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2052 – A Global Forecast for the Next Forty Years using a mix of models

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ABSTRACT

The book *2052 – A Global Forecast for the next Forty Years* (Randers, 2012) contains a description of what the author sees as the most likely scenario for global population, GDP, consumption, and ecological footprint over the next 40 years. The 2052 forecast is a "Business As Usual" scenario – in the sense that it describes the global future that will result if global society continues to make decisions in the traditional way, based on short term cost minimization. The basic assumption underlying the forecast is that individuals, corporations and nations will continue to tend to choose solutions that serve their short term interest.

The present paper focuses on the method used to arrive at the 2052 forecast. The starting point was the *The Limits to Growth* study of scenarios for the human ecological footprint and the causal structure of the World3 model. Exploratory work, based on data for the last 40 years, indicated that global warming will become the tightest planetary constraint going forwards. The study therefore focused on CO2 emissions and their effects. In the first iteration, future CO2 emissions were estimated in an open-loop model (using the "linear core" of the revised causal structure). In the next iteration, the forecast was improved by including the effects of important, but un-modelled, feedback through manual iteration. The global forecast was obtained as the sum of separate forecasts for 5 world regions.

In both stages external models (from the literature) were used to improve the quality of the forecast. But these models were not fused into one complete system dynamics model of global growth. Rather concepts and insights were borrowed wholesale, and consistency over time (and among regions) was sought through manual iteration, using spreadsheets.

The paper elaborates the weaknesses in this procedure, but argues that it is still possible to arrive at a credible forecast for the next 40 years, and to conclude that world population and GDP will grow more slowly towards 2052 than commonly assumed, but still fast enough to trigger significant global warming.

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THE RESEARCH QUESTION

How will the human ecological footprint evolve towards 2052?

Motivation for asking the question

This research was based on the fact that I – and many other policy analysts – have spent more than forty years trying to push global development in a more sustainable direction. There has been some progress, global society is certainly more aware of environmental and social constraints today than in 1970, and some legislation has been modified, some new solutions have appeared, and some helpful institutions established.

But as I see it, much too little has happened. Global society has not been willing to mend its ways in a degree sufficient to ensure a sustainable future – neither economically, environmentally, nor socially. Rather there has been broad resistance to most long term policy advice, an unwillingness to endorse most of the forward looking actions that are necessary to create a less unsustainable world.

On this background, I decided to try and find out what will *actually* happen over the next several decades. I wanted to find out and describe what future humanity is going to decide for itself. The research was based on the central assumption that the human future is created by ourselves, but also on my conclusion after a long life in the real world, that important decisions are made in a rather predictable fashion: Most players seek to maximize their short term gain. They try to solve the problems they face in the cheapest possible manner, and only once they are firmly convinced that the problem is real – which means rather close in time. This applies both at the individual, corporate, national, and global level: Action tend to be postponed until the problem is near enough in time to be perceived as real. And even then action tends to be limited to what is profitable in the short term (say on a 5 year horizon). And in those cases where society moves beyond what is profitable in the short term, the choice tends to be the cheapest of the available solutions. In summary, I believe most modern decision makers tend to maximize their short term gain – using rather high discount rates (in the range 5 – 20 % per year) in the process. The result is a global society dominated by short-termism. Of course, there are exceptions, cases where costs are incurred in the short term even if the benefit arises only far in the future. But I believe they will remain the exception. I base my analysis on the belief that global society will continue to make decisions over the next forty years in the same way as over the last forty years. That is, with a near sole focus on short term costs and benefits. Notice that this applies to democracy and capitalism – both are dominated by the short term nature of voters and investors. Continued short-termism is the most fundamental assumption underlying my forecast of what will *actually* happen over the next forty years.

To avoid drowning in detail, I chose to focus on the future of the human ecological footprint. This is a measure of the environmental impacts of human activity – resource use, emissions, biodiversity destruction and the like. So my research question is: How will the human ecological footprint evolve towards the middle of the 21st century? Or, in other words: What footprint will global society decide to create for itself on Earth over the next forty years?

My answer is described in full detail in the book *2052 – A Global Forecast for the Next Forty Years* (Randers, 2012). The 2052 forecast is in reality a "Business As Usual" scenario: it describes the global future that will result if global society continues to make decisions in the traditional way – largely guided by maximization of short term gain.

My research question was also inspired by the debate among those analysts who believe humanity will lack non-renewable resources (for example the peak oil movement), those who believe there will not be enough food (say, because of lack of fresh water or land), those who worry about impending crises in the supply of other renewable resources (for example, fish, timber), those who fear the loss of biodiversity and ecological services, and finally, those (including myself) who worry most about human emissions (for example of toxics or greenhouse gases that warm the atmosphere). I wanted to find out which of the contenders was most likely to be right.

Feasibility of a useful forecast

I choose to base my forecast on quantitative models of the global future – and started in the global system dynamics modeling tradition where I have belonged all my life. But it soon became clear that I was unable to make a complete system dynamics model of human population, GDP, and footprint which was sufficiently precise to serve my purpose. So I chose to proceed differently, using system dynamics thinking as the conceptual base, but starting with a "linear" (feedback-free) forecast of the central variables in the forecast. Then I included the relevant feedback effects through "manual iteration" at a later stage. In the process I used several other quantitative analyses (from the literature) to improve the quality and consistency of the forecast. The prime objective of this paper is to describe the forecasting method I used and discusses its strengths and weaknesses.

I took as my starting point *The Limits to Growth* system dynamics model World 3 (Meadows et al, 1972; 1992; 2004), which was made to generate and analyze scenarios for the 1970 to 2100 period. It is important to remember that World3 was not made for prediction purposes, but to promote constructive discussion of global policy. Hence some enhancements and amendments were needed before the model could be used as a basis for a credible forecast of the human ecological footprint.

I am of course fully aware of the sound skepticism in our system dynamics profession against making predictions about the future in a social system subject to noise. So I did accept from the outset that I would not be able to predict events. All I could do was to portray broad trends in the global future. But even broad trends are eventually impacted by accumulated noise and by the evolution over time of human decision making. So there is an upper length on the meaningful forecasting horizon (Forrester, 2013). I believe this horizon is around forty years for the problem at hand, perhaps a little shorter. This is the time it will take for "extra-ordinary" (un-foreseeable, surprising, un-expected) change in human decision making to have a significant impact on global trends in population, GDP and footprint. Within this time period it is unlikely that un-expected human action will impact on global trends in a significant way. Thus, this is the period over which it is possible to make a forecast with limited uncertainty bands.

For example it will take 30-40 years before human action on greenhouse gas emissions will lead to discernible differences in the concentration of CO2 in the atmosphere (IPCC, 2013). 20 – 30 years is the minimum time it will take before the energy infrastructure will be significantly changed – unless old capacity is scrapped before the end of its useful lifetime (IEA, 2013). A generation is the time it takes to change the educational level of a significant part of the labor force. Thirty years was the time it took for Deng's one-child policy from 1981 lead to a stable Chinese population. And it will take at least a generation, I contend, before global society will have learned to fear global warming sufficiently to modify the short-termism that underlie the current resistance against strong climate action.

Need for a pedagogical format

In a hope of shortening these delays, I sought to express my forecast in a format that has a chance of getting across to the interested citizen. Experience shows that mathematical equations certainly do not help in communication to a general audience. And even the traditional system dynamics message – that of a valid relationship between system structure and behavior – does not, in my experience, leave a durable imprint on the audience. But I do believe that (vulgar) forecasts (of well-known variables) spliced onto (well-known) historical time series (stretching as far back in time as the forecast is looking ahead) – tends to grasp the attention of the audience (at least that subsection that understand graphs when explained) and stick in their minds.

Thus the 2052 forecast is presented in aggregate graphs like Figure 1 showing world development from 1970 to 2050. The world forecast is the sum of 5 regional forecasts. Each includes many other variables (a total of 29 for each of the 5 regions). All quantitative detail – both historical data and the 2052 forecast – is available for inspection and modification in big spread sheets in the book website www.2052.info. The quantitative data in the website is supplemented with hundreds of pages of qualitative material in the 2052-book itself, and even more is in its references.

Before I proceed, I want to answer another obvious question: What is the point in forecasting the global future over a time period which is so short that global society won't have the time to influence the development? And why do I want to communicate my answer to that same global society? In brief, my ultimate objective is to prepare the ground for wiser global policy in the future. The 2052 forecast argues that human short-termism is the root cause of problems humanity will face on finite planet Earth over the next generation. The ultimate purpose of the 2052 forecast is to argue for a longer time-horizon in human governance. Others agree (Stern, 2007).

A long life in business, academe and civil society has taught me that man is surprisingly short term in his outlook. The short term nature of man is reflected in the short term nature of our pet institutions of capitalism and democracy. Capitalism is guided by maximum short-term profit, democracy by maximum benefit-cost ratios in this electoral period. Economists preach cost-efficiency. All are using high discount rates, placing little weight on the far future. This needs to change, I contend, in order to improve the human prospect. To prepare for such change is the ultimate purpose of the 2052 forecast.

Ironically, the fundamental short-termism of current society makes it simpler to make a forecast of global developments on a forty year horizon. If individuals, corporations, nations, regions or global society suddenly began to deviate from pursuit of their short term gain, the range of possible futures would be much broader. Much could happen if the world future was determined by the shifting whims of a dictator. I don't believe such change will occur over the next several decades. Global society will not slow its current move towards free markets and democratic government. Hence the future can be told with greater certainty. Our common future will be the sum of the short-term optima from a huge number of players. The limited exceptions will arise from the decisions made by un-democratic regimes and by “ethical” investors seeking to respect nature or responsibility for our grand-children.

THE ANSWER

The 2052 forecast

The purpose of this paper is to describe and discuss the method used to generate the 2052 forecast. In order to make the description brief and the discussion interesting, it helps to first review the 2052 forecast itself.

The future of 11 global variables

The essence of the 2052 forecast is summarized in the 11 points below. For more detail see the 2052 book and www.2052.info.

- The global population will reach a peak in 2040 around 8 billion people and be in decline in 2050, because the women of the world will choose to continue the dramatic decline in fertility that has occurred since 1970. In rich countries women will choose a career rather than more children, and women in poor urban slums will seek to avoid the high cost of raising children in this environment.

- The world GDP will continue to grow, but ever more slowly, because the labor force will peak, and productivity growth will slow to zero in mature economies (where most people already work in services and care, where it is hard to increase productivity). China and other emerging economies will grow, catching up with the “West”. But all in all world GDP in 2050 will only be 2,2 times larger than today, and as a result there will be more poverty than commonly assumed.

- Productivity growth will be further slowed as a consequence of increased labor unrest and social friction – caused by growing distributional inequity (including higher unemployment) when GDP growth slows.

- Total consumption will stagnate in the 2040s and then decline, because world society will have to use an ever larger fraction of the GDP on repair (e.g. of climate damage), to obtain ever more inaccessible resources, and to reduce pollution. This so-called non-discretionary spending (Murphy, 2011) will grow to some 10 % of the world output, requiring 10 % of the labor force, the available capital, and the energy used, and lowering the share of consumption in GDP from 75 to 65 percent.

- Global energy use will peak in 2040 and then decline, as a result of the slower growth in GDP and because of continuing decrease in energy intensity (energy use per unit of GDP). The technological advance in energy efficiency will be driven by high (but not increasing) energy prices.

- The decline in energy use after 2040 will not be caused by lack of coal, oil and gas. The world will only consume one half of the reserves currently booked as assets by the energy companies of the world.

- Global CO2-emissions will peak in 2030 and then decline rapidly as a result of slow growth in energy use and because of continuing decline in the climate intensity (CO2 emissions per unit of energy use). The gradual shift towards renewable energy sources and other low-carbon practices, will be inspired by a slowly emerging price on carbon. Prevalent short-termism will prevent global society from imposing on itself a sudden jump in the carbon price.

- The global average temperature will increase steadily – passing the internationally agreed danger level of plus 2 degrees Centigrade above pre-industrial time in 2050 – creating ever more frequent, ever more extreme, and ever more scary weather events, and a slowly rising sea level.

- The human non-energy ecological footprint (the productive land area used to produce food, fiber, fish, and to locate infrastructure) will continue to grow, but there will still be unused land in 2050 (some 20 % of the biological capacity will be left). But most wildernesses will be gone, and much biodiversity threatened.

- Other non-energy resources will be available for those who can pay, as a result of the lower GDP which will imply lower demand than commonly assumed, and because of extensive recycling of materials in an increasingly urbanized world.

- The global consumption of food will grow by some 50 % to a peak in the 2040s. Mostly through increases in land yield, but also through an increase in the area of cultivated land. This will be enough to satisfy the demand from those who can pay, but not enough to adequately feed a billion people – who still will have insufficient income to pay for the food they need to survive well.

Summary – global physical growth will slow by itself
In short, the 2052 forecast says that growth in world population and GDP will slow over the next generation or so. But not because of planetary constraints. Growth will slow "by itself" – because the world's women will choose to have fewer babies, and because the world's economists and politicians will be unable to make economies grow forever. As a result there will be resources left in the ground and more poverty on the surface. And the world will be living through ever more frequent and scary episodes of extreme weather – facing the possibility of runaway global warming in the second half of the 21st century if the tundra melts. Total consumption will decline because an ever larger fraction of the global GDP must be used to fight depletion, pollution, biodiversity loss, inequity, and to repair climate damage.

It is technically possible and not impossibly expensive to stop global warming – if humanity were able to decide to do so (Stern 2007, McKinsey 2009). All it would take is to move a few percent of global labor, capital, and energy from dirty sectors (e.g. production of fossil cars and coal fired utilities) to clean sectors (e.g. production of electric cars and windmills). But although this shift is relatively cheap, it costs more than doing nothing. As a consequence individuals, corporations, nations, and regions – all guided by short term gain – normally will choose to do nothing. Only very slow and gradual "regulation creep" will improve the picture by making investments in clean (and more costly) solutions commercially feasible.

The 2052 forecast describes the likely result. And the fact that there will be huge regional variation. From great progress in China (five-doubling per capita after-tax income over the next forty year) to stagnation and decline in the US and (less so) the rest of the rich world.

THE METHOD

Overview of the forecasting method

The 10 steps of the forecasting method used are shown in Figure 2. Making a forecast involves iteration through these steps. The final result in each step will normally arise from of a number of iterations between an initial guesstimate, which then often must be modified because it leads to inconsistent or implausible consequences elsewhere in the forecast, and a new estimate. Or the initial assumption must be modified because it conflicts with information gleaned from other models or the literature.

1. Choose the time development to be forecast (the "reference mode")
The first step is to select what social phenomenon, what time development, you want to forecast. If you want to achieve real world change – not only increased understanding – you should choose a time development of interest to your audience. You must also choose a forecasting horizon. It must be long enough to be of interest to the audience, but short enough to warrant prediction (that is short relative to the momentum of the system being modelled). Ideally there should be (quantitative) historical information available for as far back in time as you decide to look ahead.

The 2052 forecast took as its starting point the societal developments focused by the World3 model (Meadows et al, 1974; 1992; 2004). This is the (now well-known) dynamics of growth, overshoot, erosion of carrying capacity, and collapse (or, ideally, managed decline before destructive erosion) in world population, GDP and ecological footprint - which will arise when there is physical growth on the physically constrained planet. Thus World3 – a system dynamics model – is model no1in the mix of models used to create the 2052 forecast.

World3 did not tell which planetary constraint is the tightest – which limit humanity will run into first. World3 could not tell simply because there was not enough knowledge available when World3 was made and used. But today, we know much more, and during the first several iterations through the forecasting procedure in Figure 2, it gradually became clearer to me that global warming represents the tightest constraint – and not resource depletion, lack of food, or biodiversity decline. In later iterations, once the basic pillars of the forecast had been set, it became possible to check this initial assumption, by calculating how much resources of various kinds would be required (in the forecast) during the next forty years and compare with available reserves.

The answer supported the initial assumption: available global supplies are more than sufficient to cover (the forecast) human use over the next 40 years. As an example, the accumulated use of fossil fuels (in the 2052 forecast) for the period 2010-50 is only one half of the fossil reserves that are already booked as assets in the financial accounts of the energy industry. Similar reasoning and calculations led to the conclusion that sufficiency is the case not only for energy resources, but also for productive land, and for food. It may not be the case for wild fish (outside the limited number of sustainably managed fisheries), but I believe that the potential collapse of those fisheries will not significantly impact on dominate global developments toward 2052. The main effect of collapsing fisheries will be to deprive fishermen of their jobs and force many poor and middle class consumers to shift to cheaper and more ample sources of protein (like chicken).

In vulgar terms, it seems that humanity is endowed with enough resources to expand human activity sufficiently to create an insoluble climate problem. Slow growth in population and GDP will further reduce the pressure on global resources. So I chose climate for special treatment in the further study, in the belief that this is where the crucial bottleneck will arise.

2. Identify the underlying causal structure (the "basic mechanisms")

Step 2 in the forecasting method is to identify the basic mechanisms you believe cause the time development of interest. Note that Steps 1 and 2 together amount to the creation of a dynamic hypothesis in system dynamics modelling (Randers, 1980). Selecting basic mechanisms involve clarification of the system boundary, i.e. the choice of which drivers you can view as exogenous over the forecasting horizon (i.e. not subject to feedback effects from variables within the boundary) and which ones are endogenously determined.

As mentioned I chose to start from the causal structure of World3, which appears in various formats (Meadows et al, 1972, 1992, and 2004). A fourth version (Randers, 2000) focuses on the global sustainability challenge, and highlights probable societal feedbacks that are of important when the goal is to make a global forecast. But in addition I decided to make a few changes to the original structure, inspired by having spent forty years comparing the World3 scenarios with real world developments. Here is the list of modifications, centred primarily around the treatment of productivity growth, urbanisation, and fertility.

1. A negative effect on the rate of productivity growth when the economy becomes more mature. Main reason: It is simpler to increase productivity in manufacturing than in services and social care.
2. A positive effect of productivity on urbanisation. Main reason: Very high productivity requires high population density.
3. A negative effect of urbanisation on fertility. Main reason: Women choose to have fewer children in the urban setting than in the village. This comes in addition to the negative effect of high income on fertility.
4. A u-shaped effect of economic growth rate on distributional inequity. Low growth rates in the economy fosters inequity ("fewer jobs"), as do very high growth rates ("some get very rich before wealth trickles down").
5. A negative effect of inequity on productivity growth. Main reason: It is hard to fine-tune the economy when there is social friction and conflict.

Finally I chose to modify the World3 conceptualisation on two scores: I chose new variables to represent processes that were already in the World3 model

6. Use of the conventional measure of "GDP" to track the volume of economic activity ("the production of goods and services in the market economy")
7. Use a new variable called "non-discretionary investment" to track the unavoidable future costs when humanity must access more remote/less rich resource supplies, must spend more on pollution control, must repair damage from climate change, and must handle distributional inequity to avoid social turmoil. Non-discretionary investment is what society will spend after crisis has struck (because short-termism has kept us from paying up front to avoid the problem).

The resulting basic mechanisms underlying the 2052 forecast, is shown in Figure 3.

3. Select a central variable to be forecast and its direct causes (the "linear core")
Step 3 in the forecasting method represents the first deviation from good system dynamics model-building practice. Step 3 seeks to increase the precision level in the core of your forecast, and to do this in a way which simplifies communication with your audience. Step 3 seeks to exploit the fact that most audiences think in a linear fashion when they forecast the future: "Factor A will cause a change in B, which in turn will cause a change in C, and so on." Possible feedback effects are considered later, if at all.

In Step 3 you should identify a linear chain of cause and effect which is easily measured, simple to understand, and of interest to your audience. As an example, real estate investors are easily engaged in a discussion of future house prices, but usually starting from trends in demand, construction costs, and margins. Experience (Randers and Goluke, 2007) shows that investors are much less impressed by the (valid) system dynamics message concerning future profitability, namely that future margins will be reduced by overbuilding. It seems simpler to communicate potential feedback effects later in the forecasting process.

So in Step 3 you should start by identifying one central variable as the focus of your forecast. In the 2052 forecast this was "annual greenhouse gas (GHG) emissions" – since climate change had been identified as the tightest global limit (see Step 1). But since it proved impossible for find long time series for GHG emissions, I changed to a focus on CO2 (skipping the other Kyoto-gases) and, specifically, on CO2 from energy production (skipping emissions from changing use of land). The resulting variable "annual CO2 emissions from energy production" only represent two thirds of man-made GHG emissions, but this CO2-flow is well documented, and furthermore perceived as understandable and concrete by my audience.

Once you have the central variable, you should choose a linear core of cause and effect relationships that makes it simple to calculate future values for the central variable from assumptions about the future values of variables earlier in the chain.

After much trial and error, I chose the linear core shown in Figure 4 as the spine of the 2052 forecast. It illustrates the logic used when calculating a forecast of future CO2-emissions from assumptions about the future development of the other inputs to the linear core. Following the linear core from top to bottom, a forecast for the *population* is obtained from (the mathematical integration of future values for) *fertility* and *mortality*. Once the population size is known, the *potential labour force* (those aged 15-65) can be calculated once you know the age distribution. Next GDP can be obtained as the product of the potential labour force and *gross productivity* (defined as GDP per person aged 15-65). Once the GDP is known, total energy use follows by multiplying GDP with the *energy intensity* (defined as energy use per unit of GDP). And finally global CO2 emissions can be calculated by multiplication with the *CO2 intensity* (defined and CO2 per unit of energy use). The final result of applying this logic is shown in Figures 5a-f.

Experience shows that is simpler to explain and obtain credibility for a linear core of this type. Although there are obvious feedback effects (shown in Figure 3) they need not be taken into account at this first stage. The audience stays interested even if (or perhaps just because) the introduction of ("confusing, qualitative") feedback is postponed until later.

The reason why it appears useful to disregard the system feedbacks at this early stage, is not that they are unimportant in determining the long term future, but because the typical audience finds such feedback effects less tangible and more uncertain. The feedbacks typically involve variables for which there is only qualitative data. This does not bother the seasoned system dynamicist, but leaves a typical audience unconvinced. Thus better to start with a subsection of the full system, chosen in a manner which makes it simple to quantify, to represent in a spread sheet, and to make an open loop forecast using conventional linear thinking. The estimated effect of feedback can then be introduced later, as an adjustment of the linear forecast. Ideally, the linear core should be chosen is such a manner that the feedback effects are both weak and delayed towards the end of the forecasting horizon.

4. Choose the forecasting horizon

Although you will certainly have thought about the length of the forecast many times before you get to Step 4, now is the time to make a formal decision, in quantitative terms. The forecasting horizon must be shorter than the time it will take for humanity to evolve, decide upon, and implement a truly innovative response to the challenge of global overshoot. As mentioned above, my estimate – based on own experience and the very slow global response to the initial warning of *The Limits to Growth* – is that this will require at least another generation, or in other words, 40 years. Even if there would be some truly extraordinary human action taken within the current decade, we would be nearer to 2050 before one would see significant bending of the trends in Figure 1.

5. Find historical time series for the variables in the linear core

Step 5 is to find historical time series data for as many of the variables in the linear core as possible. The time series should go as far back as your forecasting horizon extends into the future. If at all possible, choose numbers (and units!) that are well known to and used by your audience. Figures 5a-f provides a model. This will help make your forecast being perceived as credible and solid. Something tangible, something one can believe in. Something that can be easily represented in the users' spread-sheet.

These time series should be plotted graphically, to facilitate your open loop forecast of their future path. The visual presentation of history and future in one graph makes it simple for your audience to assess whether your forecast is a continuation of – or a break from – past trends. Breaks should only occur if there is a reason in the basic mechanisms underlying the forecast.

Notice that normally you will want not only the variable itself to be a smooth continuation of past trends, but also its first derivative. Thus you will normally want to obtain time series data not only for important levels (e.g. the world population) but also for the major rates influencing the level (e.g. the crude birth rate and death rate). It is often simpler to make a good forecast for a level by forecasting the relevant rates manually, and then calculate the resulting level values (just like in the stepwise integration used in system dynamics software). Such integration is straightforward in a spreadsheet. This method ensures that the forecast level is a smooth continuation of its past, and that the first derivative is also smooth. If the historical time series is very noisy, one can use running averages of the historical data, and splice the forecast to the last historical value for the running average (Randers and Goluke, 2007).

In order to find sufficient data it may be necessary to adjust the conceptualization, that is, describe the future with other variables – variables for which there exist good data. Let me illustrate with one example from the 2052 forecast. There was initially the need to forecast labour productivity, defined in the traditional manner as "GDP per person-hour of effort". But we could not find long time series for productivity for more than a few countries, nor for that matter, for the number of hours per standard work-year. Hence there was no basis for forecasting productivity, nor hours worked per year, and impossible to calculate future GDP as future labour force, times productivity, times hours worked per year. But there was available data for GDP, for all nations and for the past forty years, and also for "the number of people between 15 and 65 years of age". Hence a change in conceptualisation solved the problem. Productivity was redefined as "GDP per person between 15 and 65 years of age" – called "gross productivity" for clarity. This could be multiplied with "the number of people between 15 and 65 years of age" – called "potential workforce" for clarity – to gives GDP. Both in the past and in the future.

But by shifting from the productivity of those that actually have a job ("labour productivity"), to the productivity of the potential labour force ("gross productivity") there is also a shift in perspective. For example, whereas the labour productivity can be increased by firing staff, gross productivity will stay the same even if one increases the pool of unemployed. Another example: If society shortens the length of the work-year, while holding employment stable, GDP will fall and lower both gross productivity and labour productivity. But the traditional productivity measure "output per man-hour" may well stay constant. A third example: In order for a nation to achieve very high gross productivity, a large fraction of those aged 15 to 65 must participate in the labour force.

Another example of the need to change conceptualisation in light of data availability and user interest, can be found in the choice of level of aggregation in the 2052 forecast. Global time series data are available for the linear core, but global averages are not descriptive of any nation, and less engaging to a national audience. By restricting the linear core to variables for which there exist national data, it became possible to create forecasts at the national level – and hence win the deeper interest of its citizens. However, at the national level of disaggregation, trade becomes important. And forecasting trade flows is notoriously difficult. As a compromise, I chose to split the world in 5 regions. The regions are so big that net trade flows only constitute a small fraction of the regions' activities, and hence can be handled through manual iteration (see Step 7). I chose to use the following regions: The United States ("US"), the other industrialised nations ("OECD-less-US"), China ("China"), the 14 largest emerging economies ("BRISE") and the remaining 140 mainly small and poor countries ("Rest of World").

Regional time series were achieved by adding up the national statistics for the nations in the region. See the 2052 book Appendix 2 for details.

The numbers and graphs for the variables in the linear core (for each of the 5 regions) are readily available on www.2052.info. For each region there is a collection of spreadsheets which follow the logical sequence of the linear core. And there is the global collection – which is the sum of the five regional forecasts. Each spreadsheet is set up in such a manner that it is simple for the user to introduce his/her own forecasts and thereby create an alternative forecast using the same logic. This functionality is particularly useful when there is need to convince the user that what s/he sees as a major change in assumptions has indeed limited effect. The spreadsheets in www.2052.info constitute model no 2 in the mix of models used to create the 2052 forecast.

6. Make an open loop forecast for the linear core

Step 6 is to make a forecast for the central variable and the other variables in the linear core over the forecasting horizon. First, by extrapolating the historical time series for the exogenous inputs – this was done manually in graphs (in the spreadsheets). Second, by using the forecast values for the exogenous inputs to calculate forecast values for all the other variables in the linear core – this was done recursively (in the spreadsheets) by emulating the calculation sequence in system dynamics software. And third, by splicing the result onto the last historical value for the level – and presenting the forecast as graphs, as a continuation of historical developments.

Figure 5 shows the final result of this exercise for the linear core of the 2052 forecast. In the first iteration towards this forecast we used fertility and mortality data from the UN Population Forecast (United Nations, 2011), data on energy use from BP (BP, 2011), and CO2 emissions data from Institute for Energy Analysis (Institute for Energy Analysis, 2011) – all aggregated into regional numbers from national data. Initially we used guesstimates for labour participation and labour productivity, and calculated rough estimates for future GDP. Later we moved to the "gross productivity" conceptualization described above (Step 5).

In the end we needed to extrapolate the historical time series for five exogenous inputs: fertility, mortality, gross labour productivity, energy intensity, and CO2 intensity. The history for the five were either directly available as historical data, or could be calculated (for example by calculating the historical value for energy intensity by dividing historical value for total energy use by the historical value for GDP – for each of the past forty years). The resulting historical time series were extrapolated manually – based on knowledge about the relevant World3 dynamics, real world, and common sense. Underlying the whole procedure was the important assumption that there will be no sharp break with past performance, only gradual change. And that there will be a continued desire in most cases to reduce costs in the short term.

7. Improve the open loop forecast by using other models from the literature

In Step 6 you should use other models to improve the open loop forecast of the linear core, either by improving the forecast of variables already in, or by ensuring that excluded variables can be safely excluded. There are no obvious limitations to this process, but good practice would be to focus on variables with an obvious relevance to the reference mode. The 2052 forecast provides good examples of both types of upgrades.

Increasing the quality of a specific causal link

In order to calculate future GDP, it was necessary to calculate the size of the potential work force (defined as the number of people aged 15-65 years). Initially we tried to do this by splitting the population in three age groups (including one of people aged 15-65) and track them in our spreadsheet. This did not give the necessary precision. Sufficient precision would have required numerous age groups, and we did not have data on initial values and age specific birth and death rates. Our solution was to use the age pyramids in the UN Population Forecast (United Nations, 2011) which are available for all countries and all years. It turned out that our aggregate forecast for the global population was rather close to the UN "low" alternative. Hence we chose to use the UN's detailed age structure for the UN "low" alternative as a basis for our forecast of the size of the potential work force. From the UN forecast we calculated the number of people in our three age groups 0-15, 15-65, 65+ for all the nations of the world and aggregated the result into our 5 regions. The UN Population

Forecast – a well-tested, conventional population forecast framework – is no 3 in the mix of models used to create the 2052 forecast.

In a similar manner we used the Penn World Tables – a macroeconomics database – to split our GDP forecast into its components: consumption and investment. The Penn World Tables include an amazing collection of time series for the standard macroeconomic variables for all the world's nations, on a standardised basis (Heston et al, 2011). We aggregated the national Penn data into time series for our five regions. From these results we obtained numbers for the investment share in the GDP, by dividing historical values for investment with historical values for GDP for each of the past 40 years. We then extrapolated this share over the next forty years and used the result to calculate the consumption share in the GDP (equals 1 minus the investment share). In doing this manual forecast it was necessary to consider the dramatic increase in non-discretionary investment that is likely to occur towards 2052. The work was informed (see Step 2) by the increases in the investment fraction in World3, the historical cost increase due to depletion and pollution, the projected costs for various forms of repair work (eg of hurricane damage). In the end, the 2052 forecast predicts that the investment fraction will be forced up, from 24 % historically, to 36 % in 2050 – albeit with huge regional variation. This is a significant rise, and reflects the huge non-discretionary costs that will arise from more frequent replacement of infrastructure that has been destroyed by extreme weather. The Penn World Tables – a conceptual structure and database – is no 4 in the mix of models used to create the 2052 forecast.

As a third and final example, there was the need to calculate the global warming that will result from the CO2 emissions in the open loop forecast. To this end, we used a separate dynamic simulation model, C-ROADS (Jones et al, 2011), which was originally made to help decision makers understand what will be the future effect on global warming and sea level rise of various global emission scenarios towards 2100. C-ROADS is a synthesis of a number of much more complex mathematical models of the climate system. By entering the open loop forecast of CO2-emissions from energy use into the C-ROADS model we got back a forecast telling that the global average temperature would rise linearly from +0,7°C in 2010 to +2°C in 2050 – both relative to the temperature in preindustrial times. C-ROADS also estimated that the average sea level would rise by another 30 cm from 2010 to 2050. C-ROADS did so after adding estimated emissions from land use change and in the form of other Kyoto gases, to my forecast of CO2 emissions from energy use. C-ROADS – a dynamic simulation model - is no 5 in the mix of models used to create the 2052 forecast.

Ensuring that excluded factors are unimportant
As described in Step 1 above, climate change emerged in the initial iterations of the forecasting process as the tightest planetary constraint. Hence annual CO2 emissions were chosen as the central variable to be forecast – initially based on the linear core in Figure 4. To help verify that other human impacts actually will stay below planetary limits, the 2052 forecast was extended to include forecasts for the use of fossil fuels, food, and biologically productive land. In all three cases the object was to ensure that the forecast did not implicitly assume the use of more resources than available. Three models from the literature were used to this end.

As mentioned above the detailed data of BP World Energy Review was used to split total energy use into five categories: coal, oil, gas, nuclear, and renewables (including energy from hydro, wind, sun, and biomass). From this basis, and informed by the various scenarios of the IEA World Energy outlook (IEA, 2012), we made forecasts for the future use of the various energy carriers in the 5 regions until 2052. But we needed to know that the sum of these forecasts did not exceed the available reserves. Hence we calculated the accumulated use of coal, oil and gas to 2052, and compared with the reserves of coal, oil and gas already carried on the books of the world's energy companies, following the thinking of (Carbon Tracker, 2011). Since accumulated use did not exceed one half of available reserves, we concluded that fossil resources will not run out before the globe has warmed by +2°C by mid-century and probably not before world energy has become renewable by 2100. In short, fossil energy is unlikely to become a limiting factor. IEA's World Energy Outlook – a data base and scenario modelling tool - is no 6 in the mix of models used to create the 2052 forecast.

Next, there was need to ascertain that the food used in the 2052 forecast did not exceed the planetary capacity to provide food. We calculated future food demand based on our GDP and population forecasts, estimated what amount of land and what yields this would require, and made sure the total requirement did not exceed potentially arable land and potential yield. The work was based on national statistics on arable land and yield – from the UN Food and Agriculture Organisation. The main conclusion was that the world of 2052 will require some 50 % more food than today. This can be produced if arable land is expanded by 10 % and yields by 40 %. Both are feasible, given existing land reserves and agricultural technologies. Most nations can satisfy their domestic demand with limited or no food trade. The main exception is China which will have to import food over the next 20 years or so. My forecast of food sufficiency differs from the conventional expectation of food shortage largely because I believe there will be fewer people, lower GDP, and more hunger in 2052 than is commonly assumed.

A final check was made to ensure that the amount of global warming in the 2052 forecast will not significantly reduce food production in the future. This was done – with the help of the author – based on (Lobell, 2011) which presents an estimate of the per cent reduction in agricultural yields that are likely to occur when the globe moves from +0,7°C in 2010 to +2°C in 2050. The global impact will be a limited reduction in yields, at most ten per cent. The impact is small because more CO2 in the atmosphere has two counteracting effects: A growth enhancing fertilization effect from more CO2, and a growth reducing effect from higher temperatures. Initially the fertilization effect is strongest, later excess heat takes over. There is huge regional variation: in northern latitudes plant growth is stimulated both by CO2 and warming. In the longer run – if temperatures continue to rise – the negative impact will be stronger. (Lobell, 2011) – an impact analysis based on empirical data of climate impacts on plant growth – is no 7 in the mix of models used to create the 2052 forecast.

The third and final question is whether there will be enough land, not only for food production, but for grazing, wood production, urban industrial use, and fish farming. For this purpose we used the Ecological Footprint concept and data that has been meticulously evolved, assembled, and made available by the Global Footprint Network (Global Footprint Network, 2012) for all nations and all years since 1960.

The most common definition of The Ecological Footprint does include the impact of climate gas emissions (in the form of the forest area that would have been necessary to absorb all man-made CO2-emissions). In the 2052 forecast CO2-emissions are treated separately. To avoid double counting, we therefore focused on the "non-energy footprint", which is calculated by subtracting the climate footprint from the total ecological footprint. The non-energy footprint amounts to the physical amount of productive land used by humanity to produce its food, fodder, timber, fish, and to provide space for infrastructure. It is the amount of biologically productive land which is required to run current society. The non-energy footprint is a good approximation to the common perception of "how much land humanity is using".

Although this amount of land has increased over the last forty years, it is still less than the globally available area of productive land. In other words, the non-energy ecological footprint of humanity is still below the carrying capacity of planet Earth. This situation will most likely continue. In the 2052 forecast the non-energy footprint grows to some 80 % of available capacity by 2050, but does not overshoot. This result is arrived at by 1) calculating historical values for the non-energy footprint per person (by dividing the total non-energy footprint by the population for all past years); 2) extrapolating this (rather stable) factor to 2050; and 3) calculating the future values of the non-energy footprint by multiplying this factor with the forecast population numbers. The Human Ecological Footprint – a conceptual structure and associated database – is no 8 in the mix of models used to create the 2052 forecast.

In summary, these tests show that the future global use of fossil energy, food, and land will not exceed supply before 2052. And since both population and GDP are likely to decline in the second half of the century, this conclusion may remain valid beyond the 2052 forecasting horizon.

8. Correct manually for un-modelled feedback effects (using "manual iteration")

Once you have an open loop forecast of the linear core, Step 8 is to identify those feedback processes that will be triggered by the time development in the linear core. And then to modify the forecast according to the likely effect of these feedbacks - through manual iteration.

Experienced system dynamicists know that this is difficult, and that a complete system dynamics model is needed to ensure that the modification is properly done. But in many cases the relevant feedbacks are hard to quantify in a model. Furthermore, many if not most audiences are sceptical to heroic system-dynamics-type assumptions about causal links with no measured variables. Thus one may as well describe the feedback mechanisms verbally, and try to describe the resulting modification of the forecast in words. Arguably the verbal medium better match the low level of precision in the forecast.

The important feedback effects impacting on the linear core of the 2052 forecast are described under Step 2 above and illustrated in Figure 3.

One way to help ensure that the un-modelled feedback effects are correctly handled, is to glean insights from simulations with other system dynamics models that include the same feedbacks. In the 2052 forecast much was learned from the dynamics of the World3 model. World3 does include most of the feedbacks in Figure 3 that were disregarded when making the open loop forecast. World3 includes the feedbacks:

- from per capita income to population growth (via birth and death rates),
- from accumulated production to lower capital productivity (via depletion of accessible resources),
- from accumulated emissions to clean-up investments (via environmental damage),
- from traditional investment to higher gross labour productivity (via knowledge and capital)

- from increased food use to more investment in environmental protection (via environmental damage)

The overall dynamics of these feedbacks can be learned from runs with the World3 model: they contribute to delay in global decision making and to overshoot of global resource limits.

Another system dynamics world model (Garcia, 2009; 2011) was built by adding a detailed energy sector (with fossil and renewable energy carriers) and a climate sector (several energy sources contributing to global warming) to the World3 structure. Runs from this model provide additional insights about the dynamics embedded in Figure 3. It shows for example that the gradual shift towards more expensive energy sources, once cheap energy runs out, tends to reduce the sharpness of the global collapse – at least when it occurs because of energy shortages. And the quantified climate sector in the Garcia world model indicates that the climate feedback is more long drawn than often believed, because of the relative size of human emissions and the absorptive capacity of the world's oceans, forests and the atmosphere. The Garcia model – a system dynamics World3-type model with a detailed energy and climate sectors – is model no 9 in the mix of models used to create the 2052 forecast.

But there are feedbacks in Figure 3 which are not included in the World3 or Garcia models:
a) the positive effect of productivity on degree of urbanisation
b) the U-shaped effect of consumption growth on distributional inequity
c) the slowing of productivity growth when the economy matures
d) the negative effect of an excessive footprint on the quality of life
e) the increase in social tension when the quality of life declines

These feedbacks have two main effects, I have concluded through contemplation and manual iteration. The first is to further slow economic growth rates once the economy matures, and once non-discretionary investment ("repair costs") begins to reduce consumption growth. Social tension will rise and make it more difficult to achieve further growth in the economy. The second main effect is that increased urbanisation, which goes along with high productivity, also slows population growth and ultimately creates population decline. In sum these two feedbacks work to slow the growth in population and ecological footprint over the next forty years – independent of the workings of the planetary constraints – and hence do reduce the tendency for overshoot.

But the slowing is not sufficient to avoid global warming. The modified 2052 forecast still shows the global average temperature passing +2°C in 2050 and moving up. From the literature supporting the upcoming IPCC 2013 report, one can obtain vivid qualitative descriptions of what a "plus-two-degrees world" will be like. It is a world experiencing ever more frequent extreme weather and hampered by the difficulty of planning in an increasingly unpredictable world . The multitude of recent climate reports and models – normally with a geophysical model core – that provide the basis for verbal descriptions of the effects of warming by +2 °C relative to preindustrial times, can be seen as model no 10 in the mix of models used to create the 2052 forecast.

But Step 8 remains an uncomfortable part of the forecasting method used. There is ample potential for mistakes when trying to predict the dynamic consequences of the many feedbacks in Figure 3. Manual modification based on one's own understanding of the full causal structure does not reach the rigor of runs from a complete system dynamics model.

9. Check the plausibility and communicability of the forecast
Once a modified forecast is available – including the estimated effects of the known feedbacks – you should test and evaluate the result in as many ways as possible.

The most effective procedure, I believe, is presentation to critical audiences. But in order to achieve useful commentary and critique, the forecast must be presented in an understandable and engaging fashion. This may be difficult within the time limited space of a standard lecture. And critics may not take the time required to read the full technical report. Hence your own tests of plausibility and consistency will remain important. Another technique is to publish individual, strong and forward looking, statements on an interesting element of your forecast. And then hope that the sharp rebuttals that are likely to arise highlight weak spots in your forecast – and do the necessary amendments. But this process may be hard on your scientific reputation.

In the case of the 2052 forecast, manual iteration and cross-checking for consistency seems to have eliminated obvious mistakes. No flaws were discovered during the first year after publication (involving 60.000 copies sold in 5 languages and more than 100 presentations world-wide).

10. Repeat steps 1 through 9 until the forecast is satisfactory
Needless to say, it will take many iterations through the steps of this forecasting method before you have a lucid, interesting and defensible forecast – one with which you feel comfortable in the solitude of your office. The latter is, I believe, the toughest quality test.

DISCUSSION

Strengths and weaknesses of the forecasting method

Strengths
The prime strength of the forecasting method described in Figure 2 is that it does indeed lead to a quantitative forecast. And over a forecasting horizon which is chosen based on an understanding of the underlying system structure.

Second, the method leads to a forecast which is communicable – in the form of time graphs which make it simple for the audience to evaluate the plausibility of the forecast. It helps that the graphs portray variables that the audience recognise from the public debate, and numerical values and units that match the terminology of the informed public. The graphs make the forecast more tangible and credible.

Third, the method results in a forecast which is simple to understand – because the time graphs also include forecasts of the underlying drivers of the central variable (at the end of the linear core).

Fourth, the method combines the strength of the system dynamics method with insights from other modelling traditions.

Fifth, the method provides the forecast in a format – a traditional spreadsheet – which makes it simple for interested users to test their own alternative assumptions. The sheer possibility of making such tests seems to increase user belief in the forecast.

And finally, the method opens for the building of a verbal narrative built around the quantitative core (as in the 400-page text of the 2052-book) which helps make the forecast richer and more closely connected to the real world than the traditional graphical simulation runs.

Weaknesses

Manual adjustment of un-modelled feedback

But the method has weaknesses, and one is major: the danger residing in relying on common sense – and not closed dynamic models – to predict the consequences of un-modelled feedback and interregional flows. Most system dynamics professionals know how hard it is to anticipate correctly what will be the dynamic behaviour of (even relatively simple) systems with feedback.

It is therefore a help that the overall behaviour of the 2052 forecast is not qualitatively different from simulations made with the World3 model. The 2052 forecast resembles the "pollution crisis" generated by various versions of World3 both in 1972, 1992, and 2004. Albeit with significant differences. But these differences can be explained, and thereby increase user understanding of the 2052 forecast.

The main difference between World3 and the 2052 forecast, is that in the latter growth in population and GDP slow because of decisions made by humans (women choose to have fewer children, economists fail to achieve growth in mature economies), not because of global physical constraints. Also the timing is slightly different: the climate crisis is postponed by a decade or so in the 2052 forecast. These changes are the consequence of modified assumptions (see an earlier section for the detail). In the 2052 forecast there is an additional negative effect on fertility from high productivity (via urbanisation), and an additional negative effect on productivity growth from high productivity (in mature economies). Both feedbacks work to slow growth at the end of the global upturn and postpone the crisis. Also, the crash into global limits appears sharper in World3 than in 2052 forecast. This is because World3 only has one non-renewable resource with a given environmental impact per unit used. In the 2052-case humanity can choose from a spectrum of energy sources (coal, oil, gas, nuclear and renewables) with different climate emissions per unit of energy. The speed of approach towards global climate limits is softened by an anticipatory shift towards the use of less climate-intense energy sources. This conclusion is supported by runs with the Garcia-model.

But in spite of the support found for the 2052 forecast in runs from other full system models, it remains a weakness to rely on manual iteration to guestimate the effects of un-modelled feedback and interregional flows.

As an example let us discuss the least tangible feedbacks in the basic mechanisms of the 2052 forecast, namely the effect of rising income disparity and declining quality of life on social tension and unrest. And the consequent negative effect of social unrest on productivity growth. Formal modelling would help little, I believe: The detailed behaviour of the model would depend on parameter values that are not known. All one could do was to include the causal link and test its effect for different parameter values. The effect, I believe, would be to further slow GDP growth in mature economies, and hence reduce the tendency for overshoot. And these dynamics I tried to mimic through manual modification of the forecast (in an iterative manner, checking the plausibility of the forecast after each round).

In order to study the possibility that social strife would evolve into civil war and ultimately generate global collapse through a new world war, I could do little better than carefully consider the possibility. My conclusion was that distributional inequity will continue to generate sporadic war at the national level, like in the past forty years. And similarly, since global society has avoided world war for nearly 70 years, in spite of intense pursuit of national short term interests, I also believe this will continue. The latter conclusion was supported by a one-day effort involving one colleague to identify a plausible sequence of events that would lead to world war (defined as an armed conflict where China and the US shoot at each other). We could find none.

Manual adjustment of interregional flows
The other serious drawback is the use of manual iteration to handle the effects of trade and migration. We chose manual iteration because earlier attempts at modelling trade and migration endogenously had taught us that this does not add much understanding. This is probably an acceptable approximation, since trade is less than 10% of most big national economies.

The added dynamics are typically dominated by the fine detail in the formulation of trade and migration, detail which does not necessarily reflect reality. Trade and migration flows are typically based on measures of the relative attractiveness of the nations involved. So what I did was to check manually whether implausible differences evolved, and – most importantly – that the sum of resources used does not exceed the supply available. Furthermore, it is possible to guess what will be the aggregate effect of trade and migration on the 2052 forecast: Interregional flows will accelerate the closing of regional differences. Income and quality of life would converge faster – but not much, I contend, because short-termism would quickly lead populations to interfere with trade and migration flows if they were not in their short term interest.

In conclusion, it is obvious these types of manual tests and modifications are inferior to runs of a complete model. As a first stage, the 10 models used to arrive at the 2052 forecast could have been combined into one (huge) mathematical model. I am not certain that the result would warrant the effort. The big model would be impossibly opaque and convey a spurious impression of precision. Next the un-modelled feedbacks could be included along with a specification of interregional flows. Again I am not sure the effort would warrant the increase in precision. It appears cheaper to try to learn from other separate studies and include the insight in the 2052 forecast through manual iterations.

In earlier forecasting projects, in global shipping (Randers and Goluke, 2007) and urban real estate, we did indeed include all relevant feedback and knowledge in one formal model. In this way we avoided the problem of manual iteration, but at the cost of using model variables that did not match the ones normally used by our audience. It appears that our audience – decision makers from the real world of business – would have been more comfortable with quantitative forecasts of a linear core. Which could then have been modified in verbal discussions of the feedback effects that the linear core would trigger.

Further research

There are obvious avenues for improvement both of the 2052 forecast and the forecasting method used. The most important tasks are the following:

1. Apply the 10 step forecasting method in other areas where forecasts are desired, to test its ability to provide useful results.

2. Build the complete system dynamics world model with 5 regions, trade and migration flows, and including the intangible feedbacks discussed above.

3. Study the effectiveness of the 2052 forecast in increasing voter and student understanding of global developments and in creating support for a shift in public opinion in favour of policy that better handle consequences in the long term.

Acknowledgement

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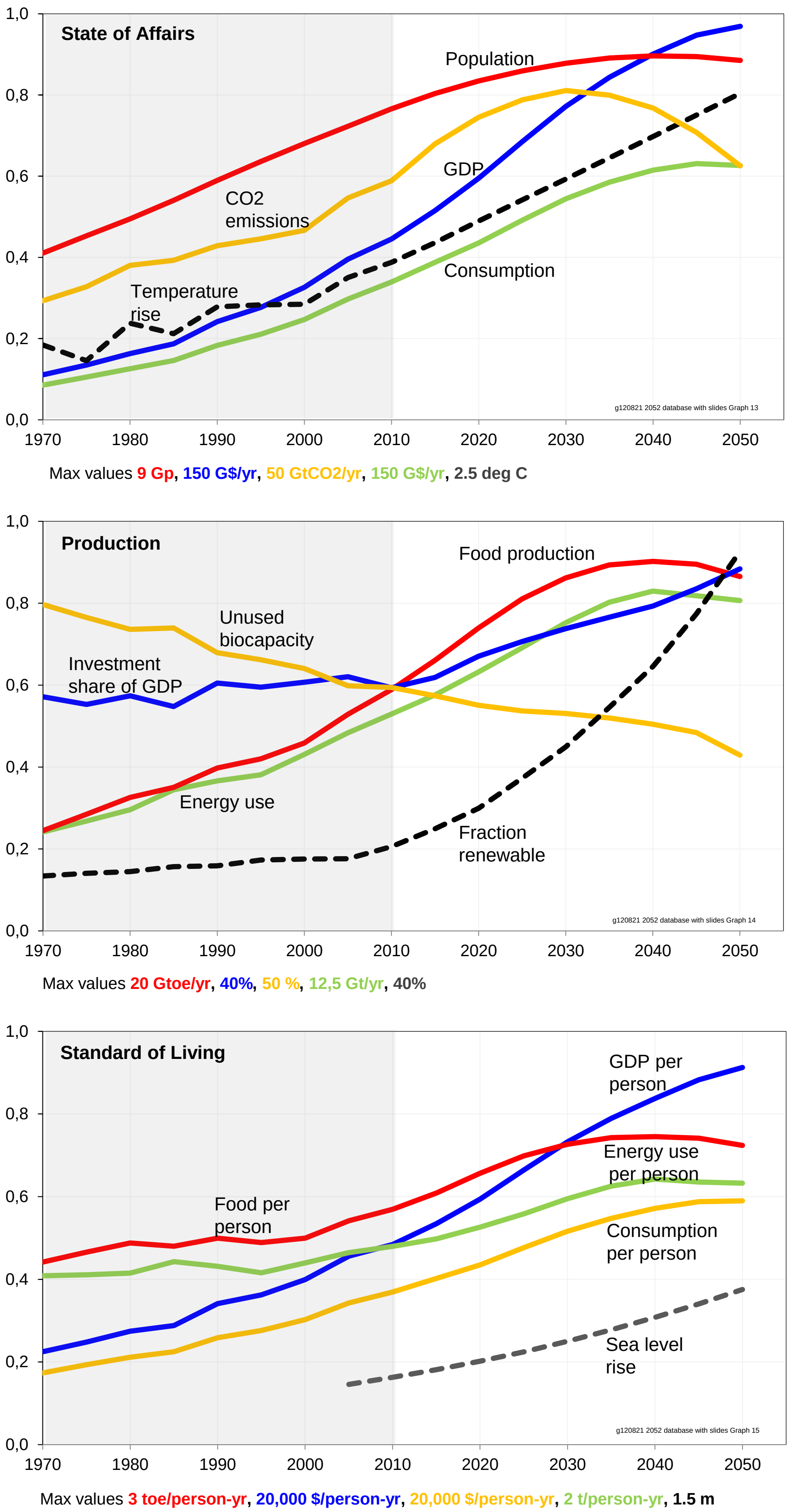

Figure 1. The 2052 forecast for the world, 1970 – 2050

THE FORECASTING METHOD

1. Choose the time development to be forecast (the "reference mode")

2. Identify the underlying causal structure (the "basic mechanisms")

3. Select a central variable to be forecast and its direct causes (the "linear core")

4. Choose the forecasting horizon

5. Find historical time series for the variables in the linear core

6. Make an open loop forecast for the linear core

7. Improve the open loop forecast by using other models from the literature

8. Correct manually for un-modelled feedback effects (using "manual iteration")

9. Check the plausibility and communicability of the forecast

10. Repeat steps 1 through 9 until the forecast is satisfactory

Figure 2. Overview of the method used to make the 2052 forecast

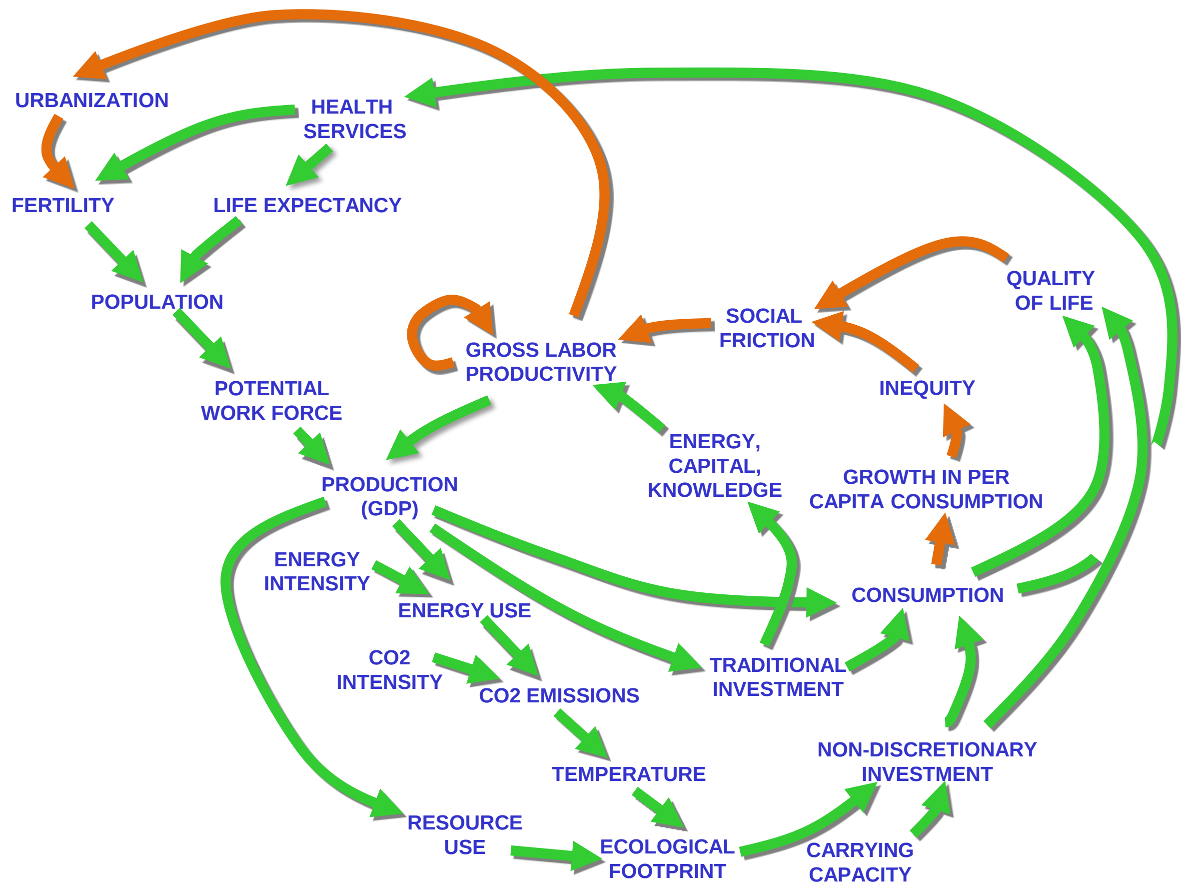

Figure 3. The basic mechanisms underlying the 2052 forecast
(Green links: World3 paraphrased. Red links: New feedbacks in 2052 forecast.)

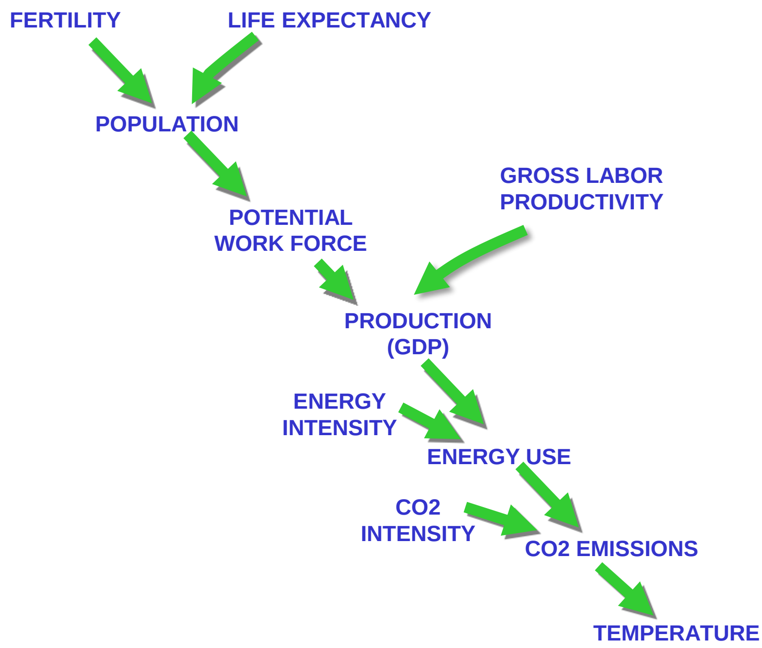

Figure 4. The linear core of the 2052 forecast
(All data for the linear core is available on www.2052.info)

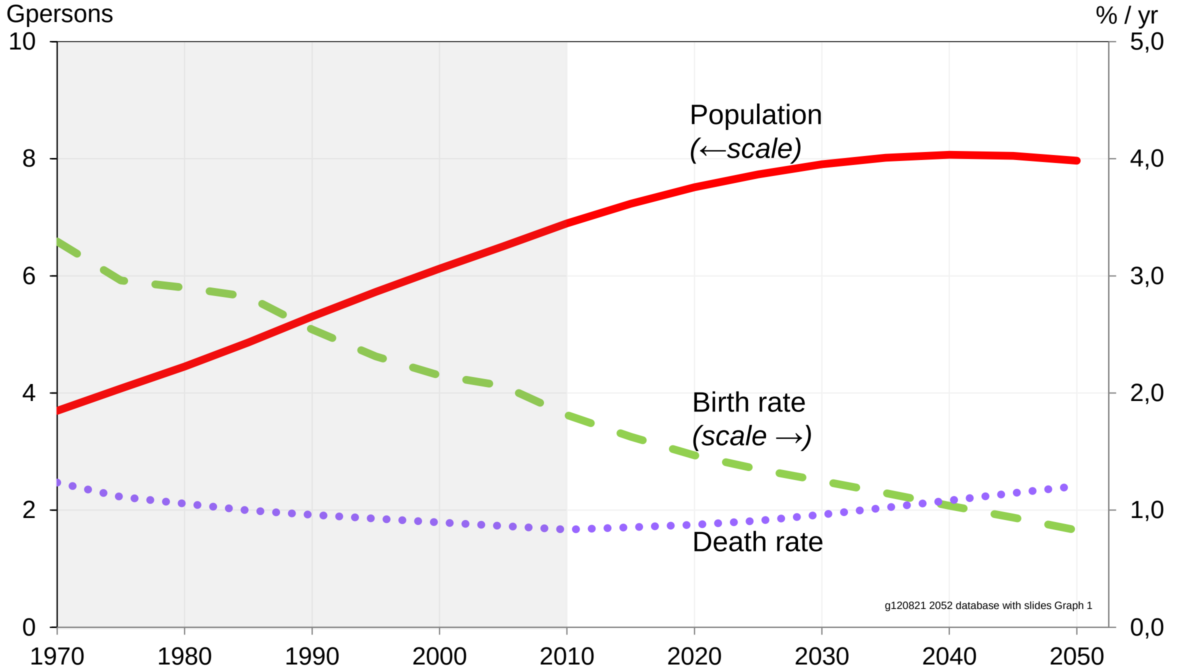

Figure 5a. First forecast for the linear core: World population will peak in 2040

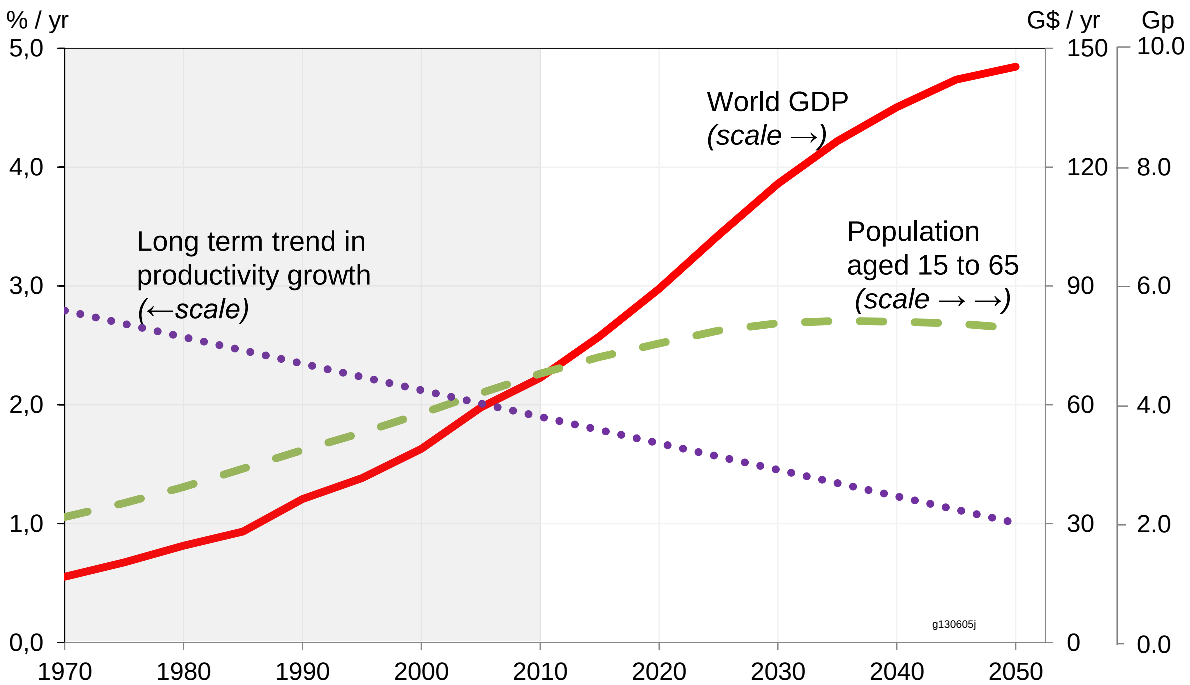

Figure 5b. Second forecast for the linear core: World GDP will slow down

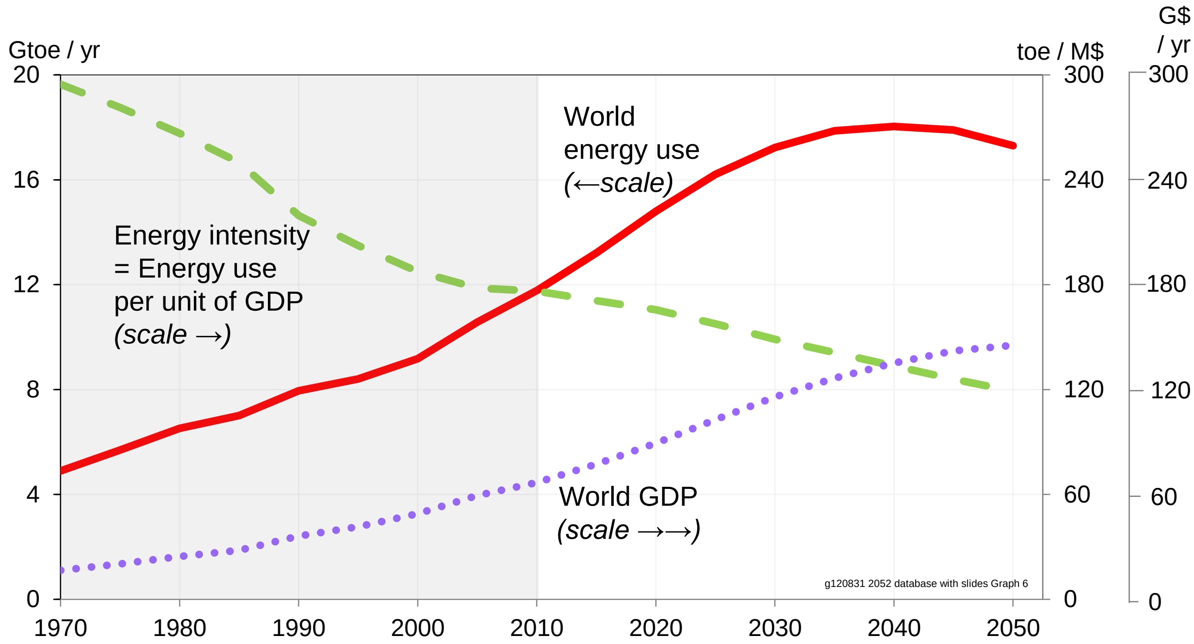

Figure 5c. Third forecast for the linear core: World energy use will peak in 2040

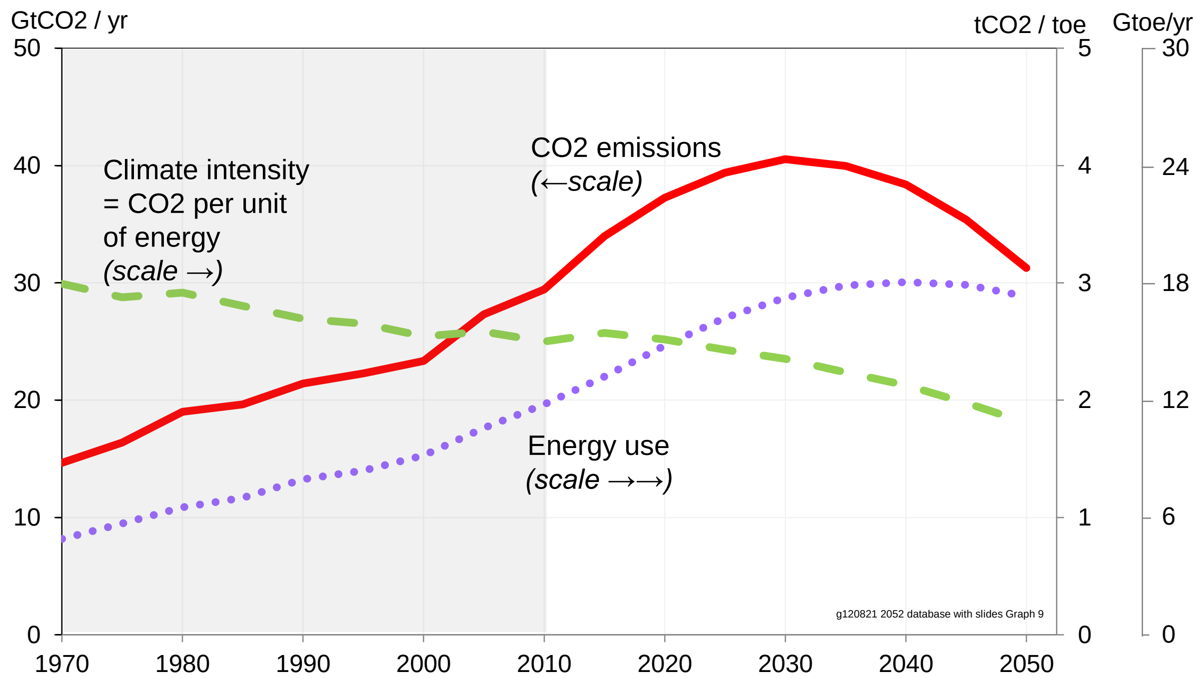

Figure 5d. Fourth forecast for the linear core: World CO2 emissions will peak in 2030

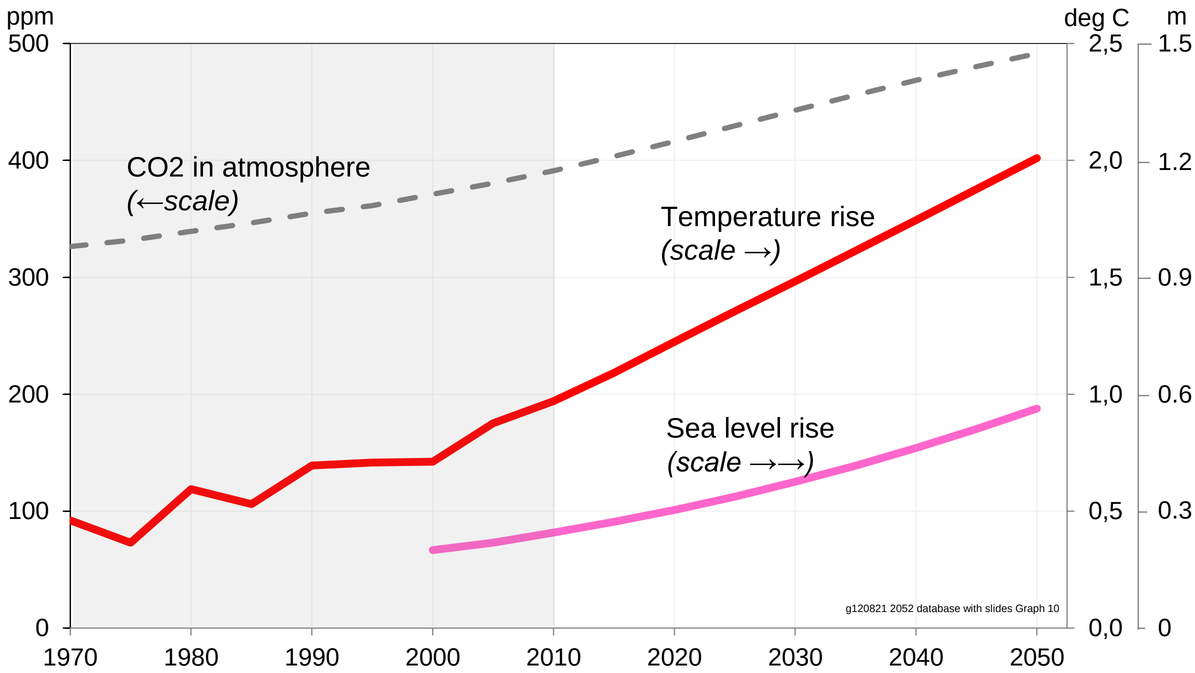

Figure 5e. Fifth forecast for the linear core: Average temperature rise will pass + 2°C in 2050

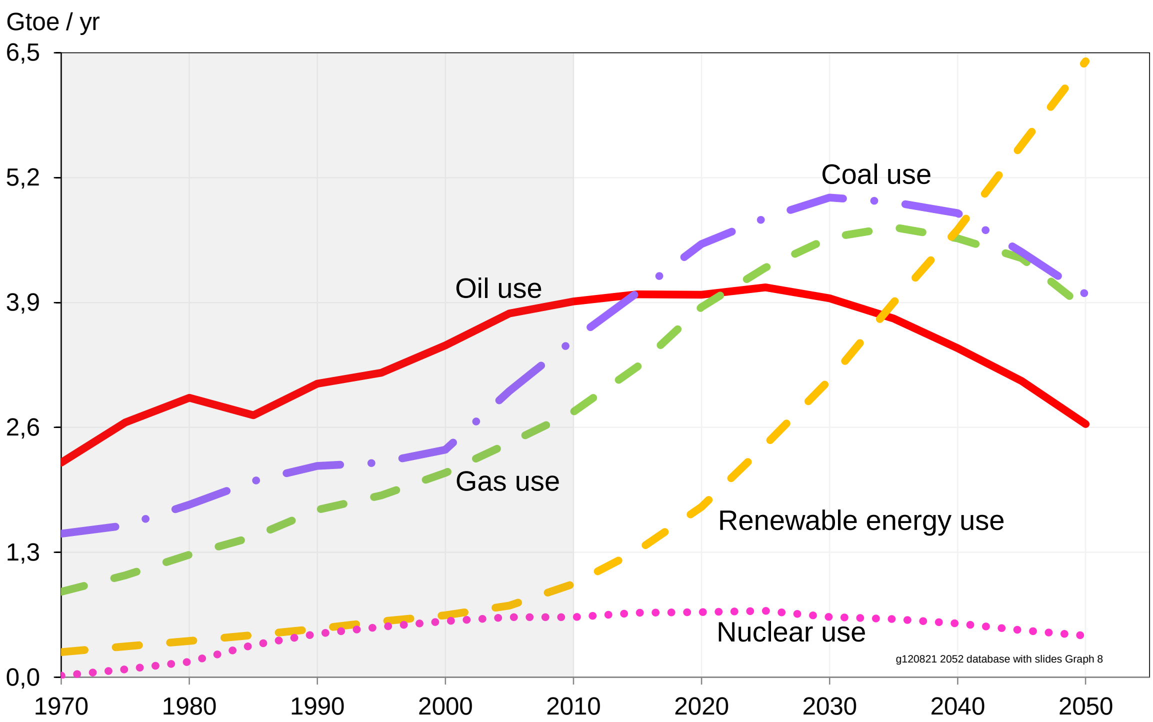

Figure 5f. First test of sufficiency: Accumulated world use of fossil energy to 2050 will amount to less than one half of existing booked reserves

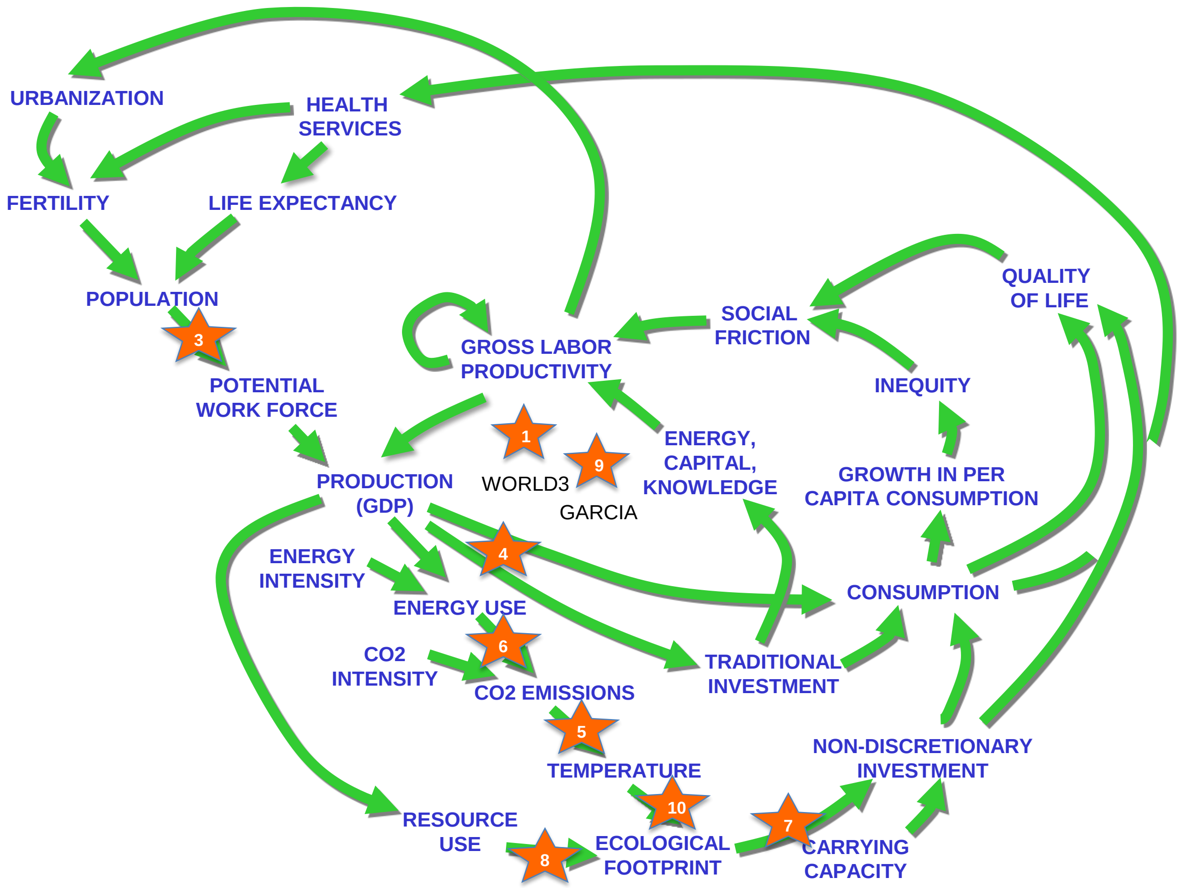

Figure 6. Overview of models used to improve the 2052 forecast