

MERGE: An Integrated Assessment Model for Global Climate Change^{*}

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Introduction

MERGE is a model for estimating the regional and global effects of greenhouse gas reductions. It quantifies alternative ways of thinking about climate change. The model is sufficiently flexible to explore alternative views on a wide range of contentious issues: costs of abatement, damages from climate change, valuation and discounting. MERGE contains submodels governing:

- the domestic and international economy
- energy-related emissions of greenhouse gases
- non-energy emissions of ghg's
- global climate change – market and non-market damages

Each region's domestic economy is viewed as a Ramsey-Solow model of optimal long-term economic growth. Intertemporal choices are strongly influenced by the choice of a "utility" discount rate.

Price-responsiveness is introduced through a top-down production function. Output depends upon the inputs of capital, labor and energy. Energy-related emissions are projected through a bottom-up perspective. Separate technologies are defined for each source of electric and nonelectric energy. Fuel demands are estimated through "process analysis".

Each period's emissions are translated into global concentrations and in turn to the impacts on mean global indicators such as temperature change. MERGE may be operated in a "cost-effective" mode - supposing that international negotiations lead to a time path of emissions that satisfies a constraint on concentrations or on temperature change. The model may also be operated in a "benefit-cost" mode - choosing a time path of emissions that maximizes the discounted utility of consumption, after making allowance for the disutility of climate change.

Individual geopolitical regions are defined. Abatement choices are distinguished by "where" (in which region?), "when" (in which time period?) and "what" (which greenhouse gas to abate?). There may be tradeoffs between equity and efficiency in these choices.

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For a model of this size and complexity (currently, 20,000 constraints), there are several possible choices of nonlinear programming algorithms. We began with an informal decomposition procedure, but soon shifted to sequential joint maximization and iterative revision of Negishi weights. Our first solver was MINOS. We then coupled this with Benders decomposition. We are currently solving these problems with CONOPT3. For a computer listing and a bibliography, see our website:

www.stanford.edu/group/MERGE

Market and non-market damages

If the model is operated in a benefit-cost mode, one must somehow quantify the benefits of slowing down the rate of climate change. Typically, these benefits are described in terms of the damages avoided. There are a number of arbitrary assumptions about the damages associated with climate change. We stress the rudimentary nature of the state of the art of damage assessment. These assumptions should be interpreted as purely illustrative. They are adopted to illustrate how a benefit-cost analysis might be carried out.

When Nordhaus (1991) made his first efforts at quantification, the benefits were expressed in terms of avoiding crop losses, forestry damage, shoreline erosion, etc. For each of these sectors, it was possible to assign market values to the losses. There are prices for crops, timber and real estate. Later, it was discovered that limited temperature changes could even lead to modest gains in some of these areas (e.g. through CO₂ fertilization). There is an emerging consensus that market damages are not the principal reason to be concerned over climate change in developed countries.

The more worrisome issue is the type of damage for which there is no market value. The “non-market damages” include human health, species losses and impacts on environmental quality. Such losses are highly uncertain. In many cases we must rely on informed judgment and introspection. This type of loss is likely to be of far greater concern to high-income regions than to those with low incomes.

In MERGE, we have allowed for both market and non-market damages, but have focused our attention on the latter. Typically, we assume a “climate sensitivity” of 2.5 degrees C, the temperature change associated with a doubling of carbon concentrations over pre-industrial levels.¹ For market damages, we interpret the literature as implying that a 2.5° temperature rise would lead to GDP losses of 0.25% in the high-income nations, and to losses of 0.50 % in the low-income nations. At higher or lower temperature levels than 2.5°, we assume that market losses would be proportional to the change in mean global temperature from its level in 2000.

For non-market damages, MERGE is based on the conjecture that expected losses would increase quadratically with the temperature rise. That is, there are no discernible losses at the temperature level of 2000, but the losses from possible catastrophes could increase

¹ Our results are particularly sensitive to the assumption regarding climate sensitivity.

radically if we go much higher. Admittedly, the parameters of this loss function are highly speculative. With different numerical values, different abatement policies will be optimal. This helps to explain why there is no current international consensus on climate policy.

The domestic economy

Within each region, intertemporal consumption and savings choices are governed by an optimal growth model. There is forward-looking behavior. Current and future prices and quantities are determined simultaneously. For a simple numerical example of this type of macro model, see the GAMS documentation for library model Ramsey.63.

The time paths of savings, investment and consumption are strongly influenced by the choice of a "utility" discount rate. This in turn may be governed by a prescriptive or a descriptive viewpoint. In the first case, one adopts a planner's perspective on how things *ought* to be managed. In the second, one adopts a utility discount rate that is intended to *describe* a market-oriented economy. For a review of different perspectives on discounting, see Portney and Weyant (1999).

Outside the energy sector, output is aggregated into a single good, the numéraire. Consumption is just one of the claimants upon total economic output, $Y_{rg,pp}$. In each region rg and projection period pp , some of the output must be allocated to investment, $I_{rg,pp}$. In turn, this is used to build up the capital stock. Other output is employed to pay for energy costs, $EC_{rg,pp}$. Some output is required to compensate for market damages, $MD_{rg,pp}$. And some output is allocated to net exports of the numéraire, $NTX_{rg,pp,nmr}$. The allocation equation is expressed as follows:

$$Y_{rg,pp} = C_{rg,pp} + I_{rg,pp} + EC_{rg,pp} + MD_{rg,pp} + NTX_{rg,pp,nmr}$$

Gross output is defined so that there is a low elasticity of price response in the short run, but a much higher response over the longer term. That is, new output is responsive to current and expected future prices, but the economy is locked in to the technology choices made in earlier years. With ten-year time intervals and 40% depreciation over a decade, we have:

$$Y_{rg,pp} = YN_{rg,pp} + .6 Y_{rg,pp-1}$$

In turn, new output is based on an economy-wide nested CES (constant elasticity of substitution) production function. The inputs to this production function are expressed as new capital, new labor, new electric and new nonelectric energy, respectively $KN_{rg,pp}$, $LN_{rg,pp}$, $EN_{rg,pp}$ and $NN_{rg,pp}$. These inputs are governed by transition equations similar to those that have just been written for gross output.

The production function is calibrated so as to allow for three types of substitution: (1) capital-labor substitution, (2) interfuel substitution between electric and nonelectric energy,

and (3) substitution between capital-labor and energy. The parameters are also adusted so as to allow for autonomous improvements in the productivity of labor and of energy. New output is written as the following function of the new inputs:

$$Y_{N_{rg,pp}} \leq \left(a_{const_{pp,rg}} K_{N_{rg,pp}}^{\rho_{rg} k_{pvs_{rg}}} L_{N_{pp,rg}}^{\rho_{rg} (1-k_{pvs_{rg}})} + b_{const_{pp,rg}} E_{N_{rg,pp}}^{\rho_{rg} el_{vs_{rg}}} N_{N_{rg,pp}}^{\rho_{rg} (1-el_{vs_{rg}})} \right)^{\frac{1}{\rho_{rg}}}$$

The international economy

International trade is expressed in terms of a limited number of tradeable goods. These are handled through the Heckscher-Ohlin paradigm (internationally uniform goods), rather than the Armington specification (region-specific heterogenous goods). Specifically, we assume that each of the regions is capable of producing the numéraire good, and that this is identical in all regions. This is a crucial simplification. It means that heterogenous categories outside the energy sector (e.g., foodgrains, medical services, haircuts and computers) are all aggregated into a single item called “U.S. dollars of 2000 purchasing power”. This is the type of simplification that is usually adopted in partial equilibrium models. Clearly, this would be inappropriate if we were dealing with short-term balance-of-payments issues for individual countries.

We assume that each of the regions may produce oil and gas (subject to resource exhaustion constraints), and that these commodities are tradeable between regions. In some versions of the model, we also allow for trade in eis (energy-intensive sectors such as steel and cement). And in other versions, we allow for trade in crt (carbon emission rights).

Generically, the tradeables are described by the index set, trd . The decision variables $NTX_{pp,rg,trd}$ may be positive (to denote exports) or negative (to denote imports). For each tradeable trd and each projection period pp , there is a balance-of-trade constraint specifying that – at a global level – net exports from all regions must be balanced with net imports:

$$\sum_{rg} NTX_{pp,rg,trd} = 0$$

Associated with each of these trade balance equations, there is a price. In a planning model, these would be described as “efficiency prices”. MERGE, however, is a market-oriented model. We therefore refer to these as projections of market prices. There is

enormous uncertainty with respect to these prices, and care should be taken in their interpretation.

Because the objective function of MERGE is stated in terms of discounted utility, each of the prices is also stated in terms of discounted utility. To improve intelligibility for the general user, we report these prices in terms of their ratio to the value of the numéraire good during each projection period. However, at the point in the computational cycle where we adjust the Negishi weights so as to ensure an intertemporal balance-of-payments constraint for each region, these are once again defined as present-value prices. For more on the Negishi adjustment process, see Rutherford (1999).

Energy-related emissions of greenhouse gases

Within the energy sector, virtually all emissions of greenhouse gases consist of carbon dioxide. For purposes of this presentation, we shall skip over the small amount of methane produced by coal mining and by natural gas extraction and transportation.

MERGE contains carbon emission coefficients for both current and prospective future technologies. These define how much carbon dioxide is produced whenever we burn coal, oil and gas in the generation of electric and non-electric energy. Carbon dioxide is *not* released when we generate electricity through nuclear, hydroelectric, geothermal, wind and solar photovoltaics. Another carbon-free option is combustion, followed by capture and sequestration. Currently, there are virtually no economical carbon-free sources of non-electric energy. It is expensive to produce hydrogen directly through the electrolysis of water, and it is also expensive to produce ethanol from crops such as grain and sugar.

Over the long term, it is possible that we could consume all of the fossil fuels contained in the earth's crust, and that this would set an upper bound on the emissions of carbon dioxide. Unfortunately – from the perspective of global climate change – this does not provide a very tight bound on greenhouse emissions. In MERGE, we are currently using the regional and global estimates of oil and gas resources that appear in U.S. Geological Survey (2000). “Undiscovered” resources are based upon the USGS F5 (optimistic) scenario for resources to be discovered during the thirty-year period 1995-2025. For our reference case, global oil and gas production reach their peak about 2050. There are, however, enormous quantities of coal resources. Coal-fired electricity generation and coal-based synthetic fuels could lead to a quadrupling of carbon dioxide emissions over the 21st century. Coal may provide energy security for a few countries (China, India, Russia and the USA), but it could lead to an unprecedented rise in global carbon concentrations.

Non-energy emissions of ghg's – afforestation sinks of CO2

For non-energy emissions, MERGE is based on the estimates provided by Energy Modeling Forum Study 21. The EMF estimated baseline projections from 2000 through 2020. For all gases but N2O and CO2, our baseline was derived by linear extrapolation.

For the abatement of non-energy emissions, MERGE is also based on EMF 21. EMF provided estimates of the abatement potential for each gas in each of 11 cost categories in 2010. We incorporated these abatement cost curves directly within the model and extrapolated them after 2010, following the baseline. We also built in an allowance for technical advances in abatement over time.

Our estimates of carbon sinks are based on the global results reported by two of the models participating in EMF 21: GCOMAP and GTM. For details on these models, see, respectively, Sathaye et al. (2003) and Sohngen and Mendelsohn (2003). Each of these is a dynamic partial equilibrium model of the timber industry. That is, both of these models take the efficiency price of carbon as an input datum. Each allows for the carbon uptake in the timber growth cycle, and each gives an estimate of timber supplies, demands and prices in individual markets.

GTM and GCOMAP were run under six standardized scenarios with respect to the global efficiency price of carbon. For each of these scenarios, the models then reported the year-by-year net absorption of carbon through afforestation sinks. In turn, the two models were each coupled to MERGE by taking a convex combination of the six time-phased scenarios – and allowing for the possibility of a delay in initiating them.

Global climate change – cost-effectiveness analysis

Ideally, one would project global climate change by estimating a series of climate related variables.. As a practical matter, the mean global temperature is the most readily available indicator that is currently available. To estimate the temperature increase from 2000, we followed the IPCC (2001, p. 358) suggestions.

Radiative forcing determines the potential for temperature increase – after *time* has elapsed for the system to come into equilibrium. In order to translate radiative forcing into the actual temperature increase, we must allow for time lags in response. Both the biosphere and the ocean systems introduce inertia into the system . Typically, we assume an average lag of about 25 years. This is modeled through a series of linear difference equations.

The end result is an estimate of the mean global temperature increase that is associated with a reference case (business-as-usual) and with alternative abatement strategies. Figure 1 is based on the MERGE estimates submitted to EMF 21. It shows a reference case leading to radiative forcing of 8.4 watts per square meter by 2150 – and a

temperature increase of 4.5°C from 2000. It also shows two control cases – both of them providing for a limit of 4.5 watts per square meter. One is based on a carbon-only abatement strategy. The other is based on a multi-gas approach. Associated with each of these strategies, there is an efficiency price path – an optimal tax on the emissions of carbon and the other greenhouse gases. See Figure 2.

Benefit-cost analysis

Figures 1 and 2 are based upon the cost-effectiveness paradigm. That is, what is the least-cost way to satisfy a given limit? For EMF21, the limit is stated in terms of radiative forcing or in terms of the mean global temperature increase. But one can also pose this as a benefit-cost problem – reaching agreement on an international control system that leads to the temperature limit which minimizes the discounted present value of abatement costs and damages. This is a more ambitious goal. It requires us to define the disutility that is associated with varying amounts of market and nonmarket damages.

In order to quantify these tradeoffs, we have assumed a specific form for the “economic loss factor”, $ELF_{rg,pp}$. For non-market damages, MERGE is based on the conjecture that expected losses would increase quadratically with the temperature rise. Figure 3 shows the admittedly speculative estimates that are currently used. Different numerical values are employed – depending upon the per capita income of the region at each point in time. These loss functions are based on two parameters that define willingness-to-pay to avoid a temperature rise: $catt$ and hsx .

To avoid a 2.5° temperature rise, Annex B (high-income countries) might be willing to give up 2% of their GDP. (2% is the total GDP component that is currently devoted by the U.S. to all forms of environmental controls – on solids, liquids and gases.) On Figure 3, this is expressed as an “economic loss factor” of 98% associated with a temperature rise of 2.5°. (The loss factor at 2.5° is circled on the two lower curves.) This factor represents the fraction of consumption that remains available for conventional uses by households and by government. For high-income countries, the loss is quadratic in terms of the temperature rise. That is, in those countries, the hockey-stick parameter $hsx = 1$. In general, the loss factor is written as:

$$ELF(x) = [1 - (x/catt)^2]^{hsx}$$

where x is a variable that measures the temperature rise above its level in 2000, and $catt$ is a catastrophic temperature parameter chosen so that the entire regional product is wiped out at this level. In order for $ELF(2.5^\circ) = .98$ in high-income nations, the $catt$ parameter must be 17.7° C. This is a direct implication of the quadratic function.

What about low-income countries such as India? In those countries, the hsx exponent lies considerably below unity. It is chosen so that at a per capita income of \$25 thousand, a region would be willing to spend 1% of its GDP to avoid a global temperature rise of 2.5°. (See loss factor circled on the middle curve.) At \$50 thousand or above, India might be willing to pay 2%. And at \$5 thousand or below, it would be willing to pay virtually nothing.

To see how these parameters work out, consider the three functions shown on Figure 3. At all points of time, the U.S. per capita GDP is so high that ELF is virtually the identical quadratic function of the temperature rise. Now look at India. By 2100, India's per capita GDP has climbed to \$25 thousand, and ELF is 99% at a temperature rise of 2.5°. In 2050, India's per capita GDP is still less than \$4 thousands, and that is why its ELF remains virtually unity at that point – regardless of the temperature change.

Caveat: Admittedly, both catt and hsx are highly speculative parameters. With different numerical values, one can obtain alternative estimates of the willingness-to-pay to avoid non-market damages. One example will be given below. Although the numerical values are questionable, the general principle seems plausible. All nations might be willing to pay something to avoid climate change, but poor nations cannot afford to pay a great deal in the near future. Their more immediate priorities will be overcoming domestic poverty and disease.

We are now ready to incorporate the ELF functions into the maximand of MERGE. The maximand is the Negishi-weighted discounted utility (the logarithm) of consumption – adjusted for non-market damages:

$$\text{Maximand} = \sum_{rg} nwt_{rg} \sum_{pp} udf_{pp,rg} \cdot \log(ELF_{rg,pp} C_{rg,pp})$$

where:

nwt_{rg} = Negishi weight assigned to region rg - determined iteratively so that each region will satisfy an intertemporal foreign trade constraint

$udf_{pp,rg}$ = utility discount factor assigned to region rg in projection period pp

$ELF_{rg,pp}$ = economic loss factor assigned to region rg in projection period pp

$C_{rg,pp}$ = conventional measure of consumption (excluding non-market damages) assigned to region rg in projection period pp

How much difference does it make if we employ different values for the parameters underlying $ELF_{rg,pp}$, the economic loss functions? Suppose, for example, that we were to double the economic loss associated with a 2.5° temperature increase. Instead of a 2% economic loss for high-income nations, *all* nations are willing to give up 4% of their economic output to avoid this temperature increase. For benefit-cost analysis, our standard case will be labeled PTO, a Pareto-efficient scenario. The alternative case will be labeled WTP, a high willingness to pay to avoid climate change.

The implications are shown in Figures 4-6. With a high WTP, the optimal temperature increase is slightly lower, carbon abatement begins earlier, and there is a higher early

efficiency price of carbon. Note, however, that these changes are gradual. Even with a high WTP, the temperature and the carbon emissions path depart only gradually from the reference case in which no damage values are assigned to temperature change. Interestingly, with a high WTP, the optimal radiative forcing turns out to be roughly the same as the EMF 21 cost-effectiveness parameter of 4.5 watts/square meter.

Algorithmic issues: LBD and ATL

This note will conclude with our experience related to two algorithmic issues. One is LBD (learn-by-doing), and the other is ATL (act-then-learn). LBD arises from the observation that the accumulation of experience generally leads to a reduction in costs. This is often described in terms of a “learning curve” – a nonlinear relation implying, for example, that a doubling of cumulative experience will result in a 20% cost reduction. This form of learning curve may be incorporated directly into a nonlinear programming model such as MERGE, but there is a difficulty. A learning curve leads to non-convexities. In turn, this means that a local optimum will not necessarily be a global optimum. For an energy-related example of a local optimum, see Manne and Barreto (2004).

Fortunately, in the case of small models, a global optimum can be recognized and guaranteed through an algorithm such as BARON. See Sahinidis (2000). MERGE, however, is too large, however, for anything like the current version of BARON. Instead we have resorted to a heuristic based on terminal conditions. Typically, this consists of specifying that at the end of the planning horizon (e.g., 2150), the cumulative experience with an LBD technology must be at least, say, 10 times the initial experience. Typically, this is a nonbinding constraint, and it does not affect the solution. If an LBD technology is attractive, it will usually end up with cumulative experience that is hundreds or thousands of times larger than the initial value.

But what if this terminal constraint is binding? With small models, our experience is that a binding constraint implies that the LBD technology is unattractive, and that it is not optimal to introduce it into the global mix. In any case, the terminal conditions heuristic has enabled us to explore the proposition that LBD leads to radically different strategies for greenhouse gas abatement. These are usually described as a rapid initial jump in the deployment of high-cost, carbon-free technologies. It is true that this can lead to cost reductions via learning, but our experience is that the optimal abatement policy is one that involves only a gradual shift rather than an abrupt departure from the business-as-usual path. See Manne and Richels (2002). Energy installations are capital-intensive, and there is too much inertia in the system for it to be attractive to abandon long-lived equipment such as oil refineries and coal-fired power plants.

What has been our experience with ATL (act, then learn) models for decisions under uncertainty? No matter what one’s views on the need for greenhouse gas abatement, ATL is an attractive paradigm. It is not a controversial proposition to say that today’s decisions must be made under uncertainty, and that some of these uncertainties will be resolved with the passage of time. The principal difficulties are: (1) reaching agreement on the subjective probabilities of the uncertainties and (2) defining a date by which these

uncertainties are likely to be resolved. There is also the fact that ATL enormously expands the difficulty of numerical solution.

With 20,000 constraints, there is no difficulty in solving MERGE with current nonlinear programming algorithms. But if we were to deal with uncertainty by considering just ten uncertain states of the world, this could lead to problems with nearly 200,000 linear and nonlinear constraints. Eventually, it should be possible to solve problems of this size, but – with the current state of the art of computing – this doesn't seem immediately feasible. Instead, we have considered two rather different approaches, and plan to report on them at a future date. One is a straightforward algorithmic development – Benders decomposition. We have already had experience with this type of decomposition on smaller scale problems. See Chang (1997). For future work, it will be essential to develop software that facilitates modifications in the Benders problem statements.

An alternative to this type of large-scale computing is to aggregate regions and technologies – not necessarily at the beginning of the planning horizon, but to do this after the lapse of several time periods. With market-oriented discount rates, we have observed that the near-term solution is dominated by one's assumptions about the next few decades. Long-term abatement considerations are important, but the exact form of these assumptions is not critical for near-term decisions.

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Figure 1. Radiative forcing - from 1750

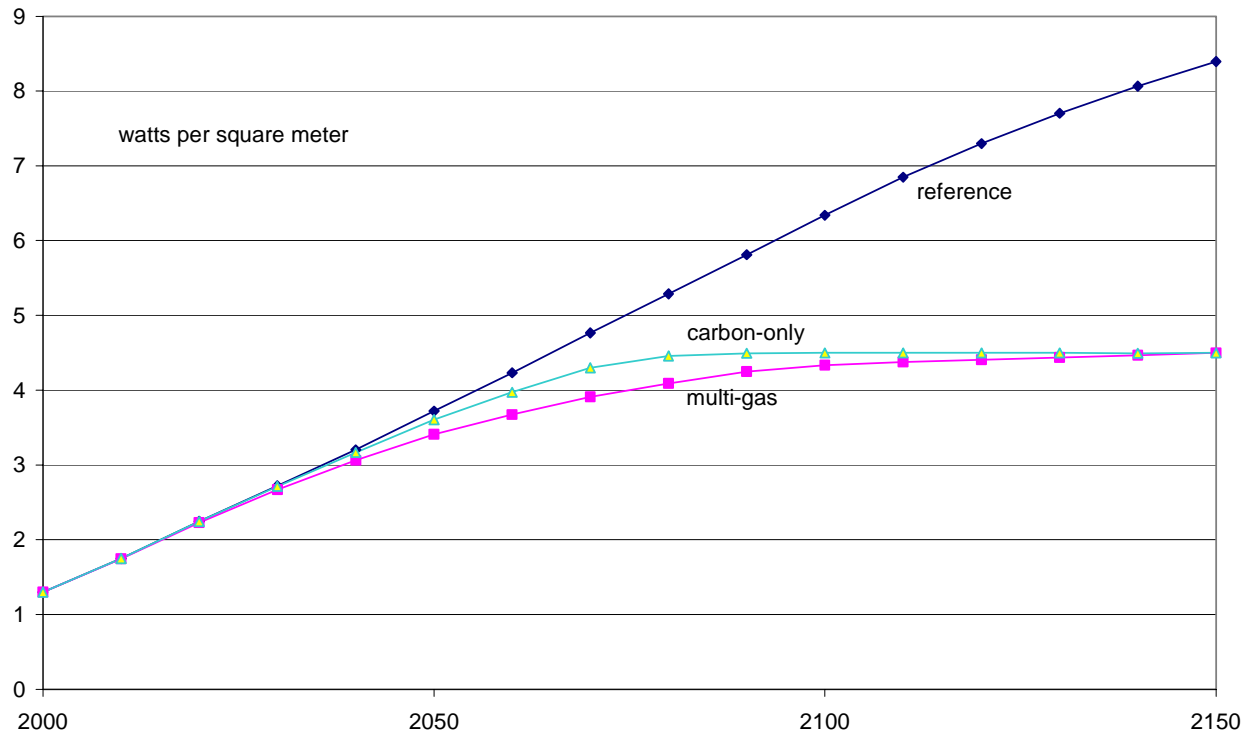
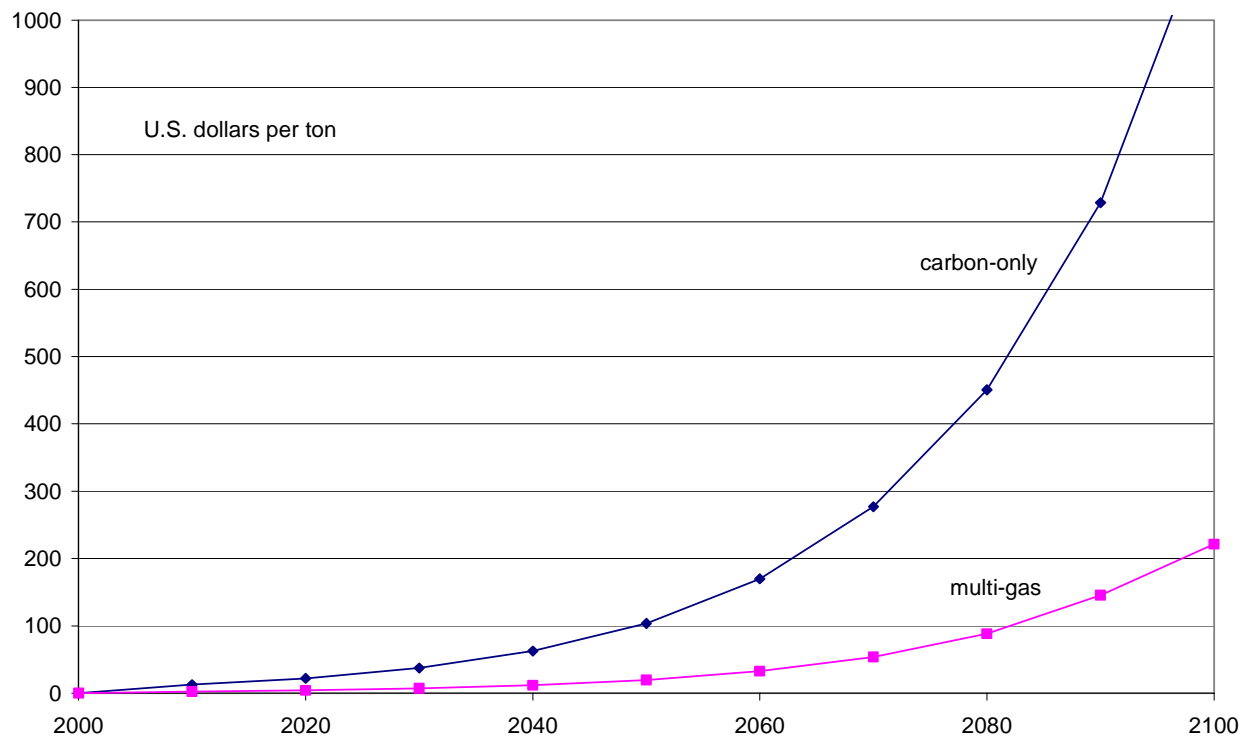


Figure 2. Efficiency price of carbon



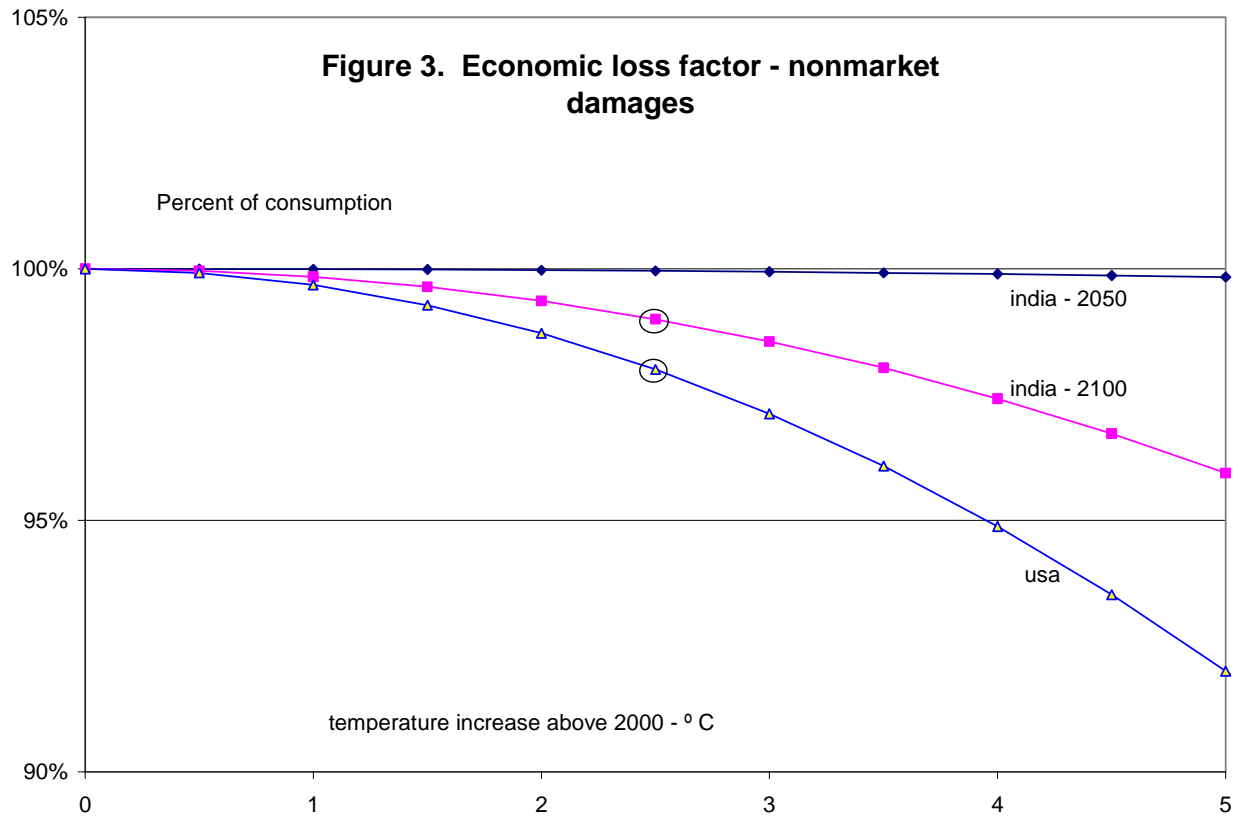


Figure 4. Temperature increase from 2000

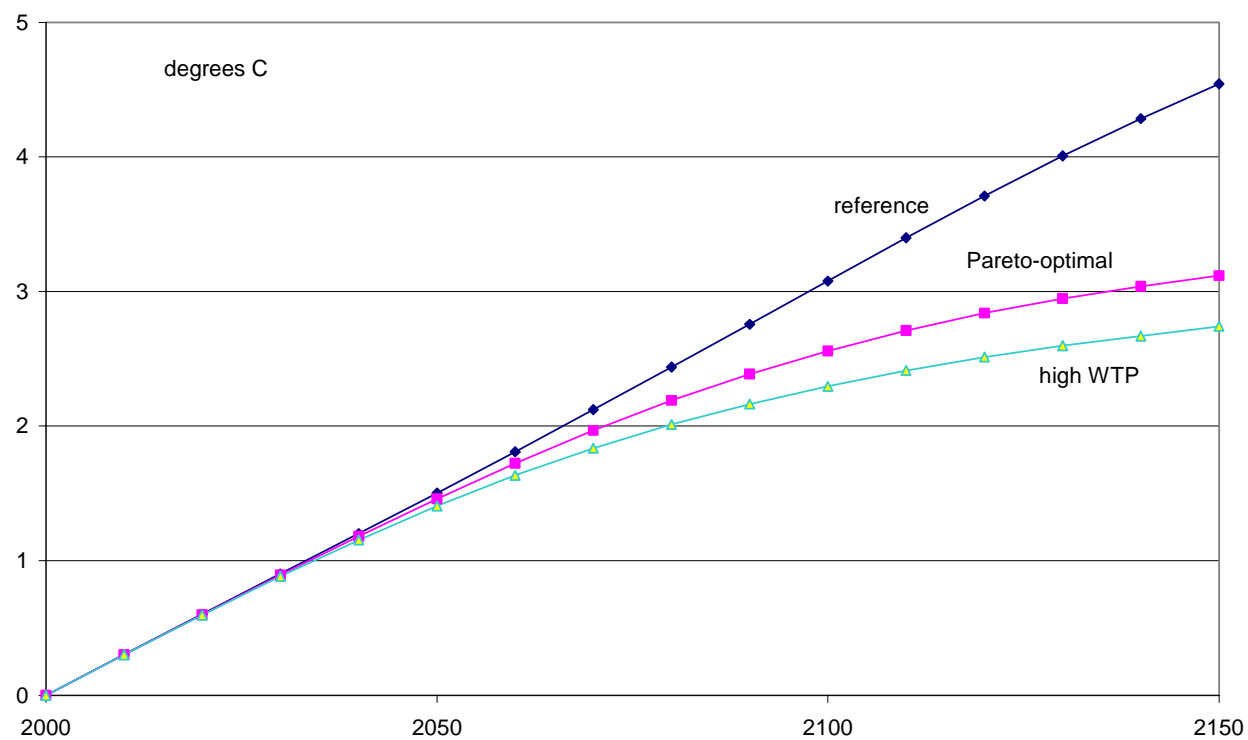


Figure 5. Total carbon emissions

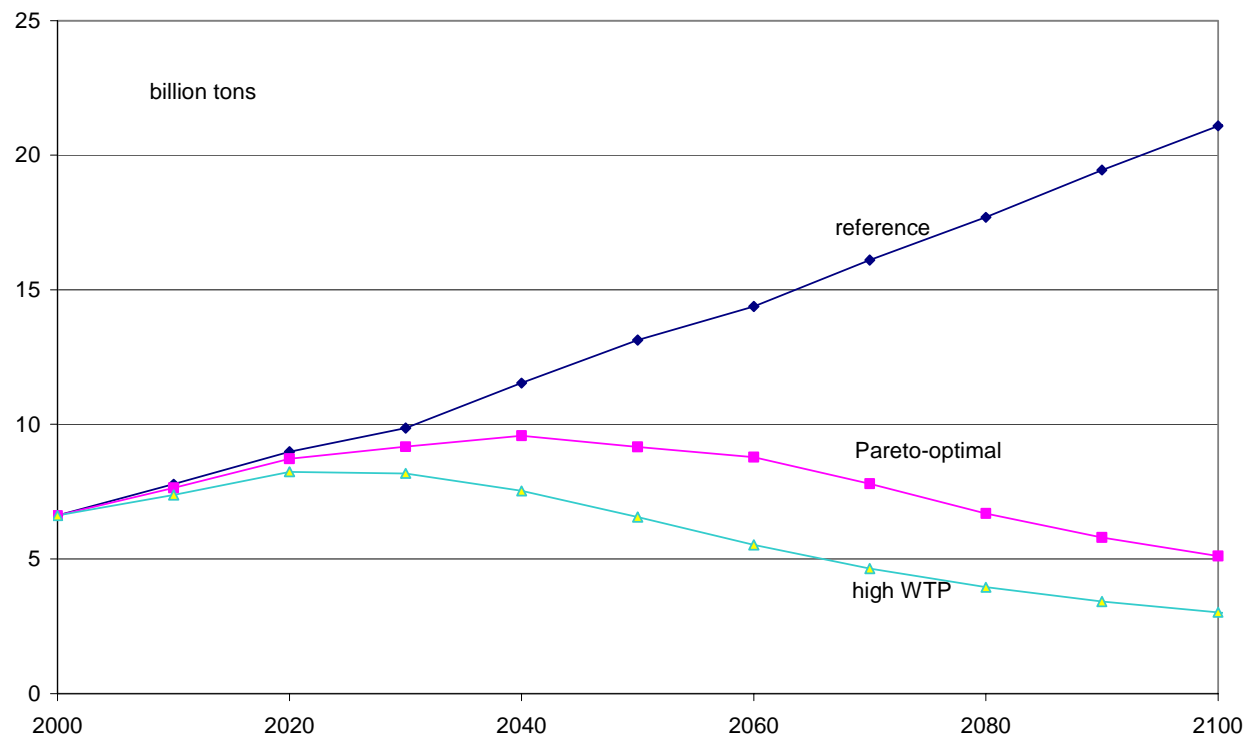


Figure 6. Efficiency price of carbon

