DECOMPOSITION OF CARBON EMISSION REDUCTION PROJECTIONS

WP 12.4

Ming-Fai Sit

January 1993

Energy Modeling Forum
Terman Engineering Center
Stanford University
Stanford, California

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To better understand how the carbon emission reduction are achieved across different models, emissions growth is typically decomposed into different components. One of many ways to do the decomposition is to break emissions growth into fuel switching, energy intensity and economic growth components. To characterize the fuel switching effect, the emission intensity (emission/energy ratio) is used. The total primary energy equivalent is used as a consistent energy consumption definition. A smaller emission intensity means more intensive use of lower carbon-emitting energy thus a bigger switching effect. The energy intensity effect can similarly be measured by the energy intensity (energy/GDP ratio). A smaller energy intensity indicates a combination of less energy use within industries and sectoral shift away from energy intensive industries. GDP is used as the economic growth index.

The decomposition is based on the identity :

$$X = \frac{X}{E} \frac{E}{GDP} GDP$$

where X = carbon emission

E = Total primary energy equivalent

writing

$$K = \frac{X}{E}$$
$$L = \frac{E}{GDP}$$
$$G = GDP,$$

the identity becomes

$$X = K\ L\ G \qquad \text{-(1)}$$

The differential form of equation (1) gives :

$$\frac{d}{X} = \frac{d}{K} + \frac{d}{L} + \frac{dG}{G}$$

-(2)

Equation (2) states that for infinitesimal changes in K,L and G, the percentage change of each will sum up to the percentage change in emissions X. The equation is not restricted to change with time, it can also be used for comparing different scenarios. However, the data we have is usually not limited to small change so that by the normal definition of percentage change, the equality will not strictly hold.

Nevertheless, if continuous compounding is assumed, the equality (2) will always hold for inter-temporal analysis. In particular, we assume :

$$X = X_o e^{x(t-t_o)}$$
$$K = K_o e^{k(t-t_o)}$$
$$L = L_o e^{l(t-t_o)}$$
$$G = G_o e^{g(t-t_o)}.$$

If t is in year, all exponential parameters x, k, l, and g are the annual growth rates. It is easy to see that by their definition,

$$x = k + l + g$$

which also satisfies equation (2).

Given two data points, the annual emission growth rate can be calculated by :

$$X = \frac{1}{T-t_o} \ln \frac{X_T}{X_o}, \qquad - (3)$$

and similarly for the other exponential parameters.

In general, the scenario runs of EMF cannot be assumed to follow an exponential growth. However, we still can use equation (3) to estimate the exponential parameters which can be interpreted as the Average Annual Growth Rate.

Figures 1 and 2 depict the Average Annual Growth Rates between the period 1990 and 2020 for the different models. The growth rates are calculated by equation (3) with T = 2020 and t_o = 1990.

Result

For the reference case, all models have the same GDP effect (2.14%) which is exogenous to the models. With the exception of MWC, the fuel switching effect is relatively small (-0.27% to 0.22%). It is positive for Global 2100, CRTM-RD, Gemini and Goulder which implies that they rely more on carbon-intensive fuels in the reference case. The other models have negative effects which indicates switching away from the carbon-intensive fuels. With a rising fossil fuel cost projection and technology advancement, one would expect the non-carbon emitting fuels to get a larger share of total fuels supply. However, it also depends on the detailed technology assumption, fuel prices and price elasticities included in the models. Since the effect is small and price data is not available, it is difficult to give further interpretation at this time. From Figure 3, it can be seen that MWC achieves fuel switching by extensive use of "Other Carbon-Free Electric".

Figure 1
Average annual growth rate between 1990 and 2020, Reference, USA

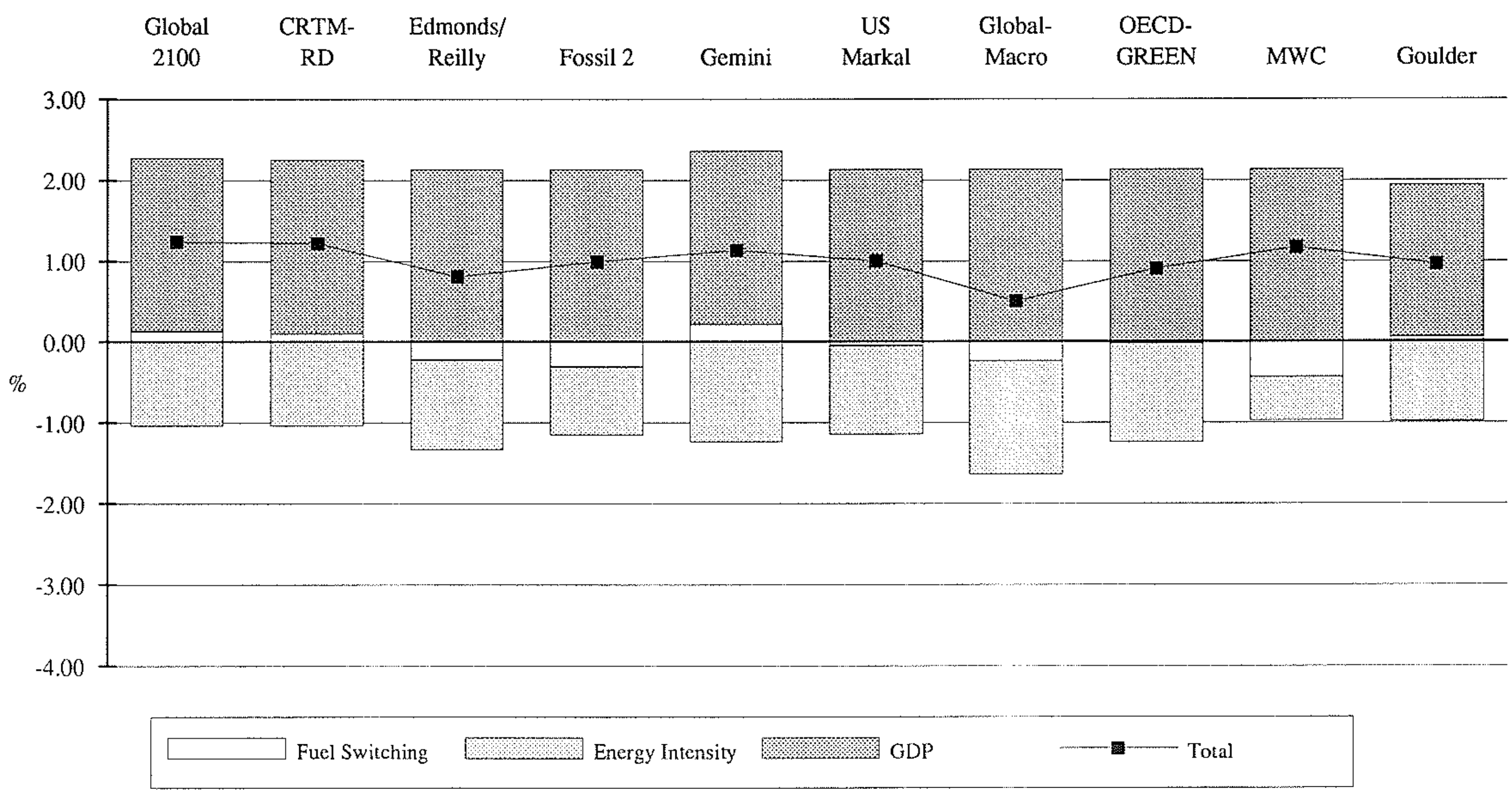

Figure 2

Average annual growth rate between 1990 and 2020, 20% Red. by 2010, USA

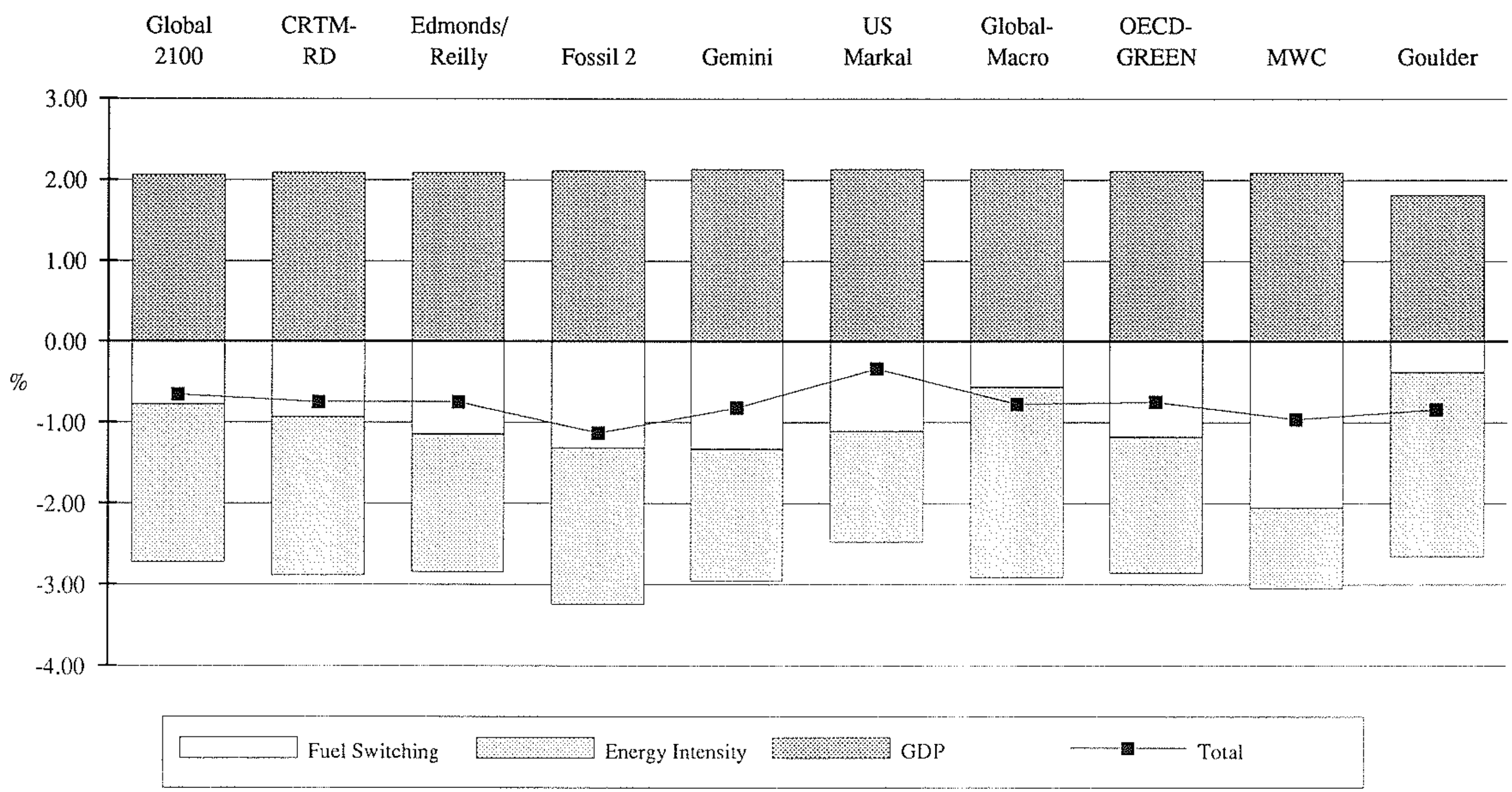

Table 1. Average Annual Growth Rate Between 1990 and 2020 Reference Scenario

	Fuel Switching (k)	Energy Intensity (1)	GDP (g)	Total (x)
Global 2100	0.14	-1.03	2.14	1.25
CRTM-RD	0.11	-1.03	2.14	1.23
Edmonds/Reilly	-0.22	-1.11	2.14	0.81
Fossil 2	0.27	-1.03	2.14	1.38
Gemini	0.22	-1.23	2.14	1.14
US Markal	-0.04	-1.11	2.14	1.00
Global-Macro	-0.23	-1.40	2.14	0.51
OECD-GREEN	0.03	-1.09	2.14	1.08
MWC	-0.43	-0.54	2.14	1.17
Goulder	0.07	-0.98	1.88	0.97

Table 2. Average Annual Growth Rate Between 1990 and 2020
20% Reduction by 2010 Scenario

	Fuel Switching (k)	Energy Intensity (1)	GDP (g)	Total	Carbon Tax $/ton
Global 2100	-0.77	-1.95	2.07	-0.65	370
CRTM-RD	-0.93	-1.96	2.10	-0.74	259
Edmonds/Reilly	-1.14	-1.70	2.09	-0.75	235
Fossil 2	-0.74	-2.11	2.12	-0.74	169
Gemini	-1.32	-1.63	2.14	-0.81	110
US Markal	-1.10	-1.37	2.14	-0.33	-
Global-Macro	-0.56	-2.35	2.14	-0.77	150
OECD-GREEN	-0.23	-2.63	2.12	-0.74	161
MWC	-2.05	-1.00	2.10	-0.95	169
Goulder	-0.37	-2.28	1.82	-0.83	81

A large part of the growth in emissions that would otherwise be caused by economic growth is offset by the reductions in energy intensity. This energy intensity effect is very similar across all models with an average of -1.1%, with the biggest being Global-Macro (-1.4%) and smallest MWC (-0.54%). Although there are different assumptions on the energy efficiency improvement (autonomous and price induced) and price elasticities, the overall results agree reasonably well on this component. With the exception of Global-Macro, the growth in total carbon emission also fall within a narrow range from 0.81% to 1.38%, although this "small" difference can lead to big discrepancy in the long run due to the compounding effect.

For the 20% Reduction by 2010 scenario, the target is to achieve carbon reduction of an average annual rate of about -0.75% over the next 30 years. The results of model indicate that the GDP loss effect is relatively insignificant, with Global 2100 has the biggest drop from 2.14% to 2.07% (note that some models do not have the GDP loss feedback). Thus, the reduction has to be achieved by a combination of fuel switching and reduction in energy intensity. All models have negative fuel switching effect this time ranging from -0.56% (Global-Macro) to -2.05% (MWC). In addition to the actual value of rate change, we can also look at the percentage point difference between this scenario and the Reference Scenario.

Table 3 and Figure 5 show the relative role of fuel switching and energy intensity reductions in moving from the Reference scenario to the 20% Reduction by 2010 scenario for the different models. MWC uses the most fuel switching implying more carbon-free electric employed, as was observed in the Reference case. Gemini and US Markal employed the next largest amount of fuel switching. One conjecture is that they have rich technology representations allowing them to more easy to make the cheapest mix of technologies. However, this effect also depends on the cost of new technologies and the price elasticities of energy demand. This conjecture cannot be verified without more detailed study. Figures 3 and 4 show

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**Table 3. Average Annual Growth Rate (1990-2020)
Percentage Point Difference Between 20% Reduction and Reference Scenarios**

	Carbon Tax	Fuel Switching	Energy Intensity	Carbon Emission
Global 2100	370	-0.91	-0.91	-1.90
CRTM-RD	259	-1.04	-0.93	-1.97
Edmonds/Reilly	235	-0.92	-0.59	-1.56
MWC	169	-1.62	-0.46	-2.13
Fossil 2	169	-1.01	-1.08	-2.12
OECD-GREEN	161	-0.25	-1.55	-1.83
Global-Macro	150	-0.32	-0.95	-1.27
Gemini	110	-1.55	-0.40	-1.95
Goulder	81	-0.44	-1.30	-1.80
US Markal	-	-1.06	-0.26	-1.33

Figure 3
Disaggregation of Total Primary Energy, In 2020 , Reference , USA

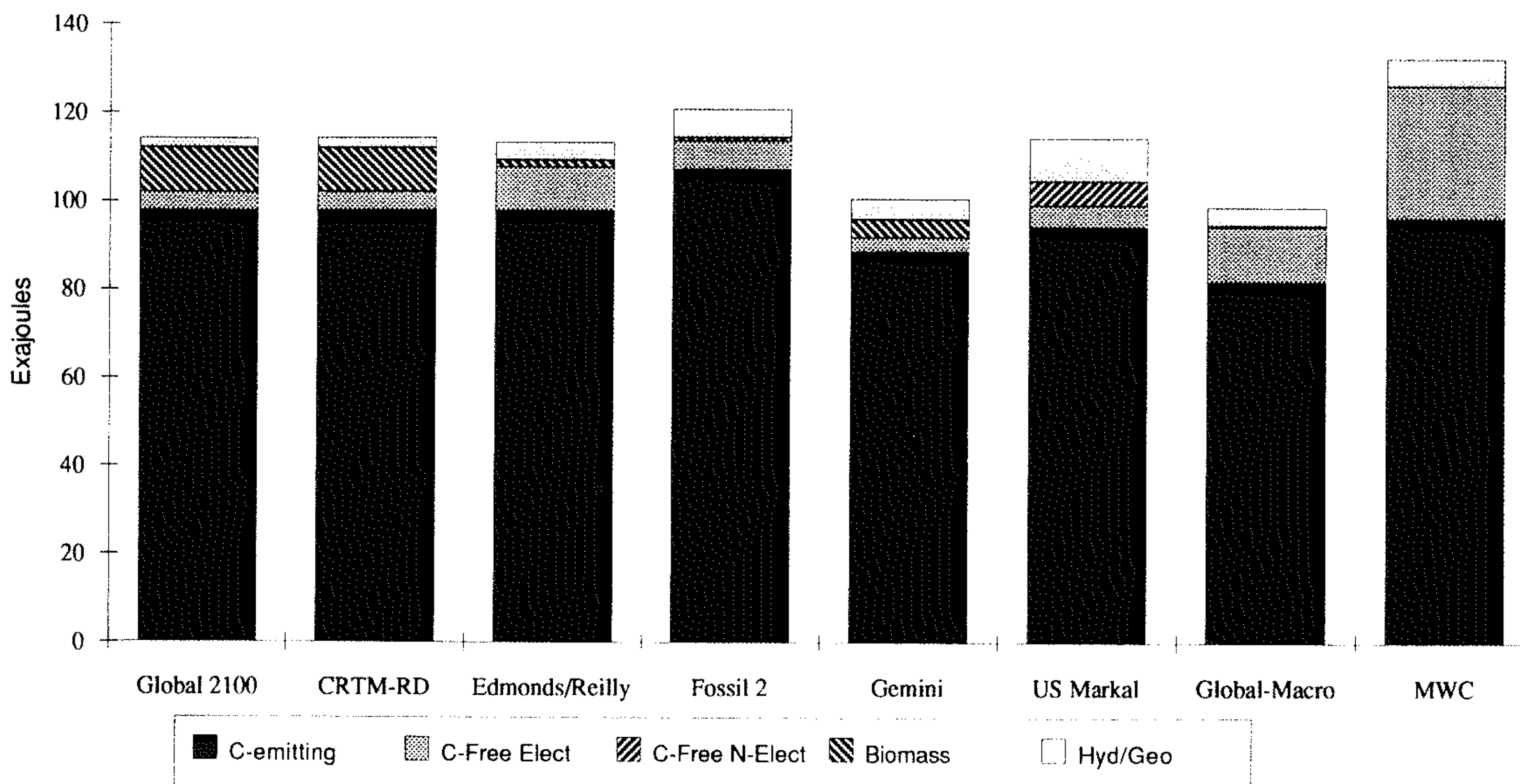


Figure 4
Disaggregation of Total Primary Energy, In 2020 , 20% Red. by 2010 , USA

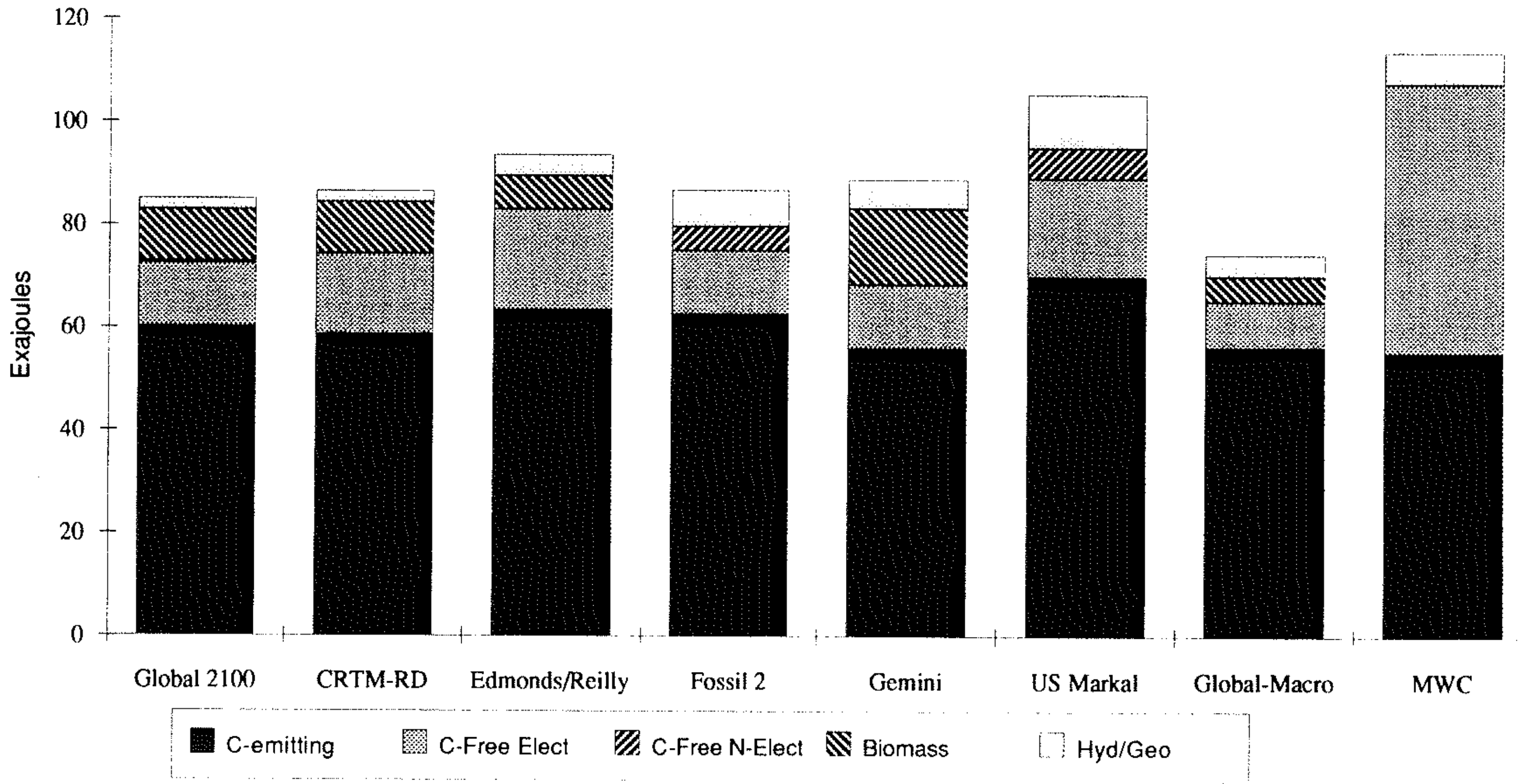
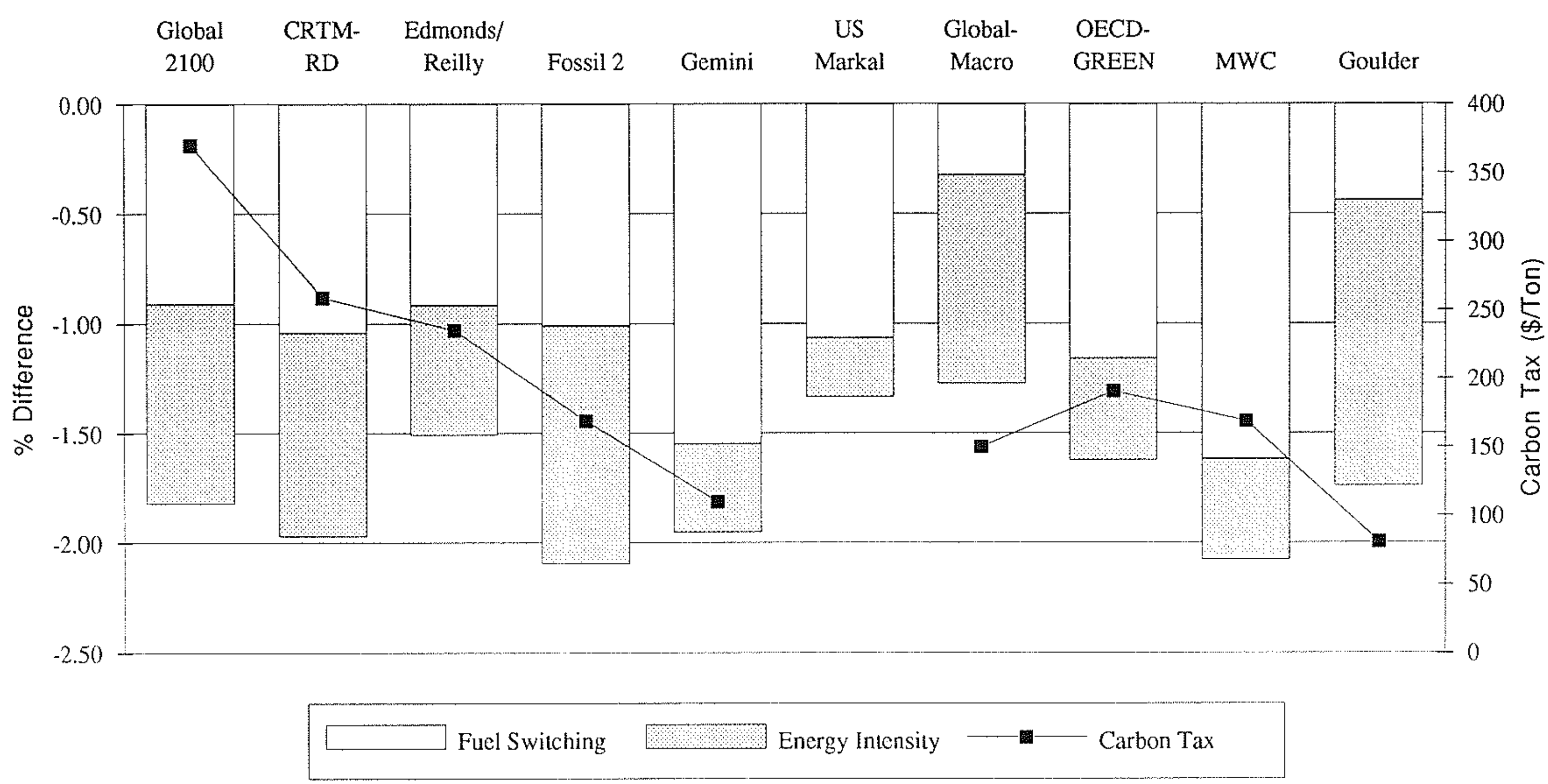


Figure 5
Average annual growth rate between 1990 and 2020, USA
Percentage point difference between 20% Reduction and Reference scenarios



that Gemini achieves its fuel switching primarily by intensive use of Biomass while US-Markal employs Carbon-Free Electric energy. Gemini requires a Carbon Tax of 110 \$/ton in 2020, which is the lowest of all models, indicates that they are relative ease to achieve the total reduction. Gemini has a much higher carbon tax in earlier years, however is only a transient effect of the dynamic of reduction. Another technology rich model, Fossil-2, also has one of the largest fuel switching effects. But it also uses nearly the same amount of energy intensity reduction as fuel switching. Fossil-2 only requires a carbon tax of 169\$/ton in 2020.

Next, we are also interested in the percentage shift of each effect per dollar Carbon Tax imposed,

$$\eta_k = -\frac{k}{T}.$$

k = % point difference between two scenarios

T = Carbon Tax

Compared with the usual definition of elasticity,

$$\varepsilon_k = -\frac{kT_o}{T}$$

T_0 = Carbon cost of reference scenario in 2020

they are only differed by a factor of Carbon cost. Carbon costs are not the same for different models. However, if we assume that Carbon costs vary little across all models and themselves are small compare with the Carbon Tax, h_k's are good approximation to the relative values of elasticity. Since h_k is related to elasticity, it is named pseudo-elasticity.

Table 4 shows the pseudo-elasticities of different effects for different models. The biggest fuel switching pseudo-elasticity (FSPE) and energy intensity pseudo-elasticity (EIPE) are Gemini(14.07) and Goulder(16.07) respectively. By excluding Glouder (who has an exceptional high EIPE) the average value of FSPE is 6.0 which is much bigger than that of EIPE (3.8). Most models have a bigger FSPE than, or nearly the same as, EIPE except for Global-Macro and

Table 4. Pseudo-Elasticity Based on 20% Reduction and Reference Scenarios

	2020 Carbon Tax	Average Carbon Tax	Fuel Switching Pseudo-Elasticity	Energy Intensity Pseudo-Elasticity	Carbon Emission Pseudo-Elasticity
Global 2100	370	178	2.46	2.46	5.12
CRTM-RD	259	254	4.02	3.59	7.61
Edmonds/Reilly	235	214	3.90	2.52	6.62
MCW	169	169	9.56	2.73	12.58
Fossil 2	169	184	5.97	6.42	12.52
OECD-GREEN	161	162	1.57	9.60	11.34
Global-Macro	150	147	2.16	6.34	8.50
Gemini	110	298	14.07	3.67	17.74
Goulder	81	89	5.40	16.07	22.25

Goulder. Figures 6 to 8 depict the plot of carbon tax against FSPE, EIPE and carbon emission pseudo-elasticity (CEPE) respectively. The plots of FSSPE and EIPE are quite scattered but a trend is apparent for the CEPE plot. The trend for CEPE makes intuitive sense that the smaller the pseudo-elasticity, the higher is the Carbon Tax and it vary in a non-linear way.

Figure 6
Carbon Tax vs Fuel Switching Pseudo-Elasticity

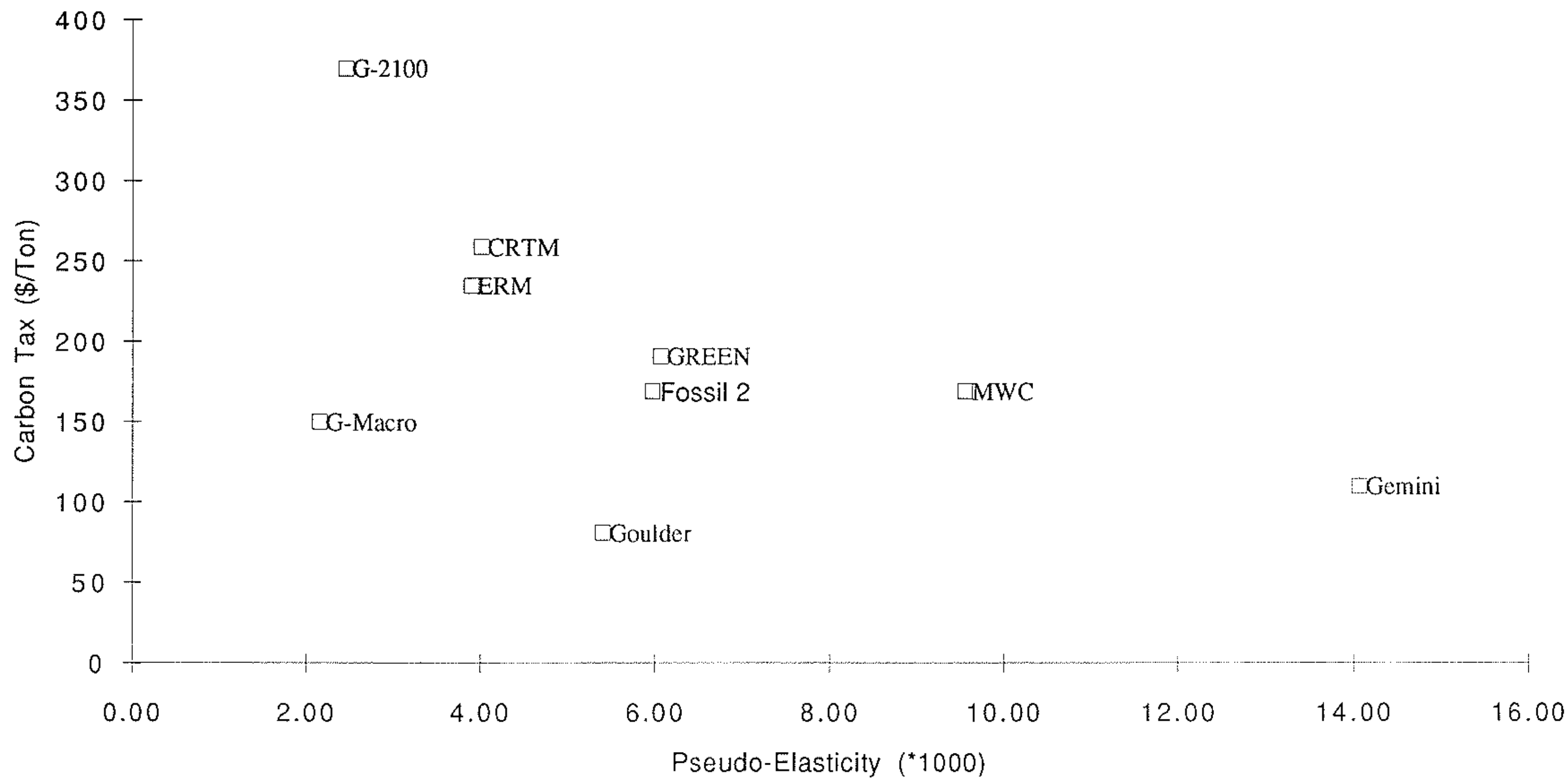


Figure 7
Carbon Tax vs Energy Intensity Pseudo-elasticity

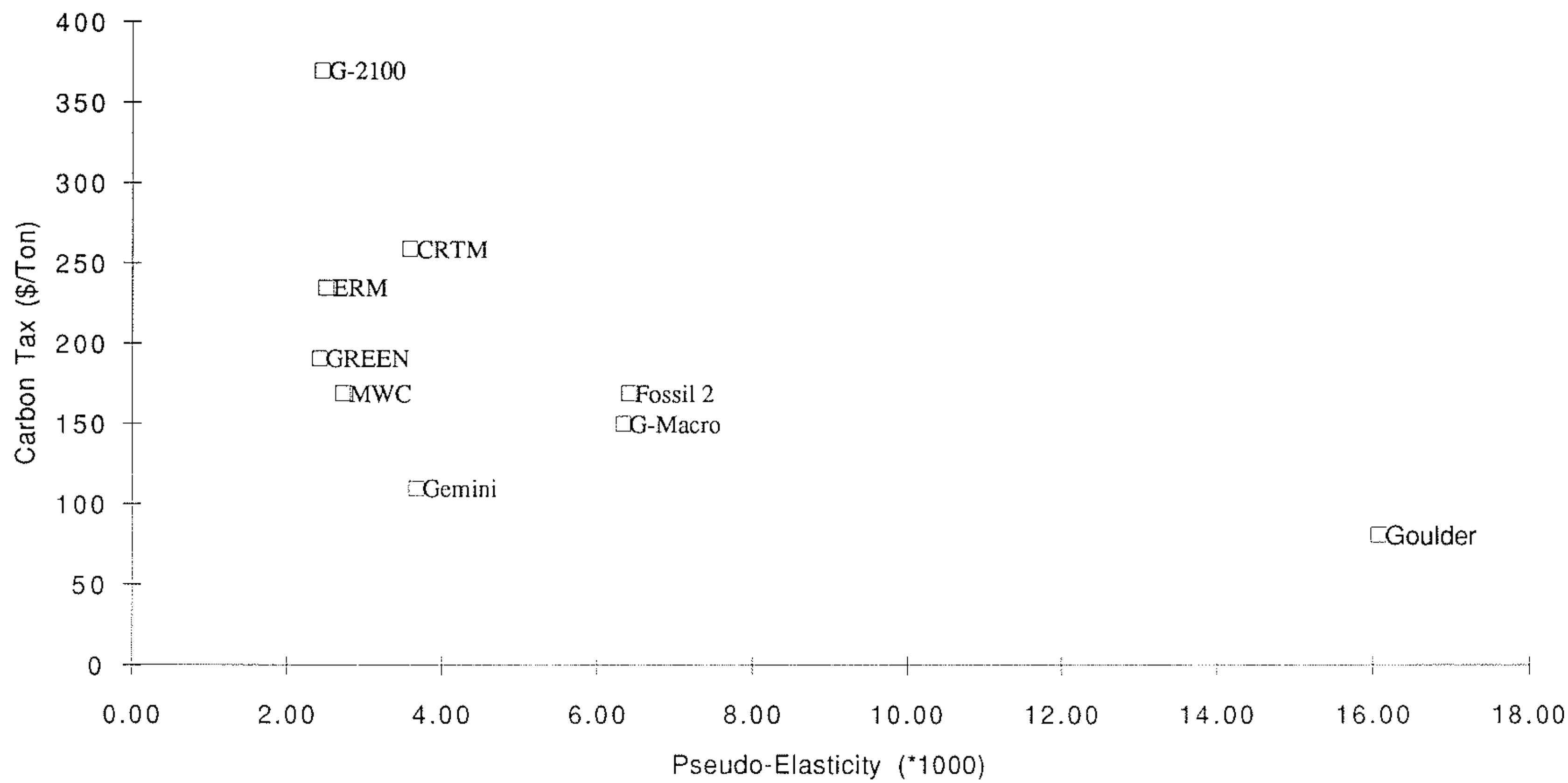


Figure 8
Carbon Tax vs Carbon Emission "Pseudo-Elasticity"