The Oil Drum: Europe
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

A New World Model Including Energy and Climate Change Data

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This is a guest post from Dolores García, an independent researcher based in Brighton, UK. This paper was presented at the "Mission Earth" seminar, ETH, Zurich, January 2009. This seminar was reported on at The Oil Drum here.

Abstract: *An updated systems model of global climate, resources, and energy extending the original World3 ("Limits to Growth") model by inclusion of climate change and it's interaction with resources and energy. Outcomes are derived for total energy resources, human population, nutrition, consumption, economic activity and other parameters. Long-term outcomes are derived for a 1900 C.E. to 2100 C.E. time sequence, with human population decline.*

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1. Introduction

Perhaps the best known global model of all is World3, popularized in the book *The Limits to Growth, A report to the Club of Rome,* by Donella H. Meadows, Dennis L. Meadows, Jørgen Randers, and William W. Behrens III. I have taken some of the equations in the latest version of the World3 model (World3-03) and I have added some more data and feedback loops to reflect some of our present knowledge of climate change and energy issues (there aren't any energy variables in the model, the closest one is "non-renewable resources"). The aim is to have a model that is more useful for the purpose of testing in theory different policies that could be applied to resolve some of the current challenges our world is facing, that have all at the root the fact that we are reaching the limits to growth.

2. The broader issues

Before going into the details of the model I propose, it's worth asking if there's any purpose in the exercise at all. Specifically, these two questions need asking:

1. Is a global model useful at all?
2. If global models can be useful, is it appropriate to use the equations of World3 as a base for a new model?

These are my personal answers to those questions:

2.1. Is a global model useful at all?

One of the criticisms levelled at World3, that has been often repeated with other global models, is that there is so much uncertainty in so many of the relevant variables, that there isn't any point in the exercise of modelling at all. While it's true that there is a lot of uncertainty, it's worth remembering that this won't stop people making models of the world. Even if there were no computer models of the world at all, people still have mental models, rough ideas of where the world is heading in many different aspects. And what's more, decision-making and policies will be based on those mental models. So there is a very valid justification for any attempt to make those mental models as correct as we can, with whatever tools we have. A computer model containing the best available data and reviewed by experts seems likely to produce insights into the future of a better quality than the hunches of policy makers.

2.2. If global models can be useful, is it appropriate to use the equations of World3 as a base for a new model?

Modelling has advanced a lot since the original World3, and there are good arguments to say that incorporating new equations and variables to World3 isn't appropriate. However, I believe there are several advantages to this approach, the main one that many experts have already studied World3 and are familiar with it, and their observations may be also relevant to a new model that contains many of its equations.

3. The proposed model

3.1. Energy variables

Energy variables are conspicuously absent from World3. The closest thing to an energy variable is "non-renewable resources", that is meant to include not only fossil fuels, but also minerals and other resources. When considering how to best include energy in the model, I chose to eliminate the variable "non-renewable resources", on the grounds that, in a world with unlimited energy, any chemical compounds useful as a raw material but not as an energy source could be easily obtained (if necessary, elements found rarely on Earth could be mined from other parts of the Solar System, or created with the appropriate nuclear reactions). Fossil fuels are the only true non-renewable resources.

To incorporate energy issues in the New World Model, I had to create three new sets of equations: equations about energy supply, equations about energy demand, and equations about energy source allocation. Most models I have seen model only energy demand or supply, but this is clearly insufficient. Modelling energy demand and assuming that it will somehow be met ignores the important issues of fossil fuel depletion. Modelling energy supply and ignoring demand doesn't help to judge the soundness of policy proposals to switch usage of fossil fuels by "clean electricity", which often sweep under the carpet the question of where the electricity may come from and the energy losses of any conversion of other energy sources to electricity.

3.1.1. Modelling energy supply

To model energy supply, I distinguished six types of energy sources: coal, oil, gas, nuclear power, renewable electricity, renewable thermal and biomass. The distinctions were made based on the differences between them in renewability and usability for the different types of demand. Energy sources similar in both counts were grouped together.

The estimates on ultimate reserves for fossil fuels were taken from Jean Laherrere. Fossil fuel production was determined by two factors: demand and possibility of supply. When it's possible to supply the demand, production equals demand. When demand falls sharply, production will drop but keep some inertia. When demand goes up, production may or may not increase, depending on the amount of fossil fuel remaining. The equation that determines the maximum increase in production for fossil fuels is:

Increase in production = 0.2*(fraction of fossil fuel remaining-0.5)*current production

This means that at the beginning of exploitation of a resource it's possible to increase production very quickly, up to 10% a year. When half of the reserves have been produced, production reaches its peak and can't increase any more. From that point onwards, production will always decline.

One important aspect of the modelling of energy supply was calculating declining EROEIs (Energy Returned On Energy Invested) of non-renewable resources. The available data on EROEI is very spotty, but it's such a crucial concept to explain what may happen in the future with energy sources that I believe a model would be inaccurate if it didn't include it in some way. The energy source that has been most studied for declining EROEI in time is oil. Available data for oil in the USA is the following (Charles Hall, 2008):

- 1930 – About 100:1
- 1970 – About 30:1
- 2000 – About 11-18:1

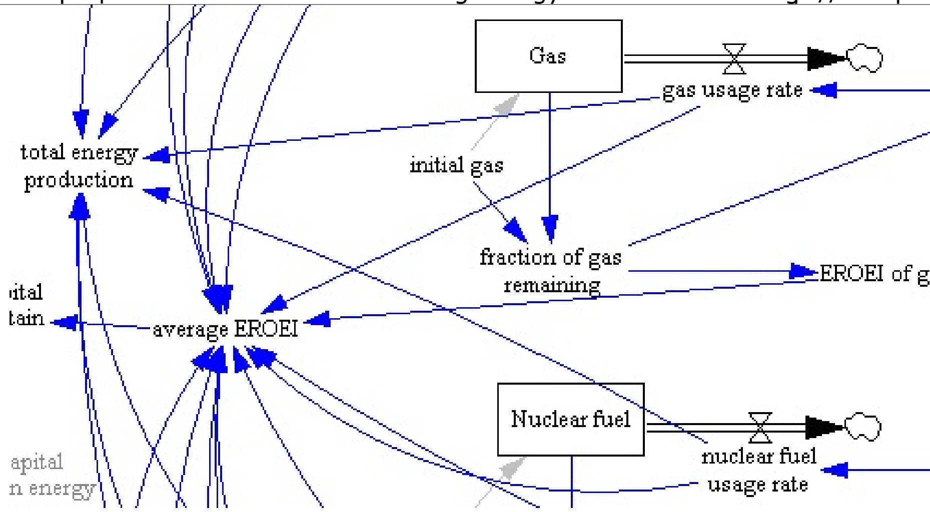
This suggests a relationship between EROEI and the fraction of remaining oil that is approximately proportional to the square of the fraction of oil remaining:

EROEI of oil = (fraction of oil remaining^2)*100

An additional reason to go for this simple relationship is because it has the following property: it takes the same amount of energy to extract the first half of the oil as it takes to extract half of the remainder (a quarter), and so on. This fits well with the intuitive idea of declining EROEI.

However, the data is too limited to say this formula holds true with any certainty, and I'm using it only as a best guess. The results of the model are similar if other declining functions are used.

Once the EROEIs of all energy sources are calculated, the weighted average is then used to estimate the fraction of industrial capital needed to obtain energy. This again is speculative, but a couple of datapoints are known: at an EROEI of 1:1, 100% of the industrial capital would be needed. At high EROEIs, it appears that 5% of the industrial capital is used (from the "cheese slicer model" by Charles Hall, Robert Powers, and William Schoenberg, 2008). The intermediate points can be estimated by assuming that the fraction of industrial capital needed is roughly proportional to the amount of energy needed as an input for energy production.

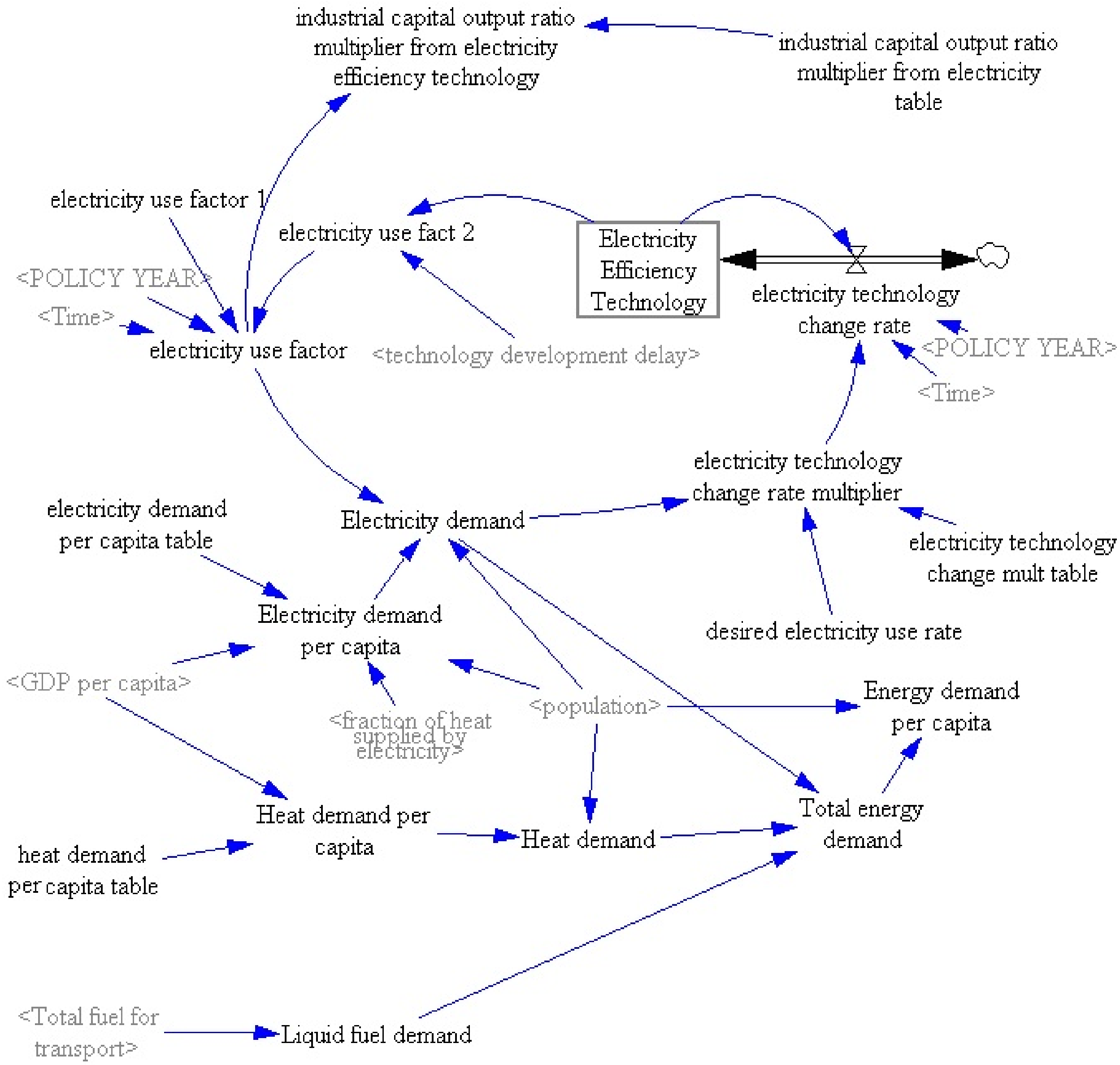


Graph 3.1.1.1 – A section of the flow diagram of the equations used to model energy supply. Click to see whole flow diagram.

3.1.2. Modelling energy demand

One factor that many energy models seem to forget is that people don't demand energy sources like oil, nuclear power or hydro. What people actually demand is electricity, heating and transport.

Electricity demand is calculated in the model as a function of GDP, with the data based on historical data for electricity consumption from the World Development Indicators Database. Heating demand is calculated as a constant of 400kg oil eq. per capita per year. Transport demand is calculated as the sum of the transport needed for freight and for passenger transport. I couldn't find world data on freight and passenger transport, but it appears that both in the USA and the EU about 25% of the energy use goes into freight and 75% into passenger transport. So I assumed the relationship holds for the rest of the world. The total energy used for transport was deduced from the historical data on oil consumption.



Graph 3.1.2.1 – Flow diagram of the equations used to model energy demand. Click to open in a new window.

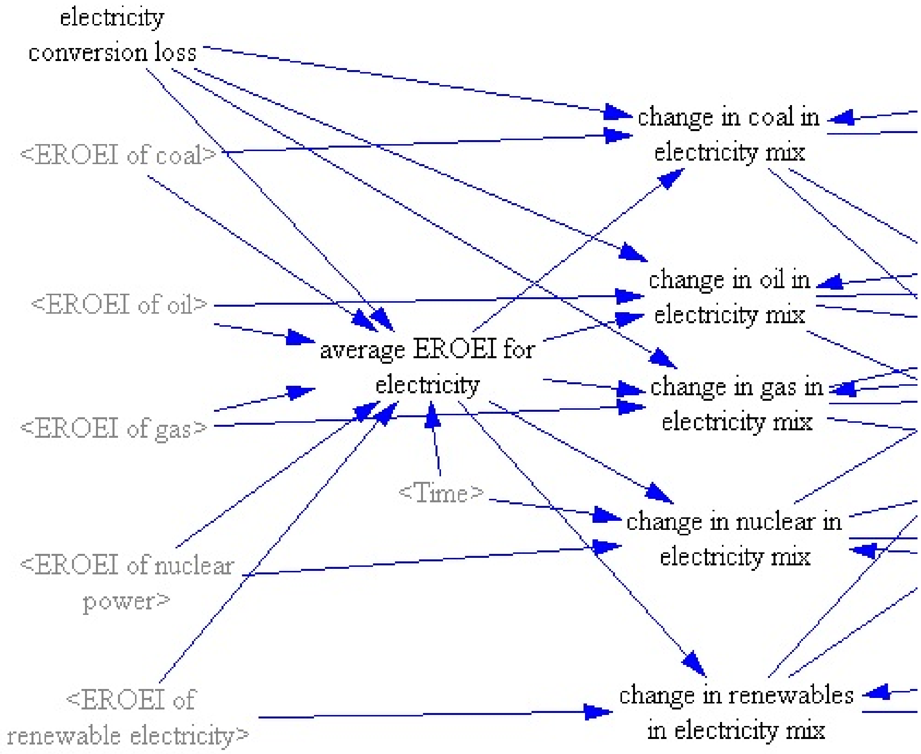
3.1.3. Modelling energy source allocation

Once demand and supply are calculated, matching them is a non-trivial exercise, as anybody who has looked at the electricity mix of any country can tell.

There are two fundamental ideas that I have used to do the matching:

1. Market forces follow EROEI: the most efficient sources of energy are also the most profitable. This seems to make sense intuitively but is disputed.
2. Energy companies are conservative: they will not start reducing the usage of an energy source until its EROEI falls below the average of all sources. Also, the reduction or increase in any energy source is gradual.

My model successfully reflects historical changes in use of different energy sources with no other input but the variations of EROEI in time, which suggests that the approach can't be entirely misguided. The production data the model generates is only a rough approximation of the real data, but clearly on the right track, and further work on the relevant parameters could refine the results. For a comparison, historical data on world production of fossil fuels can be found in work by the Netherlands Environmental Assessment Agency.



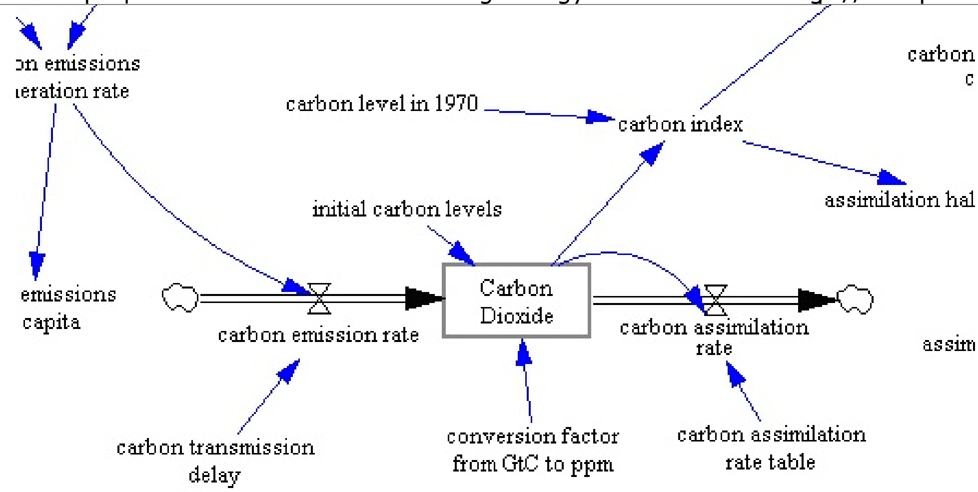
Graph 3.1.2.2 – A section of the flow diagram of the equations used to model energy source allocation.

3.2. Carbon emissions

Carbon emissions and climate change are absent from World3, mostly because there wasn't much knowledge on the matter at the time. For the purposes of including carbon emissions in the model, I took the equations for pollution in World3 and modified them. Unfortunately, this means that the New World Model lost the original pollution equations (clearly designed to represent chemical pollution), which may need to be re-introduced.

The calculation of carbon emissions is, of course, fundamentally different than the calculation of pollution, and is made by adding up the emissions from each of the fossil fuels and from land development (deforestation). Another important difference is the assimilation rate, which is clearly different for carbon dioxide and for chemical pollutants. I couldn't find reliable information on carbon sinks, so the model only contains data for the known historical levels of carbon assimilation by the Global Carbon Budget Team, and extrapolates linearly from there, which is probably excessively conservative.

The model doesn't attempt to make any detailed analysis of climate change, but only an estimation of the levels of carbon dioxide in the atmosphere and its possible consequences for food production. Climate change models can provide much greater detail into specific consequences of climate change, but this isn't the aim of this model. The aim, instead, is to estimate how climate change may affect other important variables in the world.



Graph 3.2.1 – Flow diagram of the equations used to model carbon emissions. Click to see whole flow diagram.

3.3. Food production

The equations for agriculture were taken straight from the World3 model, with two importnt changes:

1. The land yield is affected by the levels of carbon dioxide in the atmosphere. There is still a lot of uncertainty on the effects on food crops of different levels of carbon dioxide, but there is agreement that climate change will reduce crop yield. The model assumes 2% reduction on yield at 370 ppm, based on current data on the reduction in crop yield so far (David B Lobell and Christopher B Field, 2007). There is still a lot of discussion on future reductions on crop yield due to climate change. This model assumes a 10% reduction at 500 ppm, which seems like a reasonable figure based on the IPCC data. If there are better figures available, I will include them.
2. Food production is reduced in proportion to the amount of biomass production.

3.4. Economy

World3 has several variables measured in dollars and some variables relevant to the economy, such as jobs. This was never meant to model the economy such as understood by financial institutions, but rather the physical economy, the real things on the Earth that have physical limits.

Even so, it’s surprising that the model didn’t contain a GDP variable, representing in some way the “real” GDP, meaning with this not inflation-adjusted but representing some aggregate measure of agriculture, industry and services produced. I have added this variable to the New World Model, which also helps in the calculation of other minor variables that traditionally are based on GDP but that in World3 were using industrial output as a proxy for GDP.

3.5 Demographics and carrying capacity

Because population is such a critical variable in the model, additional demographic variables were added to track if the historical values of population were on the right track: the global crude birth rate and the global crude death rate. Adjustments were done whenever the demographic variables were going far off the track.

Two calculations of the carrying capacity of the Earth were added to the New World Model:

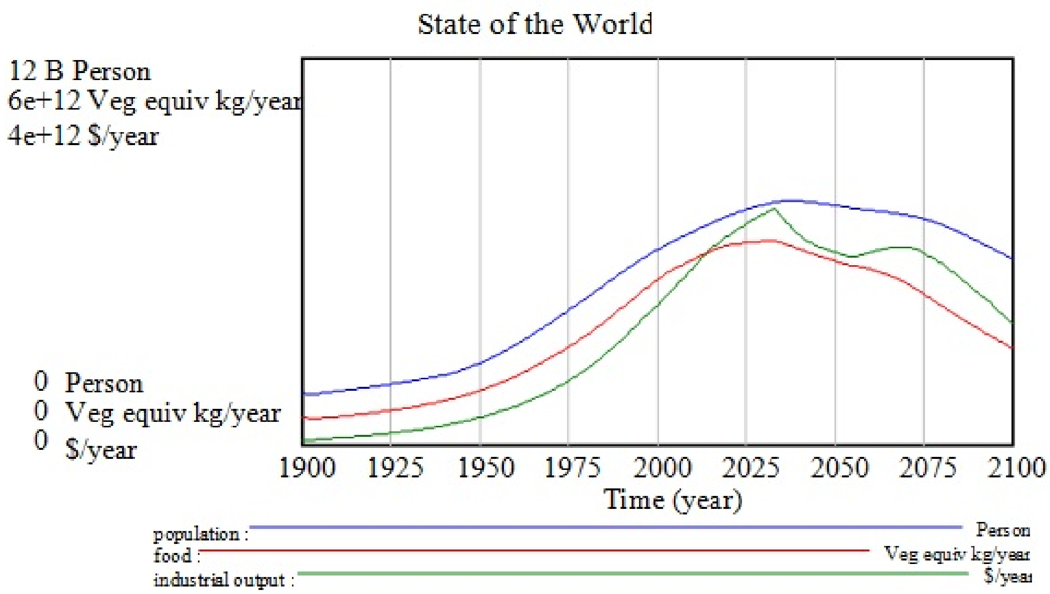
1. The maximum feedable population, representing the maximum population that could be fed at subsistence level with the current food production.
2. The maximum sustainable population, representing the maximum population that could live on the planet if the total human footprint was allowed to rise to 1 planet. The calculation of human footprint was done by adding arable land, urban land and the land needed to absorb the current rate of generation of carbon emissions.

Both values vary with time as food production and human footprint change with time.

4. The results of the model for the "business as usual" scenario

4.1. Main variables: population, food and industrial output

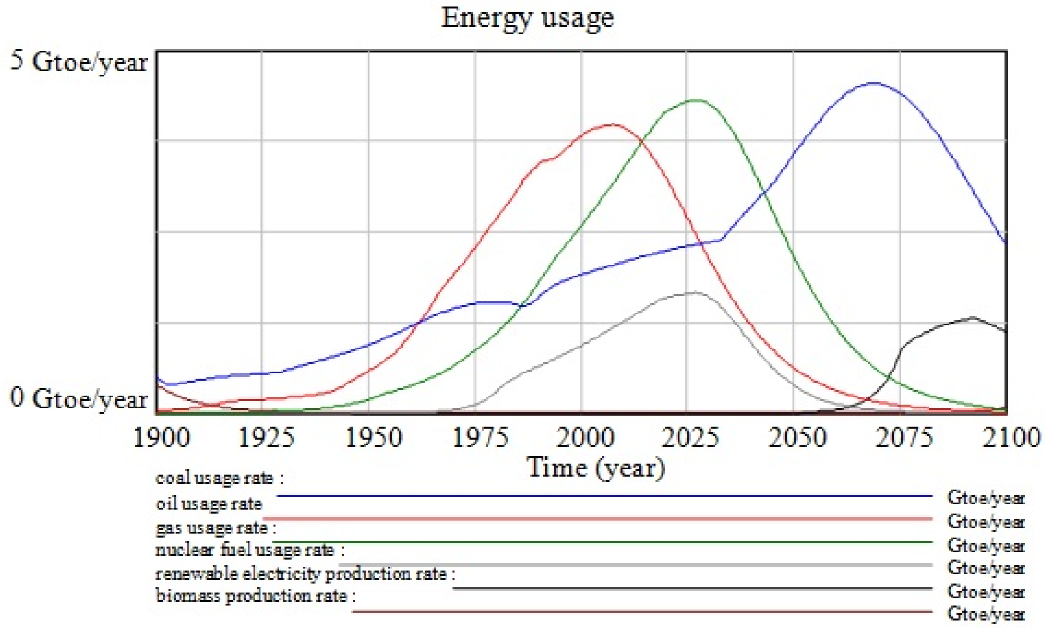
In the "business as usual" scenario the pattern was one of collapse of human population, food production and industrial output, in a way similar to what happens in the World3 business as usual scenario. The decline is gradual, starting somewhere around 2030:



Graph 4.1.1 – Food production and industrial output in the New World Model

4.2 Energy usage

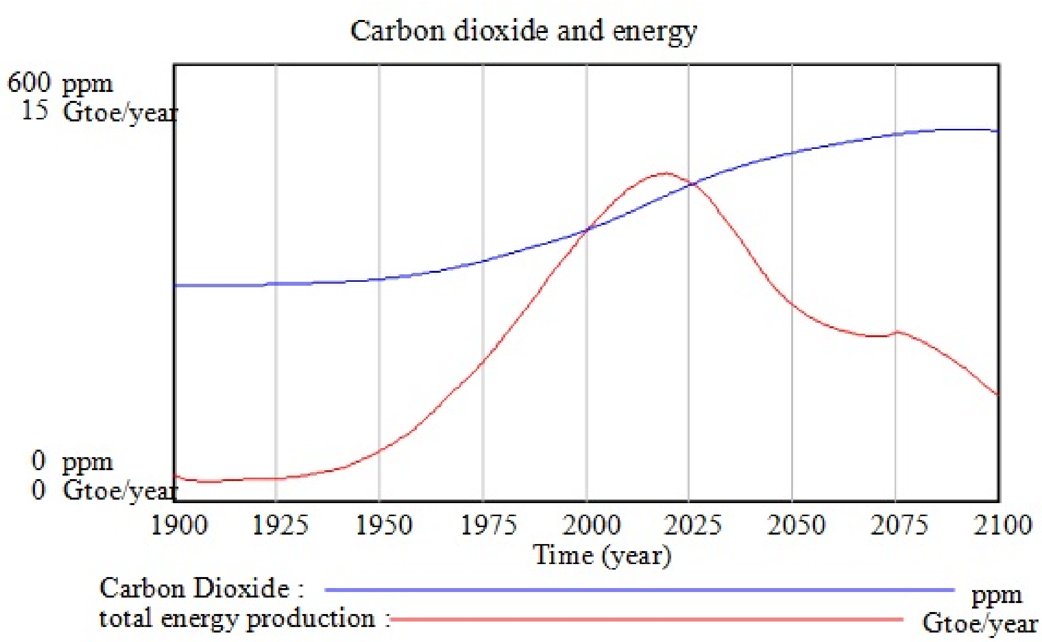
Energy supplies are substituted for each other as EROEI declines, but eventually all fossil fuels and nuclear fuels are used up. Renewables aren't used until the end of the 21st century, due to their low EROEI:



Graph 4.2.1 – Energy usage graph

4.3 Carbon dioxide

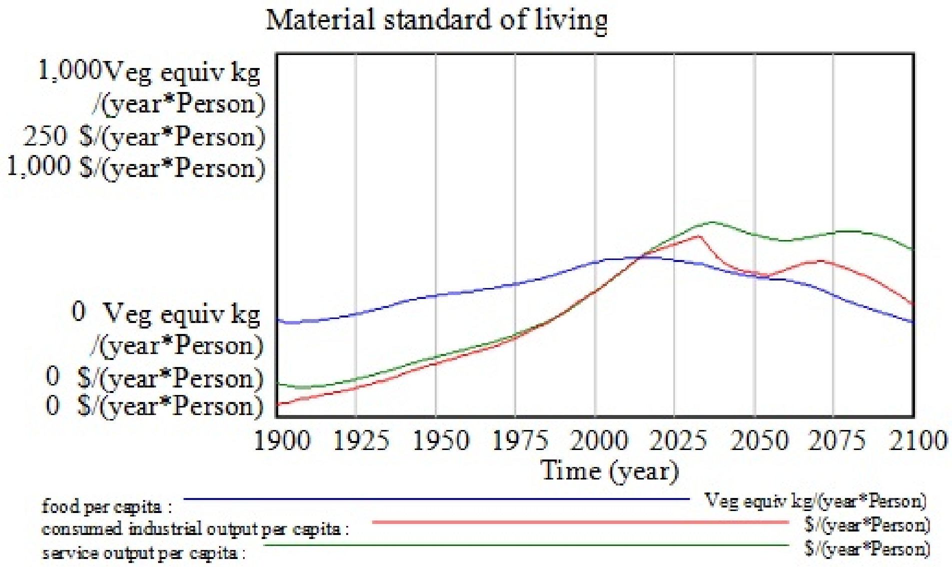
A remarkable result of the model in the business as usual scenario is that carbon emissions don't go very high, peaking at 510ppm, which is lower than some of the emissions scenarios of the IPCC. The reason for this is double: Firstly, the limits on fossil fuel reserves mean that not as much carbon can reach the atmosphere as assumed by the IPCC even when all fossil fuels are burned. Secondly, the estimations of carbon sinks may be too favourable in the model.



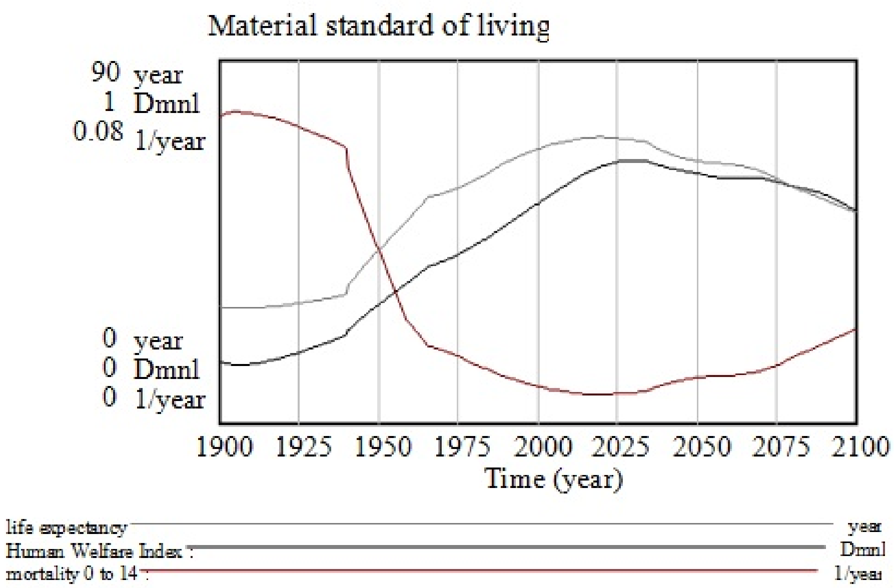
Graph 4.3.1 – Carbon dioxide and energy

4.4. Standard of living

The standard of living declines clearly by all the reasonable measures that can be made in the model: food per capita, industrial output per capita, services per capita, life expectancy, human welfare index and child mortality. The levels of food per capita by the end of the 21st century are similar to the beginning of the 20th century and are in a path of continuous decline. However, this shouldn't be taken as any kind of prediction, because the model cannot possibly include all the relevant data.



Graph 4.4.1 – Food per capita, industrial output per capita and service output per capita in the New World Model

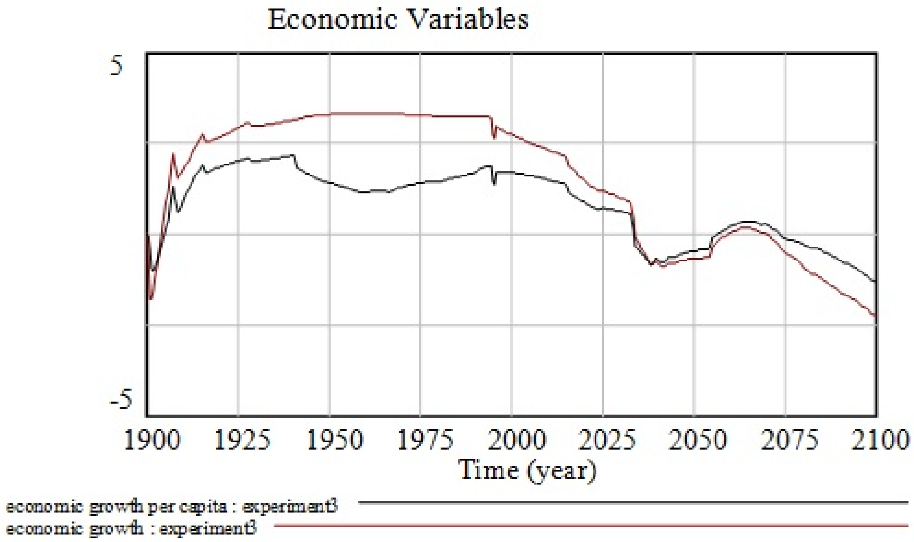


Graph 4.4.2 – Life expectancy, human welfare index and child mortality

4.5. Economic growth

The most interesting result of calculating GDP is that it allows for the estimation of economic growth. This should not be understood as the figure that economists produce, but some kind of numeric estimate of the yearly change in all the goods and services produced in the world. Interestingly, at the point of collapse, it falls dramatically, but it starts declining many years before that, providing an early warning signal.

It's also worthwhile noting that the point of peak oil is marked by a drop in economic growth. It's very tempting, but not really justified, to relate this to our current economic crisis. Certainly, if we were at the early stages of the collapse in economic growth that the model estimates, it's to be expected that a major economic crisis would happen, and a big overhang of debt is one of the logical ways for it to happen, as a result of an effort from central banks to maintain a level of economic growth that isn't justified by the fundamentals. But I don't have enough data at present to confirm or deny if our current situation reflects that we are at the beginning of the great contraction estimated by the New World Model.



Graph 4.5.1 – Economic growth in the New World Model

5. Conclusions

The main conclusion of the results of the New World Model is that, if the world continues behaving as we have so far, decline is inevitable in the long run. This isn't a surprise and the fact that we are on an unsustainable path can be deduced from much simpler and reliable calculations. What this model provides is some slightly more refined ideas about how this could happen and, more importantly, it's a tool where we can experiment with our ideas on how to solve this problem.

I am aware that I may have made many mistakes in producing this model, and I may have used data that is out of date or otherwise incorrect. Please consider this as a first draft, and I welcome any input you may want to provide. I would like to make this a collaborative effort. The whole model can be downloaded from here.

The software to run the model is Vensim PLE, that can be downloaded from: www.vensim.com

Finally, I would like very much to receive input on possible policies to avoid decline and eventual collapse (when all fossil fuels are consumed) that could be included in this model to see what results they produce. The Transition Network has already expressed interest in using this model for the timeline they are writing for all Transition Towns to help them design their own Energy Descent Action Plans. Of course, this will only be useful if the model includes the policies that need to be implemented for a successful transition to a sustainable world.

6. References

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