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Haavelmo on the climate issue

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Haavelmo on the climate issue[*]

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Abstract

Although environmental issues were not the main theme of most of Haavelmo's writings, issues related to the environment are discussed in many publications with a broader focus. Haavelmo was also concerned about continued rapid population growth, and argued at several occasions that continued rapid population growth would have a detrimental effect on the development of environmental quality. We show that this concern was well founded; the future population development is extremely important for how the future climate will develop.

Keywords: *Haavelmo, climate, environment, population*

JEL classification: J11, O44, Q50, Q54

Haavelmo on the climate issue

Haavelmo's most active period of research lasted till the early 1980's. During this period there was very little economic research on the climate issue.[1] Nor did Haavelmo write anything directly focusing on the climate issue. Haavelmo has a few publications where the main focus is environmental issues; we shall discuss a couple of these in more detail in section 4. Although environmental issues were not the main theme of most of his writings, issues related to the environment are discussed in many publications with a broader focus. Another theme appearing in several of Haavelmo's publications is issues related to population size and population growth. Haavelmo was concerned about continued rapid population growth, and argued at several occasions that such growth may have negative consequences for the economy. In particular, there are many formulations indicating that he believed that continued rapid population growth would have a detrimental effect on the development of environmental quality.

In section 2 we give some examples indicating Haavelmo's concern about rapid population growth, and the negative impact this may have on the economy, and in particular on the environment. In section 3 we demonstrate that the future population development is extremely important for how the future climate will develop. Section 4 discusses in more detail a couple of Haavelmo's publications where the main focus is environmental issues, and in particular the one publication that is most relevant for the climate issue. Section 5 concludes.

Haavelmo and population growth

As mentioned in the Introduction, there are not many of Haavelmo's publications where the main explicit focus is environmental issues. One exception is Haavelmo (1971), which will be discussed further in Section 4. Here we shall present one quotation illustrating Haavelmo's concern about population growth and population pressure[2]:

> Unless there is a drastic reduction in the population pressure, ideas about environmental policy at the global dimension are ei-

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[1] Nordhaus (1977) is perhaps the most important exception.

[2] Norwegian: Hvis det ikke kommer i stand en drastisk reduksjon i befolkningspresset, er idéene om miljøvernpolitikk i global målestokk enten snakk, eller de bygger implisitt på forutsetninger om en verden der fortsatt de få har mens de mange ikke har.

> ther just talk, or they build on an implicit assumption about a world in which a minority has while the majority doesn't have.

A similar concern about population growth is expressed in Haavelmo (1977). The topic of this article is "welfare policy for future generations". The article presents several interesting insights related to issues such as discounting, hyperbolic discounting, uncertainty, sustainability, and irreversibility. Environmental issues are also explicitly discussed in this article, and linked to the discussion of sustainability and irreversibility. Haavelmo writes[3]

> What is important for future generations is what they receive as real production and life possibilities. There is of course nothing wrong with calculating the value of these possibilities in money. But what prices should be used to get meaningful calculation? The prices that the current generation has in mind need not be particularly relevant for future generations.

This issue goes right to the heart of the climate issue: The future value of a "good climate" relative to the value of material consumption is one of the most important factors determining the optimal amount of current greenhouse gas emissions, see e.g. Hoel and Sterner (2007) and Sterner and Persson (2008).

In the same article Haavelmo expresses his concern about the possibility of giving future generations a good living standard if population increases too rapidly[4]:

> If we seriously accept as a fact (as some international institutions have) that the population in year 2000 will be twice as high as today, it is difficult to be motivated for any type of planning for the future at all.

When Haavelmo wrote this article, the word population was 4.162 million. It did not double by the year 2000, it "only" reached 6.095. However, the population has now passed 7 billion, and in most projections it is expected to pass 8 billion before the middle of this century. The implications of this

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[3] Norwegian: Det som vil ha betydning for etterslekten er overførte reelle produksjons- og livsmuligheter. I og for seg er det sevfølgelig ikke noe galt i å rekne verdien av disse muligheter i penger. Men hva slags priser skal folk bruke for å få mening i reknestykket? De priser folk her og nå tenker behøver ikke være særlig relevante for kommende slektsledd.

[4] Norwegian: hvis vi for alvor godtar som et datum (slik f.eks. visse internasjonale institusjoner har gjort) at folketallet i år 2000 er fordoblet, så er det vanskelig å bli motivert for noen framtidsplanlegging i det hele tatt.

for the possibility of avoiding large climate changes is discussed in the next section.

In his article "The Race between Population and Economic Progress" (Haavelmo, 1961), Haavelmo presents a simple Solow type growth model to illustrate how rapid population growth can make it difficult to achieve growth in income per capita.[5] The staring point is a production function for a country or a region given by $X = F(N, K)$, where N is labor (assumed proportional to population), K is capital, and X is output.[6] Output per capita is x, implying

$$\frac{\dot{x}}{x} = (\varepsilon_N - 1)\frac{\dot{N}}{N} + \varepsilon_K \frac{s}{r}$$

where ε_N and ε_K denote the partial elasticities of production with regard to labor and capital, respectively. Moreover, to quote Haavelmo, "$r = K/F$ is the current capital-output ratio and $s = \dot{K}/F$ the current savings ratio. (s and r are, of course, functions of time.)"

It is immediately clear from the equation above that for given values of ε_N, ε_K, s and r, growth in output per capita is lower the more rapidly population is increasing, and output per capita will decline if $\frac{\dot{N}}{N} > \frac{s\varepsilon_K}{r(1-\varepsilon_N)}$.

We know from Solow (1956) that if there are constant returns to scale ($\varepsilon_N + \varepsilon_K = 1$) and if the savings ratio s and the population growth rate both are constant, the long-run growth in per capita output will be zero, but the level of output per capita will be lower the larger is the population growth rate. With labor-augmenting technological progress we get a similar result, except that the long-run growth in output per capita is now positive (but still independent of the population growth rate).

In his article, Haavelmo assumes $\varepsilon_N + \varepsilon_K \leq 1$, and describes the case of $\varepsilon_N + \varepsilon_K = 1$ as "the favorable case". With a scarce natural resource as a third input, it does not seem unreasonable to assume that $\varepsilon_N + \varepsilon_K < 1$. If the third factor "resources" is constant[7], and the production function is Cobb-Douglas with labor augmenting technological progress, long-run growth per capita is given by (see Appendix 1 for details)

$$\frac{\dot{x}}{x} = \frac{\varepsilon_N m - (1 - \varepsilon_N - \varepsilon_K)n}{1 - \varepsilon_K}$$

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[5] Haavelmo claims in the Introduction that "The problem discussed below has no novelty about it, except perhaps for the way of presentation, which I have found useful in the classroom."

[6] In order to have reasonably consistent notation throughout our paper, our notation differs from Haavelmo's at some places - also in direct quotations.

[7] See Hoel (1977) for the case where the third factor is a non-renewable resource that must decline over time.

where m is the rate of technological progress and n is population growth. Hence, if the Solow growth model is modified so that $\varepsilon_N + \varepsilon_K < 1$, long-run growth in output per capita is lower the higher is the population growth (while this growth rate is equal to m if $\varepsilon_N + \varepsilon_K = 1$).

Given the results of his formal model, Haavelmo argues for a population policy directed towards reducing the birth rate. Moreover, he argues that such a policy may be desirable not only for developing countries, but for all countries:

> there are some important reasons why a restrictive population policy may be necessary or at least desirable even after a relatively advanced stage of economic development has been reached.

and justifies this as follows:

> large families mean...that the next generation of adults will exercise a greater pressure against available productive resources. This effect, as seen from the individual family's point of view, is only of the order of 1/N, while the actual total effect per capita is of an order N times as large. It is clearly only some sort of collective action or planning that could really take account of this global factor.

This is also a theme in Haavelmo (1972, section VI.4). Although Haavelmo in this paper gives a somewhat more formal discussion of the issues above, he does not give a full formal treatment of the externalities associated with the decision of having children. To our knowledge, the first formal analysis of this is by Harford (1998), "The Ultimate Externality". Harford considers an economy where there is an environmental externality that is internalized via a Pigovian tax. The number of children in each family is determined endogenously by the parents, who realize that more children means either more costs to parents or that each child is less wealthy. However, due to the 1/N-effect discussed by Haavelmo in the quotation above, each family does not take into account that more children imply a larger negative impact on the environment, even if the environmental externality is correctly priced. Compared with a cooperative outcome, families hence choose to have too many children.

Climate and population growth

In this section we focus on the relationship between population growth, CO_2 emissions and global warming. Emissions of greenhouse gases at a given point in time are the product of three factors: population; GDP per capita; and emissions per unit of GDP. Insofar as estimating the trajectory of any of these factors is a highly uncertain undertaking, projecting greenhouse gas emissions will clearly come up against the same uncertainty. And the further ahead, the wider the margins. In this section we review our assumptions on these variables, before presenting calculations that show the importance of population growth for solving the climate challenge.

Demographic projections

For population growth we have constructed a population model consisting of seven regions; Africa, China, India, Latin-America, Other developing countries, USA, and Other developed countries. The model has time steps of five years. We use the medium variant in the UN's latest projections as our starting point for our MED scenario. The UN's projections take us up to 2050, see UN (2009). For the years following 2050 we assumed that the fertility rate of all regions converges towards 2.0 children per women (in the MED scenario). In this scenario global population passes 8 billions already in 2025 (cf. Haavelmo's concern in Haavelmo 1977) and peaks at 9.3 billion in 2075, and falls back towards 8.1 billions by the end of the 22nd century, see Figure 1.

(Figure 1 in here).

The developing countries play a crucial role in all population projections. While China's population, due to this country's birth control, now shows little growth and peaks around 2035, the remaining developing countries as a group will most likely show high population growth over most of the 21st Century, see Figure 2.

(Figure 2 here)

In addition to the MED scenario, we present four alternative population growth scenarios, see Figure 1. In the LOW scenario the fertility rate in all regions converges towards 1.4 children per woman by approximately 2065. This rapidly declining fertility rates mean that global population peaks at 8.04 billion in 2040.

In the XLOW scenario the fertility rates drops very quickly in all regions and converge towards 0.9 children per woman by 2025. In this scenario world population peaks at 7.1 in 2020 and world population is slightly below 2 billion in 2100 and is below 90 million in 2200.

In the HIGH scenario the fertility rates converge towards 2.2 children per woman by the end of the 21st Century leading to a global population of 14.0 billion in 2100 and 8.4 billion in 2200. And finally, in the XHIGH scenario the fertility rates in all regions converge towards 2.5 children per woman by the end of the century leading to a global population of 14.3 billion in 2100 and 29.0 billion in 2200.

The extreme scenarios XLOW and XHIGH are included mainly for illustrative purposes; it seems most likely that the future population development will lie somewhere between LOW and HIGH.

CO_2-emissions

With regard to the 21st century, CO_2 emissions per capita are as in the IPCC's A1 Message scenario, see IPCC (2000). The emission rate per capita is the product of GDP per capita and emissions per unit of GDP. In its A1 Message scenario, the IPCC assumes a 2.6 per cent yearly rise in GDP per capita during the 21st century. This is a relatively high growth rate compared with global per capita growth of the 20th century. Indeed, GDP per capita grew globally by 2.9 per cent between 1950 and 1973, but in the years between 1913 and 1950, yearly growth was 0.88 per cent, and from 1973 to 2003, 1.56 per cent (Maddison, 2008, p. 71). On the other hand, the A1 Message scenario relies on a fall in CO_2 emissions per GDP unit (the CO_2 intensity for short) of 2.0 per cent per year: a significantly steeper gradient than the historical trend. For instance, from 1990 to 2006, there was an average yearly fall in CO_2 emissions per GDP unit of 1.4 per cent.

A yearly 2.0 percent CO_2 intensity drop, would imply that the the global CO_2 intensity will be approximately at 15 per cent of today's level in 2100. IPCC's assumption at this point is not only based on an assumed widespread adoption of energy efficiency measures, but also on an assumed increasing use of renewable energy and nuclear power. While fossil fuels today account for about two thirds of global energy supplies, in IPCC's A1 Message this percentage drops to 25 per cent by 2100. To some observers these assumptions are way too optimistic for a BaU scenario, see for instance Pielke et al. (2008). That said, we need to repeat how uncertain these estimates actually are. However, for our purpose, which is to consider the effects of population growth, not to estimate the seriousness of global warming, these types of uncertainties are not very disturbing.

With the assumptions made, emissions per capita in developed countries will remain relatively stable for the first half of the century, and be falling in the second half, see figure 3. Emissions per capita in developing countries will grow at an average rate of 1.16 per cent in the twenty-first century, though with levels falling off towards the end of the century.

We have in addition assumed that the estimated fall in CO_2 emissions per capita in the latter half of the twenty-first century continue into the twenty-second century across all regions, leaving a largely decarbonized global economy by the end of the 22nd century.

For simplicity we have assumed that per capita emissions are equal in all the five demographic scenarios.

The modeling of temperature

As mentioned above, the exact connection between emissions of greenhouse gases and climate change/global warming remains uncertain. The estimates of future temperature response presented in this article are calculated by using the standard Bern 2.5 CC carbon cycle model, see Chum et al. (2007). The model means that a doubling of the CO_2 concentration of the atmosphere leads to a 3 °C temperature rises (a climate sensitivity of 3 °C). But the model includes inherent inertia mechanisms, which reduce momentary temperature rises.

Given the assumed emission path, the concentration of CO_2 under MED/BaU scenario will reach concentrations of 680 parts per million (ppm) by 2100 and peak at 770 ppm in the second half of the 22nd century. The BaU trajectory predicts a 2 °C rise in global temperature by 2050, 3.8 °C by 2100 and 4.8 °C by 2200 over pre-industrial levels.

The effect of emission reductions

Before we present the relationship between population growth and the speed of global warming, we will present two scenarios illustrating the effect of emission cuts by different groups of countries. Here we divide the world into three regions; developed countries, China, and other developing countries. The population growth in the MED scenario of these three regions is shown in Figure 2.

The purpose of this exercise is to illustrate the importance of the regions of the world with very low per capita CO_2 emissions, but having high population growth. We will show that if only the regions of the world with stagnating population growth carry out large emission cuts, this will not help very much, as long as the regions with high population growth are not part of the effort.

We examine only emission rates of CO_2 from the combustion of fossil fuels, keeping land use change (deforestation) and emissions of other greenhouse gases unchanged. References below to CO_2 emissions should therefore be understood as emissions from the burning of fossil fuel.

We disregard carbon leakages from countries reducing their emissions to countries where emissions are not being cut. We thus disregard the normal reaction of countries to cuts by a group of other countries, which is to increase their own emissions, both because emission intensive industries could be tempted to move to countries without emission restrictions, and also because reduced demand for a fossil fuel in one place will lower the price and increase consumption of the fuel in the rest of the world. Carbon leakage is usually estimated to be in the range 5 to 20 percent, see for example Hourcade et al. (2001). However, others, for example Babiker (2005) claims that the carbon leakage rate is likely to be significantly larger. Hence, if we had taken carbon leakage into account, our argument would have been significantly stronger.

Consequences of emission cuts

The first computation shows the impact of emissions abatement action by the developed countries and China. At the moment, the developed countries emit 12 tonnes CO_2 per capita (tCO_2/cap); the global average is 4.2 tCO_2/cap.

Figure 3 illustrates a situation in which developed countries and China jointly reduce their CO_2 emissions per capita by an average of 3.5 and 2.2 per cent per year, respectively, from 2010 to 2100. This results in a 80 per cent decline in developed countries' emissions by 2050 and 96 per cent by 2100 from current levels. They would be exceptionally deep cuts, and possibly more than is politically and practically feasible. Nevertheless, the 80 per cent cut by 2050 is what President Barack Obama originally stated as his goal.

China's current CO_2 emissions amount to 4.6 tCO_2/cap, and have shown rapid growth in the last years. Indeed, as recently as 1990, emissions by China were only 2.1 tCO_2/cap. Under the BaU construction, growth will continue until 2070, form a plateau and start falling as renewable energy generation and nuclear power are phased in, see Figure 3.

China currently accounts for about 23 per cent of global CO_2 emissions. Under the BaU scenario, the share increases somewhat, reaching 25 per cent by 2050 but falling to 14 per cent by 2100 as a result of projected growth in other developing economies. In the scenario with emission cuts China's emissions are assumed to peak before 2030 and then follow a per capita path similar to that of the developed countries, see Figure 3.

Figure 4 shows the impact of these actions on global temperature. Compared to the BaU scenario, global temperature would in this scenario fall by 0.04 °C in 2025; by 0.31 °C in 2050; by 0.76 °C in 2100; and by 0.85 °C in 2200.

It is thus clear that even if the developed world were to take decisive, comprehensive action, and got China to do the same, it wouldn't be nearly enough to stabilize global temperature at 2 °C above pre-industrial levels. A scenario which sees temperatures stabilizing at this level is shown in figures

5 and 6, however. Here, the developed countries and China cut emissions by the same amount as above, but now with other developing countries reducing emissions to 1.2 tCO_2/cap by 2050 and 0.3 tCO_2/cap by 2100. This makes a big difference and a stabilization of global temperatures close to 2 °C is now very close. This is despite the fact that average emissions in these countries are currently below 2 tCO_2/cap, that is, about 10 per cent of levels in the US. Nevertheless, due to these countries' large population that is still growing, we are completely dependent on these countries adopting comprehensive emission abatement policies if we are to stand any chance of stabilizing global warming at 2 °C, the target adopted by the EU.

Population growth and global warming

In order to illustrate further Haavelmo's concern with regard to the relationship between the environment and population growth, we will now study global warming in the five population growth scenarios described above.

Global temperature change in the MED scenario, assuming no emission cuts, is already shown with the broken curve in Figures 4 and 6. In Figure 7 global temperature in all population scenarios are shown, and it is evident that population growth matters, although even the extremely low fertility rates in the XLOW scenario are not sufficient if the goal is to prevent global warming above two degrees Celsius. Obviously, however, lower population growth in combination with abatement efforts would do a lot.

At a first glance it may be surprising that the temperature trends in XHIGH and HIGH are relatively close, although the population growth paths in these scenarios are very different. However, this is explained by the logarithmic relationship between CO_2 concentration and temperature, which means that the marginal warming effect of additional CO_2 in the atmosphere is decreasing.

Haavelmo on environmental issues

As mentioned earlier, there are not many of Haavelmo's publications where the main explicit focus is environmental issues. One exception is Haavelmo (1970), which is a written version of a conference presentation. This paper gives a general discussion of externalities, and how appropriate pricing of activities that create negative externalities can lead to a desirable outcome. However, Haavelmo was also sceptical about how much priority most people would give to having a good environment. He writes[8]:

> I am afraid that if there is an unavoidable choice between preserving nature and the environment and acquiring more material goods for each of us, the last purpose would be a clear winner.

Haavelmo argues that this is partly due to peoples discounting of the future. He also raises the question of[9]

> whether some traditional individual rights, so called human rights, that until now have been taken for granted or at least are high ideals, really are consistent with the demands that are expressed with regard to environmental protection, if we interpret these demands as wide-reaching as they are expressed.

Also in this article population issues are mentioned; as an example of the above he writes[10]

> We have the question of the right to decide over the size of our own family

He concludes his discussion about people's preferences as follows[11]:

> I am afraid a lot of the big words one can hear about environmental protection and measures to improve the environment, represent an unrealistic dream about getting something back or getting something at a quite low cost. It is a dream about getting back or keeping elements from the so called good old days while we simultaneously get rid of the bad sides, the material poverty.

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[8] Norwegian: Jeg er redd for at hvis det er tale om et uunngåelig valg mellom det å bevare natur og miljø og det å skaffe mer varer og tjenester i vanlig betydning til hver enkelt, så vil det siste formålet vinne stort.

[9] Norwegian: hvorvidt visse tradisjonelle individuelle rettigheter, såkalte menneskerettigheter, som hittil er tatt som selvfølge eller som høye idealer, i virkeligheten er forenelige med de krav som kommer til uttrykk angående miljøvern, hvis en skal ta disse kravene som så vidtgående som de lyder til.

[10] Norwegian: Vi har spørsmålet om retten til å bestemme over størrelsen av egen familie

[11] Norwegian: Jeg er redd for at mye av de store ord som en kan høre om naturvern og tiltak for et bedre miljø, representerer en lite realistisk ønskedrøm om å få noe tilbake eller få noe ganske billig. Det er en ønskedrøm om å få tilbake eller beholde de gode sider ved de såkalte gode gamle dager mens vi samtidig kvitter oss med de onde sidene, de materielle savn.

Haavelmo's doomsday model

One of Haavelmo's most explicit discussions of environmental issues is his 1971 article "The problem of pollution from an economic point of view". This paper discusses a model of a stock pollutant, and is hence highly relevant for the climate issue. The equations in his model are

$$
\begin{aligned}
\dot{Z}(t) &= kN(t)c(t) && (1)\\
u &= u\left(\underset{+}{c}(t), \underset{-}{Z}(t)\right) && (2)\\
V &= {}_{0}^{\infty} e^{-\rho t} u\left(c(t), Z(t)\right) dt && (3)
\end{aligned}
$$

where

$Z(t)$ is the stock of pollutant at time t, Haavelmo calls this the society's entropy

$N(t)$ is population at time t

$c(t)$ is consumption per capita at time t

u is instantaneous utility or wellbeing

V is the present value of all future utility levels

ρ is a utility discount rate

k is a constant parameter

Haavelmo doesn't present a formal solution of maximizing V or the constraints that an outcome must satisfy. As is often the case with Haavelmo's publications and lectures, some basic equations are presented as a background for a discussion that goes far beyond the formal equations. Among the issues discussed in the article are

- flows versus stocks
- short-run benefits and long-run (persistent) costs
- distribution within and between generations
- policies to modify the relationship between Nc and $\dot{Z}$
- issues related to population and population growth

The term "doomsday model" in the section heading is not Haavelmo's. We use it because the model, with some additional assumptions, leads to "doom" in the long run. A reasonable definition of doom is that the utility level falls below some lower threshold u^*.

Haavelmo is somewhat vague about the exact properties of the function u. However, the following assumptions seem reasonable:

$$\begin{aligned} u(c,Z) &< u^* \text{ for all } Z \text{ if } c < c^* \\ u(c,Z) &< u^* \text{ for all } c \text{ if } Z > Z^* \end{aligned}$$

where c^* and Z^* are some positive numbers

With these assumptions, equations (1)-(2) lead to doomsday for any population path that is bounded away from zero, i.e. for $N(t) > \varepsilon > 0$ for all t. This conclusion follows directly from the properties of the utility function:

$$\begin{aligned} \text{Either } c(t) &\to 0 \text{ implying } u < u^* \\ \text{or } Z(t) &\to \infty \text{ implying } u < u^* \end{aligned}$$

This pessimistic conclusion is modified if we let population gradually approach zero. If e.g. $\frac{\dot{N}(t)}{N(t)} = -\delta < 0$ and we choose $c(t) = c_0$ we obtain (choosing units so $Z(0) = 0$)

$$\begin{aligned} Z(t) &= \frac{kN_0c_0}{\delta}\left(1 - e^{-\delta t}\right) \to \frac{kN_0c_0}{\delta} \\ u &= u\left(c_0, \frac{kN_0c_0}{\delta}\left(1 - e^{-\delta t}\right)\right) \to u\left(c_0, \frac{kN_0c_0}{\delta}\right) \end{aligned}$$

If $\max_{c_0} u\left(c_0, \frac{kN_0c_0}{\delta}\right) > u^*$ doomsday is avoided. However, in the long run the human population dies out, which is another type of doomsday.

Haavelmo did not explicitly model constraints on what consumption paths are feasible, although he in his informal discussion of the model expresses the obvious fact that consumption paths are constrained by the production possibilities. One way of formalizing this could be to add the following equation (with obvious notation):

$$N(t)c(t) = F(N(t), K(t)) - \dot{K}(t)$$

All feasible consumption paths must satisfy this equation combined with a given initial value of the capital stock K and the non-negativity constraint $K(t) \geq 0$. Obviously, adding such a constraint on the class of feasible consumption paths does not change the conclusion above about the inevitability of doomsday.

One could argue that Haavelmo's equation (1) is too pessimistic. Other literature from the early 70's on these issues often assumed natural depreciation of the stock pollutant, and often modeled this as (1) being modified to[12]

$$\dot{Z}(t) = kN(t)c(t) - \gamma Z(t) \text{ with } \gamma > 0 \tag{4}$$

Haavelmo discusses this, and argues that the depreciation function might be concave with a maximum value instead of the linear function γZ. If γZ is replaced by a concave function $h(Z)$ that is maximized for $Z = \hat{Z} < Z^*$, and the initial value of Z is below $\hat{Z}$, all feasible time paths of $c(t)$ and $N(t)$ satisfying

$$c(t)N(t) \leq h(\hat{Z}) \tag{5}$$

are potential non-doomsday paths. However, if population is growing and unbounded above, doomsday must be reached either in the form of $c(t) < c^*$ or (5) being violated, leading eventually to $Z(t) > Z^*$. With a constant or declining population, however, there may exist time paths of $c(t)$ satisfying (5) and $c(t) > c^*$ for all t.

What can be said about depreciation of CO_2 and other greenhouse gases in the atmosphere? It is quite common, at least in theoretical analyses, to assume a linear depreciation as in (4). At least for CO_2, however, this is not a very good approximation to the complex interaction of carbon in the atmosphere and other carbon sinks (in particular, the ocean). According to Archer (2005), about 25% of all CO_2 emitted to the atmosphere remains in the atmosphere for ever (or at least for thousands of years). Hence, for long-run climate effects of carbon emissions, Haavelmo's equation (1) is a better approximation to reality than the more commonly used (4).

The pessimistic conclusions following from Haavelmo's model are to a large extent caused by the assumed proportionality between consumption (or output) and the growth of the entropy $Z(t)$. Haavelmo himself admits that the assumption of an exogenously given proportionality factor k is rather drastic. He writes (with our notation and equation numbering)[13]:

> In equation (1) the parameter k may perhaps to some extent be considered as something that can be influenced by people through

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[12] See e.g. Keeler et al. (1972), Plourde (1972), Smith (1972) and Strøm (1973).

[13] Norwegian: I relasjonen (1) kan kanskje parameteren k delvis oppfattes som et uttrykk for noe som kan påvirkes av menneskene selv ved f. eks. å endre sammensetningen av $c(t)$, eller ved at $c(t)$ reduseres og den derved lediggjorte kapasitet brukes til opprydning.

> changing the composition of $c(t)$, or by reducing $c(t)$ so that the capacity thereby made available is used for "tidying up".

This is very similar to what Nordhaus (2008) assumes in his DICE model: Ignoring the effect of climate on output and exogenous changes in technology, aggregate output X and carbon emissions E are in DICE given by

$$\begin{aligned} X &= (1-b(\mu))F(N,K) \\ E &= (1-\mu)vF(N,K) \end{aligned}$$

The term $(1-\mu)v$ corresponds roughly to Haavelmo's parameter k. In the DICE model it can be decreased by increasing what Nordhaus calls the "emissions-control rate" μ. However this comes at a cost, as $b(\mu)$ has the properties $b(0)=0$, $b' > 0$ and $b'' > 0$.

In many integrated assessment models carbon emissions are modeled somewhat differently than by Haavelmo and Nordhaus. Carbon energy is often modeled as an explicit input in an aggregate production function so that we instead of (1) have (for constant $N = 1$):

$$\begin{aligned} \dot{Z}(t) &= E(t) \\ c(t) &= F(K(t),E(t)) - \dot{K}(t) \end{aligned}$$

The following has been shown by Dasgupta and Heal (1978, section 7.2)[14]: With a constraint $Z(t) \leq \bar{Z} < Z^*$ it is possible to avoid doomsday (i.e. have $c(t) > c^*$ for all t) if the initial capital stock is sufficiently large (the critical value being higher the higher is the initial value of Z) and the elasticity of substitution between K and E is either larger than 1 or equal to 1 with the output elasticities ε_K and ε_E satisfying $\varepsilon_K > \varepsilon_E$.

Several empirical studies conclude that the elasticity of substitution between energy and capital is less than 1, see e.g. van der Werf (2008). The elasticity of *carbon* energy and capital may nevertheless be larger than 1. In the Appendix we give an example of a nested production function where the elasticity of substitution between carbon energy and non-carbon energy is larger than one, but the elasticity of substitution between the aggregate energy composite and capital is lower than 1. In this example we can have $c(t) > c^*$ for all t even if the elasticity of substitution between the energy composite and capital is zero.

From the discussion above it seems reasonable to conclude that Haavelmo's basic model (1)-(3) model – taken literally – might be too pessimistic. With reasonable modifications, it is possible to avoid doomsday, at least with a

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[14] See alse Hoel (1977) for the Cobb Douglas case.

constant or declining population. This brings us back to Haavelmo's concern about the population development, and his pessimism with regard to the future unless the world's population stops growing relatively soon.

Concluding remarks

We have shown that Haavelmo's concern about the difficulties of combining population growth with a reasonably good future environmental quality is very relevant with respect to the future climate. At least in most European countries, there is wide support for a climate policy that will prevent global mean temperature to increase more than about 2-3°C. While this explicit policy goal is relatively new, it is not very different from what Nordhaus (1977) recommended already 35 years ago:

> The most careful study to date [...] predicts that a doubling of atmospheric concentrations of carbon dioxide would eventually lead to a global mean temperature increase of 3°C.

and

> ...it seems reasonable to argue that the climatic effects of carbon dioxide should be kept well within the normal range of long-term climatic variation. A doubling of the atmospheric concentrations of carbon dioxide is a reasonable upper limit to impose at the present stage of knowledge.

We have shown that with the world's population growing to about 9 billon before it stabilizes, it will be extremely difficult to reach a goal of only 2-3°C warming. Policies to reduce population growth and perhaps even giving a decline in world's population might be an important contribution to avoiding dramatic future climate change.

Appendix

Economic growth with decreasing returns to scale

Consider the production function $X = \Phi(K, L, V)$ where L now is labor multiplied by a factor representing technological progress and V is a third factor that we can interpret as natural resources. Assume that Φ is CRS and CD and that V is constant and normalized to 1. Then

$$X(t) = K(t)^{\varepsilon_K} L(t)^{\varepsilon_N}$$

Labor and population are assumed to grow at the rate n, and the rate of labor augmenting technological progress is m. Normalizing the initial value of L to 1 hence gives

$$X(t) = K(t)^{\varepsilon_K} \left(e^{nt} e^{mt}\right)^{\varepsilon_N}$$

which may be rewritten as

$$X(t) = K(t)^{\varepsilon_K} \left(e^{\frac{\varepsilon_N (n+m)}{1-\varepsilon_K} t}\right)^{1-\varepsilon_K}$$

This production function is simply a special case of the function $F(K(t), L(t))$ where F has constant returns to scale and L is growing at the rate

$$g = \frac{\varepsilon_N (n+m)}{1-\varepsilon_K}$$

We know from the standard Solow model that this production function in combination with a constant saving rate gives a long-run growth rate in output equal to g. Long-run per capita growth is hence given by

$$\frac{\dot{x}}{x} = g - n = \frac{\varepsilon_N m - (1 - \varepsilon_N - \varepsilon_K) n}{1 - \varepsilon_K}$$

The elasticity of substitution between capital and carbon energy

Even if the elasticity of substitution between energy and capital is below 1, we can have positive output without the use of carbon energy if the elasticity of substitution between carbon energy and non-carbon energy is larger than 1. To see this, consider the production following production function (assuming constant population and labor):

$$X = F(K, E) = \max_R \Phi\left(\phi(E, R), K - gR\right) \tag{6}$$

where R in non-carbon energy is produced using gR units of capital. There is thus $K - gR$ capital available for producing an aggregate good together with an input "useful energy" (a term used by e.g. Popp, 2004). Assume that the function ϕ has constant returns to scale and a constant elasticity of substitution equal to σ, i.e.

$$\phi(E, R) = \left[\alpha E^{\frac{\sigma-1}{\sigma}} + \beta R^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$$

We immediately see that if $\sigma > 1$

$$\phi(0,R) = \beta^{\frac{\sigma}{\sigma-1}} R \equiv fR \tag{7}$$

Assume moreover that the elasticity of substitution between the two inputs in Φ is zero, so that

$$\begin{aligned} X &= a(K-gR)^{\varepsilon} & (8) \\ \phi(E,R) &= b(K-gR) & (9) \end{aligned}$$

Equations (6)-(9)imply that

$$F(K,0) = a\left(1 - \frac{gb}{f+gb}\right)^{\varepsilon} K^{\varepsilon}$$

Even without the use of carbon energy, output can hence be made arbitrarily large for a sufficiently large value of K. Notice also that the marginal productivity of capital is larger the smaller is g/f, which is a measure of how much capital is needed per unit of useful energy produced when carbon energy is constrained to be zero.

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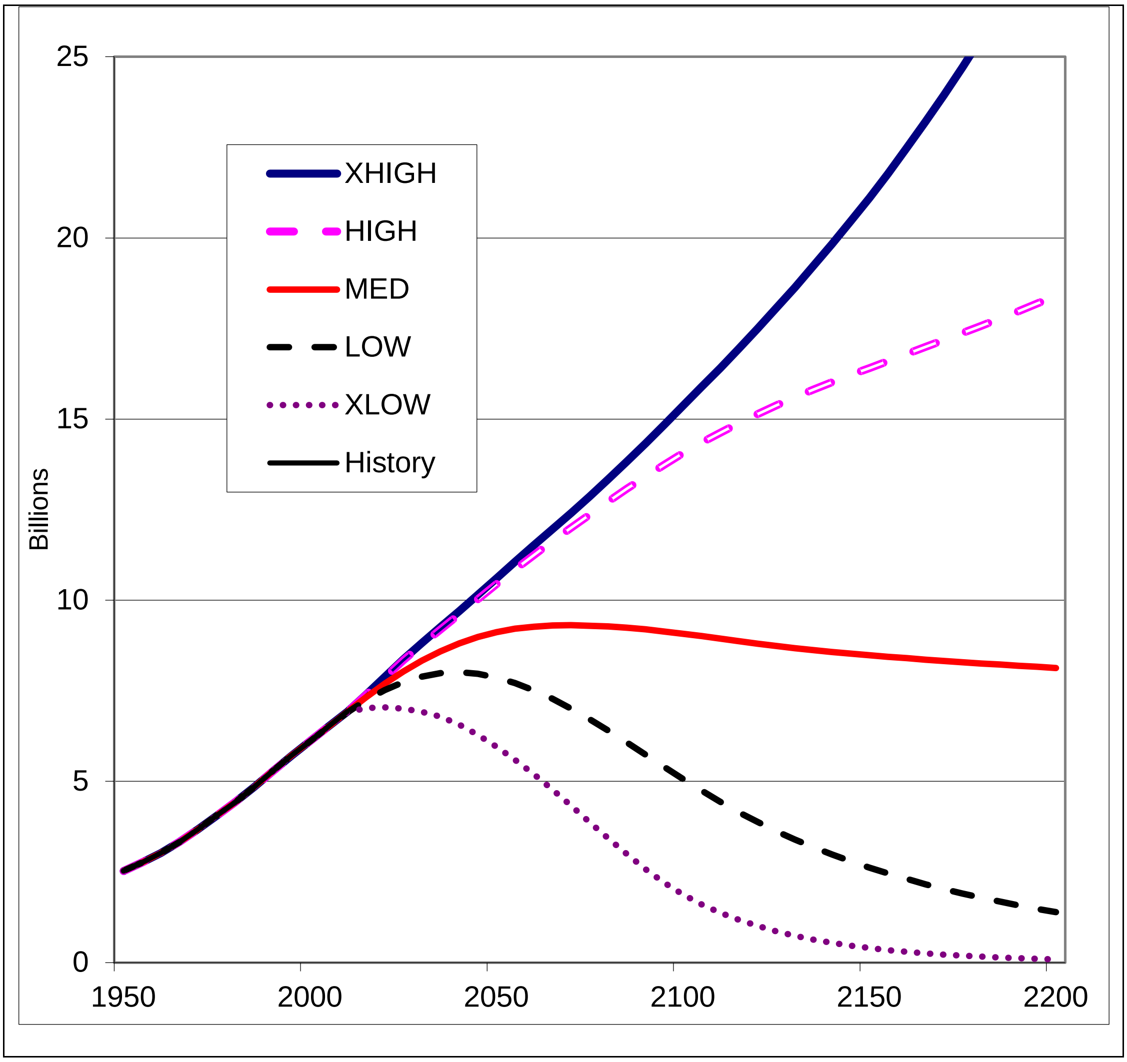

Figure 1. World population, historically, and in the five different population scenarios considered.

Sources: United Nations (historical data) and Statistics Norway (scenarios).

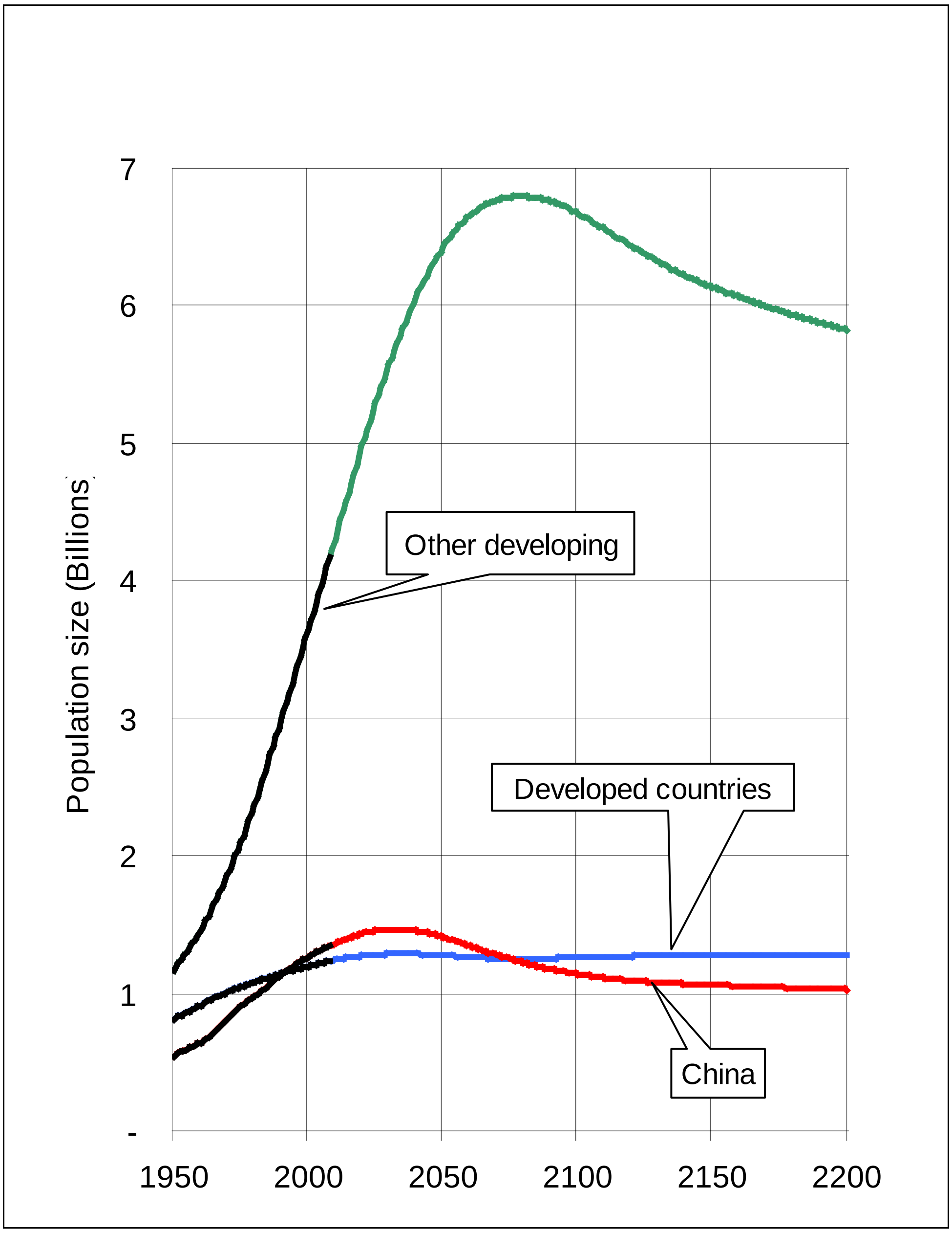

Figure 2. Population in the MED scenario. The medium variant in the UN's 2009-projections are followed for the years to 2050. For the rest of the simulation period the fertility of all regions converge towards 2.0 children per women.

Sources: UN and Statistics Norway

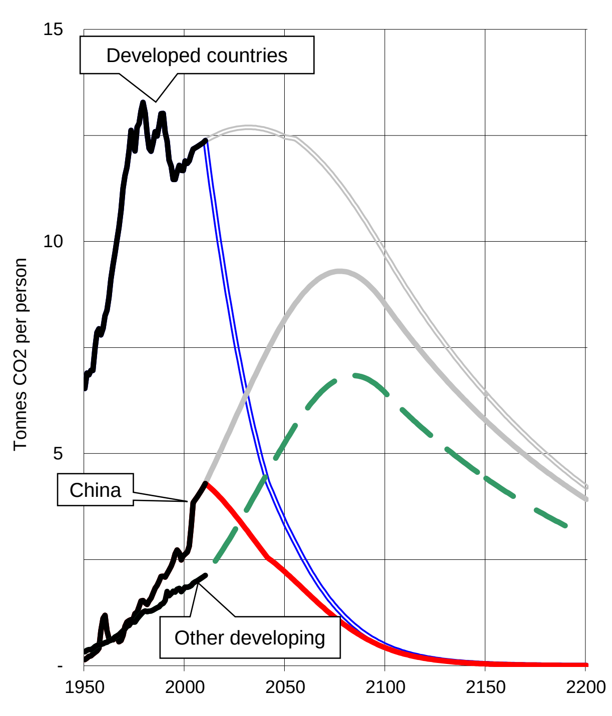

Figure 3. All developed countries cut emissions by 80 and 98 per cent (colored curves) relative to current levels (grey curves) by 2050 and 2100 respectively at the same time as China cuts emissions by 53 and 96 per cent respectively by 2050 and 2100.

Sources: US Department of Energy (historical data) and Statistics Norway

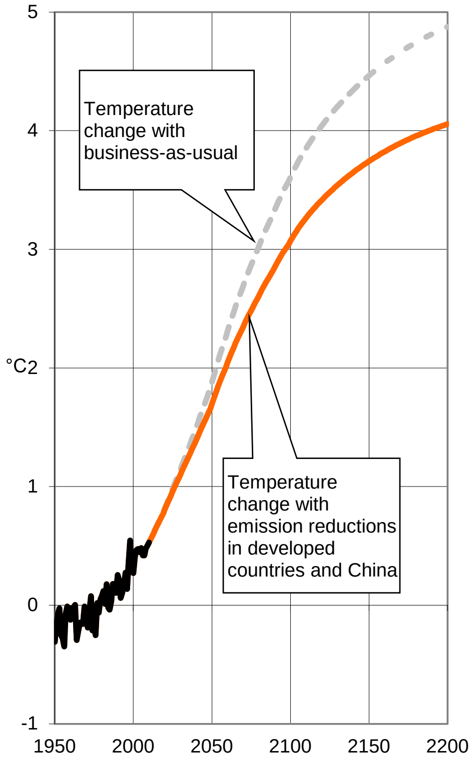

Figure 4. Impact on global temperature of all developed countries cutting emissions by 80 and 98 per cent (colored curves) relative to current levels (grey curves) by 2050 and 2100, respectively, at the same time as China cuts emissions by 53 and 96 per cent, respectively by 2050 and 2100.

Sources: Hadley Centre (historical data) and Statistics Norway

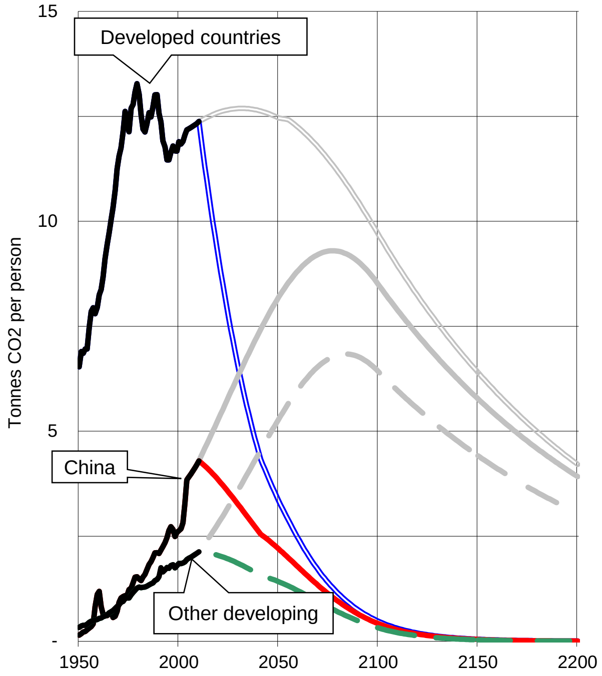

Figure 5. All countries cut emissions.

Sources: US Department of Energy (historical data) and Statistics Norway

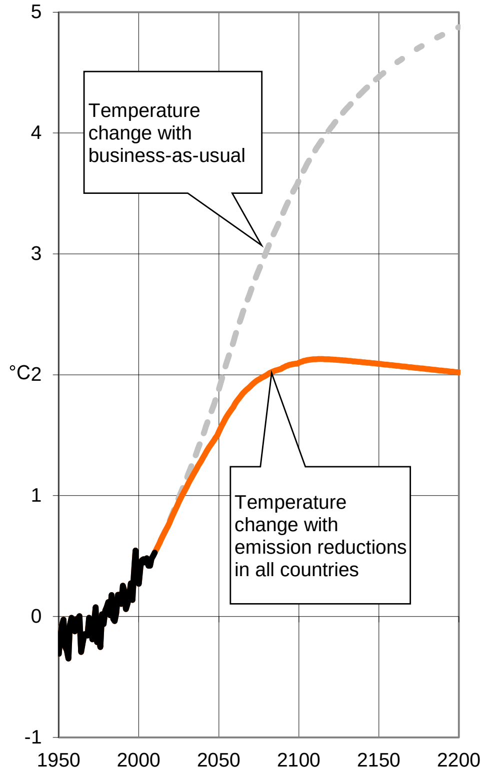

Figure 6. Global temperature compared to pre-industrial levels across two scenarios: BaU (grey curve) and if China and the developed world were to take concerted action to cut emissions.

Sources: Hadley Centre (historical data) and Statistics Norway

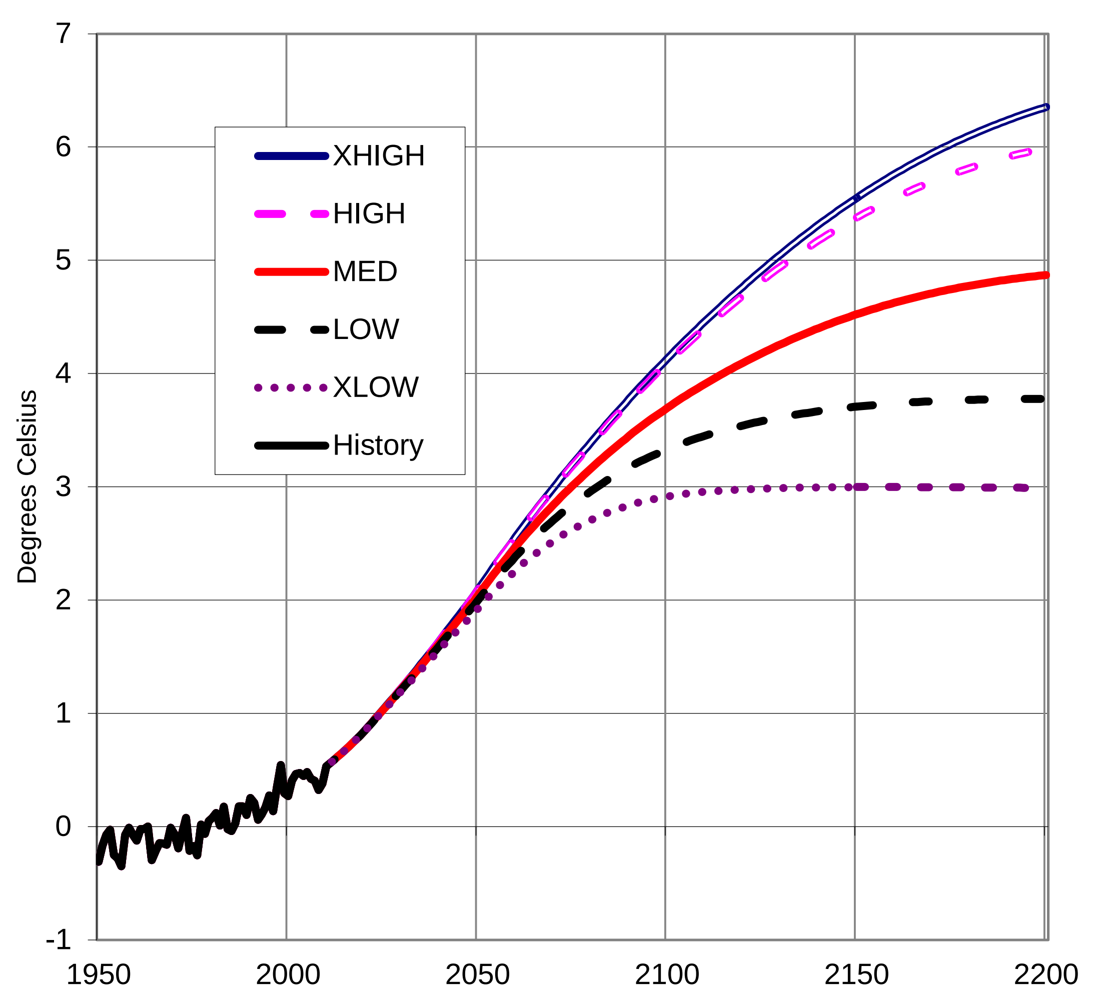

Figure 7. Temperature trends in the five different population scenarios considered.

Sources: United Nations (historical data) and Statistics Norway (scenarios).