IMPACTS OF PEAK OIL AND FOOD BASED BIOFUEL PRODUCTION ON LONG-TERM FOOD SECURITY

A DYNAMIC POLICY MODEL

Sven Sandvik
sven.sandvik@gmail.com

Master's Programme in System Dynamics

Department of Geography

University of Bergen

Supervised by Professor Erling Moxnes

Spring 2008

IMPACTS OF PEAK OIL AND FOOD BASED BIOFUEL PRODUCTION ON LONG-TERM FOOD SECURITY

A DYNAMIC POLICY MODEL

Abstract

It would, for the sake of food security, be rational to start an agricultural transition to a system less dependant on fossil fuels in good time before a possible energy crisis. It therefore seems a paradox that policy makers choose to do the opposite; establish an additional link between the food and energy market through subsidization of food based biofuel production, thus putting food security even more at the mercy of energy supply. The dynamic policy model presented in this thesis illustrates how growth in food based biofuel production enhances the link between the energy and food market. An alternative policy example is developed and tested using the model to simulate future scenarios. The model simulations suggest the current policy of supporting food based biofuel, combined with a peak in oil production, could lay the foundation of a future food crisis and that an alternative policy needs to be implemented as quickly as possible; most importantly, before policy makers receive feedback signals in the form of a continuous rising food price trend.

Key words: food security, energy security, biofuel, peak oil, system dynamics, policy model, simulation, sustainable development.

Acknowledgements

I would like to thank:

My supervisor, professor Erling Moxnes:
For introducing me to System Dynamics and for guiding me back on a feasible thesis pathway.

Lecturers, student assistants and fellow students:
For making the years of System Dynamics studies so inspiring, interesting and informative.

My wife, Ragnhild Maria:
For listening, for discussions, draft reading and for her unconditional love and support (both economical and psychological).

Table of contents

List of figures

List of tables

IMPACTS OF PEAK OIL AND FOOD BASED BIOFUEL PRODUCTION ON LONG-TERM FOOD SECURITY

A DYNAMIC POLICY MODEL

1. Introduction

The eager support, in the United States, the European Union and Brazil, for food based biofuel as substitute for petroleum in combustion engines, has provoked a general debate about the sustainability of biofuels. An important aspect of this debate is the notion of an emerging resource conflict between poor people and car owners; both demanding the photosynthetic energy produced on limited agricultural land. The purpose of this thesis is to explore possible long-term food security impacts of food based biofuel production in combination with peak oil, through the construction and testing of a dynamic policy simulation model. The model is in short a highly aggregated representation of the oil, food and biofuel market and their main interconnections, constructed using the tools and methodology of System Dynamics.

Simulation results suggest the current policy of supporting food based biofuel production could be laying the foundation of a future food crisis and that an alternative policy needs to be implemented as quickly as possible; most importantly, before policy makers receive feedback signals in the form of a continuous rising food price trend.

The expression “food based biofuel”, as used here, refers to both biofuel produced using food crops as feedstock and feedstock grown on land suitable for food production. Virtually all biofuel produced today is food based; even Brazilian ethanol from sugarcane. The value of sugarcane for human nutrition is limited, but sugar plantation land could be used to produce food crops of higher nutritious value. Therefore, according to the definition above, biofuel from sugarcane is “food based”.

About half of Brazil’s sugarcane yield is currently used to produce Ethanol (World Bank, 2008). Ethanol production has a long history in Brazil; the domestic market is large, well established and flexible. A growing share of Brazilian sugar mills can produce both sugar and ethanol (Schmidhuber, 2006). When oil price is high enough to enable competitive cane based ethanol production, these producers will only sell sugar at a price equivalent to the oil price or above. As Brazil is the leading sugar exporter, these shifts between sugar and ethanol production determine the availability of sugar on the world market and therefore also the sugar price. The effect is a sugar price tightly linked to oil price (Schmidhuber, 2006).

Whilst sugar is a luxury commodity, other feedstock's such as maize, potatoes, wheat, and cassava are essential to human nutrition. If the growing biofuel market for these commodities over time should cause a linkage to oil price similar to the sugar-oil linkage we see today, a surge in oil price could risk bringing food price along with it.

This would disfavor low income consumers; particularly affecting poor urban populations with limited possibility to grow their own food. In low income countries nearly half (about 47 per cent) of the household budget is spent on food; first and foremost on low value staples, such as cereals. High income consumers use about 13 per cent of their household budget on food and a large share of this is spent on meat and dairy products (Regmi, 2001). The poorest and least flexible consumers, ironically, experience the per cent wise largest price rise because they eat goods with a lower level of processing, meaning that a larger share of the consumer's food price is affected by price changes at the primary production level. When food prices rise, high income consumers have more flexibility to increase their food budget or substitute some of the high value foods with cheaper staples.

The narrowing down of focus, to food based biofuel in place of bioenergy in general, is enabled by the premise that as long as it is profitable and legal to produce food based biofuel, market forces will ensure that this is done. If it also should become profitable, or even more profitable, to produce second generation biofuel using residues from forestry or other alternative feedstock's, the use of these are not in conflict with food based production unless the quantity becomes large enough to create a surplus in energy supply.

Given the premise of a peak in oil production and a continuation of current growth in energy demand, the achievement of an energy supply surplus seems unlikely. About one per cent of the worlds available arable land was in 2006 used to produce biofuel supplying one per cent of global transportation fuel (IEA, 2006). The introduction of second generation biofuel, which enables the use of celluloses in stalks, leaves, grasses, and tree trunks, will make it possible to also produce biofuel using biomass that is not grown on land suitable for food production. This technology is still at the research stage and large scale implementation could be several decades of: "The demonstration plants now being built are all well below commercial scale. If they are successful, larger-scale demonstration plants will be needed. Investors will need to see these in operation for some time before they invest significant capital in such novel technologies" (Childs, 2007). Whilst second generation biofuels enable the use of alternative feedstock's, they also enable a more efficient use of food based feedstock. How the established food based biofuel industry should choose to use the technology is an open question. A particularly promising technology, still at the research and demonstration stage, is algae based biofuel. The company GreenFuel Technologies, has successfully converted CO_2 emissions from a power plant in Arizona into biofuel using algae grown in a bioreactor. CO_2 from the smokestack is used to fertilize the algae, which in turn are extracted and used as feedstock in conventional biofuel production (Childs, 2007).

The remaining thesis text will be structured in the following way: An overview of the structure, the main feedback loops and the interconnections between the model sectors will be presented in chapter *2. Model overview*. In the tree following chapters, the sectors will be presented in more detail and connected together step by step. First, in chapter *3. Oil sector,* the oil sector will be presented alone. All simulation results and sensitivity tests in this chapter are without any influence from the biofuel sector or the food sector. In chapter *4. Reference mode: the food and oil sector together,* the food sector will be presented and connected to the oil sector. The oil and food sector together serve the purpose of a reference mode. They simulate a world without food based biofuel production. Then, in chapter *5. Biofuel sector: Linking together the food and energy market,* the biofuel sector (which exclusively produces food based biofuel) is connected to the food and oil sector and the models behavior with this extra food-energy linkage is compared to the reference mode. Chapter *6. Development and testing of an alternative policy,* gives an example of how the model can be used to test policies and scenarios. Finally, concluding remarks and suggestions for further research are presented in Chapter *7. Conclusion.*

2. Model overview

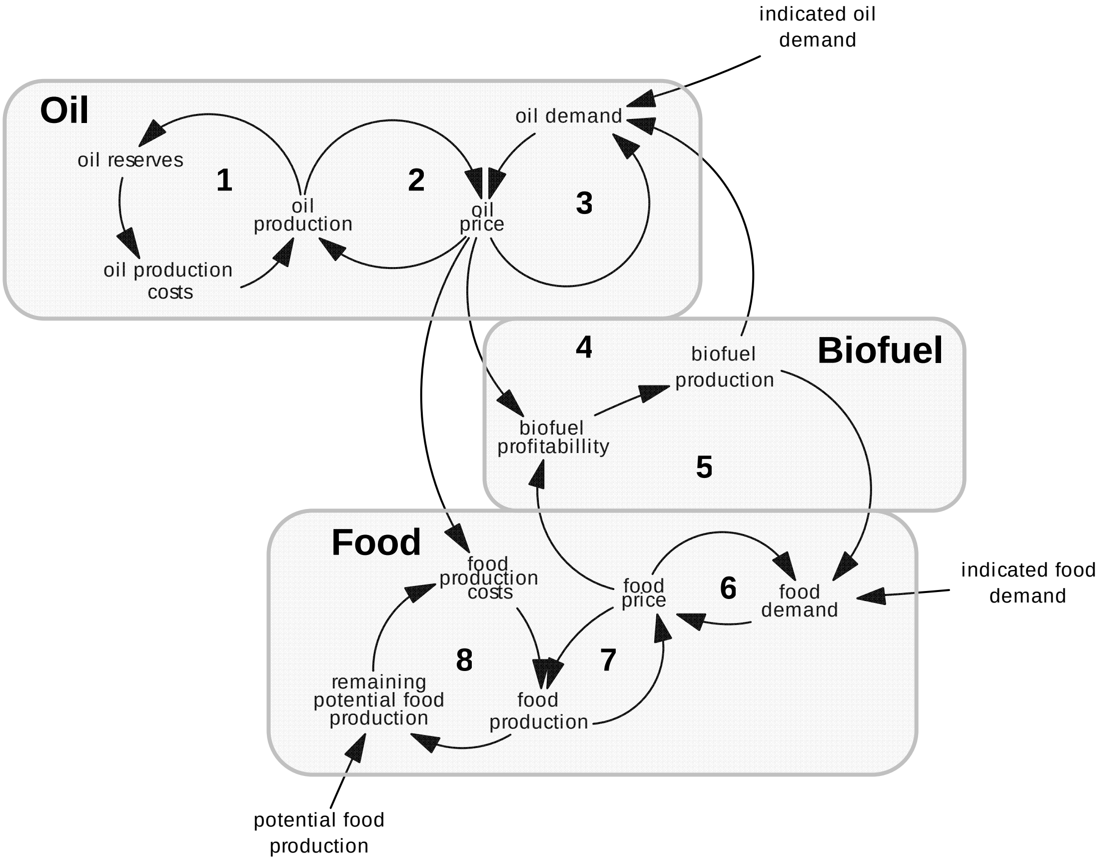


Figure 1: Causal loop diagram of model structure

Figure 1 is a causal loop diagram showing the main structure of the model and the connections between its three sectors. The arrows between the variables indicate cause and effect, a change in one variable affects the next. The feedback loops, numbered one to eight, are circular chains of cause and effect. They will be discussed further in a moment. Notice that the oil sector has two connections to the food sector; one directly from oil price to food production costs and one indirectly from oil price to food demand going through the biofuel sector. There is a fundamental difference between these two connections: The indirect connection is weak and hardly noticeable when the biofuel sector is small, but it gains momentum when the sector grows. The direct connection starts out relatively strong but would, in response to a rising oil price, get weaker over time due to the adoption of less oil intensive farming practices. We will now go through the eight loops one by one.

Loop one represents the oil depletion process. Oil production causes oil reserves to decrease and sooner or later the last barrel of fossil oil will be produced and consumed. This historic event will not happen because the oil reserves are completely tapped but because oil production costs eventually will exceed the value of the oil itself. The models hundred year long time horizon, stretching from 1950 to 2050, will not allow this absolute limit to be reached but loop one will cause a peak in oil production which starts a chain of counteractions rebounding through the other loops:

Loop two counteracts the decline in production by raising the oil price. When oil production falls short of demand, there will be an upward pressure on oil price. A higher oil price stimulates investment and enables the production of less accessible oil reserves.

Loop tree counteracts rising oil price by reducing the demand. When price goes up demand goes down. This takes time since the short-run oil demand is fairly inelastic.

Loop four responds to a rising oil price by increasing biofuel production. The biofuel sector only includes biofuel produced using food crops or crops grown on land suitable for food crop production. We assume perfect substitution between oil and biofuel so that the price of one energy unit of biofuel is equal to the price of an equivalent energy unit of oil based fuel. If enough biofuel is produced to compensate for a declining oil production, the oil price incentive to further growth in biofuel production is removed. It is probably possible, technically, to substitute an oil demand of over 11 000 Mtoe with food based biofuel in 2050 using second generation biofuel technology (IEA, 2006), but the food consumption of nine billion people will most likely make loop five more dominating.

Loop five counteracts biofuel production by raising food prices. When the biofuel sector expands it demands more of the primary food production and food prices are pushed upwards. The general price level of food affects biofuel profitability because the cost of purchasing food used to produce biofuel accounts for around 50% of total production costs (IEA, 2006).

Loop six counteracts rising food price by reducing the demand for primary food production. This change in food demand is primarily caused by poor people moving downward in the food chain, eating less milk and meat products.

Loop seven responds to rising food prices by increasing food production. Although this market mechanism may seem fairly straight forward it is worth mentioning that a counteraction of rising prices also could be driven by other factors; for example public policy aiming to prevent social unrest and food riots.

Loop eight sets the boundary for loop seven. Potential food production is the primary food production assumed possible using existing agricultural land and technology. When food production increases, the remaining potential decreases and it becomes harder and more resource consuming to increase production further.

3. Oil sector

The purpose of the oil sector is to simulate an emerging shortage in transportable energy caused by the depletion of oil reserves; including crude oil, gas condensate and natural gas liquids (NGL's). The shortage caused by a peak in production effects the other model sectors through a surge in end use oil price. As oil price rises a smooth and quick technological transition to other sources of transportable energy is assumed, in effect setting a crude oil price roof at approximately 200 real 2006 USD per barrel in the base case simulation.

After the behavior and sensitivity of the oil sector base simulation has been presented, we will look more closely at the model structure of the sector.

3.1 Behavior of the oil sector

In the oil sector base simulation and sensitivity tests there is no feedback from the biofuel or food sector. The parameter values used are the same as the ones we will use in the reference mode and the base case simulation in chapter four and five. Figure 2 shows the oil production and oil price of the oil sector base simulation compared to historic data and the distribution of sensitivity test runs using parameters and ranges as displayed in table 1. The sensitivity test was done using Latin Hypercube Sampling as recommended in the literature (Ford, 1999). Alternative scenarios will be presented for the size of reserves and the speed of technological progress, these assumptions are therefore not part of the base case sensitivity test. The pattern of behavior is the same in all of the oil sector sensitivity simulations: An s-shaped transition from abundant cheap oil to a higher price level and a temporary peak in production during the transition from conventional reserves to alternatives such as tar sands, coal to liquid and renewable energy sources other than food based biofuel. The assumption of a smooth technological transition avoids an oil price overshoot (see 3.2.) The overshoot in the 1970's was caused by a relatively small shortage. A global peak in oil production could possibly cause an even larger overshoot. The model is not built to capture short term price developments or oscillations and its lack of feedback from oil price to economic growth makes it unsuitable for simulations with extreme oil prices.

Parameter	Min value	Base value	Max value	Unit
long term price elasticity of oil demand	-0.2	-0.6	-1	dimensionless
short term price elasticity of oil demand	-0.01	-0.08	-0.5	dimensionless
oil price sensitivity	2	8	20	dimensionless
long term price effects delay	5	15	30	year
short term price effects delay	0.25	0.75	3	year

Table 1: The parameters and ranges used in the sensitivity test

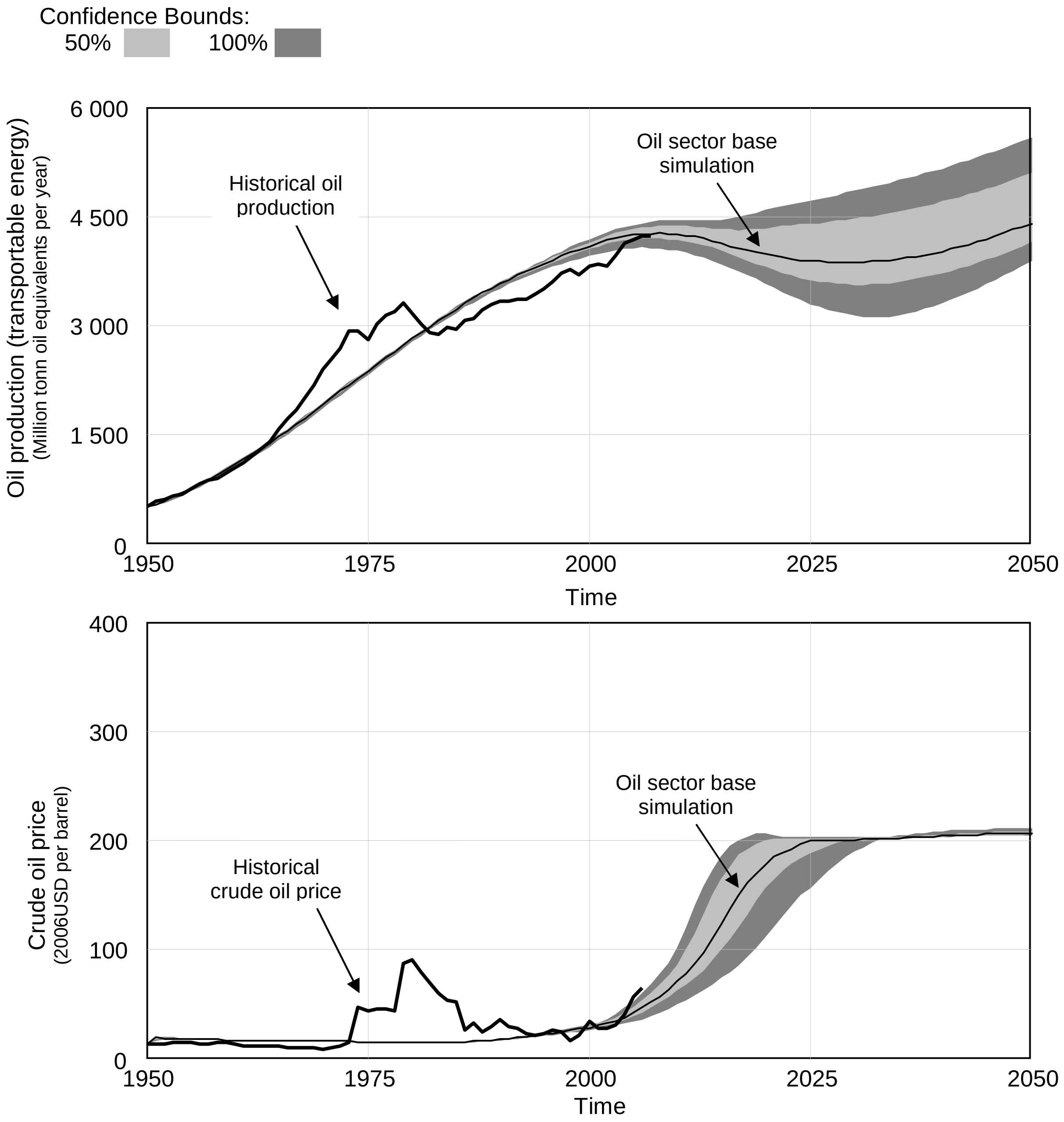


Figure 2: Oil sector base simulation and its sensitivity to the parameters in table 1.

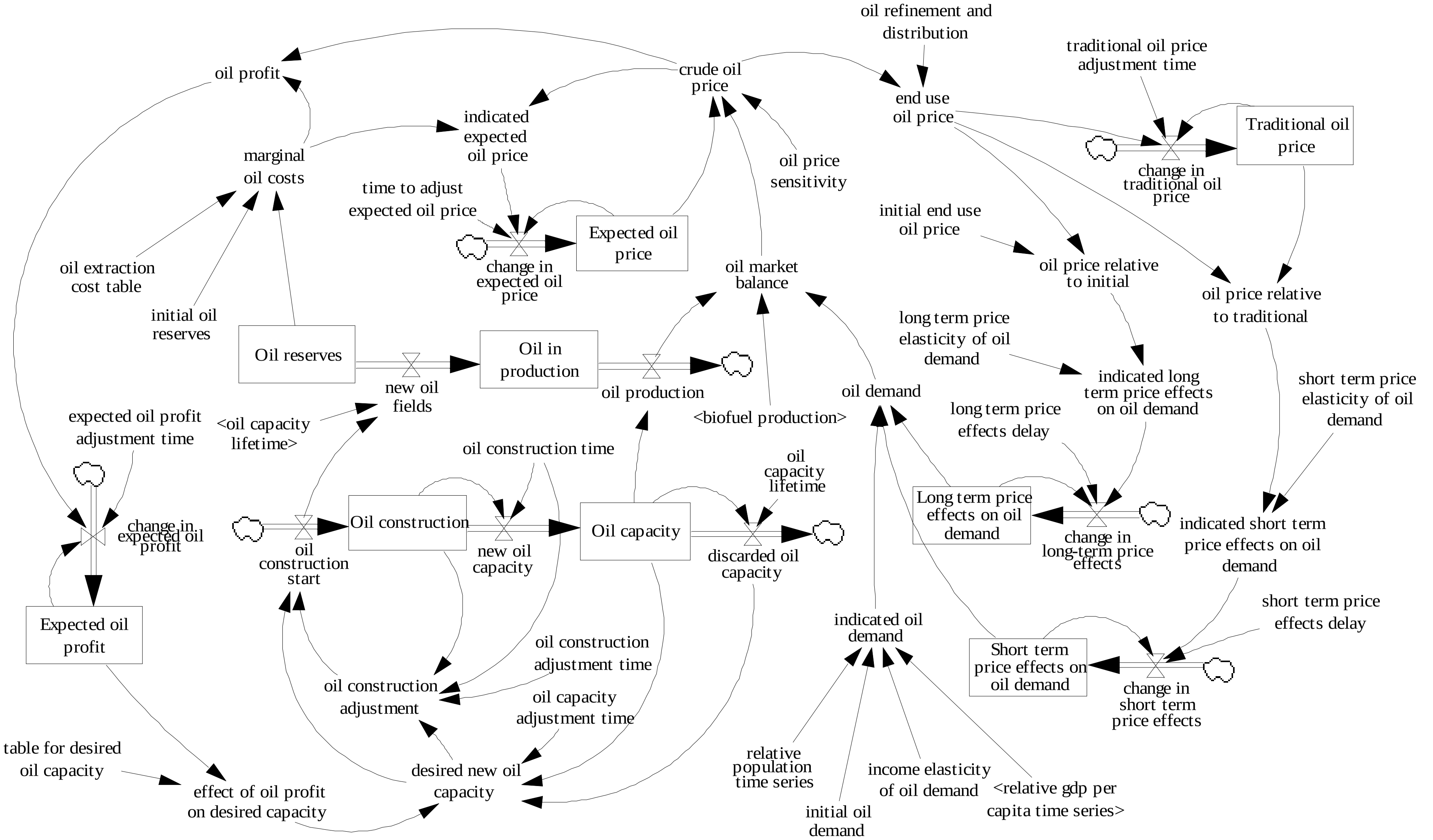
3.2 Oil reserves and marginal cost

The oil sector (figure 3) is sensitive to assumptions about the size of reserves and the speed of technological progress. The initial reserve size used was found by combining data from British Petroleum's statistical review (BP, 2007) and an oil production time series from World Policy Institute[1]. BP define oil reserves as "generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can

---

[1] Source: compiled by Earth Policy Institute http://www.earth-policy.org/Books/PB3/data.htm (10.05.08)

Figure 3: Oil sector overview



		Mtoe	Data source
	Oil produced 1950-2006	145519	WRI, 2007
+	Proved reserves 2006	164798	BP, 2007
=	Oil reserves 1950	310317	
-	Oil in production 1950	13000	model approximation
≈	Initial oil reserves	300000	

Table 2: Calculation of oil reserves used in oil sector base case and reference mode

be recovered in the future from known reservoirs under existing economic and operating conditions”(BP, 2007). These reserves include gas condensate and natural gas liquids (NLG’s) but not Canadian tar sands beyond those already under active development. BP reports an estimate of 23 700 Mtoe for total Canadian tar sand reserves, of which roughly 6% are considered to be under active development. As the conventional reserves are depleted, a transition is assumed to tar sands and other alternatives like coal to liquid or transportable renewable energy (apart from food based biofuel, which will be covered by the biofuel sector). These alternatives are, as a simplification, produced by the oil sector once the conventional reserves are empty, causing the stock of reserves to go negative. A scenario with larger conventional reserves will be tested later.

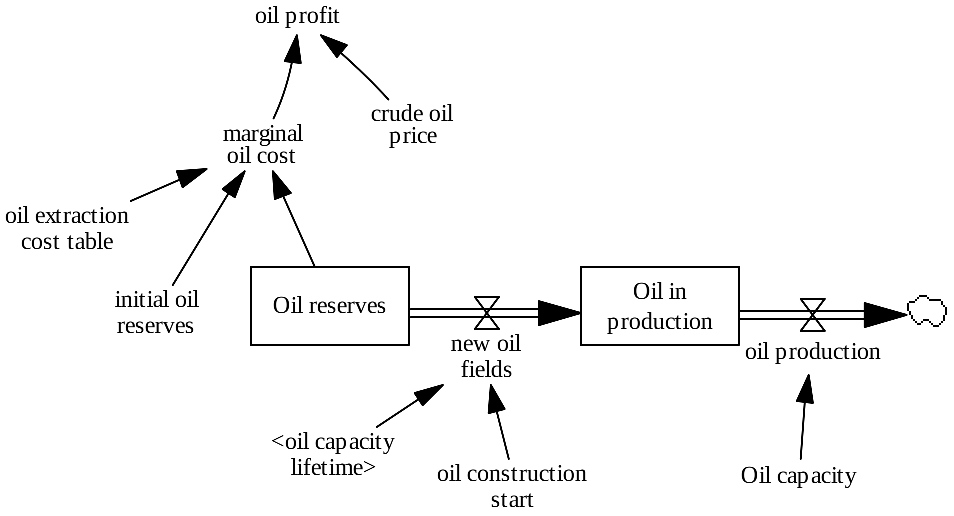


Figure 4: Oil reserves and marginal cost structure

Oil reserves = INTEGAL(–new oil fields, Oil reserves (t_0))

Oil reserves (t_0) = initial oil reserves

Oil in production = INTEGRAL(new oil fields – oil production, Oil in production (t_0))

Oil in production (t_0) = (Oil capacity+Oil construction)*oil capacity lifetime

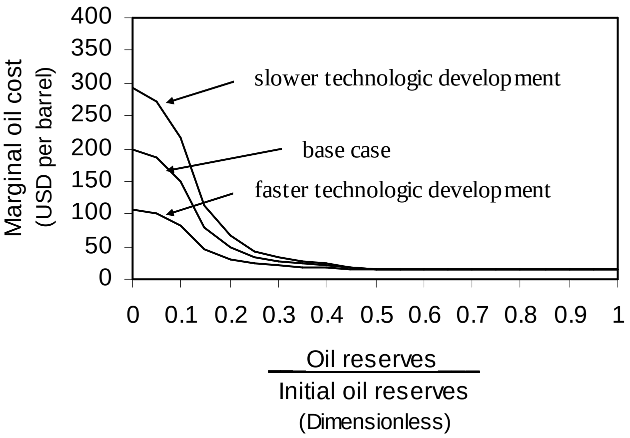
new oil fields = oil construction start * oil capacity lifetime

oil production = Oil capacity

It is for simplicity assumed that oil production always equals oil capacity. This has some effect on the models ability to explain cyclical behavior. The model divides reserves into oil reserves and oil in production (figure 4)[2]. As soon as a new oil project is started the total oil reserve of that field moves over to the stock of oil in production. The size of new oil fields brought into production is found by multiplying oil construction start (the amount of annual production capacity entering construction this year) by the total lifetime of capacity. Oil in production is therefore initialized using both oil capacity and oil capacity under construction.

$$\text{oil profit} = \frac{(\text{crude oil price} - \text{marginal oil cost})}{\text{crude oil price}}$$

Oil profit is not an absolute number, it is a relative, dimensionless number representing the balance between crude oil price and marginal oil cost. These two are in balance when oil profit is zero. Marginal oil cost is the average cost of producing one barrel of oil (including a normal surplus). When oil profit is greater than zero, the industry is more profitable than normal, when it is below zero the average producer has a deficit or a smaller surplus than desired.



Base case table

MOC	OR / IOR
0.00	200
0.05	185
0.10	150
0.15	80
0.20	50
0.25	33
0.30	27
0.35	23
0.40	20
0.45	17
0.50	15
0.55	14.2
0.60	14
1.00	14

Figure 5: Oil production cost table, base case and alternative scenarios with faster and slower technological development

---

[2] Structure adopted from unpublished material by Erling Moxnes

$$\text{marginal oil cost} = f\left(\frac{\text{Oil reserves}}{\text{initial oil reserves}}\right)$$

Marginal oil cost is defined as a function of oil reserves over initial oil reserves. Figure 5 displays the oil production costs table used in the base simulation of the oil sector and two alternative scenarios used to test the model. The main assumption of the curve is a rising marginal cost, since the most convenient and accessible oil fields have a tendency to be developed first and exploration is more successful when there is still a lot of oil left to find.

Developments in extraction technology are assumed to offset the rise in costs for some time but eventually production costs start rising exponentially. The effect saturates as costs start to reach the cost of alternative sources. The base case cost table assumes an oil price of 200 USD would be sufficient to enable a smooth technological transition to other sources. The lower curve represents a scenario with faster technological development where 100 USD per barrel is sufficient, and the higher one represents a slower technological development scenario where a price of 300 USD per barrel is needed. The technological scenarios are in figure 6 combined with a scenario with 50 per cent higher oil reserves. The main effect of larger oil reserves is that the peak in oil production, and rise in price, is postponed another 15 years. The simulated oil prices follow the pattern of their respective production cost curves. These scenarios; Larger oil reserves, slower and faster technologic development, will in chapter six be used to test the robustness of an alternative policy.

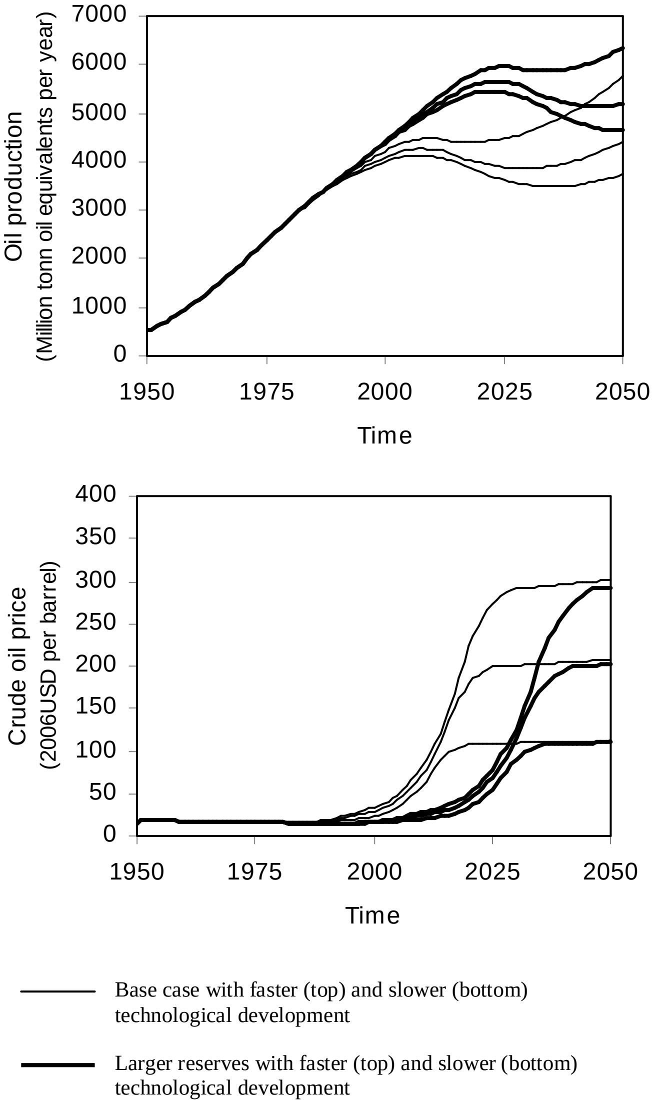


Figure 6: Base case oil price and production compared with scenarios of larger reserves, faster and slower technological development

3.3 Oil production capacity

The structure chosen to represent oil production capacity (Figure 7) is taken from the generic commodity market model in Business Dynamics (Sterman, 2000). It is based on an anchor and adjustment heuristic where the anchor is current capacity and the adjustment from the anchor point depends on the expected profitability of future investments and the time decision makers need to make plans and reach a final investment decision.

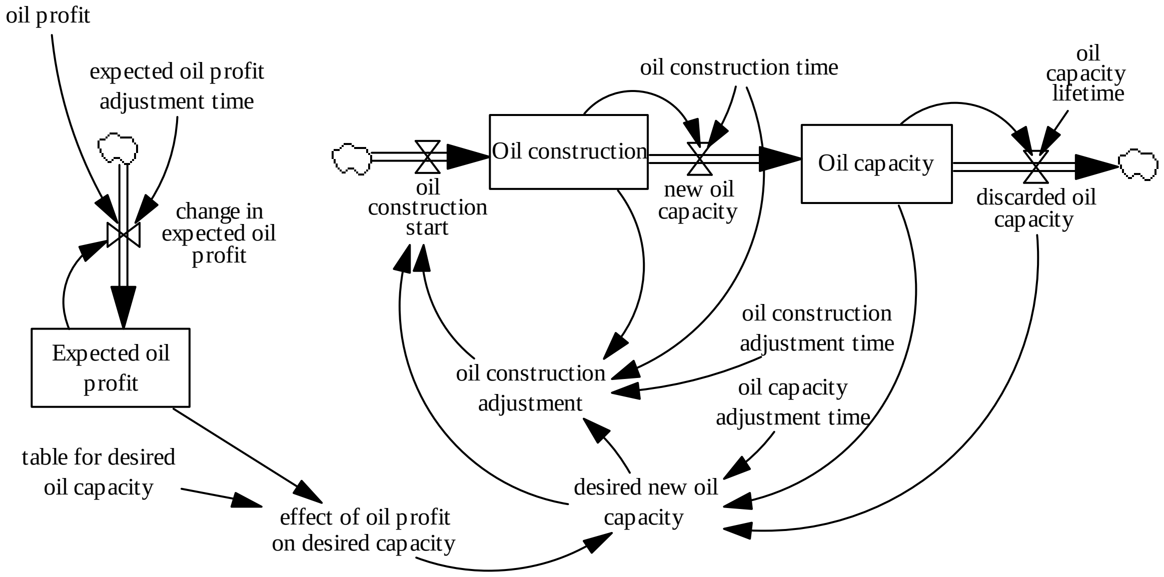


Figure 7: Oil capacity structure

$$\begin{array}{c}\text{desired new}\\ \text{oil capacity}\end{array} = \left[\frac{((\text{Oil capacity} * \text{effect of oil profit on desired capacity}) - \text{Oil capacity})}{\text{oil capacity adjustment time}}\right] + \begin{array}{c}\text{discarded}\\ \text{oil capacity}\end{array}$$

The equation for desired new oil capacity first calculates the desired oil capacity by multiplying current oil capacity with the effect of oil profit on desired capacity. Then current capacity is subtracted from desired and divided by the adjustment time to find desired capacity adjustment. Finally, the expected loss of capacity, the discarded oil capacity, is added.

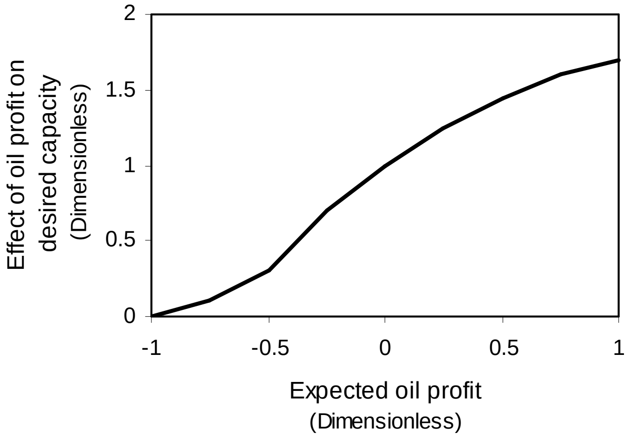
$$\text{effect of oil profit on desired oil capacity} = f(\text{Expected oil profit})$$

$$\text{Expected oil profit} = \text{INTEGRAL(change in expected oil profit, Expected oil profit } (t_0))$$

$$\text{Expected oil profit } (t_0) = \text{oil profit } (t_0)$$

$$\text{change in expected oil profit} = \frac{(\text{oil profit} - \text{Expected oil profit})}{\text{expected oil price adjustment time}}$$

The effect of oil profit on desired oil capacity is a nonlinear function of the expected oil profit. Figure 8 shows the function used. Expected oil profit is zero when the average marginal cost of production = the price of crude oil. At this point there is no desire to adjust capacity; or, in other words, the sum of desired upward and downward adjustment breaks even. The larger the expected profit is, the larger the effect is on desired capacity. The effect saturates because there are limits to the financing and absorption of new capital. Likewise, when the average expected oil profit moves below zero the producers with the highest production costs, or the most pessimistic future expectations, start investing less than what is needed to replace discarded capacity.



EOP	EOPDC
-1.00	0.00
-0.75	0.10
-0.50	0.30
-0.25	0.70
0.00	1.00
0.25	1.25
0.50	1.45
0.75	1.60
1.00	1.70

Figure 8: Table for desired oil capacity

$$\text{oil construction adjustment} = \frac{((\text{desired new oil capacity} * \text{oil cunstruction time}) - \text{Oil construction})}{\text{oil construction adjustment time}}$$

When desired new oil capacity is found an adjustment needs to be made for the capital already under construction. The expression above the fraction line determines if there is a gap between current construction and the construction needed to complete new oil capacity at the rate desired. The oil construction adjustment time is the time needed to close the gap. This can be seen as a reflection of the quality and availability of information about the actual gap and the attention decision makers pay to this information.

The use of this structure does, however, imply a risk of getting models that over-estimate the rationality of decision makers. The short oil construction adjustment time used in this model (see Appendix) is probably a deliberate example of such overestimation. The motive was to guide attention away from oscillations and focus on the long term effect of the depletion process. The model was not constructed with the purpose of simulating oscillations in oil price. To do that properly capacity utilization and probably also some representation of OPEC policy and other important stakeholders would need to be incorporated.

Oil capacity = INTEGRAL(new oil capacity – discarded oil capacity, Oil capacity (t_0))

$$\text{discarded oil capacity} = \frac{\text{Oil capacity}}{\text{oil capacity lifetime}}$$

$$\text{new oil capacity} = \frac{\text{oil construction}}{\text{oil construction time}}$$

The choice of using a first order delay for capacity construction was also partly motivated by a wish to suppress oscillations. The variable oil construction time is an aggregate of the time it takes to search for oil and construct the necessary capital to extract and refine it. The delay is first order because the formulation of new oil capacity as a stock divided by an adjustment time, assumes perfect mixing. This means that all construction projects, regardless of being old or new, are weighted equally. A boost in construction start one year would make the completion rate of new oil capacity increase during the same year. This behavior might seem unrealistic and could be prevented using a delay of higher order; distinguishing old from new construction. The smoothness’ of the first order delay can, however, be interpreted as a representation of short term adjustments in capacity utilization that otherwise might need explicit modeling to avoid large oscillations.

Oil construction = INTEGRAL(oil construction start – new oil capacity, Oil construction (t_0))

Oil construction (t_0) = discarded oil capacity*oil construction time

oil construction start = MAX(0, desired new oil capacity + oil construction adjustment)

Oil construction start equals desired new oil capacity adjusted for the capacity already under construction. If current construction activity is large and the desired new capacity very small the sum of the two could be a value below zero. To avoid negative numbers the oil construction start rate is formulated to take the maximum value of zero and the sum of the two input variables. Oil construction is initialized at the level needed to replace discarded capacity

3.4 Oil price

end use oil price = crude oil price + oil refining and distribution

The end use oil price (figure 9) is the price paid by consumers. The constant oil refining and distribution cost used in the model corresponds roughly to the average refining and distribution cost assumed in the annual international fuel prices survey conducted by the Deutche Gesellschaft für Technische Zusammenarbeit (GTZ, 2007). Gasoline taxation is omitted due to a large uncertainty regarding the response of decision makers to future changes in oil price.

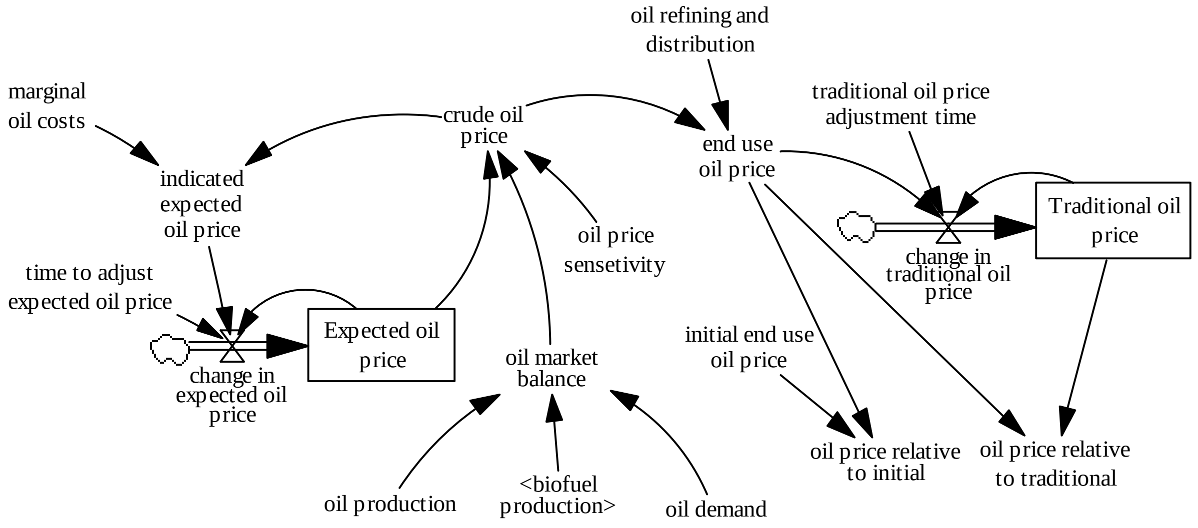


Figure 9: Oil price structure

$$\text{crude oil price} = \text{Expected oil price} * (\text{oil market balance}^{\text{oil price sensitivity}})$$

$$\text{oil market balance} = \frac{\text{oil demand}}{(\text{oil production} + \text{biofuel production})}$$

Crude oil price is modeled as the oil price expected by traders multiplied by the effect of current balance between supply and demand. All inventories have been excluded with the aim of keeping the model as small and simple as possible. This causes a small discrepancy between oil produced and consumed, but by far not enough to effect model behavior.

Biofuel is treated as a perfect oil substitute and has a direct effect on the oil market balance. This is a slight simplification of reality since the logistics are a little bit different and there are currently limits to the fraction of ethanol that can be blended in gasoline used in conventional cars (Childs, 2007). The strength of modeling oil market balance this way is that it captures the maximum possible feedback from biofuel production to oil price. Pro biofuel rhetoric focusing on potential CO_2 reductions and gained energy security both tend to be based on the assumption that biofuel substitutes oil. To the extent biofuel actually does this it could be relevant to ask how much of the oil demand it could cover, and if it covers enough to effect oil price; how large would the effect of cheaper oil be on oil demand? How much would it eat up of the assumed substitution benefit?

$$\text{Expected oil price} = \text{INTEGRAL(change in expected oil price, Expected oil price } (t_0))$$

$$\text{change in expected oil price} = \frac{(\text{indicated expected oil price} - \text{Expected oil price})}{\text{time to adjust expected oil price}}$$

$$\text{indicated expected oil price} = \frac{(\text{m arg inal oil costs} + \text{crude oil price})}{2}$$

Traders adjust their price expectations to fit the reality they perceive. Current price is seen as a good indicator of what the trading price should be. The indicated expected oil price is assumed to be the average between current price and the marginal oil costs.

$$\text{oil price relative to initial} = \frac{\text{end use oil price}}{\text{initial end use oil price}}$$

$$\text{initial end use oil price} = \text{end use oil price } (t_0)$$

$$\text{oil price relative to traditional} = \frac{\text{end use oil price}}{\text{Traditional oil price}}$$

$$\text{Traditional oil price} = \text{INTEGRAL(change in traditional oil price, traditional oil price } (t_0))$$

$$\text{change in traditional oil price} = \frac{(\text{end use oil price} - \text{traditional oil price})}{\text{traditional oil price adjustment time}}$$

Price is a relative expression. The oil price in the 1990’s was high compared to the price level of the 1960’s, but low compared to 1975 – 1985 prices. The model uses two different relative oil prices: The first one, oil price relative to initial, is the absolute change in oil price relative to 1950. The reference point, oil price in 1950, is constant. The second, oil price relative to traditional, refers to a dynamic reference; the traditional oil price. This is the long term average price level that society has adapted to through its development of habits and through technology choices. Short term consumer responses to price are based on the traditional price whilst the long term adaptation of society is based on the price relative to initial.

3.5. Oil demand

$$\text{oil demand} = \begin{matrix}\text{indicated oil}\\ \text{demand}\end{matrix} * \begin{matrix}\text{Long term effects}\\ \text{on oil demand}\end{matrix} * \begin{matrix}\text{Short term effects}\\ \text{on oil demand}\end{matrix}$$

$$\text{indicated oil demand} = \begin{matrix}\text{initial oil}\\ \text{demand}\end{matrix} * \begin{matrix}\text{relative population}\\ \text{time series}\end{matrix} * \left(\begin{matrix}\text{relative GDP per}\\ \text{capita time series}\end{matrix}^{\text{income elesticity of oil demand}}\right)$$

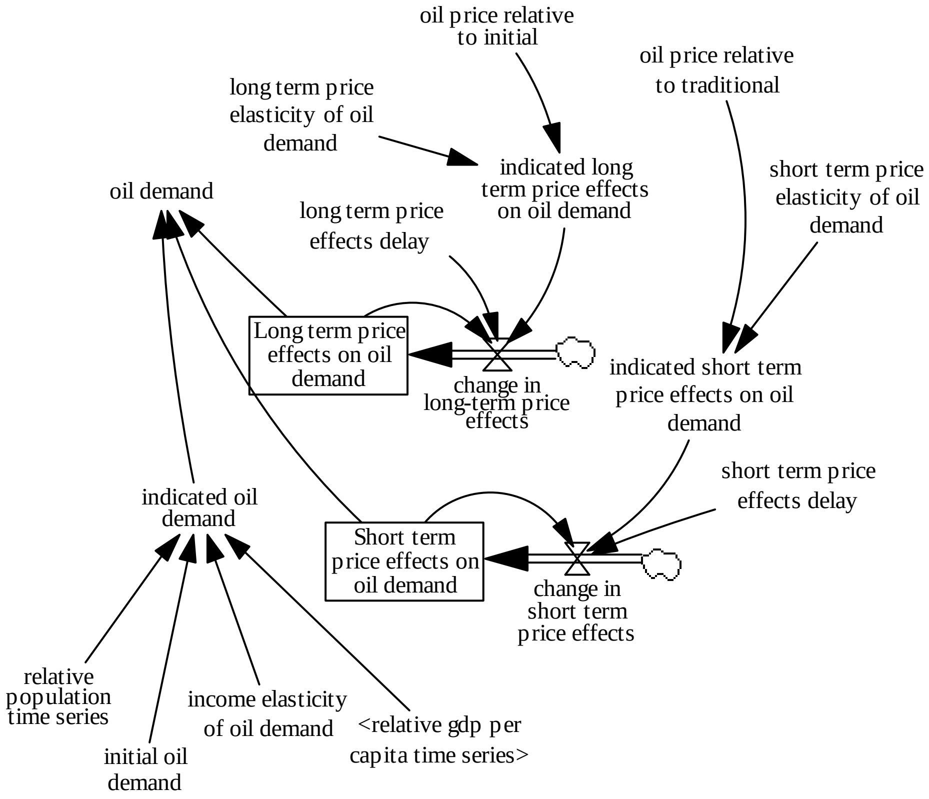


Figure 10: Oil demand structure

Oil demand (figure 10) is modeled using an exogenous underlying demand (the indicated oil demand) multiplied by short and long term effects of oil price. A reasonable historical fit was found when the indicated oil demand was based on growth in GDP per person and an income elasticity of 0.9 (see figure 2). Future projection of indicated oil demand is based on a constant annual GDP growth rate of 2 per cent and UN's medium population projection[3].

$$\begin{matrix}\text{Longt term price effects} \\ \text{on oil demand}\end{matrix} = \text{INTEGRAL}\left(\begin{matrix}\text{change in long term} \\ \text{price effects}\end{matrix}, \begin{matrix}\text{Longt term price effects} \\ \text{on oil demand}\end{matrix}(t_0)\right)$$

$$\begin{matrix}\text{change in long term} \\ \text{price effects}\end{matrix} = \frac{\left(\begin{matrix}\text{indicatedlong term price} \\ \text{effects on oil demand}\end{matrix} - \begin{matrix}\text{Long term price effects} \\ \text{on oil demand}\end{matrix}\right)}{\text{long term price effects delay}}$$

$$\text{indicated long term price effects on oil demand} = \text{oil price relative to initial}^{\text{long term price elasticity of oil demand}}$$

---

[3] Source: World Resource Institute from: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. 2007. *World Population Prospects: The 2006 Revision.* Dataset on CD-ROM. New York: United Nations.

Long term effects of oil price on demand could for example be a technologic transition to more fuel efficient cars, improvement of the public transport systems or a change in peoples attitudes and thinking about oil consumption.

$$\begin{matrix}\text{Short term price effects}\\ \text{on oil demand}\end{matrix} = \text{INTEGRAL}\left(\begin{matrix}\text{change in short term}\\ \text{price effects}\end{matrix}, \begin{matrix}\text{Short term price effects}\\ \text{on oil demand}\end{matrix}(t_0)\right)$$

$$\begin{matrix}\text{change in short term}\\ \text{price effects}\end{matrix} = \frac{\left(\begin{matrix}\text{indicated short term price}\\ \text{effects on oil demand}\end{matrix} - \begin{matrix}\text{Short term price effects}\\ \text{on oil demand}\end{matrix}\right)}{\text{short term price effects delay}}$$

$$\begin{aligned}&\text{indicated short term price effects on oil demand}\\ &\quad = \text{oil price relative to traditional}^{\text{short term price elasticity of oil demand}}\end{aligned}$$

Short term effects could for example be people choosing to drive less to save money to pay their bills. Figure 11 shows the long and short-term effects of oil price on oil demand in the base case simulation of the oil sector. The long-term effects are by far the most significant since short-term consumer response to oil price is assumed to be quite inelastic.

The following numerical example could serve as an illustration of why the short-term effect is so little: In November 2006 the average world market price of crude oil was slightly above 60 USD per barrel and the average price of gasoline at Norwegian gas stations was 180 US cents per liter. Crude oil accounted for 38 cents, refining and distribution costs approximately 15 cents, and taxation 127 cents (GTZ, 2007). Let us assume oil price suddenly rose from 60 to 240 USD per barrel. Keeping the taxation level, refining

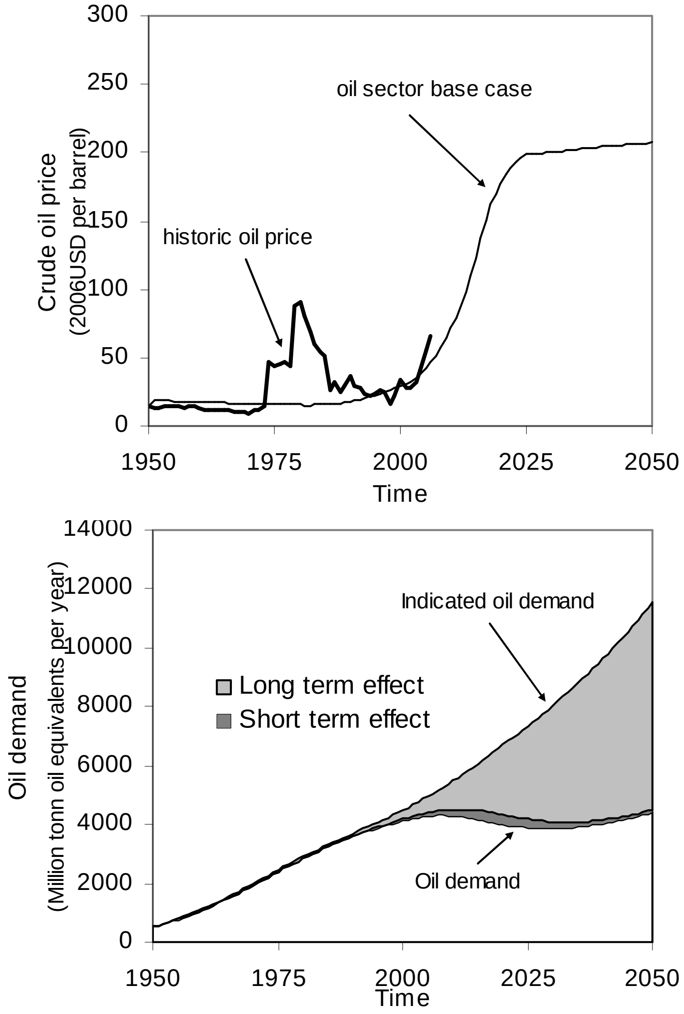


Figure 11: Long- and short-term effect of oil price on oil demand in the oil sector base case simulation

and distribution costs constant the approximate effect on Norwegian gasoline price would be:

$$\frac{(38 * 4) + 15 + 127}{38 + 15 + 127} = \frac{294 \text{ cents per litre}}{180 \text{ cents per litre}} = 63\% \text{ increase}$$

An imagined four fold increase in oil price, from 60 to 240 USD per barrel in the year 2006, would, according to the rough estimate above, not cause more than a 63 per cent increase in Norwegian gasoline price. Gasoline and motor oil accounted for 3.4 per cent of the annual expenditures of Norwegian households in the period 2004-2006[4]. A 63 per cent increase in gasoline price would be the equivalent of 2.1 per cent rise in annual household expenditures, all else being equal.

Norway is, with its population of 4.7 million, high wages and gasoline taxation, not a representative country. Let us do the same estimate for a major gasoline consumer, the United States: The result is 180 per cent rise in gasoline price due to the low gasoline taxation level (10 cents). Despite cheaper gasoline American households spent a larger share (4.3 per cent) of their annual expenditures on gasoline and motor oil in 2005[5]. A 180 per cent rise in gasoline price would, in the United States, be equivalent to 7.7 per cent rise in annual household expenditures.

---

[4] Source: Statistics Norway (SSB): http://www.ssb.no/emner/05/02/fbu/tab-2007-09-10-01.html (09.06.08)

[5] Source: U.S. Bureau of Labor Statistics: http://www.bls.gov/cex/csxann05.pdf (09.06.08)

4. Reference mode: The food and oil sector together

The purpose of the reference mode simulation is to show how the model behaves when no food or food land is used to produce biofuel. Food price rises after year 2000 independently of effects from biofuel production or oil price in the reference mode simulation.

The behavior of the food sector will first be presented, after that we will take a closer look at the model structure. Two alternative potential food production scenarios will be presented.

4.1. Behavior of the food sector

Figure 12 shows the reference mode behavior, where the food and oil sector is connected, compared to historic data and a model run where the oil sector is disconnected so that the increasing oil price has no effect on food production costs. Oil price hardly has any visible effect on food production, but a slight effect can be seen in food price and in the fraction of potential food production capacity used. Notice that the food price rises in both cases, even when the effect of a rising oil price is removed.

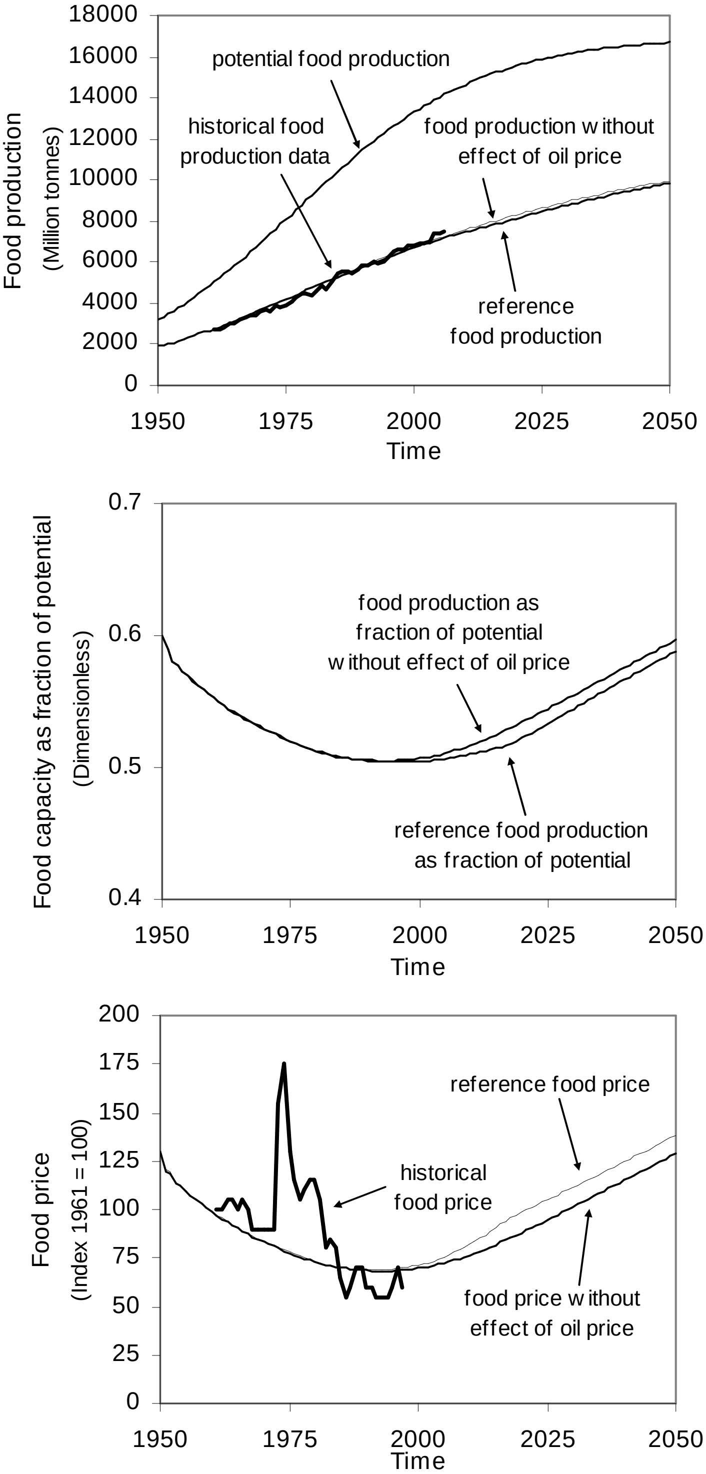
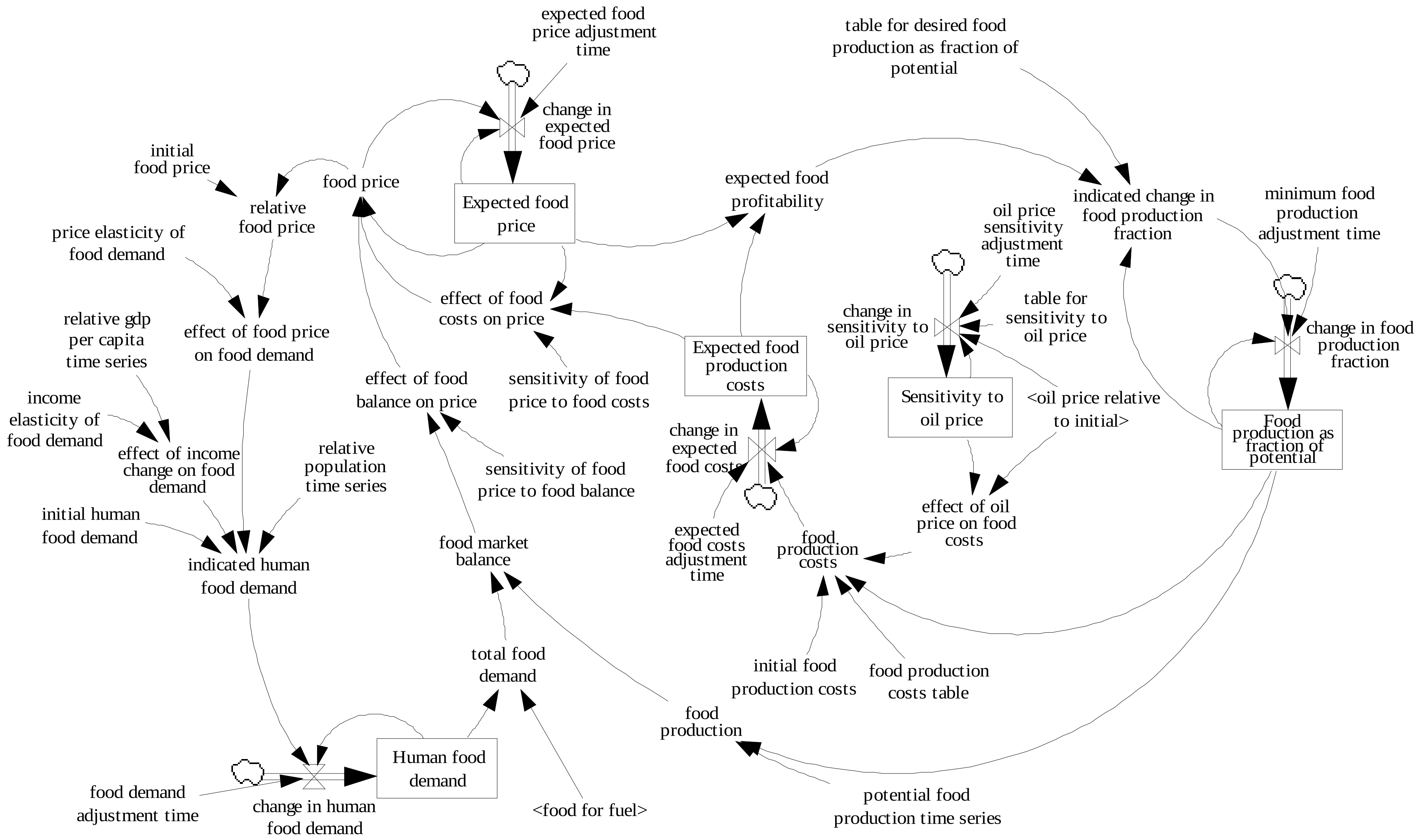


Figure 12: Behavior of food sector, reference mode and a run without the effect of oil price on food price. Historical data sources: Food price from IMF and food production from FAO.

Figure 13: Food sector overview



4.2. Food production

The model is sensitive to assumptions about the development of potential food production. Figure 14 shows reference food production and price compared with a scenario where technology is able to keep on expanding the production potential and a scenario where environmental problems erode it. Potential food production is an exogenous time series representing the primary food production assumed possible using the agricultural land and technology available at a given point in time. Data from the Food and Agricultural Organization indicate that we were utilizing roughly 50 per cent of the potential in the year 2000 (FAO, 2003). If we accept this as a reference point, how large was the potential before that, and how is it likely to develop?

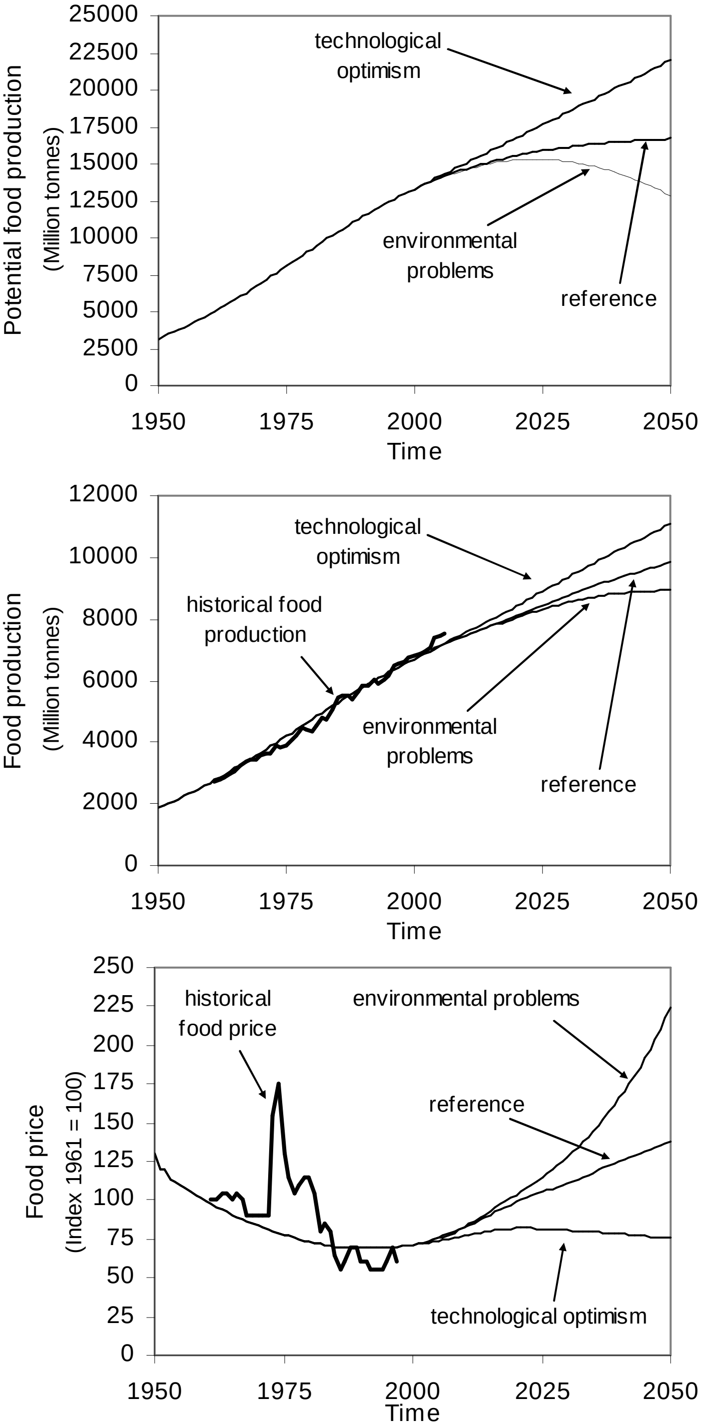


Figure 14: Effect of production potential. Reference mode compared with an optimistic technology scenario and a scenario with environmental problems.

An informed guess regarding the food production potential before 2000 is that it has been growing faster than demand and production. The high yielding varieties of wheat and rice introduced during the green revolution have together with other agro-scientific discoveries expanded the production possibilities, whilst a continuous expansion of agricultural land has compensated for the land lost to urbanization, salinization, erosion and exhaustion.

After 2000 the growth in food production potential is assumed to saturate in the reference mode.

Land is a limited resource, and the most fertile land is already in use. It will be more and more difficult to keep expanding at a rate high enough to replace losses. The size of yields attainable is constrained by biological limits – for example in plant physiology (FAO, 2003). Whether current science is close to these limits or not makes little difference to the base assumption of saturation: As yields increase the potential for further increase shrinks and increasing yields further becomes a little bit more difficult.

In the yield technology optimism scenario it is assumed that attainable yields continue rising and a widespread adoption of sustainable land use practices minimizes the loss of land. Food price remains low in this scenario, apart from a slight rise during the transition from oil to other sources. Production continues its growth without saturation.

The environmental problems scenario takes account of uncertainty about the future state of the planet. It assumes climate change and the sum of human activity over time erodes more food production potential than what is gained through technologic progress and land expansion. Food production saturates, prices rise exponentially.

These three scenarios imply a dramatic span in food price and they will, together with the scenarios of larger oil reserves and faster or slower development presented in the previous chapter, be used to test the robustness of an alternative policy in chapter 6.4. Now we will take a closer look at the model formulation of food production:

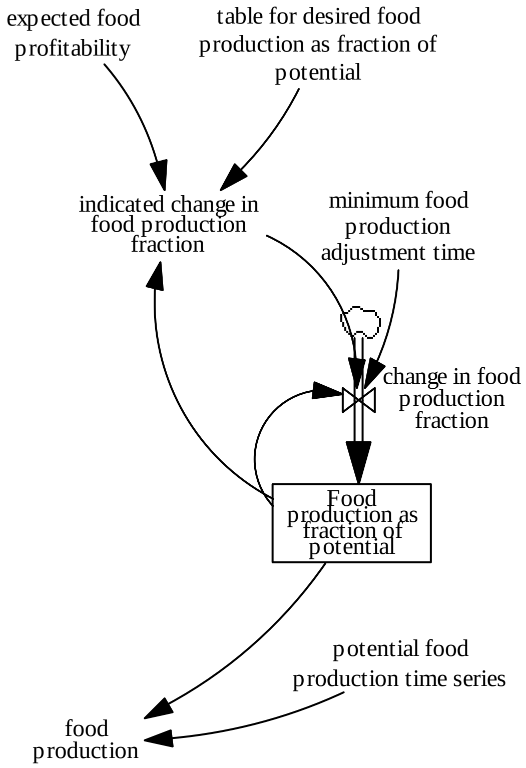


Figure 15: Food production structure

$$\text{food production} = \text{potential food production} * \text{Food production as fraction of potential}$$

$$\text{Food production as fraction of potential} = \text{INTEGRAL}\left(\begin{matrix}\text{change in food}\\ \text{production fraction}\end{matrix}, \begin{matrix}\text{Food production as}\\ \text{fraction of potential}\end{matrix}(t_0)\right)$$

$$\text{change in food production fraction} = \frac{\text{MAX}\left(0, \begin{matrix}\text{indicated change}\\ \text{in food production}\\ \text{fraction}\end{matrix} * \left(1 - \begin{matrix}\text{Food production}\\ \text{as fraction}\\ \text{of potential}\end{matrix}\right)\right) + \text{MIN}\left(0, \begin{matrix}\text{indicated change}\\ \text{in food production}\\ \text{fraction}\end{matrix} * \begin{matrix}\text{Food production}\\ \text{as fraction}\\ \text{of potential}\end{matrix}\right)}{\text{minimum food production adjustment time}}$$

indicated change in food production fraction
= desired food production as fraction of potential - food production as fraction of potential

$$= \left(\begin{matrix} \text{food production as} \\ \text{fraction of potential} \end{matrix} * f \left(\begin{matrix} \text{expected} \\ \text{food profitabillity} \end{matrix} \right) \right) - \begin{matrix} \text{food production as} \\ \text{fraction of potential} \end{matrix}$$

The stock food production as fraction of potential (figure 15), represents current primary food production relative to potential food production. One could think of it as a parallel to capacity utilization; the potential food production time series is the capacity and food production as fraction of potential is the utilization.

Desired food production as fraction of potential is anchored to current and adjusted up or down from this point depending on the profitability of production. The function used is identical to the table for desired oil capacity (see figure 8).

The adjustment needed to close the gap between desired and actual state is the indicated change in food production fraction, and the time it takes food producers to close it depends on current utilization and the direction of change. An example of why the direction of change matters could be a situation where food production is very high: The potential for further production increase is limited, but the reduction potential is as large as the production itself. Downward adjustment should in this case be easier and faster than upward adjustment. The combination of a MAX and a MIN function enables differentiation between adjustment directions and prevents the production fraction from going below zero or over one.

4.3. Food production costs

Food production costs (figure 16) are effected by the fraction of potential production utilized (intensity), and oil price. A food price index, with 1961 as base year, is used to represent both food production costs and food price.

$$\text{expected food profitabillity} = \frac{(\text{Expected food price - Expected food costs})}{\text{Expected food price}}$$

Expected food production costs
= INTEGRAL(change in expected food production costs, Expected food production costs(t_0))

Expected food production costs(t_0) = initial food production costs

$$\begin{matrix} \text{change in expected} \\ \text{food costs} \end{matrix} = \frac{(\text{food production costs - expected food production costs})}{\text{expected food costs adjustment time}}$$

$$\text{food production costs} = \begin{matrix} \text{initial food} \\ \text{production costs} \end{matrix} * f \left(\begin{matrix} \text{Food production as} \\ \text{fraction of potential} \end{matrix} \right) * \begin{matrix} \text{effect of oil price} \\ \text{on food costs} \end{matrix}$$

The food production costs table (figure 17) rises exponentially. At the bottom of the curve there is no production at all and it takes little effort to increase it; one could just throw out seeds at random and wait for the result. Returns diminish as production gets closer to potential production; more capital, inputs, human labor and knowledge is needed to increase it further. At the very top of the curve one could imagine a team of agricultural specialists carefully monitoring each field.

The output of the food production cost curve is multiplied by initial food production costs and an effect of oil price on food costs.

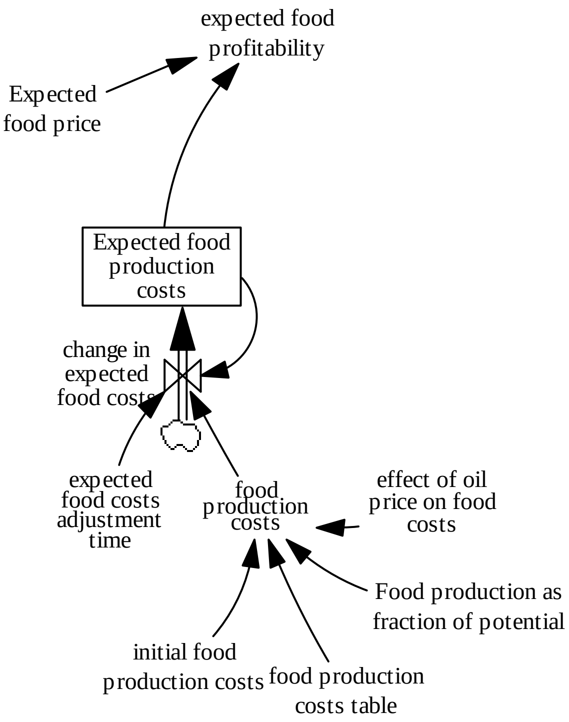
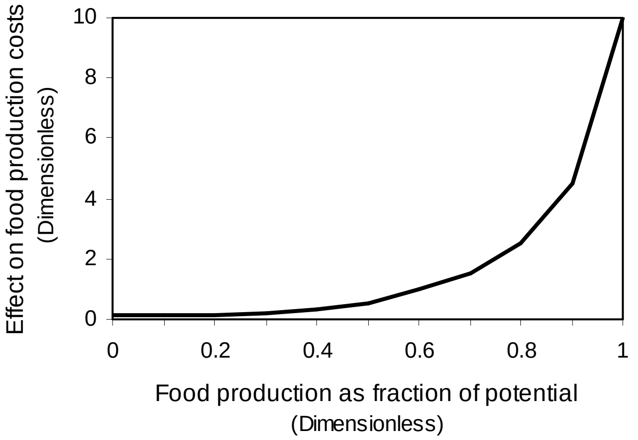


Figure 16: Food production costs structure



FPFP	EFPC
0.00	0.10
0.10	0.12
0.20	0.15
0.30	0.20
0.40	0.30
0.50	0.50
0.60	1.00
0.70	1.50
0.80	2.50
0.90	4.50
1.00	10.00

Figure 17: Food production costs table

4.4. Sensitivity of food production costs to oil price

The sensitivity of food production costs to oil price depends on the energy intensity (the amount of energy used per unit produced), the type of energy used and the energy fraction of total production costs. These factors are dynamic; they change over time because agricultural practice gradually adapts to its surroundings. To capture this adaptation process, sensitivity to oil price is modeled as a stock (figure 18).

effect of oil price on food costs = oil price relative to $\text{initial}^{\text{Sensitivity to oil price}}$
Sensitivity to oil price = INTEGRAL(change in sensitivity to oil price, Sensitivity to oil price(t_0))

$$\text{change in sensitivity to oil price} = \frac{(f(\text{oil price relative to initial}) - \text{Sensetivity to oil price})}{\text{oil price sensitivity adjustment time}}$$

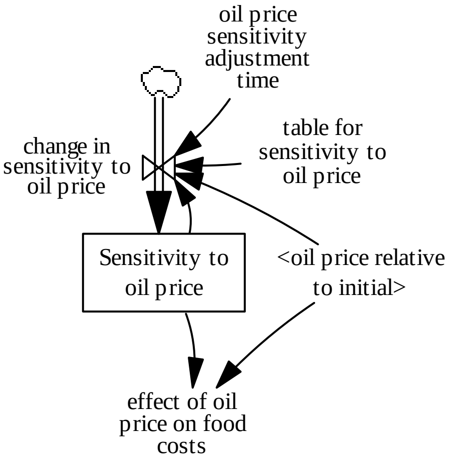


Figure 18: Sensitivity to oil price structure

Recall the gap in figure 12 between reference food price and food price without the effect of oil price. This gap shows what the effect of the sensitivity to oil price structure is. The behavior causing this gap can be seen in figure 19. The line labeled indicated sensitivity to oil price is the output of the table for sensitivity to oil price (figure 20). Sensitivity adjusts gradually towards indicated. The initial gap between them is large because agriculture was more traditional in 1950 and cheap fossil fuel represented an enormous potential energy input. Research and farming practice has over time learnt to utilize this energy potential.

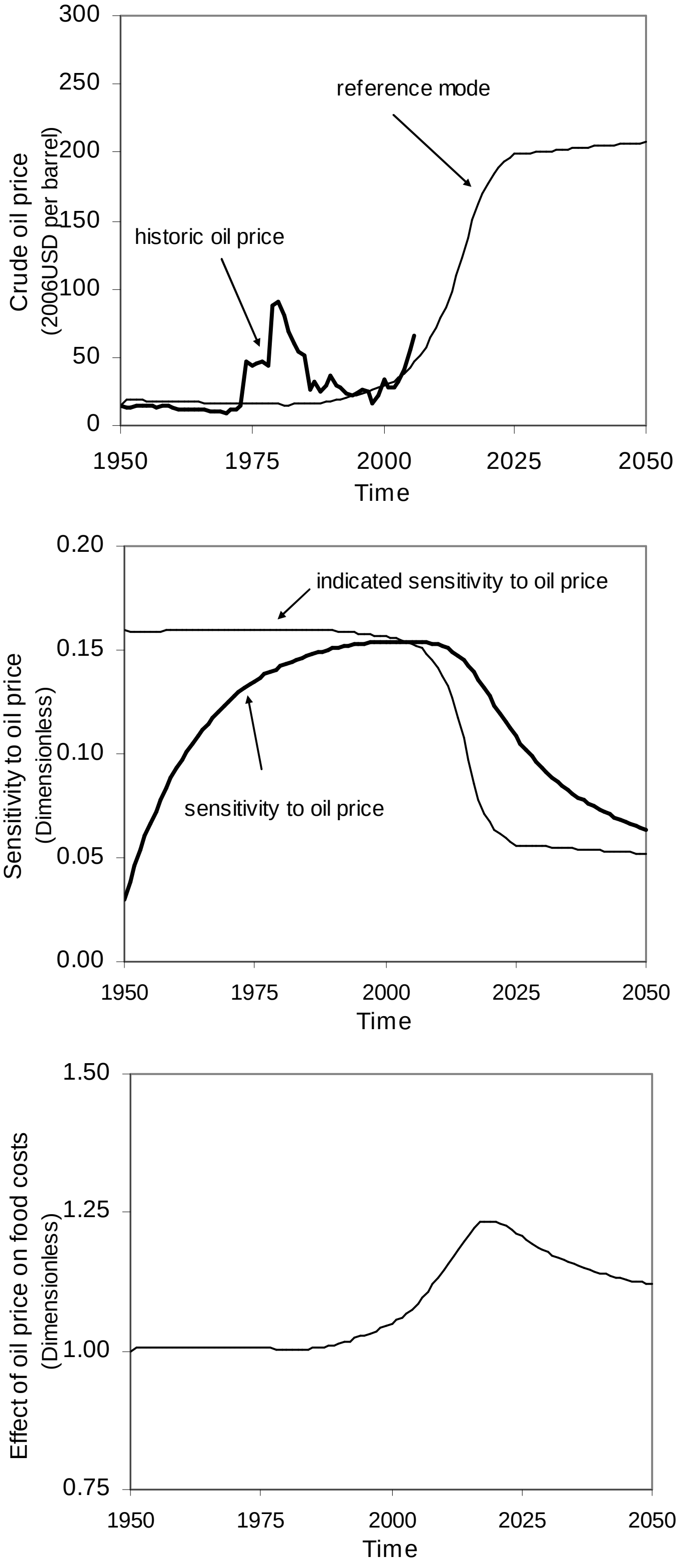
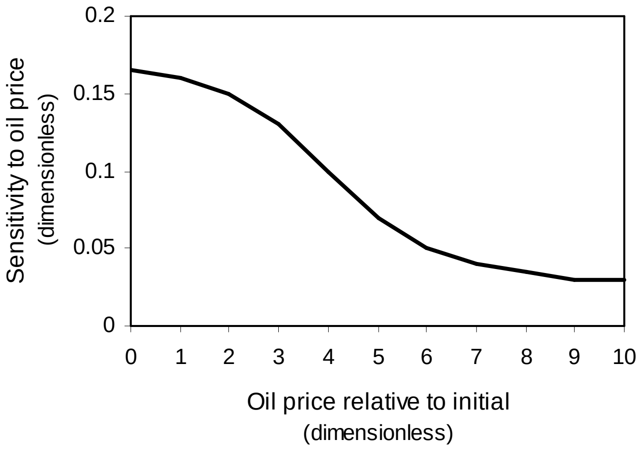


Figure 19: Effect of oil price on food production costs



OPRI	SOP
0	0.165
1	0.16
2	0.15
3	0.13
4	0.1
5	0.07
6	0.05
7	0.04
8	0.035
9	0.03
10	0.03

Figure 20: Table for sensitivity to oil price

4.5. Food price

$$\text{food price} = \begin{matrix}\text{Expected}\\ \text{food price}\end{matrix} * \begin{matrix}\text{effect of food}\\ \text{costs on price}\end{matrix} * \begin{matrix}\text{effect of food}\\ \text{balance on price}\end{matrix}$$

Expected food price
= INTEGRAL(change in expected food price, Expected food price (t_0))

Expected food price (t_0) = initial food price

$$\text{change in expected food price} = \frac{\text{(food price - Expected food price)}}{\text{expected food price adjustment time}}$$

$$\text{effect of food balance on price} = \text{food market balance}^{\text{sensitivity of food price to food balance}}$$

$$\text{food market balance} = \frac{\text{total food demand}}{\text{food production}}$$

$$\begin{matrix}\text{effect of food}\\ \text{costs on price}\end{matrix} = 1 + \begin{matrix}\text{sensitivity of food}\\ \text{price to food costs}\end{matrix} * \left[\frac{\text{Expected food production costs}}{\text{Expected food price}} - 1\right]$$

Food price is, like oil price, modeled using a stock representing traders expected equilibrium price (figure 21). Price is anchored to expected price and adjusted according to inventory levels, here represented by market balance[6], and changes in production costs. The formulation used for effect of food costs on price makes it possible to adjust assumptions about the quality of information traders have about production costs and the extent of attention paid to this information. If sensitivity of food price to food costs = 0, traders completely ignore

---

[6] See discussion in 3.4. Oil price

information about costs. If it = 1, traders ignore the expected equilibrium price and base their price setting on expected costs (Sterman, 2000).

The sensitivities used in the model, both regarding food price and food demand, were found through model calibration to historical production and price data. More time could be spent in the future to recover good estimates of these variables if this could strengthen the model. Even if precise estimates were found, we have no guarantee that observations of the past can explain behavior more than 40 years ahead.

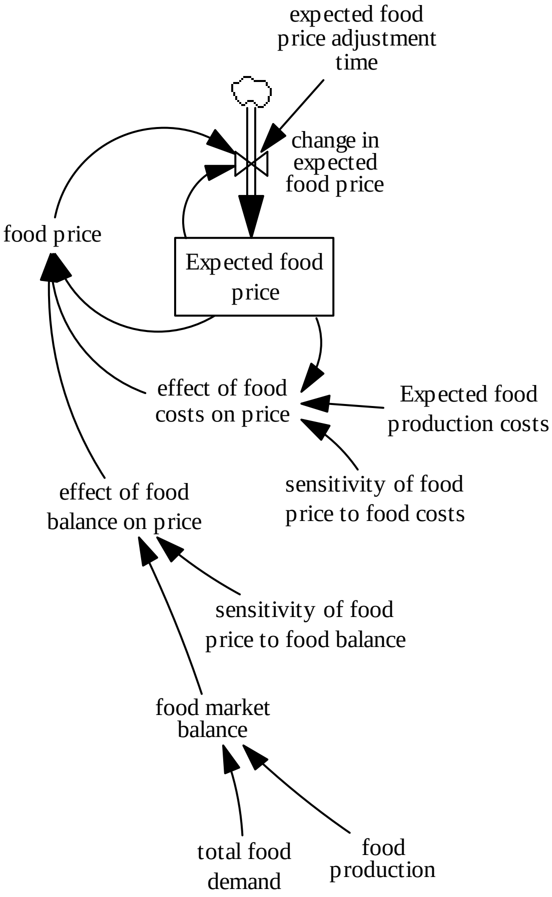


Figure 21: Food price structure

4.6. Food demand

total food demand = Human food demand + food for fuel

Human food demand = INTEGRAL(change in food demand, Human food demand (t_0))

$$\text{change in human food demand} = \frac{(\text{indicated human food demand} - \text{Human food demand})}{\text{food demand adjustment time}}$$

$$\text{indicated human food demand} = \frac{\text{initial human}}{\text{food demand}} * \frac{\text{Relative}}{\text{population}} * \frac{\text{effect of income}}{\text{change on food demand}} * \frac{\text{effect of food price}}{\text{on food demand}}$$

$$\text{effect of income change on food demand} = \text{relative GDP per capita}^{\text{income elasticity of food demand}}$$

$$\text{effect of food price on food demand} = \text{relative food price}^{\text{price elasticity of food demand}}$$

$$\text{relative food price} = \frac{\text{food price}}{\text{initial food price}}$$

Population growth is the main driving factor of food demand (figure 22). Changes in food price and income effect the food chain level of eating. A diet higher up in the food chain includes a larger fraction of meat and dairy products and requires more primary production due to the energy loss from fodder to animal product. The population and GDP per capita time series used to model food demand are identical to those used for oil demand.

Food for fuel is the food used as feedstock for biofuel production. This is added to human food demand to find total food demand. As already mentioned, the reference mode simulation's and all other simulation results presented so far, omit food for fuel. This will be added in the next section when the biofuel sector is connected to the food and oil sector.

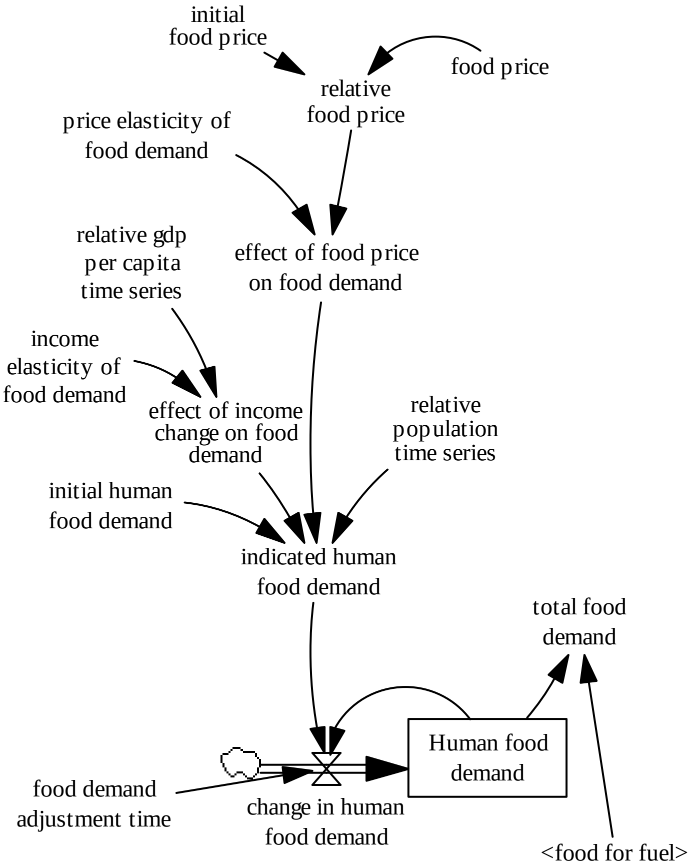


Figure 22: Food demand structure

5. Biofuel sector: Linking together the food and energy market.

In this chapter the food and oil sector is connected to the biofuel sector, the base case behavior of the complete model is analyzed and the structure of the biofuel sector presented. The biofuel sector simulates the production of biofuel using food crops or crops grown on land suitable for food crop production. The production of transportable energy using other sources of biomass happens in the oil sector as part of the transition to alternatives as conventional oil is depleted. The model behavior of the base case simulation will first be presented. After that we will look more closely at the structure of the biofuel sector.

5.1. Base case model behavior

The base case simulation, where all three model sectors are connected together, is not meant to represent the most likely future scenario, it is simply a scenario where the current policy of supporting biofuel production is kept and where all parameter values in the oil and food sector are equal to their reference mode values. The output of the base case simulation is, when compared to the reference mode, the effect of adding an extra link between the food and oil sector (figure 23). Notice how small the effect is at first and how quickly it grows.

The two graphs on the left hand side represent gains of food based biofuel production whilst costs (apart from the cost of the support measures themselves) are represented by the two graphs on the right.

Assuming perfect substitutability between oil and biofuel, a total of nearly 46 000 million tonnes oil is substituted with biofuel and the surge in oil price is counteracted temporarily, gaining another thirty years before it approaches a 200 USD per barrel level. This could, for many nations, be a valuable contribution to energy security, both in terms of saved oil import expenses and the extra time gained to adopt to a higher oil price. The oil substitution would most likely also represent a net CO_2 reduction but the size of this depends on the average CO_2 budget of the biofuel produced, which again depends on technologic development and policy choices. The World Resource Institute has compiled estimates of the life cycle reductions in greenhouse gas emissions of different feedstock’s when biofuel is used in place of fossil fuel (Childs, 2007). The ranges between high and low estimates and between different feedstock’s are large. Corn is, for example, only estimated to give a reduction of 15 to 40 per cent per unit fossil fuel displaced while estimates for sugar cane range between 60 and 90 per cent. Indirect effects, that a life cycle analysis is unable to capture, could make the reduction even smaller:

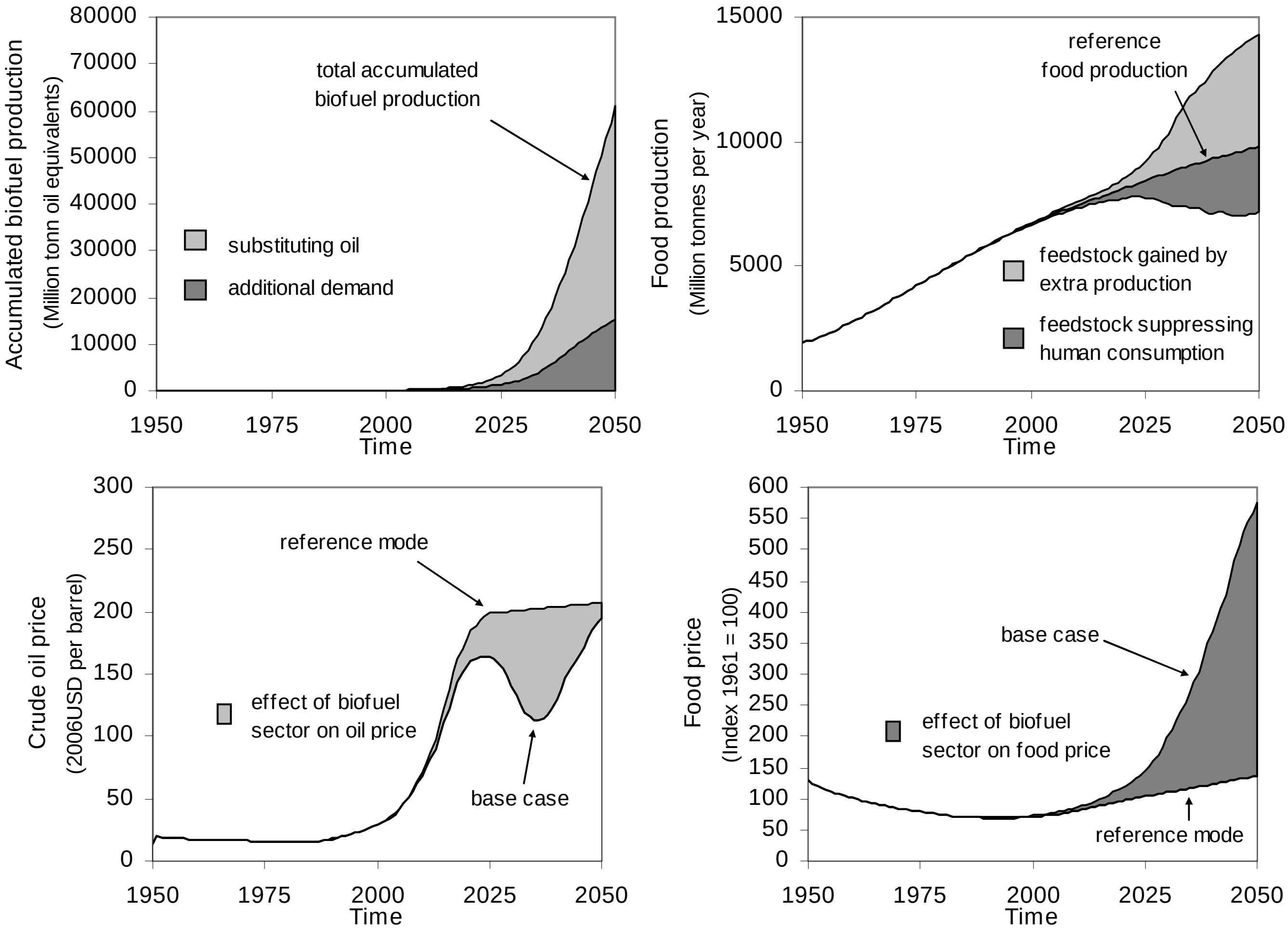


Figure 23: Base case model behavior

“If sugarcane is planted on land that was previously being used for other productive purposes, such as growing other crops or grazing livestock, these activities may be displaced. This land-use pressure could ultimately lead to deforestation elsewhere, and therefore carbon emissions indirectly attributable to ethanol production” (Childs, 2007). The net CO_2 equivalent greenhouse gas reduction gained by the oil substitution in the base case simulation, is highly uncertain and could in the worst case, using feedstock’s that only yield small reductions and also displace rainforests, even be negative.

Base case food price is, in 2050, more than four times as high as the reference mode. The total shaded area in the top right graph represents the amount of food used as feedstock for biofuel production; accounting for about 50 per cent of total food production in 2050. A two way pressure is created by this feedstock demand; an upward pressure on agricultural land and forests due to increased intensification and land expansion and a downward pressure on, primarily poor food consumers that are overbid by richer car owners to exemplify.

Figure 24: Biofuel sector overview

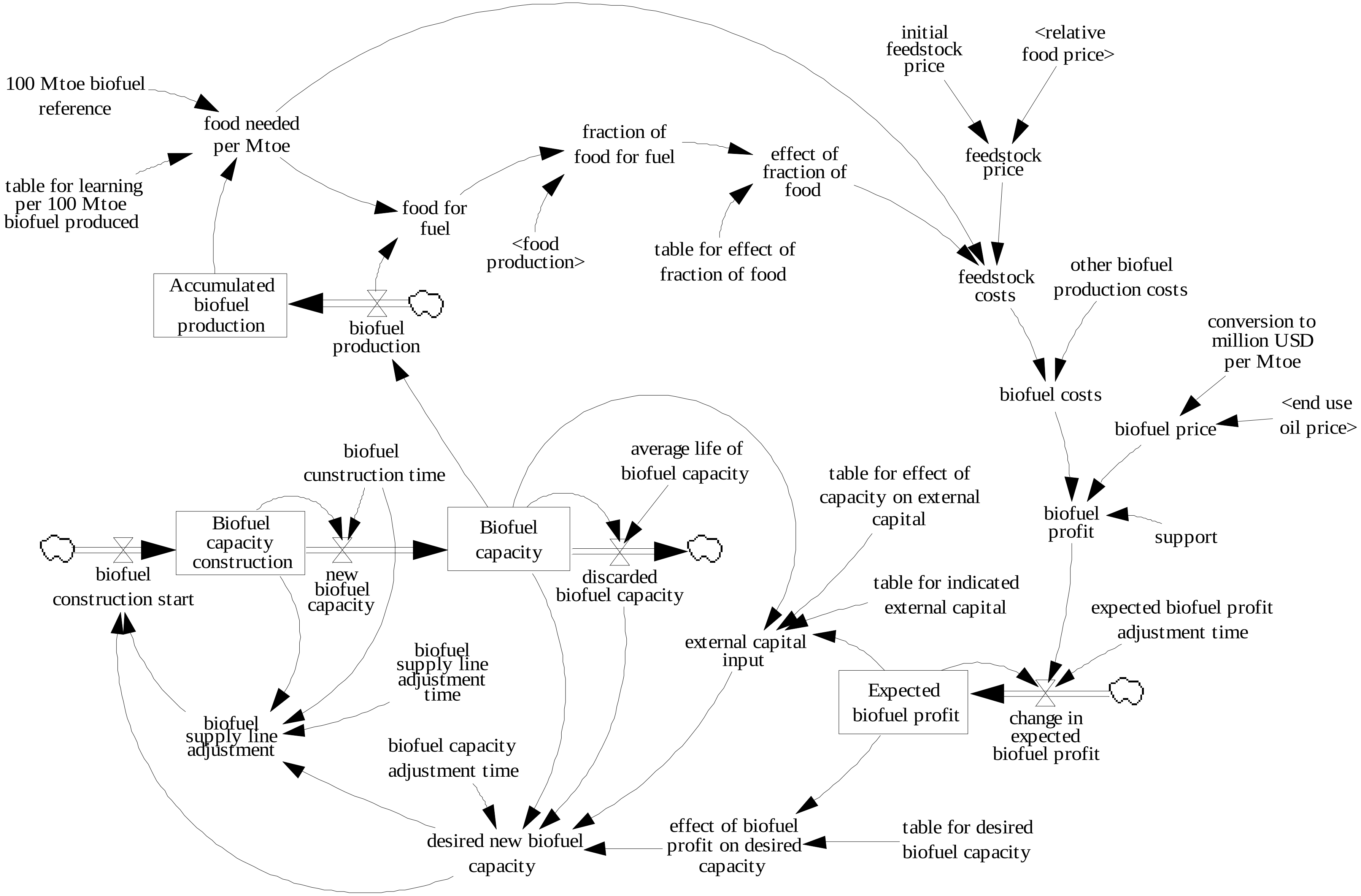


Figure 24 shows the structure of the biofuel sector. Half of it has close resemblance with the oil sector and will therefore only be briefly commented. The remaining structure is quite easily understandable in figure 24. The reader is inquired to refer back to this figure as we proceed with the presentation.

5.2. Profitability of biofuel production

$$\text{biofuel profit} = \frac{(\text{biofuel price} - \text{biofuel costs} + \text{support})}{\text{biofuel price}}$$

The profitability of biofuel production is, like in the oil sector, expressed by a dimensionless number representing the balance between price and costs, but a variable representing public support is also included in the equation. We will look at the tree variables defining biofuel profit one by one, starting with support:

$$\text{support} = 0 + \text{STEP}(170, 1975)$$

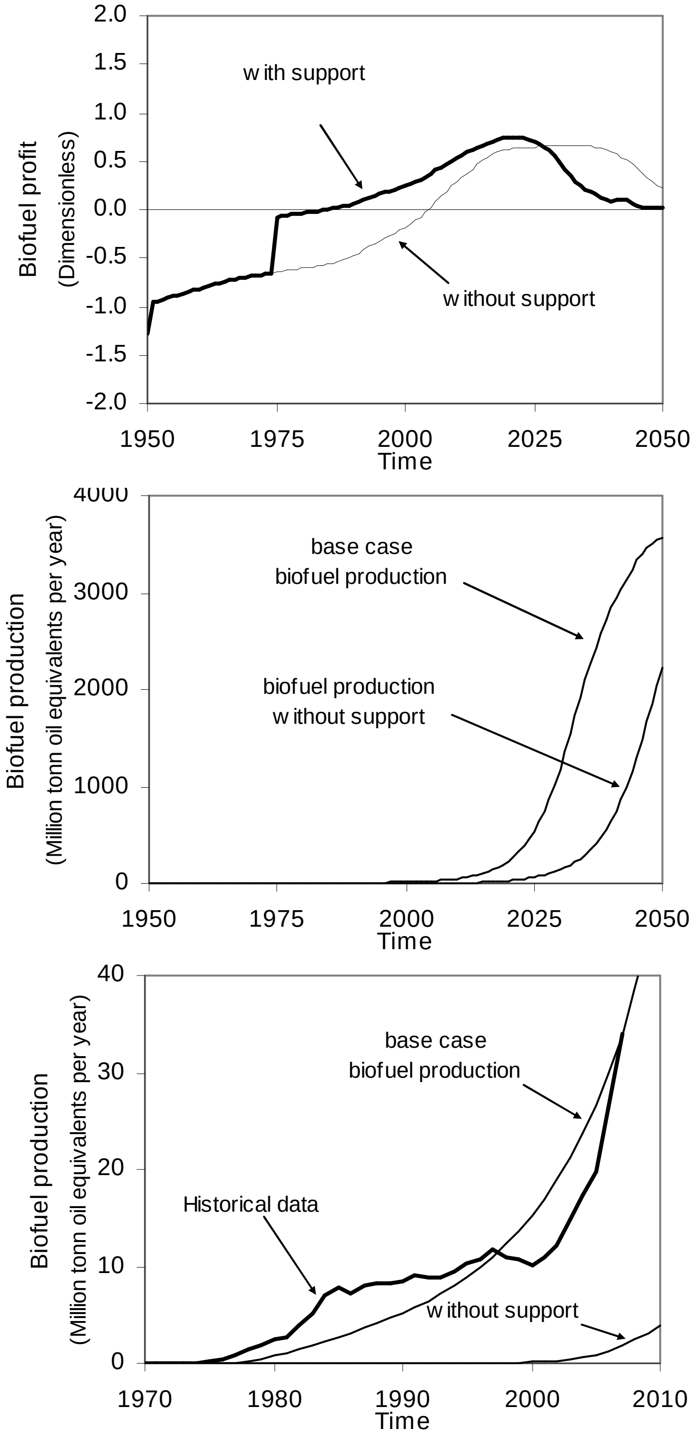


Figure 25: Base case biofuel profit and production and a test simulation without support.

The support variable is an aggregate of all public support measures. It is modeled using a STEP function which is zero in the beginning and steps up to a constant support level of 170 million USD per Mtoe in 1975 (the start of the Brazilian ethanol program). This support level corresponds to about 0.15 USD per litre gasoline; or 30 to 40 per cent of what the World Bank considers to be the cost of current support measures in the United States (World Bank, 2008). As can be seen in figure 25 the support level chosen is just enough to make sugar cane based ethanol production profitable in 1975 and to support a growth in biofuel production that fits with historic data[7]. In a test simulation excluding support, production is not profitable before 2005; the year simulated crude oil price rises above 40 USD per barrel. Table 3 shows, for different feedstock's and without support, the approximate range of crude oil price within biofuel could be produced with profit in the year 2005 (IEA, 2006). This relatively large range in production costs could, in addition to mere qualities of the feedstock's themselves, be attributed to socio-economic and geographical differences between the three major biofuel producers (Brazil, the United States and the European Union).

Feedstock	Profitable at oil price USD per barrel	Major producer
Sugar Cane	40 to 80	Brazil
Maize and sugar beet	95 to 125	United States
Wheat and oil seeds	110 to 160	European Union

Table 3: Production cost ranges of biofuel in 2005 using different feedstock's.
source: (IEA, 2006)

biofuel price = end use oil price * conversion to million USD per Mtoe

Since perfect substitution is assumed between oil and biofuel (see chapter 3.4.), biofuel price is equal to end use oil price. It is converted from USD per barrel to million USD per million tonn oil equivalent to be consistent with the unit used for biofuel production.

biofuel costs = feedstock costs + other biofuel production costs

The purchase of feedstock typically amounts to more than 50 per cent of total biofuel production costs (IEA, 2006). Other biofuel production costs are an aggregate of all other costs including; capital, labor, maintenance, energy and chemicals. Treating this variable as a constant can be justified for a rough model like this because the energy fraction of costs does not depend heavily on transportable energy and is so small that it would largely have been overshadowed by the effect of oil on biofuel price. Further more, the scope of significant reductions in running costs and capital costs is small for conventional biofuel production since the technology used is mature. Feed stock costs, on the other hand, depend on food price and they could be reduced significantly through technologic development.

feedstock costs = feedstock price * food needed per Mtoe * effect of fraction of food

---

[7] Source: compiled by Earth Policy Institute http://www.earth-policy.org/Books/PB3/data.htm (10.05.08)

The price of the feedstock is multiplied by the quantity needed per produced energy unit and an effect associated with the fraction of total food production used by the biofuel industry.

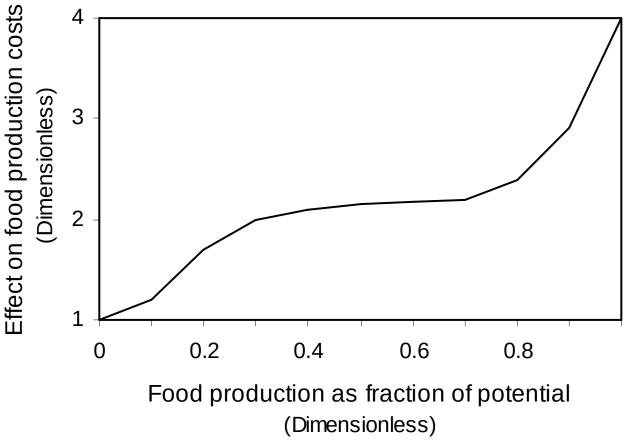
feedstock price = initial feedstock price * relative food price

effect of fraction of food = f(fraction of food for fuel)

$$\text{fraction of food for fuel} = \frac{\text{food for fuel}}{\text{food production}}$$

food for fuel = biofuel production * food needed per Mtoe

Feedstock price is assumed to follow the same development as food price. Different climatic and geographic regions favor different crops and have different corresponding production costs (table 3). This is what the nonlinear effect of fraction of food for fuel (figure 26) attempts to capture. The effect is neutral at the foot of the curve. At this point a crude oil price of 40 USD makes it profitable to produce for the most efficient producers using feedstock from the best sugar cane areas. The first exponential rise represents the cost distribution of sugarcane based production. Around 20 per cent of the worlds primary agricultural production is sugar cane according to production statistics from FAO[8]. Costs continue rising as areas favoring maize and sugar beet (about 15 percent of primary production) are taken into account. Once it also becomes profitable to use oil seeds and cereals (other than maize) the



FPFP	EFPC
0.0	1.00
0.1	1.20
0.2	1.70
0.3	2.00
0.4	2.10
0.5	2.15
0.6	2.17
0.7	2.20
0.8	2.40
0.9	2.90
1.0	4.00

Figure 26: Table for effect of fraction of food

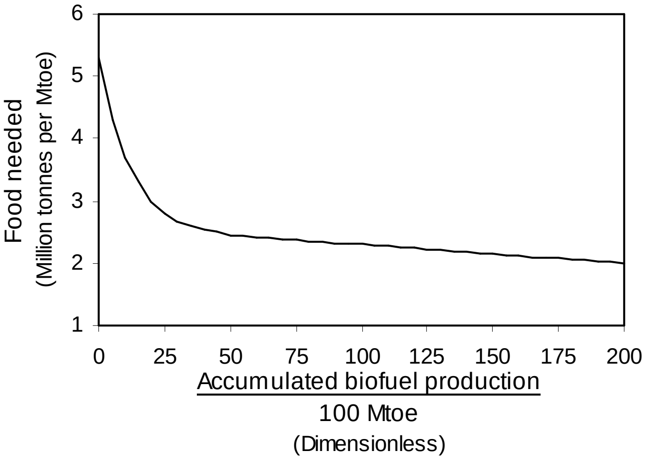
---

[8] Source: FAOSTAT: online statistical database. http://faostat.fao.org/ (09.06.08)

rise in costs nearly flattens out because it is distributed over such a large group of crops. Eventually costs rise exponentially again as feedstock from the least suitable areas is used.

$$\text{food needed per Mtoe} = f\left(\frac{\text{Accumulated biofuel production}}{\text{100 Mtoe biofuel}}\right)$$

The table for learning per 100 Mtoe biofuel produced (figure 27) is a learning curve representing improvements of the conversion factor from biomass to fuel, and the adoption of specialized crops that yield more usable biomass per hectare. The output of the table is the food needed per million tonn oil equivalent biofuel produced. The input, accumulated biofuel production, is used as an indicator of the industries accumulated experience.



$\frac{\textbf{ABP}}{\textbf{100 Mtoe}}$	**FN**
0	5.30
5	4.30
10	3.70
15	3.30
20	3.00
25	2.80
30	2.67
35	2.60
40	2.55
45	2.50
50	2.45
200	2.00

Figure 27: Table for learning per 100 Mtoe biofuel produced

Conventional grain based ethanol production is based on the fermentation of starch utilizing only the kernel of the crop. The conversion factor from biomass to fuel can be improved significantly by using new technology that enables the utilization of celluloses in stalks, leaves, grasses, and tree trunks. This cellulosic ethanol technology, often called ”second generation fuels”, opens the door for new crops that still have a large potential yield improvement. Switchgrass yields are, for example, lower than corn yields at present, but they are expected to double after a period of intensive breeding and crop engineering. The potential fuel return per hectare of switchgrass is for this reason assumed to be nearly 60% higher than the potential of corn (Childs, 2007).

The learning curve only captures the additional yield gained by using specialized crops in place of traditional food crops. General food yield improvements are captured by the growing production capacity in the food sector and do not have any effect on the food needed per unit biofuel produced. Learning saturates as the potential for further improvement shrinks.

5.3. Biofuel production capacity

Accumulated biofuel production
= INTEGRAL(biofuel production, Accumulated biofuel production (t_0))

biofuel production = Biofuel capacity

Biofuel production is, as in the oil sector, equal to the production capacity. The following formulation of biofuel capacity is, with the exception of desired new biofuel capacity, identical to the oil sector:

Biofuel capacity
= INTEGRAL(new biofuel capacity - discarded biofuel capacity, biofuel capacity (t_0))

$$\text{discarded biofuel capacity} = \frac{\text{Biofuel capacity}}{\text{average life of biofuel capacity}}$$

$$\text{new biofuel capacity} = \frac{\text{Biofuel capacity cunstruction}}{\text{biofuel construction time}}$$

$$\begin{matrix}\text{Biofuel capacity}\\ \text{construction}\end{matrix} = \text{INTEGRAL}\left(\begin{matrix}\text{biofuel}\\ \text{construction start}\end{matrix} - \begin{matrix}\text{new biofuel}\\ \text{capacity}\end{matrix}, \begin{matrix}\text{Biofuel capacity}\\ \text{construction}\end{matrix}(t_0)\right)$$

$$\begin{matrix}\text{Biofuel capacity}\\ \text{construction}\end{matrix}(t_0) = \begin{matrix}\text{discarded}\\ \text{biofuel capacity}\end{matrix} * \begin{matrix}\text{biofuel}\\ \text{construction time}\end{matrix}$$

biofuel construction start
= MAX(0,desired new biofuel capacity + biofuel supply line adjustment)

$$\begin{matrix}\text{biofuel supply}\\ \text{line adjustment}\end{matrix} = \frac{\left(\left(\begin{matrix}\text{desired new}\\ \text{biofuel capacity}\end{matrix} * \begin{matrix}\text{biofuel}\\ \text{cunstruction time}\end{matrix}\right) - \begin{matrix}\text{Biofuel capacity}\\ \text{construction}\end{matrix}\right)}{\text{biofuel supply line adjustment time}}$$

desired new biofuel capacity

$$= \left[\frac{\left(\left(\begin{matrix}\text{Biofuel}\\ \text{capacity}\end{matrix} * \begin{matrix}\text{effect of biofuel profit}\\ \text{on desired capacity}\end{matrix} + \begin{matrix}\text{external}\\ \text{capacity financing}\end{matrix}\right) - \begin{matrix}\text{Biofuel}\\ \text{capacity}\end{matrix}\right)}{\text{biofuel capacity adjustment time}}\right] + \begin{matrix}\text{discarded}\\ \text{biofuel capacity}\end{matrix}$$

effect of biofuel profit on desired capacity = f(Expected biofuel profit)

Expected biofuel profit
= INTEGRAL(change in perceived biofuel profit, Expected biofuel profit (t_0))

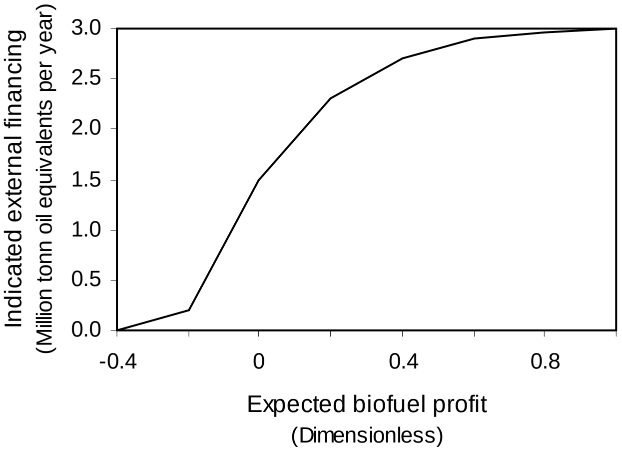
Expected biofuel profit (t_0) = biofuel profit (t_0)

$$\text{change in expected biofuel profit} = \frac{(\text{biofuel profit} - \text{expected biofuel profit})}{\text{expected biofuel profit adjustment time}}$$

Desired new biofuel capacity differs from desired new oil capacity with the addition of an external capital input. Before an industry has had time to grow and build up own capital, there is likely to be little financial capital available on the inside. The external capital input gives the biofuel industry a flying start. As the biofuel industry gets larger, further expansion is assumed to be financed more by capital from within the industry and less by external capital. This effect is modeled using a combination of two table functions:

external capacity financing = ƒ(Expected biofuel profit) * ƒ(Biofuel capacity)

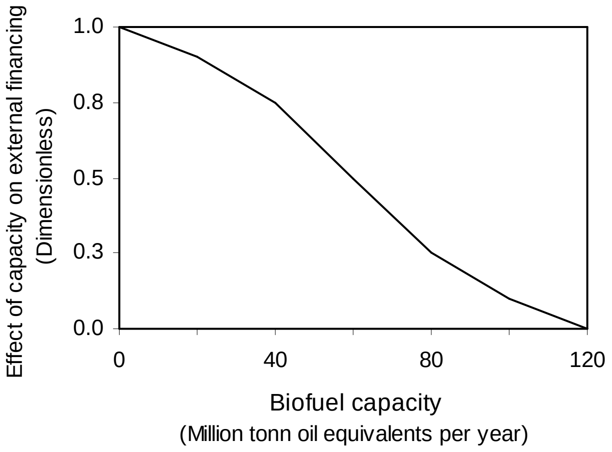
The first, table for indicated external capacity financing (figure 28), represents the capacity external investors wish to finance. The more profitable the industry is expected to be, the more interesting it is for external capital. External capital comes inn even when expected profitability is below zero. This is due to a distribution of profitability; part of the industry is still profitable when the average is not. Some investors may also be more optimistic than others and think the industry will be profitable in the future. The effect of profitability on indicated external capacity financing saturates at the approach of limits to financing and capital absorption.



EBP	**IEF**
-0.4	0.00
-0.2	0.20
0.0	1.50
0.2	2.30
0.4	2.70
0.6	2.90
0.8	2.97
1.0	3.00

Figure 28: Table for indicated external financing

The second, table for effect of capacity on external financing (figure 29), makes sure the input of external capital saturates as the industry grows. The curve is slightly s-shaped because there are more potential external investors before the industry has grown large, investors that where external in the beginning might gradually become part of the industry and as the industry grows the need for external capital also diminishes.



BC	ECEF
0	1.00
20	0.90
40	0.75
60	0.50
80	0.25
100	0.10
120	0.00

Figure 29: Table for effect of capacity on external financing

6. Development and testing of an alternative policy

In this chapter an alternative policy is developed and tested using the model. The purpose of the chapter is primarily to provide an example of how the model can be used. The alternative policy developed involves three components: Removal of current biofuel support, the introduction of a fee on biofuel production and a campaign improving energy efficiency and conservation. The robustness of the alternative policy is tested using scenarios developed in the preceding chapters. Finally, the effect of delaying the alternative policy implementation is tested.

6.1. Remove support and introduce a fee on biofuel production

In the base case scenario biofuel production is supported with a constant sum per produced unit from 1975 and throughout the rest of the simulation. This is, of course, not realistic. Readers may think a simplification such as this makes the simulated behavior unnecessary dramatic. A sector that is financed by public support is also under public control; if the biofuel industry should start to get too large or pressure the food market, policy makers can pull the brakes by adjusting down the support level.

This could probably have been the case if there was no peak in oil production and oil price remained low. Figure 30 shows the simulated food price in a policy test where all support is withdrawn in 2020. There is hardly any effect because the biofuel industry has already been given time to grow large and the soaring oil price makes it profitable to produce without subsidies. Let us assume far-sighted policymakers understand the potential food crisis and decide to withdraw all biofuel support already next year (2009), and in addition to this introduce a fee on biofuel production as large as the former support level (170 million USD per Mtoe). Even this would not be sufficient. The post peak oil energy shortage causes such good biofuel prices that the majority still keep on producing.

Stronger measures, like introducing even higher fees, production quotas or a complete prohibition of food based biofuel production could be advisable, but in a situation with voters complaining about soaring gasoline prices, the political feasibility of such measures could be discussed. We will neither pursue these policies or the discussion about their feasibility any further here.

Let us instead take a closer look at the oil price. The soaring oil price, which itself is a problem in terms of energy security, makes biofuel production so profitable that a new problem is created (a food security problem). Policies that close the gap between energy demand and supply could potentially solve two problems. The gap can be closed both through policies that increase supply and policies that reduce demand.

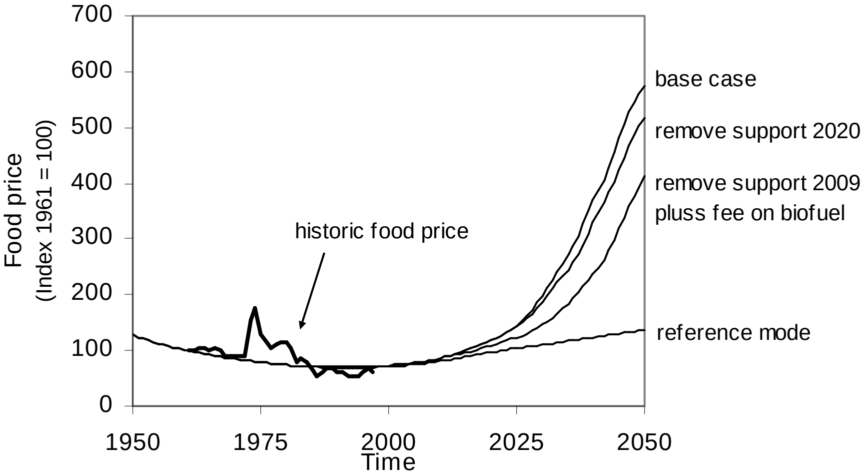


Figure 30: Food price. Effect of removing biofuel support 2009 and introducing a fee

6.2. Increase supply?

We have, in the base case support of biofuel where the shortage in transportable energy was met with a policy stimulating growth in production, already seen an example of a supply side policy. Other supply side policies could for example be subsidization of fossil fuels based on tar sands and coal to liquid, or a support of electric, plug-in hybrids and hydrogen fuel cell vehicles that expand the pool of energy available for transport. There is, however, a danger that also these supply side policies could yield undesirable side effects. The first two examples are clearly in direct conflict with climate policy goals, the second two could be so indirectly; by increasing the total demand for electricity and therefore possibly also increase the pressure for more coal- and gas-based power. There is much disagreement, debate and uncertainty associated with energy supply policies.

Physical growth of the economy is constrained by ecological limits making it harder and harder to expand without putting additional pressure on ecosystems already under serious tension. Yet, it seems as if policymakers and decision makers have a tendency to look for solutions involving growth first. If the problem is a traffic jam the solution is to build more roads, if there is energy shortage we produce more energy and in the case of unemployment the prescription is production of more goods and services. Even the World Commission on Environment and Development pointed out growth as the core policy: “The Commission’s overall assessment is that the international economy must speed up world growth while respecting the environmental constraints” (Brundtland, 1987). This combination of speeding up growth and respecting the environmental constraints may be possible in theory, but in practice it has proven to be a quite complicated and difficult task.

It is, likewise, complicated and difficult to outgrow the problem of energy shortage. A general policy advice is to look first for simple, feasible and effective solutions, with little risk of undesirable side effects. Following this advice leads us over to the demand side of the energy gap.

6.3. Reduce demand

Reducing demand through conservation and improvements in energy efficiency is, according to the Princeton professors Rob Socolow and Stephen Pacala, probably where the largest policy potential is (Socolow, 2004). A seemingly unlimited access to cheap energy has enabled modern society to establish habits, structures and technical solutions that consume energy at a rate far beyond what is needed to support the current standard of living. A wide range of technologies ideas and principles are available and ready for large scale implementation, many of which could even yield short term economic benefit. One could for example support short-term efficiency and conservation measures in current buildings, introduce low energy standard claims for new buildings and a two price system for electric power disfavoring consumption over a certain minimum level. These measures could free large quantities of electric energy and give room for a wide scale promotion of electric and plug-in hybrid vehicles that are three to four times as energy efficient as conventional combustion vehicles. Paper recycling and digitalization of information could free forest biomass for production of second generation biofuels. Policy makers could also use incentives and restrictions to twist the conventional car stock over towards smaller cars with smaller and more efficient engines and tires with less rolling resistance. Smart urban planning, mass transit and telecommuting could reduce the overall demand for cars and the average distance traveled per car.

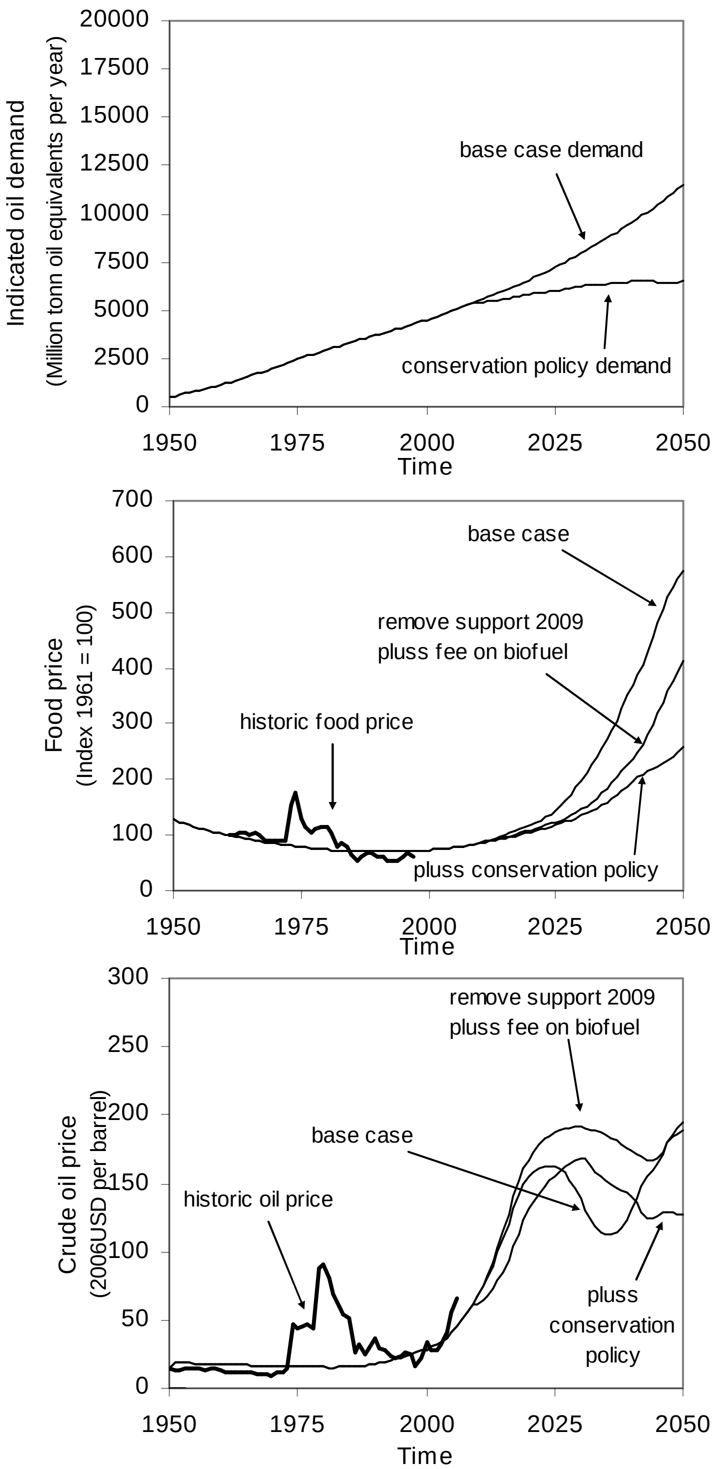


Figure 31: Effect of energy efficiency and conservation policy on food price and oil price

Let us assume, in addition to the removal of biofuel support and introduction of a fee in 2009, that indicated oil demand is reduced with 5000 Mtoe by 2050 through policies improving energy efficiency and conservation (figure 31). The policies have a dampening effect on oil price making biofuel production less profitable, thereby reducing the demand for feedstock and relieving some pressure from the food market. The result is a lower food price.

If measures that further reduce the gap between energy supply and demand are desired to dampen the rise in oil and food price even more, the efficiency and conservation policy makes it less complicated and more likely to identify a sustainable and robust mix of supply side policies. It must, after all, be easier to cover a demand of around 6500 Mtoe than a demand of 11500 Mtoe by 2050. The damping of oil price could also make it easier to gain political support for tough restrictions on food based biofuel production, both because it implies a smaller biofuel industry than otherwise and because voters are likely to be less dissatisfied with energy prices and supply. This policy combination, removal of support, introduction of a fee and improvement of energy efficiency and conservation starting in 2009, is the alternative policy developed in this chapter. The use of the expression “alternative policy” will from now on be referring to this policy combination.

6.4. Robustness of alternative policy

Finding a robust policy is more valuable than finding an optimal policy when complexity and uncertainty is large. A robust policy yields desirable results over a wide range of scenarios.

In figure 32 simulations testing the robustness of the alternative policy, using the scenarios developed in the preceding chapters, are compared with business as usual simulations using the same scenarios. Business as usual means that there are no policy changes; the base case biofuel support policy is kept in all these simulations. The scenarios reflect uncertainty about sensitive model parameters.

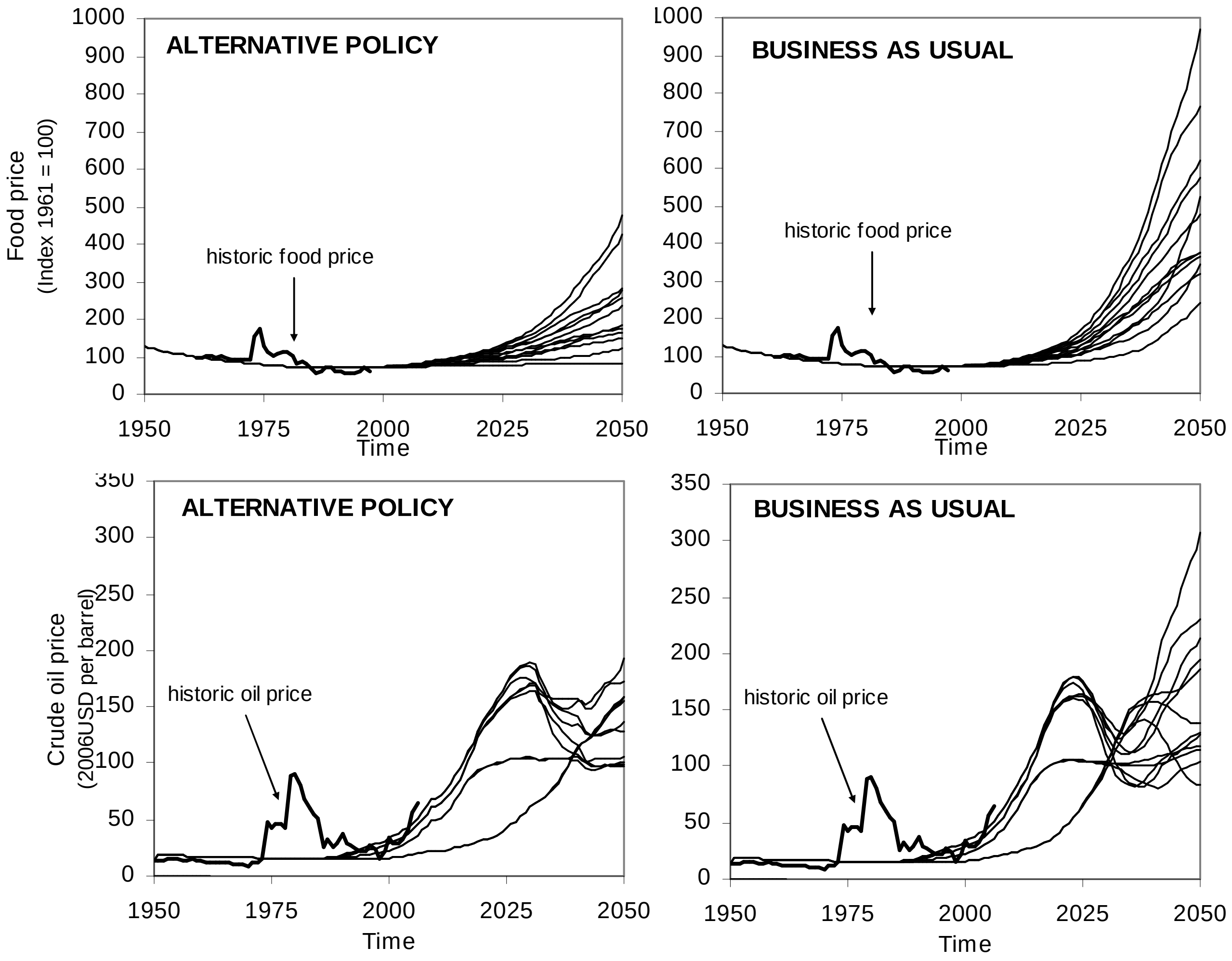


Figure 32: Robustness of alternative policy

Let us take a quick review of the scenarios developed in the preceding chapters: Assumptions about the size of oil reserves and the speed of technologic development can have a large effect on the development of oil price (chapter 3.2.). The larger oil reserve scenario has a reserve of 450000 Mtoe instead of 300000 Mtoe in 1950. Figure 5 in chapter 3.2. displays the effect of faster or slower technological development on marginal oil costs. The assumption is that a faster technologic development allows a smooth transition from conventional sources to alternatives at 100 USD per barrel, rather than 200 USD per barrel, whilst a slower development would require 300 USD per barrel.

The exogenous time series used to represent the development of potential food production was in chapter 4.2. altered to create two alternative scenarios (see figure 14 in chapter 4.2.): The optimistic yield technology scenario, where the production potential continues rising linearly, and the environmental problems scenario where climate change and the sum of human activity over time erodes more food production potential than what is gained through technologic progress and land expansion. Many of the simulation runs in figure 32 also combine two scenarios (for example environmental problems and slower technologic development).

The alternative policy seems quite robust when it comes to keeping food price down. Two of the simulation runs, both involving the environmental problems scenario, give a food price notably higher than the rest, suggesting that environmental policies reducing the risk of loosing production potential also should be implemented. The two highest prices of the alternative policy are still only mid range in comparison with the business as usual policy. The highest business as usual food price is twice as high as the alternative policy.

The alternative policy also has a stabilizing effect on oil price compared with business as usual.

6.5. Effect of delaying alternative policy implementation

Given the risk that oil production could peak in the near future and cause a soaring oil price, time for effective political action seems short. Simulations where the alternative policy start is delayed eight, sixteen and twenty four years (figure 33) indicate a disproportionate relationship between delay time and policy effect. The alternative policies must be implemented before policymakers receive feedback signals in the form of a continuous rising food price trend (short-term oscillations could mask the trend). Waiting eight years is enough to loose much of the effect.

Suppose policymakers wait 24 years and then in 2033, observing a food price nearly 3 times as high as in 2008 and a biofuel industry claiming 35 per cent of global food supply, propose that this has now become such a large problem that an alternative policy must be implemented straight away. Unless measures more extensive and drastic than the alternative policy developed in this chapter were to be implemented, the policy would have little effect over the time scale of the simulation. The food price, already considered an acute problem in 2033, would double once more by 2050.

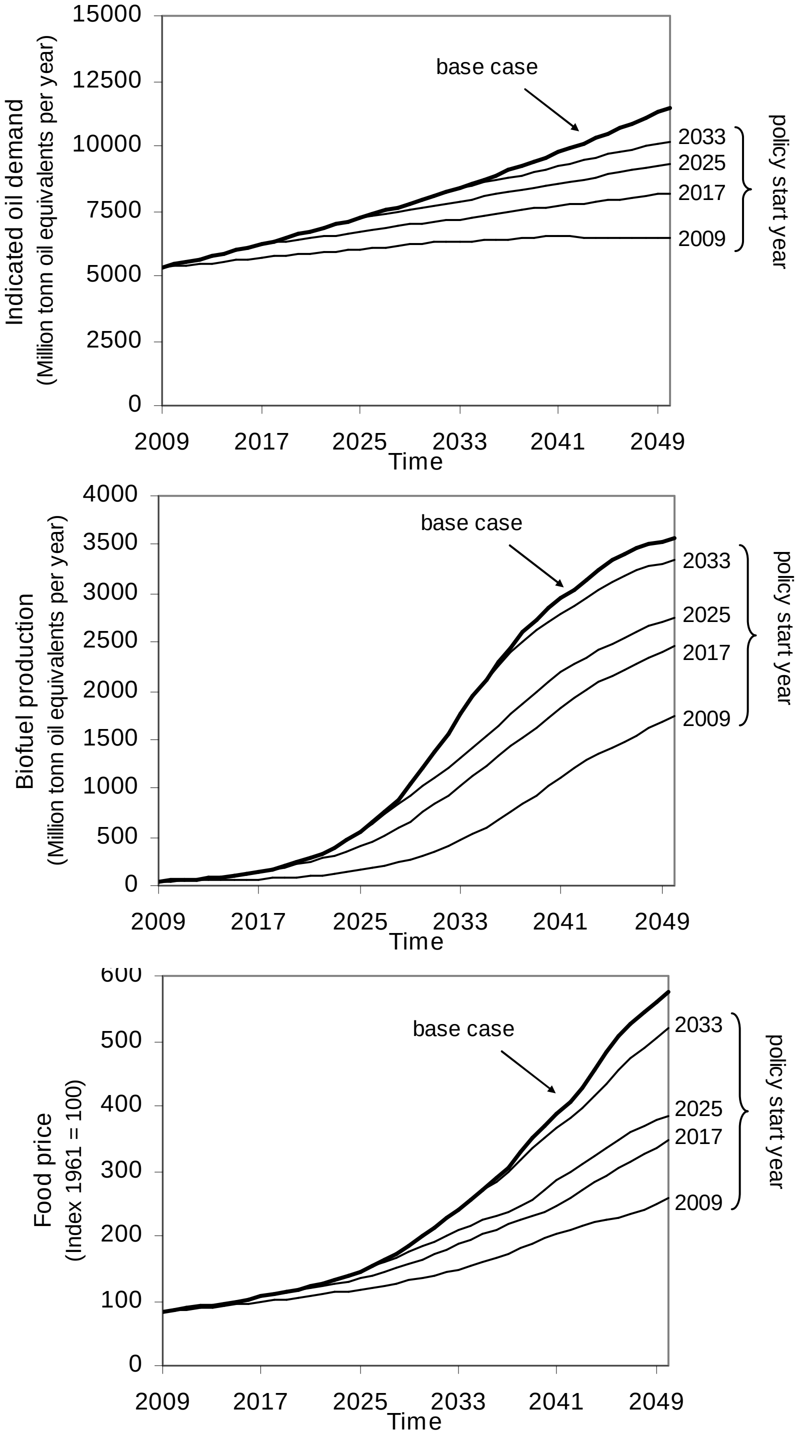


Figure 33: Effect of delaying the alternative policy implementation

7. Conclusion

The process of model building is cyclical and never ending. Taking it as a given that there in the near future is a risk of an oil production peak causing a sharp rise in oil price, simulations using the current model version suggest the policy of supporting food based biofuel production could be laying the foundation of a future food crisis and that an alternative policy needs to be implemented as quickly as possible; most importantly, before policy makers receive feedback signals in the form of a continuous rising food price trend.

Algae based biofuel, second generation biofuels and other new technological solutions and discoveries could of course help increase the supply of both energy and food, but the principle of precaution makes it more advisable to base planning on technologies, ideas and principles already available, tested and proven.

The alternative policy example developed in this thesis could be one of many alternatives and is most certainly not the best, cheapest or most robust policy option available.

It could, in view of the author, be hazardous to base policy decisions regarding issues, with such degree of complexity and uncertainty as long-term food and energy security, exclusively on precise econometric models or the random individual mental models of decision makers. All models are wrong (including mental models), but some are more precisely wrong than others. Robustness, feedback richness and structural consistency is in this case of more value than decimal precision. The use of dynamic computer models can help systematize and connect qualitative and quantitative information together to a structurally consistent whole and, at least potentially, be a useful tool to gain insight about the real world.

If the model presented in this thesis could be of use to others, some of the following research ideas might be worth consideration:

Further research:

The model had a focus on transportable energy. It could be useful to incorporate all energy sources, including non commercial energy, because there are some substitution and reorganization options; for example the substitution of electric heating with bioenergy, the use of more electricity for transport and increasing the efficiency of non commercial energy use. This could also make it possible to avoid using a negative oil reserve stock to represent the transition to alternatives.

Incorporating an OPEC effect into the oil sector could allow longer oscillations and perhaps make the model capable of replicating long cycles in oil price. This could help build model confidence and make it possible to introduce policies at different points in the cycle to test if this affects model behavior.

A more dynamic representation of indicated oil demand would be desirable. The indicated demand should ideally involve a stock that makes future demand growth depend on history and not a predefined theoretic pathway. Attempts were made at this during the modeling process, but a satisfying solution was not found.

It could be interesting to model the key producers of food and biofuel more explicitly. The international food market is dominated by a few major exporters and the three major biofuel producers are amongst these. It could be useful to be able to test scenarios where for example a crop failure in key exporting nations is combined with export restrictions and growth in biofuel production.

Food demand is characterized by such extreme disparities that the current aggregation of demand makes it difficult to assess food security consequences. A division of demand into high middle and low income demand could be one option. It could for this purpose also be useful to distinguish between people owning agricultural land (that can produce their own food), and others.

An alternative to adding detail could be further aggregation to close some loops. The exogenous variables could be made endogenous by incorporating the model into a global model such as World 3-03 (Meadows, 2004). This would, for example, enable feedback from the rising oil price to economic growth and both economic growth and food price could feed back to population. A combination of economic depression and record high food and fuel prices could affect family planning in poor countries, speed up population growth and cause a destructive reinforcing feedback loop.

References:

BP (2007). BP Statistical Review of World Energy June 2007. British Petroleum Available online at: http://www.bp.com/statisticalreview (18.04.08)

Brundtland, Gro Harlem (1987). Our common future. World Commission on Environment and Development. Oxford University Press. Oxford.

Childs, Britt. Bradley, Rob (2007). Plants at the pump: Biofuels, Climate Change and Sustainability. World Resource Institute. Available online at: http://www.wri.org/publication/plants-at-the-pump (09.06.08)

FAO (2000). Energy for agriculture chapter 2. in Environment and Natural Resources Working Paper No. 4. Food and Agriculture Organization. Rome. Available online at: http://www.fao.org/docrep/003/x8054e/x8054e05.htm#P361_53876 (25.04.08)

FAO (2003). The scope of yield increases, chapter 11.1 in: World agriculture: towards 2015/2030. An FAO perspective. Food and Agriculture Organization. Earthscan Publications Ltd. London. Available online at: http://www.fao.org/docrep/005/y4252e/y4252e00.htm#TopOfPage (25.04.08)

Ford, Andrew (1999). Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems. Island Press, Washington

GTZ (2007). International Fuel Prices 2007: 5th Edition - More than 170 Countries. Deutche Gesellschaft für Technische Zusammenarbeit, Eschborn. Available online at: http://www.gtz.de/de/dokumente/en-international-fuelprices-final2007.pdf (18.04.08)

IEA (2006). The Outlook for Biofuels, chapter 14 in World Energy Outlook 2006. International Energy Agency. OECD/IEA.

Meadows, Donella. Randers, Jørgen. Meadows, Dennis (2004). Limits to Growth: the 30-year update. Chelsea Green Publishing. Vermont

Regmi, Anita. ed. (2001). Cross-Country Analysis of Food Consumption Patterns, in Changing Structure of Global Food Consumption and Trade / WRS-01-1. Economic Research Service/USDA. Available online at: http://www.ers.usda.gov/Publications/WRS011/ (08.05.08)

Schmidhuber, Josef (2006). Impact of an increased biomass use on agricultural markets, prices and food security: A longer-term perspective. Paper prepared for the "International symposium of Notre Europe", Paris, 27-29 November, 2006.

Socolow, Rob. Pacala, Stephen (2004). Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. Science 305. 2004: 968-972.

Sterman, John D. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin/Mc Graw-Hill, Boston

World Bank (2008). Biofuels: The Promise and the Risks. Agriculture for Development Policy Brief from World Development Report 2008. available online at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2007/11/08/000310607_20071108120207/Rendered/PDF/41382optmzd0Br1sk0WDR0200801PUBLIC1.pdf (09.06.08)

Appendix

Model constants:

Parameter	Value	Units
Oil sector		
expected oil profit adjustment time	0.1	Year
Initial expected oil price	14.39	USD per barrel
Initial long term price effects on oil demand	1	Dimensionless
Initial oil capacity	520	Million tonn oil equivalents per year
initial oil demand	520	Million tonn oil equivalents per year
initial oil reserves	3000000	Million tonn oil equivalents
Initial short term price effects on oil demand	1	Dimensionless
long term price effects delay	15	Years
long term price elasticity of oil demand	-0.6	Dimensionless
oil capacity adjustment time	3	Years
oil capacity lifetime	15	Years
oil construction adjustment time	0.1	Year
oil construction time	10	Years
oil price sensitivity	8	Dimensionless
oil refinement and distribution	25	USD per barrel
short term price effects delay	0.75	Year
short term price elasticity of oil demand	-0.08	Dimensionless
time to adjust expected oil price	1	Year
traditional oil price adjustment time	15	Years
Food sector		
expected food costs adjustment time	1	Year
expected food price adjustment time	1	Year
food demand adjustment time	1	Year
price elasticity of food demand	-0.2	Dimensionless
initial human food demand	1900	Million tonnes per year
initial food price	130	Index (100=1961)
Initial food production as fraction of potential	0.6	Dimensionless
Initial sensitivity to oil price	0.03	Dimensionless
minimum food production adjustment time	1	Year
oil price sensitivity adjustment time	15	Years
sensitivity of food price to food costs	0.2	Dimensionless
sensitivity of food price to food balance	2	Dimensionless
Biofuel sector		
100 Mtoe biofuel reference	100	Million tonn oil equivalents
average life of biofuel capacity	20	Years
biofuel capacity adjustment time	3	Years
biofuel construction time	4	Years
biofuel supply line adjustment time	1	Year
conversion to million USD per Mtoe	7.33	Million USD per Mtoe / USD per barrel
expected biofuel profit adjustment time	1	Year
Initial accumulated biofuel production	0	Million tonn oil equivalents
Initial biofuel capacity	0	Million tonn oil equivalents
initial feedstock price	80	Million USD per Million tonn oil equivalent
other biofuel production costs	235	Million USD per Million tonn oil equivalent