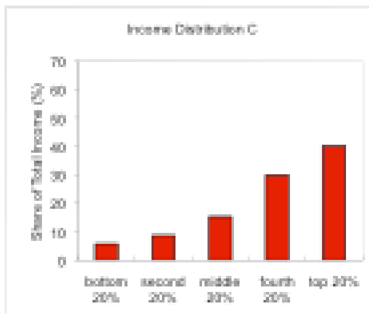
[source: Box IB-1]

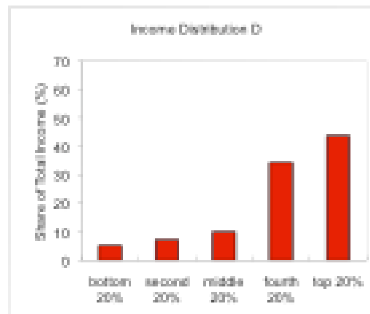
The five displays illustrate the sorts of income distributions that characterize different countries. See the key at the bottom.

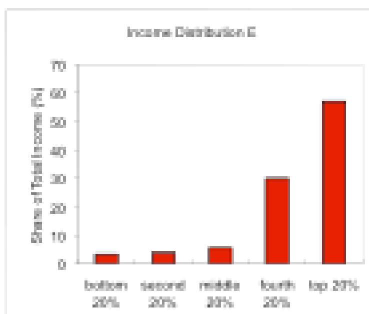
	income share (%)
Distribution A:	
bottom 20%	8.6
second 20%	13.2
middle 20%	15.3
fourth 20%	27.4
top 20%	35.5
Distribution B:	
bottom 20%	6.3
second 20%	9.6
middle 20%	15.3
fourth 20%	30.2
top 20%	38.6
Distribution C:	
bottom 20%	5.8
second 20%	8.7
middle 20%	15.3
fourth 20%	30.0
top 20%	40.2
Distribution D:	
bottom 20%	5.1
second 20%	7.1
middle 20%	9.9
fourth 20%	34.2
top 20%	43.7
Distribution E:	
bottom 20%	3.4
second 20%	4.0
middle 20%	5.6
fourth 20%	30
top 20%	57











Income Distribution	descriptions	mean Gini	mean 80/20	Typical Examples
A	20 most equal countries, ranked by Gini	27.6	4.1	Canada, Russia, Spain, Bangladesh
B	next 20 countries, ranked by Gini	34.5	6.1	Germany, Indonesia, Ghana, India
C	next 20 countries, ranked by Gini	35.5	6.9	Japan, USA, China, Nigeria
D	next 20 countries, ranked by Gini	43.5	8.5	Australia, Peru, Uganda, Iran
E	28 most unequal countries, ranked by Gini	54.1	17.1	Mexico, Kenya, Thailand, Brazil

BOX A4-2. Changes in Income Distribution Needed to Change the Gini Coefficient of the United States by 1 Point

quintiles		current % shares ('92)	Transfers between Quintiles: Q5 => Q4	Q5 => Q3	Q5 => Q2	Q5 => Q1
Q1	lowest 20%	4.5	-	-	-	5.15
Q2	second 20%	10.7	-	-	11.6	-
Q3	middle 20%	16.6	-	17.9	-	-
Q4	fourth 20%	24.1	26.6	-	-	-
Q5	top 20%	44.1	41.6	42.8	43.2	43.45
Gini		0.37	0.36	0.36	0.36	0.36
80/20		9.8	9.2	9.5	9.6	8.4

		mean income	Q5 => Q4	Q5 => Q3	Q5 => Q2	Q5 => Q1
Q1	lowest 20%	5553	-	-	-	6355
Q2	second 20%	13204	-	-	14314	-
Q3	middle 20%	20484	-	22089	-	-
Q4	fourth 20%	29739	32824	-	-	-
Q5	top 20%	54419	51334	52815	53309	53617

		gross tax & transfer (%)	Q5 => Q4	Q5 => Q3	Q5 => Q2	Q5 => Q1
Q1	lowest 20%	-	-	-	-	14.4%
Q2	second 20%	-	-	-	8.4%	-
Q3	middle 20%	-	-	7.8%	-	-
Q4	fourth 20%	-	10.4%	-	-	-
Q5	top 20%	-	-5.7%	-2.9%	-2.0%	-1.5%

		amounts transferred	Q5 => Q4	Q5 => Q3	Q5 => Q2	Q5 => Q1
Q1	lowest 20%	-	-	-	-	802
Q2	second 20%	-	-	-	1110	-
Q3	middle 20%	-	-	1604	-	-
Q4	fourth 20%	-	3085	-	-	-
Q5	top 20%	-	-3085	-1604	-1110	-802

APPENDIX 5 DEFINITIONS OF GROWTH, WELL-BEING AND RELATED KEY CONCEPTS

As most commonly used, the word "growth" simply means an increase. In many contexts "growth" applies more generally to any change over time, and thus allows negative growth. In these notes we might be interested in the growth, or change over time, of output, consumption, utility (or welfare, well-being or happiness), throughput (or resource use), population, pollution, the stock of natural or human-made capital, information, complexity or any of many other things.

For our purposes it is particularly important to have clear definitions of *well-being, throughput* and *output.* There is a large literature on how these might be defined and measured, but the rough definitions below will serve our purposes for now.

"Well-being" refers to the most general, inclusive sense of human satisfaction and contentment. The question "what determines well-being?" is among the most important questions there are.

"Throughput" is the flow of natural resources used to generate output. Some throughput generates output directly, but most becomes output only after a series of manipulations. During these manipulations some of the throughput becomes waste. Particular flows of resources can be easily measured but there is no practical common unit with which to measure throughput in the aggregate.

"Output" is throughput manipulated by human activities intended to increase well-being. It can equivalently be defined as all final goods and services produced by an economy during a time period. To the extent that prices reflect value, output can be measured as the sum of the prices of these goods and services, or gross domestic product (GDP). The proper measurement of output, or GDP, should include imputed prices for both positive and negative non-market goods. While any particular act of producing output is intended to increase well-being, it may not. As defined here output has an important bearing on well-being but is hardly synonymous with it. In these notes the term “economic growth” is used to mean the growth of output.

Well-being, throughput and output can each increase, decrease or remain constant. We can imagine 3^3 = 27 scenarios, some more plausible than others, showing how these three variables might change with respect to one another over time. Three scenarios are shown in Figures 1, 2 and 3 in **A5-1**.

Figure 1 illustrates a conventional interpretation of the historical experience of the industrial world over the past three centuries or so. Greater throughput enables production of more output, which increases well-being.

Figure 2 is a “green” scenario. Technological innovation allows a constant level of output to be produced with less throughput, while skillful craftwork changes qualities of that output in such a way that well-being increases.

Figure 3 is a mixed bag. A constant level of throughput is maintained, perhaps because a transition to a renewables-based economy has been successfully completed. And technological innovation is robust enough to generate a steady increase in output. But well-being declines nonetheless, perhaps because this materially sustainable, technologically productive world is being run as an increasingly authoritarian police state.

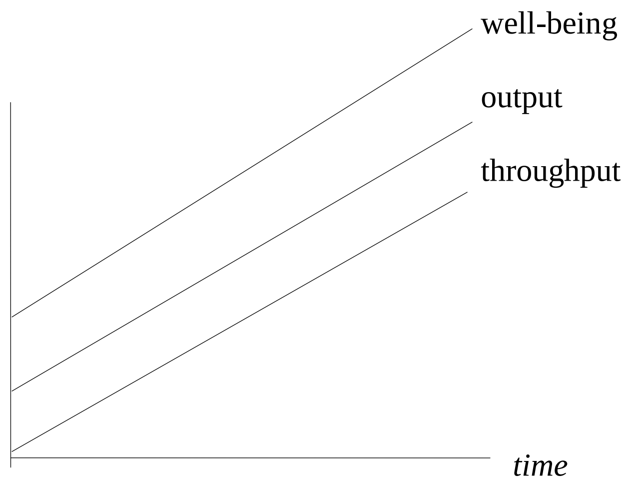
As defined, output represents a link between the fundamentally more important variables of well-being and throughput. Output is of interest to us primarily because it contributes to well-being and uses throughput.

The five scenarios shown in Figures 1 through 5 in **Box A5-2** dispense with “output” and illustrate different sorts of relationships that may obtain more directly between the level of well-being and the level of throughput.

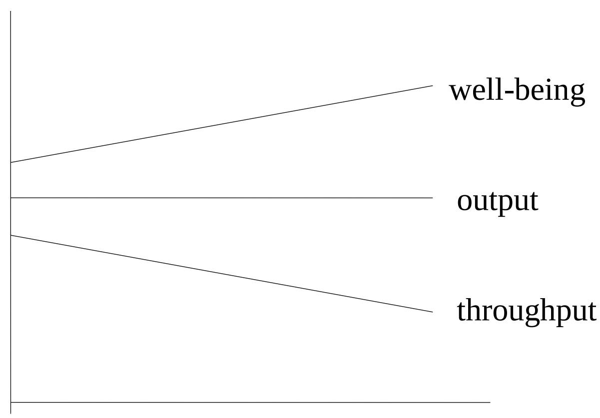
BOX A5-1. WHAT GROWS? (1)

The figures show well-being, output and throughput increasing, decreasing and remaining constant over time.

1.

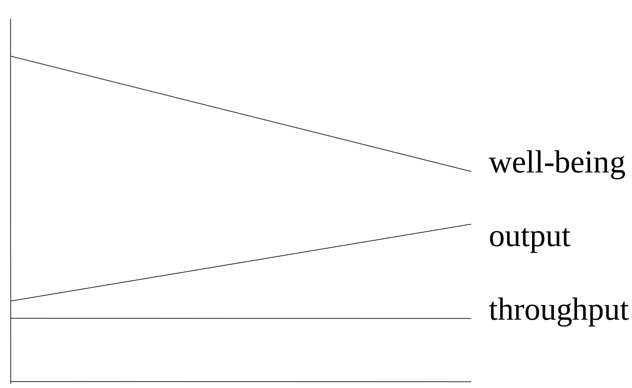


2.



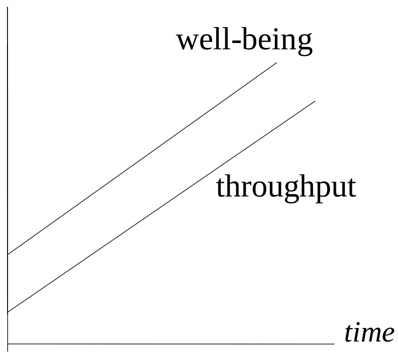
3.

.

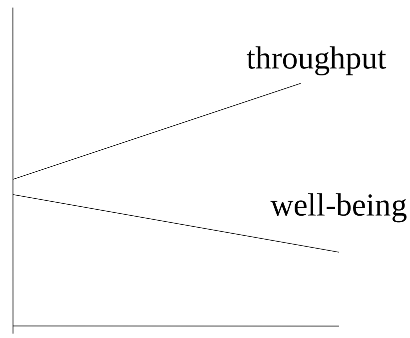


BOX A5-2. WHAT GROWS? (2)

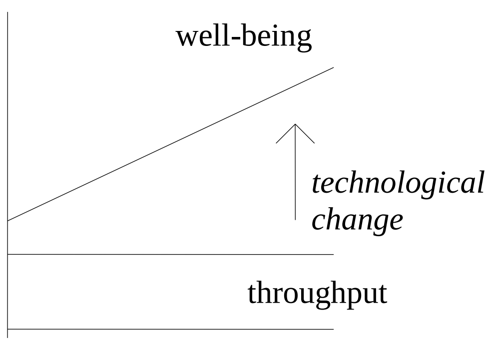
The figures show different ways that trajectories of throughput might bear upon trajectories of well-being, as discussed in the text.



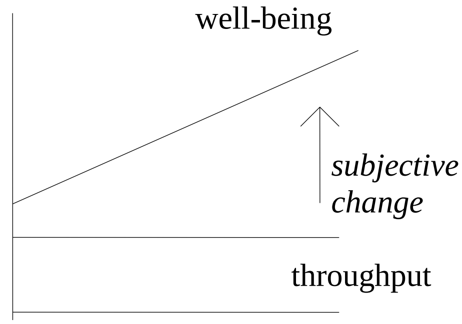
1. “the metal eaters”



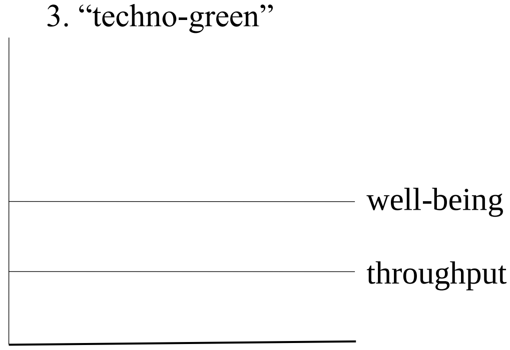
2. “gloomy Sunday”



3. “techno-green”



4. “subjective green”



5. “green minimal claim”

Figure 1 illustrates, once more, the conventional account.[3]

Figure 2 shows the unhappy case in which throughput continues to grow but well-being declines.

Figures 3 and 4 are both green scenarios and show the same formal relationship between throughput and well-being, but they are driven by very different processes and represent very different outcomes. Figure 3 shows the "techno-green" scenario. Human technological skill allows a constant level of throughput to be manipulated in increasingly efficient and innovative ways. As a result, human well-being can increase without endangering the environment.

Figure 4 is the "subjective-green" scenario. It shows a constant level of throughput, but this time there are no technological improvements. The same stuff is made in the same way, century after century. However, the quality of the services provided by the output improves. The design and construction of a saxophone may not change over the course of a century, but the beauty and variety of the compositions written for it, and of the performances given with it, can grow indefinitely.

There is a second, more subtle interpretation of the scenario shown in Figure 4. Neither the saxophone, the compositions, nor the performances change over the course of time, but the listeners develop an increasingly keener appreciation for the music. Throughput remains constant but well-being grows.

Figure 5 is the "green minimal claim" scenario. The minimal claim is simply that a constant level of throughput can indefinitely support some constant, fulfilling level of well-being.

Limits and constraints on the rates and levels of growth

The phrase "limits to growth" is ambiguous because the thing whose growth is limited is unspecified. It is also ambiguous because "growth" can refer either to the growth *rate* or to the *level* to which something can grow. We can say that output (for example) is limited to a growth

[3] "The metal eaters" is a translation of "Металлические едоки," used by Russian environmentalists to describe the institutions of industrial civilization.

rate of 2% per year, or that output is limited to an absolute level of $30 trillion. Note that a limit to the level of growth implies an eventual limit to the rate of growth, i.e., 0%.

The term "limits" can be used to mean either an absolute level that cannot be exceeded, or a softer set of constraints short of an absolute limit. In this exercise we try to use "limits" when speaking of values that cannot be exceeded, and "constraints" for the more general set of impediments. As used here, "constraints" is the inclusive term: a limit is a very strong constraint, but a constraint need not, although it might, impose a limit.

Thus we can speak, hopefully unambiguously, of limits to the level to which something can grow, limits to the rate at which something can growth, constraints on the level to which something can grow, and constraints on the rate at which something can grow.

The Rhetoric of Growth

President Ronald Reagan once offered the opinion that "there are no limits to growth, because there are no limits to the human imagination." Put less succinctly but more precisely, he might have been expressing the opinion that "there are no limits to the ability of technology to manipulate any given level of throughput such that human well-being continues to increase."

Some environmentalists say, "There are limits to growth, but not to well-being." One interpretation of this statement might be that technology will allow us to manipulate an environmentally sustainable, constant level of throughput in a way that can allow human well-being to increase indefinitely.

Other environmentalists say, "There are limits to *throughput,* but there are *no* limits to *growth*." In the previous statement "growth" referred to throughput, but here it could refer to well-being, or to output, or to both well-being and output.

Can We Measure Well-Being?

The Standard National Accounts were developed in the 1940's in order to track the flows of economic variables, including output, consumption, saving and public spending, that were needed to help develop policies intended to ensure steady output growth and low unemployment.

In the wake of the Great Depression and the Second World War, a steady growth in output was experienced by most persons as a major contribution to well-being. The availability of GDP as an analytically convenient measure of output led to its identification among professionals and the public as a measure of well-being.

The inadequacies of conventional GDP as a measure of both output and well-being are well known. Its major inadequacy as a measure of output is that it doesn't account for goods or bads external to the market.

Attempts to deal with the shortcomings of the GDP have gone in two directions. One is to strengthen its use as a measure of output, while disclaiming any role for it as a measure of well-being. This entails converting as many non-market goods and bads as possible into dollar terms and incorporating these into the national income accounts, and other reforms.

A second direction seeks to devise genuine measures of well-being which over time could supplant GDP in that role. One approach involves the use of (fully inclusive) GDP in association with satellite accounts of variables that are judged to have a bearing on well-being, such as literacy rate, longevity, infant mortality, or stocks and flows of natural resources. A second approach is to combine these measures into a single statistic by means of an indexing formula. The choice set of satellite accounts, and any indexing weights they might be given, are of course strongly normative statements.

Some examples of efforts along the lines described are shown in **A5-3.** Figure 1 shows the measure that Nordhaus and Tobin (1989) call Net Economic Welfare (NEW). NEW takes Net National Product, which is GNP less depreciation, and adds the value of leisure time, domestic activities, "underground" transactions, and other non-market goods. It subtracts non-market bads such as economic damages resulting from pollution and urban congestion. Nordhaus defines NEW as "an adjusted measure of total national output that includes only consumption and investment items that contribute directly to economic well-being." In general, the growth rate of NEW has paralleled the growth rate of conventional GDP.

BOX A5-3. MEASURING WELL-BEING

These figures illustrate how differing measures of "well-being" have changed in recent years.

Figure 1. Net Economic Welfare
(Reprinted from Samuelson and Nordhaus, 1989, p 119)

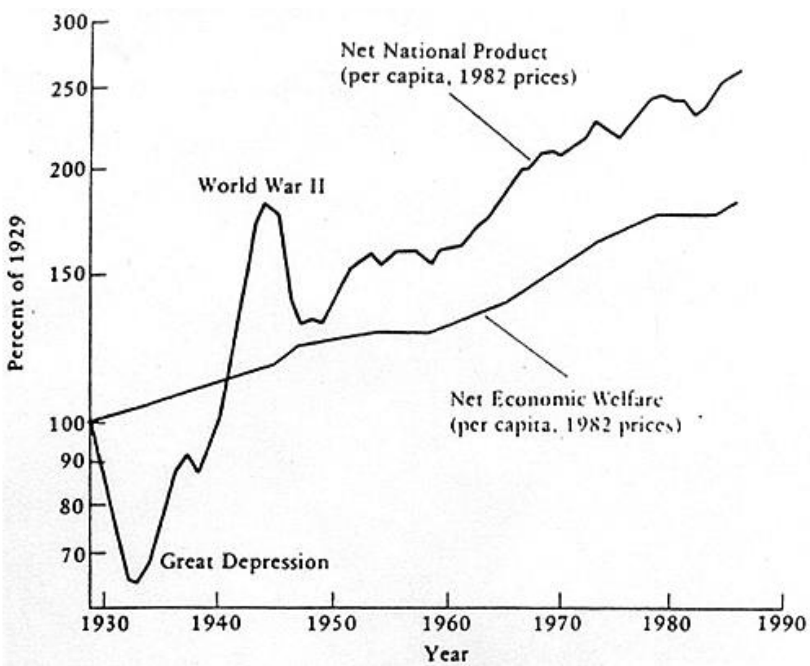
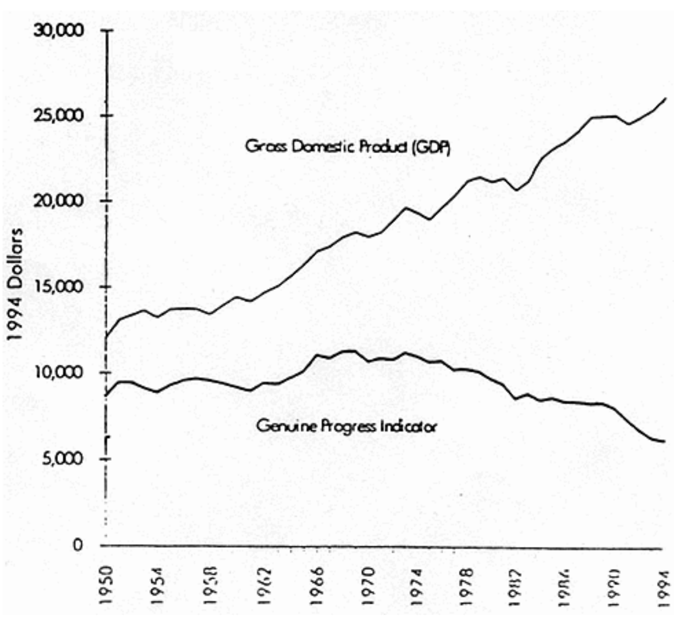


Figure 2. GPI versus GDP
(Reprinted from Redefining Progress, 1995)



Box A5-3. MEASURING WELL-BEING (cont.)

Figure 3. Human Development Index, 1960-1993
(United Nations Development Program, Human Development Report, 1996)

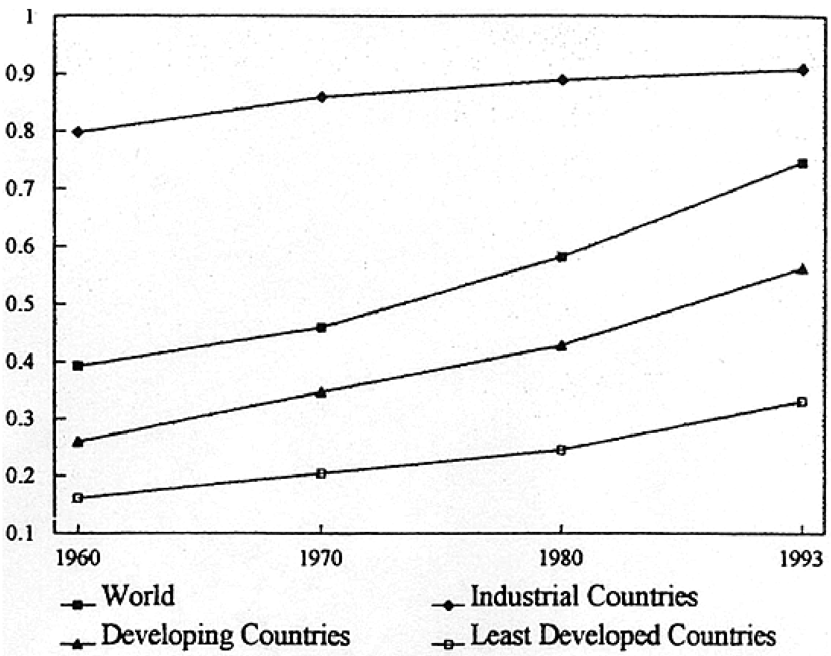
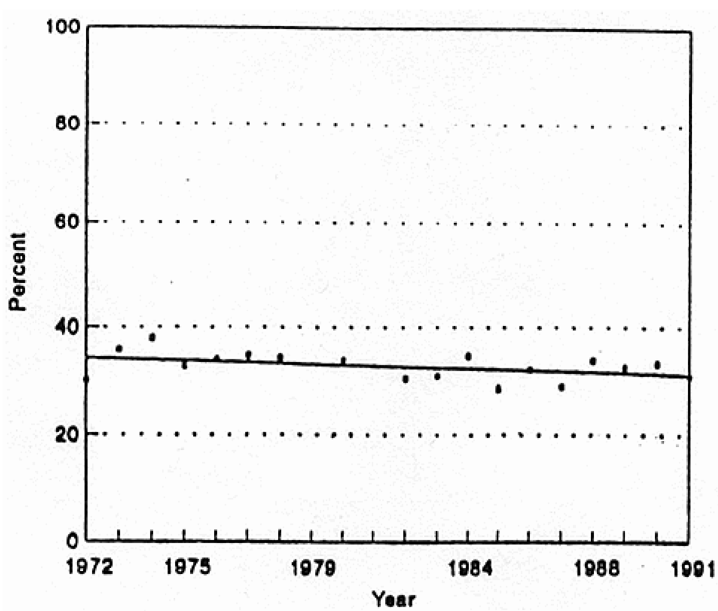


Figure 4. Happiness
(Reprinted from Easterlin, 1995)



The vertical axis shows the "percent very happy," based on National Opinion Research Center for Genetics and Society surveys through 1991.

Figure 2 displays the Genuine Progress Indicator (GPI) developed by the organization Redefining Progress (1995), based on work by Daly and Cobb (1989). Like NEW, the GPI adds the value of domestic activities to GDP. However, the GPI shows a decrease in leisure time rather than an increase. In the GPI environmental pollution and resource depletion reduce GDP by larger amounts than they do in the NEW. In addition, GPI incorporates an indexing factor that records the growth of economic inequality as a decrease in well-being. These plus other modifications of the GDP accounts generate a path over time very different from that displayed by NEW.

Figure 3 shows the Human Development Index developed by the United Nations Development Program (1996). This relatively simple index has three components: life expectancy, educational attainment (based on adult literacy rates and mean years of schooling), and adjusted income. Income is GDP per capita computed on a Purchasing Power Parity basis, subject to a strongly diminishing marginal index value.

Easterlin (1995) doubts that any set of objective measures can accurately model all the determinants of well-being, and suggests that surveys of how people assess their own well-being can provide a better guide. Figure 4 shows how people in the United States responded to a question asking them how happy they are. The slight trend shown by the regression line is not statistically significant. Reported happiness in the United States over the past twenty years has been constant, despite a major increase in output during that time.

Applied to the United States, these alternatives to conventional GDP move in different ways over time. The NEW and HDI increase, the GPI decreases, and the proportion of people stating that they are happy remains unchanged.

APPENDIX 6. ESTIMATES OF STOCKS OF ENERGY RESOURCES

Boxes A6-1 through **A6-7,** below, show the source data used to estimate stocks of energy resources used in Section IIA.2.a. **Box A6-8** shows the conversion factors used to convert all estimates to terawatt years.

Box A6-1. HOLDREN
source: Energy & Resources 200 course handout:
Recent World Energy and Economic Data, 10/95.

Estimated Remaining Recoverable Resources of Fuels (TWy)

oil				
petroleum liquids	500			
oil shale	30000			
heavy oils	500			
natural gas				
conventional	500			
unconventional	1000			
coal	5000			
TOTAL Fossil Fuels	37500	7500	(w/o oil shale)	
uranium (in LWRs)	3000			
uranium (in LMFBRs)	3000000			
lithium (DT fusion)	1.4E+08			
deuterium (fusion)	2.5E+11			

Box A6-2. World Energy Council
(source: Global Energy Perspective to 2050 and Beyond. Report, 1995. p 36.)

Estimates of Energy Reserves, Resources and Occurrences
(GTOE)

		Reserves	Resources	Resource Base	Additional Occurrence	ultimately recoverable		
oil								
conventional		150	145	295		200		
unconventional		193	332	525	1900	553	(511-595)	
natural gas								
conventional		141	279	420		220		
unconventional		192	258	450	400			
hydrates					18700			
coal		606	2794	3400	3000	3400		
TOTAL Fossil Fuel:		1282	3808	5090	24000			
uranium (LWRs)		57	203	260	150			
uranium (LMFBRs)		3390	12150	15540	8900			
TOTAL ALL:		4729	16161	20890	33050			
World Energy Council: conversion to terawatt years								
Estimates of Energy Reserves, Resources and Occurrences								
(TWy)	1GTOE =	1.42	TWy					
		Reserves	Resources	Resource Base	Additional Occurrence	ultimately recoverable		
oil								
conventional		213	206	419		284		
unconventional		274	471	746	2698	785		
natural gas								
conventional		200	396	596		312		
unconventional		273	366	639	568			
hydrates					26554			
coal		861	3967	4828	4260	4828		
TOTAL Fossil Fuels		1820	5407	7228	34080			
uranium (LWRs)		81	288	369	213	(+ 17,000 tons U		
uranium (LMFBRs)		4814	17253	22067	12638	ultimately recoverable)		
TOTAL ALL:		6715	22949	29664	46931			

Box A6-3. IPCC
(source: IPCC, Climate Change 1995: Impacts, Adaptations and Mitigations of Climate Change. Working Group II Report)

(EJ)			Conventional Resources			Unconventional Resources:			Resource	Additional
		Reserves	to be discovered. w/ probability:			a. currently	b. recoverable with		Base	Occurance
		Identified	0.95	0.5	0.05	recoverable	technological progress			(> than...)
oil										
conventional		6000	1800	2500	5500				8500	10000
unconventional		7100					9000		16100	
natural gas										
conventional		4800	2700	4400	10900				9200	10000
unconventional		6900				2200	17800		26900	22000
hydrates										800000
coal		25200				13900	86400		125500	130000
TOTAL Fossil Fuels		50000	4500	6900	16400	16100	113200		186200	987000
uranium (LWRs)		1800		2300		4100	6000		14200	1000000
TOTAL ALL:		51800	4500	9200	16400	20200	119200		200400	1987000

IPCC: conversion to terawatt years

(TWy)										
1 EJ =	0.03175	TWy								
			Conventional Resources			Unconventional Resources:			Resource	Additional
		Reserves	to be discovered. w/ probability:			a. currently	b. recoverable with		Base	Occurance
		Identified	0.95	0.5	0.05	recoverable	technological progress			
oil										
conventional		191	57	79	175				270	318
unconventional		225					286		511	
natural gas										
conventional		152	86	140	346				292	318
unconventional		219				70	565		854	699
hydrates										25400
coal		800				441	2743		3985	4128
TOTAL Fossil Fuels		1588	143	219	521	511	3594		5912	31337
uranium (LWRs)		57		73		130	191		451	31750
TOTAL ALL:		1645	143	292	521	641	3785		6363	63087

Box A6-4. ENERGY MODELING FORUM
(source: Demographic, Economic, and Energy Assumption, EMF 14. http://soe.stanford.edu/ees/design.html)

(EJ)									
		Reserves	Undiscovered		ultimately recoverable				total
			Resources, 95%-ile		resources				
crude oil +									
nat. gas liquids		7362	6833						14195
natural gas		5537	10805						16342
coal					300000				300000

ENERGY MODELING FORUM: conversion to terawatt years
(source: Demographic, Economic, and Energy Assumption, EMF 14. http://soe.stanford.edu/ees/design.html)

(TWy)									
1 EJ =	0.03175	TWy							
		Reserves	Undiscovered		ultimately recoverable				total
			Resources, 95%-ile		resources				
crude oil +									
nat. gas liquids		234	217						451
natural gas		176	343						519
coal					9525				9525

Box A6-5 . HERMAN KAHN: THE NEXT 200 YEARS (1976)
(10^18 Btu)

source		proven reserves	long term potential resources		
oil		3.7	14.4		
natural gas		1	15.8		
coal		95	170		
shale oil		19	2000		
tar sands		1.8	1.8		
total fossil fuels		120.5	2202		
U-235 (free world)			15		
U-235 (oceans)			3000		
Uranium for breeders			100000	+	
Li-6 (D-T fusion)			320		
Deuterium (D-D fusion)			1E+09	+	

HERMAN KAHN: THE NEXT 200 YEARS (1976)

	Conversion toTerawatt years				
10^18 Btu =	33.49	TWy			
source		proven reserves	long term potential resources		
oil		124	482		
natural gas		33	529		
coal		3182	5693		
shale oil		636	66980		
tar sands		60	60		
total fossil fuels		4036	73745		
U-235 (free world)			502		
U-235 (oceans)			100470		
Uranium for breeders			3349000	+	
Li-6 (D-T fusion)			10717		
Deuterium (D-D fusion)			33490000000	+	

BOX A6-6. ROGER HINRICHS: Energy: Its Use and Environment (text; 1996)
10^18 Btu

		proven reserves				
oil		5.9				
natural gas		5				
coal		50				
tar sands		1.7				
shale oil		0.87				
total fossil fuel		63.47				

ROGER HINRICHS: Energy: Its Use and Environment (text; 1996)

	Conversion to Terawatt years					
10^18 Btu =	33.49	TWy				
		proven reserves				
oil		198				
natural gas		167				
coal		1675				
tar sands		57				
shale oil		29				
total fossil fuel		2126				

BOX A6-7. Freeman & Jahoda: WORLD FUTURES, 1978

(10^9 tce)

		proven &		ultimately	
fuel		possible reserves		recoverable resources	
coal		1000		7700	
oil		375		2760	
natural gas		200		1500	
shale oil		-		1200	
tar sand		-		225	
sub-total, for					
fossil hydrocarbons		1575		13385	
Uranium thermal		100			?
Uranium breeder		0		5000	+
Thorium breeder		0		4000	+
Fusion		0		virtually unlimited	
geothermal wet rock		60		1500	
geothermal dry rock		0		50 million	
TOTAL (excl fusion &					
geothermal dry rock)		1735		23885	
Freeman & Jahoda: WORLD FUTURES, 1978					
	Conversion to Terawatt years				
(10^9 tce)					
10^9 tce =	0.929	TWy			
		proven &		ultimately	
fuel		possible reserves		recoverable resources	
coal		929		7153	
oil		348		2564	
natural gas		186		1394	
shale oil				1115	
tar sand				209	
sub-total, for					
fossil hydrocarbons		1463		12435	
Uranium thermal		93			?
Uranium breeder		0		4645	+
Thorium breeder		0		3716	+
Fusion		0		virtually unlimited	
geothermal wet rock		56		1394	
geothermal dry rock		0		50 million	
TOTAL (excl fusion &					
geothermal dry rock)		1612		22189	

BOX A6-8. CONVERSION FACTORS

The conversion factors used in Boxes A6-1 through A6-7 are:

1 EJ = 10^18 J
1 TWy = 31.5 EJ
1 EJ = 3.175 x 10^-2 TWy
1 J = 9.484 x 10^-4 Btu
1 Btu = 1055 J
1 Q = 10^18 Btu
1 bbl = 5.8 x 10^6 Btu = 6.12 x 10^9 J
1 ton U235 = 70 x 10^12 Btu
1 mbdoe = 50 x 10^6 tons oil equivalent/year = 2.2 x 10^18 J/yr
10^15 Btu = 36 x 10^6 tons coal equivalent

where:

EJ = Exajoule
TWy = Terawatt year
Btu = British thermal unit
Q = Quad
bbl = billion barrels of oil equivalent
mbdoe = million barrels per day oil equivalent

APPENDIX 7. Calculation of Global Warming Trajectories

Section II.A.2a offered several scenarios in which anthropogenic global warming is prevented from exceeding 3.6° C, as displayed in Box IIA-15. These scenarios were generated using my extension (Hayes 1995) of the model developed by Cline (1992).

The key equations of the extended Cline model are shown and described below.

We begin with Cline's equations for income and population:

$$(1) \quad y_t^D = y_t^D (1 + g_D)^t$$

$$(2) \quad y_t^L = y_t^L (1 + g_L)^t$$

$$(3) \quad P_t^D = P_0^D (1 + n_D)^t$$

$$(4) \quad P_t^L = P_0^L (1 + n_L)^t$$

where:
y = per capita income
P = population
D = developed countries
L = less developed countries
t = time; t = 1 in 1991
g = per capita growth in income
n = per capita growth in population

These give Gross World Product, Y:

$$(5) \quad Y_t = y_t^D P_t^D + y_t^L P_t^L$$

Cline's proposed carbon emissions ceiling (K) [4 Gt/year] is subtracted from baseline emissions (E) to give the needed amount of annual emissions reductions (R):

$$(6) \quad R_t = E_t - K$$

The amount of global warming (W) in any given year (t) is given by the linear functions:

$$(7) \quad W_t = \Delta S + [(W^* - S)/225]\,(t - 60); \quad t \geq 60$$

$$(8) \quad W_t = S(t/60); \quad t < 60$$

where:

S = climate sensitivity parameter
[1.5°, 2.5°, and 4.5° for low, medium and high cases]
W* = equilibrium warming under very-long-term global warming conditions
[6°, 10° and 18° for low, central and high climate sensitivity parameters]

I extended Cline's model to allow alternative warming trajectories to be calculated. The equations are shown below. Further details can be found in Hayes (1995).

First apply the subscript t to K, to show that K can vary with time, with $t_0 = 1966$.

(9) $$R_t = E_t - K_t$$

Next we add the climate model, beginning with equations for atmospheric CO2 stock and concentration. For this purpose I used an equation from the Nordhaus (1996) DICE model. The superscript B denotes business-as-usual values.

(10) $$M_t^B = [590 + \beta E_t + (1-\delta_M)(M_{t-1}^{\beta} - 590)]$$

In this equation 590 is the pre-industrial carbon stock (in GtC), β is the short-term emissions retention fraction (.64), E_t are emissions, and δ_M is the long-term CO2 decay constant, set at .00825.

Next we multiply by the constant .47 to convert atmospheric stock to a concentration:

(11) $$CON_t^B = .47M_t^B$$

Next we use the standard formula to calculate radiative forcing due to CO2:

(12) $$RFC_t^B = 6.3\ln\left[\frac{CON_t^B}{280}\right]$$

Then we add the radiative forcing that results from trace gases:

(13) $$RFT_t^B = -0.184 + 1.8024(RFC_t^B) - 0.047(RFC_t^B)^2; \qquad RFC_t^B \le 6$$

(14) $$RFT_t^B = 1.45RFC_t^B; \qquad RFC_t^B > 6$$

Now we calculate warming commitment:

(15) $$WC_t^B = RFT_t^B \lambda\beta\alpha$$

In this equation λ is .3 w/m^2 and the feedback variable β takes upper bound, central case and lower bound values of 3.4, 1.9, and 1.1, respectively, which generate climate sensitivity factors of 1.5, 2.5 and 4.5 degrees C. The factor α, set at 1.18, adjusts for the masking effects of SO2, NOx and O3, and for the use of Nordhaus' stock equation.

Finally we get warming at any time t by adjusting for the 25-year-lag:

$$(16) \quad W_t^B = WC_{t-25}^B; \qquad t \geq 25$$

$$(17) \quad W_t^B = 0; \qquad t < 25$$