A Dynamic Analysis of Socio-Technical Transition towards Bio-Economy

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Abstract

Bio-economy is a complex socio-technical system undergoing rapid change. There is a significant risk of not achieving the full potential of bio-economy due to suboptimal solutions, and therefore a system dynamics model applied to analyse transformation from fossil based economy into bio based economy is introduced. The model is based on interviews conducted with Finnish bio-economy stakeholders, literature review, and VTT bio-economy experts. The purpose of the model is to act as an interaction and dissemination enabler as well as evaluation and specification tool for stakeholders and a basis for further research.

Contribution of this paper is to analyse the interconnections and feedback structures of fossil and bio-economies. These two economies are co-existing side by side, fossil-economy being currently the dominant one. However, there is significant political will on national and EU level to shift towards bio-economy. This idea is mainly driven by the climate change, i.e. need to reduce greenhouse gas emissions. Interviews show that there is a wide understanding concerning the importance of bio-economy, however, something is lagging or preventing the transition. The purpose is to analyse restrictions hindering and enablers accelerating the transition.

1 Introduction

It is difficult to debate the bioeconomy and the related changes in the socio-technical systems because the stakeholders have differing definitions for the term “bio-economy”. Some consider only the aspects regarding production and use of renewable resources (Valtioneuvoston kanslia 2010), while others also take social sustainability (Asveld et al. 2011) and wider change throughout the society (Luoma et al. 2011; Kuisma 2011) into account. In the broader definitions bio-economy challenges the siloed industries of the prevailing economic system. Therefore, transition to bio-economy means a whole new paradigm with new business models and new kind of national and international policies.

There are many drivers for bio-economy; the most important may be the battle against climate change. The EU has demanding goals for greenhouse gas emission reductions and the quote from the European Commission’s climate action website explains this policy.

> “Preventing dangerous climate change is a strategic priority for the European Union”
> (European Commission 2012)

The EU target for the year 2020 is 20% decrease in emissions in comparison with the 1990 levels and the target for 2050 is an 80-95% decrease in comparison with 1990 levels. The use of biomass in energy production is one way of achieving these targets (European Commission 2012).

The bio-economy case presented in this paper involved researchers from VTT with different backgrounds and competences: system dynamics modelling, discourse analysis, stakeholder analysis, foresight, and impact assessment. Eleven interviews were conducted during the first phase of the case. Interviewees were representatives of different bio-economy stakeholders, such as authorities, funders, industry, R&D, NGOs, and influential independent thinkers. After the interviews feedback was gathered from VTT bio-economy experts.

The project started by interviewing the key stakeholders. The semi-structured interviews were then analysed to identify the prevailing discourses in the bio-economy debate. The point in discourse analysis is to shed light on how stakeholders understand bio-economy. This was an important step as the underlying assumptions affect the way bio-economy is promoted and constructed, which further influences, for instance, which industries and sectors of administration are seen important in the transition. For example, one interviewee expressed his frustration about how the prevailing discourse underestimates new bio-innovations and rather focuses on energy questions only.

The current regime needs to be challenged but the interviewees disagreed on the actual future paths. They, however, shared a view that radical changes are needed and many of them promoted niche innovations. However, there is significant path dependency in the system, and the existing regime is not easily replaced by niches or other novel formations. Another possible option is endogenous transformation, in which existing companies change the regime (Bouza et al. 2009). Here, however, the risk is that existing companies only concentrate on incremental improvements.

Based on the interviews, a stakeholder analysis was carried out to understand who has legitimacy, power, and vision. Eight different stakeholder groups were formed based on this division: sleeping, discretionary, demanding, dominating, contender, dependent, definitive, and outsiders. Stakeholder analysis included identifying stakeholders' theories about the future transition paths, i.e. identifying the most likely and the most desired transition paths. This was a major step in the process, because at the moment the field is spread out among different actors and no one has a clear picture of who actually has salience. Multi-level perspective (MLP) approach (Geels 2004; Geels 2012) was used to map the transition paths of niches, regimes, and landscape. From a system dynamics point of view this helps identifying who can affect specific parts of the system, and the transition paths can be used, in a sense, as reference modes.

Understanding the current discourse and roles of the stakeholders is highly important in bio-economy, because the topic is politically sensitive, and therefore, for example, if proceeding into workshops it is important to understand the possible tensions between the stakeholders to ensure a productive and innovative atmosphere.

2 Modelling Bio Economy

The research question clarified during the interviews and can be crystalized as follows: Which factors support and which restricts sustainable transition from fossil economy to bio-economy? How are the fossil and bio-economy linked together dynamically?

To the modelling process, the interviews were invaluable in identifying key variables and their interconnections. Therefore, we started the model sketching at the same time the interviews started and the model was updated after every interview. Also possible carriers and barriers were identified during the interviews, e.g. regulation, raw material price changes, lack of business skills, and risk avoidance.

The most important feedback loops in the model are: 1) economic growth through investments (D. H. Meadows et al. 1972; Randers 2000), 2) resource depletion (Bossel 2007), 3) pollution, and 4) learning by doing (Struben & Sterman 2008). The same structure is used for both fossil and bio-economy with minor modifications in the equations. The rough division of fossil and bio-economy in the model is as follows: bio-economy contains all renewable raw materials and fossil economy contains all non-renewable raw materials. Other feedback loops and variables were also identified from the interviews and not all are covered in this paper. A simplified simulation model is presented in Figure 1.

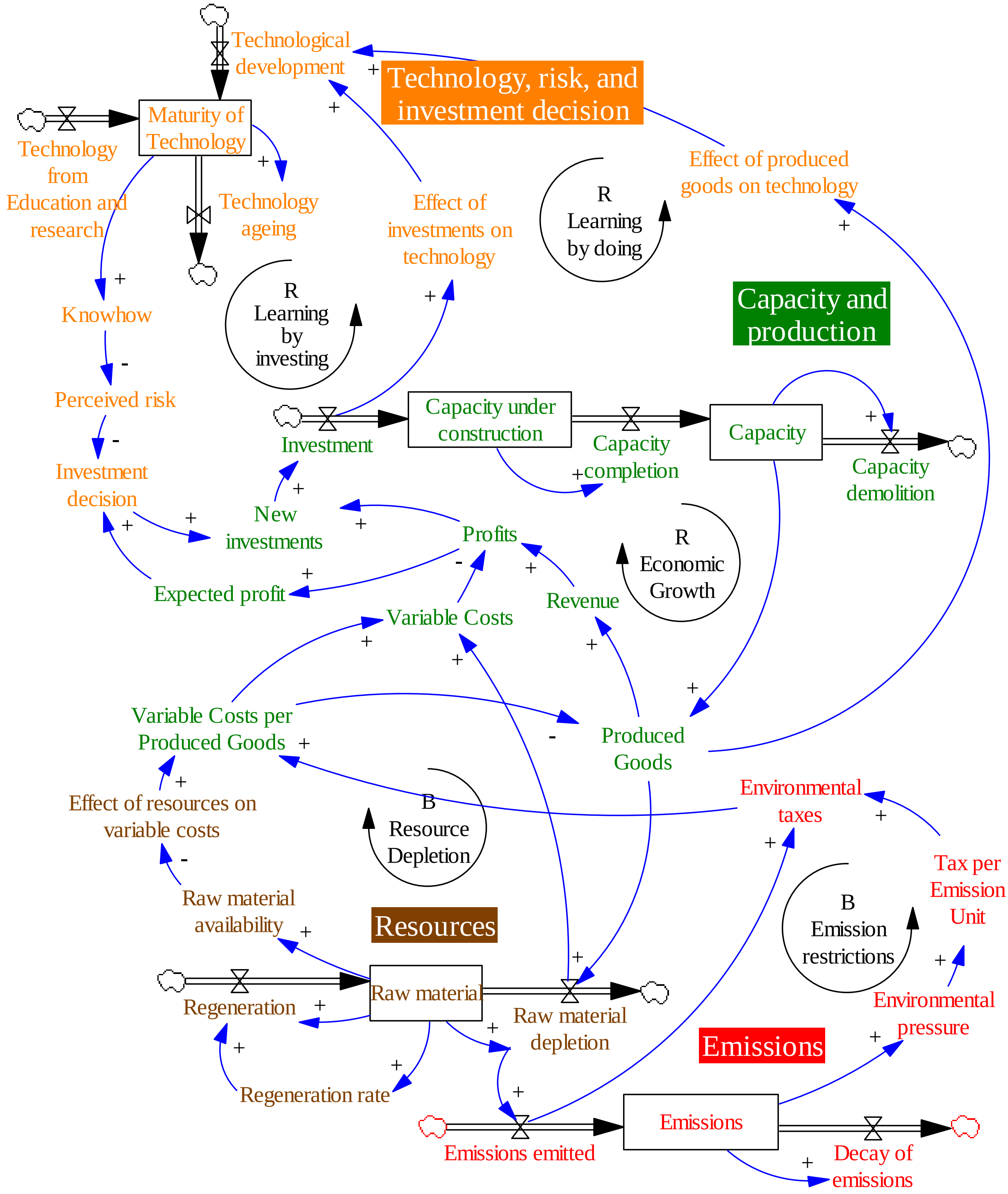

Figure 1: A simplified simulation model.

2.1 Capacity

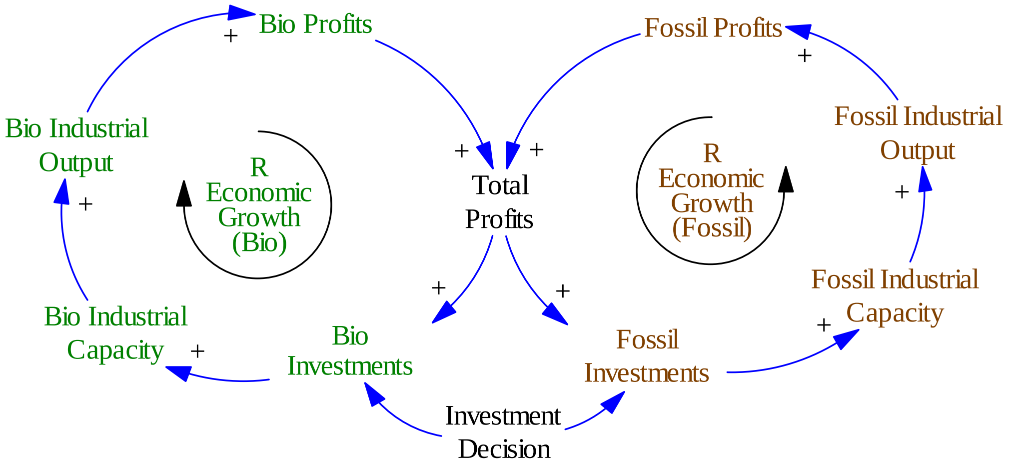

Figure 2: Economic Growth from bio and fossil economy perspective

The model is built based on the positive feedback loop, *Economic Growth* (Figure 2), describing the idea behind the exponential growth in economic output (D. H. Meadows et al. 1972; Randers 2000). The economic growth is divided into fossil and bio sub models. As seen in Figure 2, these two economies are linked through total profits and investment decision, and therefore decisions in fossil economy affect bio-economy. For example, if fossil economy shrinks before bio-economy increases, then there may not be profits to invest. Thus the shift from fossil to bio-economy should take place in a way where the total profits increase all the time; this means that bio investment options should be profitable and desirable before possible restrictions to fossil based economy.

Capacity is divided into capacity under construction and capacity. This way risky investments are taken into consideration in the model; the more risk taken, the more capacity completion failure is actualized.

$$x = \begin{array}{l} f = fossil, \\ b = bio \end{array} \tag{1}$$

$$\frac{d}{dt} Capacity_x = Capacity\ completion_x + Capacity\ demolition_x \tag{2}$$

$$Capacity\ completion_x = \frac{Capacity\ under\ construction_x}{Capacity\ completion\ time} * Capacity\ success\ \% \tag{3}$$

$$Capacity\ demolition_x = \frac{Capacity_x}{Average\ lifetime\ of\ capacity} \tag{4}$$

$$\frac{d}{dt} \begin{array}{c} Capacity\ under \\ construrtion \end{array}_x = \begin{array}{r} Investment_x + Capacity\ completion\ failures_x \\ - Capacity\ completion_x \end{array} \tag{5}$$

$$Capacity\ completion\ failure_x = \frac{Capacity\ under\ construction_x}{Capacity\ completion\ time} * (1 - Capacity\ success\ \%) \tag{6}$$

Profits from fossil and bio-economy are added together, and depending on the investment decision and target growth rate they are allocated to fossil or bio investments. In this model only profits can be invested, i.e. capital stock is not modelled, which may be taken into consideration in updated model version. Capital stock would give time to have negative profits and still investing, and therefore preventing death spiral in the short-term.

$$Profits_x = Revenue_x - Fixed\ Costs_x - Variable\ Costs_x \tag{7}$$

$$Total\ profits = \sum_x Profits_x \tag{8}$$

$$\begin{aligned} Investment_x = {} & IF\ THEN\ ELSE\ (Target\ growth\ rate < Total\ profits, \\ & Target\ growth\ rate, Total\ profits) \\ & * \frac{Investment\ decision_x}{Capacity\ value} \end{aligned} \tag{9}$$

Profits depend on revenue, fixed costs, and variable costs. Revenue depends on produced goods and the price they are sold. Price is treated as a constant in this model, i.e. price is not depending on demand and supply.

$$Revenue_x = Price_x * Produced\ Goods_x \tag{10}$$

$$Fixed\ costs_x = Capacity_x * Fixed\ Costs\ per\ Capacity\ Unit_x \tag{11}$$

$$\begin{aligned} Variable\ costs_x = {} & Raw\ material\ utilization_x \\ & * Variable\ Costs\ per\ Resource\ Unit_x \end{aligned} \tag{12}$$

$$\begin{aligned} {Variable\ Costs\ per\ Resource\ Unit}_x = {} & Default\ variable\ costs_x \\ & + Effect\ of\ resources\ on\ variable\ costs_x \\ & + \text{Environmental taxes} \end{aligned} \tag{13}$$

$$Price_x = Default\ price_x \tag{14}$$

$$Capacity\ success\ \%_x = Effect\ of\ risk_x \tag{15}$$

Variable	Value	Unit	Description
$Average\ lifetime\ of\ capacity$	20	$Year$	Average lifetime of capacity
$Target\ growth\ \%$	0.015	$\frac{1}{Year}$	Target growth of capacity
$Capacity\ under\ construction\ INITIAL_x$	0.6, 0.1	$Capacity\ Unit$	Initial amount of capacity under construction
$Capacity\ INITIAL_x$	5, 0.6	$Capacity\ Unit$	Initial amount of capacity
$Default\ variable\ costs_x$	0.7, 0.7	$\frac{€}{Resource\ Unit}$	Default resource unit cost
$Fixed\ Costs\ per\ Capacity\ Unit$	0.1	$\frac{€}{Capacity\ U. * Year}$	Amount that keeping a capacity unit costs annually
$Default\ price$	1	$\frac{€}{Goods}$	Price gained from producing goods
$Capacity\ value$	1	$\frac{€}{Capacity\ Unit}$	The value of capacity

2.2 Maturity of Technology, Investment Decision, and Risk

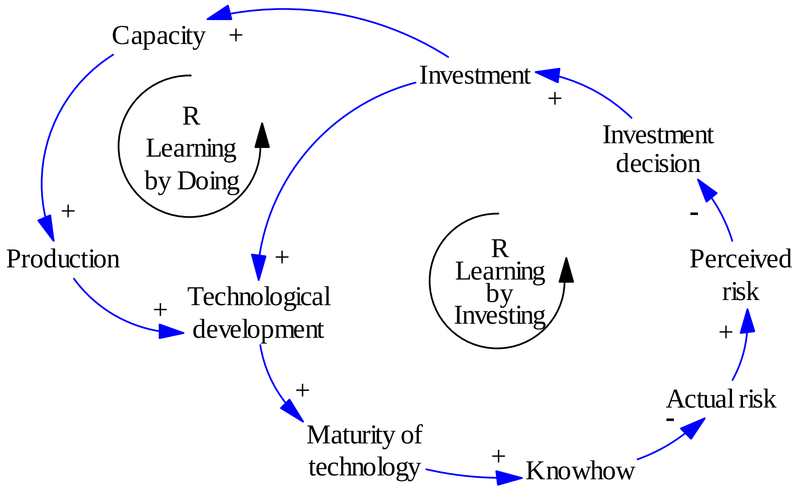

Figure 3: Learning-by-doing and learning-by-investing

*Learning-by-*Doing and *Learning-by-Investing* are reinforcing loops, which are the same for both fossil and bio economies. When producing goods or building new capacity technological development will take place. Research and education are exogenous variables increasing the maturity of technology.

*Learning-by-*Doing and *Learning-by-Investing* strategies may cause stress to the ecosystem. Asveld et al. (2011) mention, that large scale usage of biomass does not ensure sustainability, because when starting to use underdeveloped processes the first generation products may be unsustainable. This effect may cause undesired response in demand and in media, which may slow down the transition to bio-economy. *Learning-by-doing* is mainly promoted by trade and industry (Asveld et al. 2011). On the other hand, research is mainly promoted, unlike learning-by-doing, by environmental organisations, because of the fear that learning-by-doing may harm the environment and society, as has happened on some level with biofuels (Asveld et al. 2011). New innovations and knowhow will decrease industry's emissions, and therefore it will decrease environmental impact.

Maturity of Technology increases when new technology is developed and research is done, and decreases when technology is ageing. *Research* is an external variable.

$$\frac{d}{dt} Maturity\ of\ Technology_x = New\ technology_x + Research_x - Technology\ ageing_x \tag{16}$$

$$New\ technology_x = Effect\ of\ investments\ on\ experience_x + Effect\ of\ produced\ goods\ on\ experience_x \tag{17}$$

$$Technology\ ageing_x = \frac{Maturity\ of\ Technology_x}{Average\ lifetime\ of\ technology} \tag{18}$$

$$Effect\ of\ produced\ goods\ on\ technogy_x = Produced\ Goods_x * EoPG \tag{19}$$

$$Effect\ of\ investments\ on\ technogy_x = Investments_x * EoI \tag{20}$$

Variable	Value	Unit	Description
$EoPG$	0.004	$\frac{Technology\ Unit}{Goods}$	Effect of produced goods on technology multiplier
EoI	0.04	$\frac{Technology\ Unit}{Capacity\ Unit}$	Effect of investments on technology multiplier
$Average\ lifetime\ of\ technology$	30	$Year$	
$Education\ and\ research\ DELAY$	10	$Year$	How long it takes on average for the research and education to affect the technology

Most of the interviewees mentioned risk, especially low risk taking ability, as a reason why new bio-economy firms and investments are rare. This was mentioned to be a problem not only in the field of bio-economy, but also overall in Finnish society. At the moment bio investments are seen highly risky due to low technological maturity and knowhow. There is also a strong need for successful bio investment examples. In the model investment decision is done based on the expected profit and the perceived risk.

Knowhow depends on maturity of technology, i.e. technology determines what kind of knowledge is available for the economies. Because of spillover, knowledge can be drawn also from other field. Spillover parameter (sp) describes how much of the technological advantages of fossil economy can be utilized in bio economy, and vice versa. Exponent α describes the sensitivity of knowhow to maturity of technology.

$$Knowhow_f = Knowhow\ REF_f * \left(\begin{matrix} sp * \left(\frac{Maturity\ of\ Technology_f}{Maturity\ of\ technology\ REF}\right)^{\alpha} \\ +(1-sp) * \left(\frac{Maturity\ of\ Technology_b}{Maturity\ of\ technology\ REF}\right)^{\alpha} \end{matrix} \right)^{\frac{1}{\alpha}} \quad (21)$$

$$Knowhow_b = Knowhow\ REF_b * \left(\begin{matrix} sp * \left(\frac{Maturity\ of\ Technology_b}{Maturity\ of\ technology\ REF}\right)^{\alpha} + \\ (1-sp) * \left(\frac{Maturity\ of\ Technology_f}{Maturity\ of\ technology\ REF}\right)^{\alpha} \end{matrix} \right)^{\frac{1}{\alpha}} \quad (22)$$

Perceived risk depends on knowhow. Exponent β describes the sensitivity of perceived risk to knowhow.

$$Perceived\ risk_x = Risk\ REF_x * \left(\frac{Knowhow_x}{Knowhow\ REF_x}\right)^{-\beta} \quad (23)$$

Expected profit percentage is simply the current profit percentage without negative values.

$$Expected\ profit\ \%_x = MAX(0, Profit\ \%_x) \quad (24)$$

Investment willingness depends on perceived risk and expected profit. Parameter δ describes the emphasis between risk avoidance and profit seeking, i.e. $\delta = 0$ means that investment willingness is based only on expected profit and $\delta = 1$ means that investment willingness is based only on perceived risk. Interviewed stakeholders see Finland as a highly risk avoidant country. Parameter γ describes the sensitivity of investment willingness to perceived risk and expected profit.

$$Investment\ willingness_x = Investment\ willingness\ REF * \left(\begin{array}{c} \delta * \left(\frac{Perceived\ risk_x}{Risk\ REF_x}\right)^{-\gamma} \\ +(1-\delta) * \left(\frac{Expected\ profit\ \%_x}{Profit\ \%\ REF}\right)^{\gamma} \end{array} \right)^{\frac{1}{\gamma}} \tag{25}$$

Investment decision is made based on investment willingness. However, always at least 5% of the investments are going to both of the economies, because it is assumed that bio products cannot replace all fossil based products and vice versa.

$$Investment\ decision_f = \frac{Investment\ willingness_f}{\sum_x Investment\ willingness_x} \tag{26}$$

$$Investment\ decision_b = \frac{Investment\ willingness_b}{\sum_x Investment\ willingness_x} \tag{27}$$

High risk taking affects the amount of capacity under construction which will fail.

$$Effect\ of\ risk_x = (1-EoR) + \left(1 - \frac{Perceived\ risk_x}{\sum_x Perceived\ risk_x}\right) * EoR \tag{28}$$

In their main findings Gustafsson et al. (2011) state that one important aspect needed for blooming bio economy is the ability to work as a part of the system. This means co-operation instead of competition. Furthermore they suggest that incentives for co-operation (benefit and risk sharing) need to be developed by some stakeholder. In the model investment decision is based on risk and expected profits. Profits can be affected, for example, by taxes and subsidies, but perceived risk is more difficult to affect. The emphasis between risk avoidance and profit seeking is affected by culture and may therefore be very difficult to manipulate.

Variable	Value	Unit	Description
α	1	$Dmnl$	Sensitivity of knowhow
β	1	$Dmnl$	Sensitivity of perceived risk
γ	1	$Dmnl$	Sensitivity of investment willingness
sp	0.9	$Dmnl$	Spillover parameter: (1 – sp) determines how much fossil technology benefits from bio technology and vice versa.
Maturity of technology REF	1	$Technology\ Unit$	Reference value for maturity of technology
Knowhow REF	1	$Knowhow\ Unit$	Reference value for knowhow
Risk REF	1	$Risk\ Unit$	Reference value for risk
Investment willingness REF	1	$Investment\ willingness\ Unit$	Reference value for investment willingness
Profit % REF	0.1	$\frac{1}{Year}$	Reference value for profit percentage
δ	0.7	$Dmnl$	Emphasis between risk avoidance and profit seeking.
EoR	0.1	Dmnl	Effect of risk on capacity completion failure

2.3 Resources and production

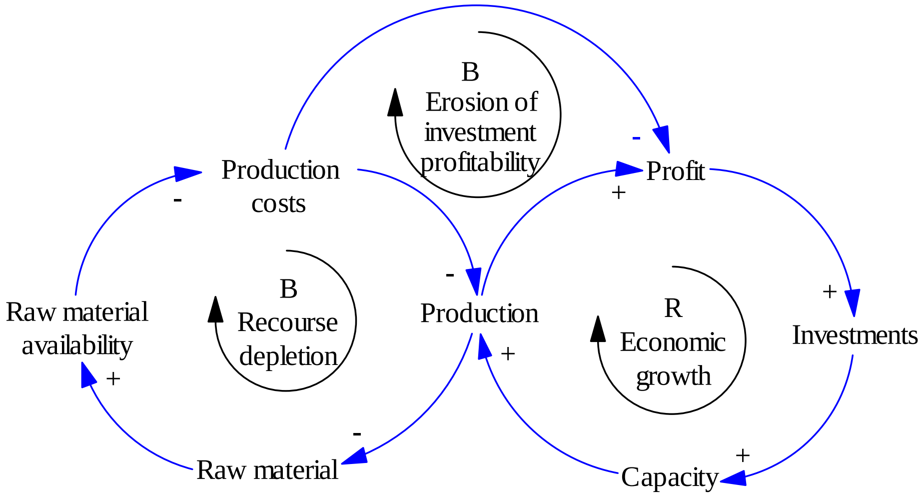

Figure 4: Natural resource depletion, economic growth, and erosion of investment profitability

Natural Resource Depletion and Erosion of investment profitability are balancing feedback loops limiting the economic growth in long-term. The basic ideas of these loops are the same for fossil and bio-economy, but because of the renewability of bio resources they work a bit differently. Fossil economy confronts resource depletion inevitably leading to decline in fossil based industrial output in long-term. The growth of bio-economy will also be restricted by the same loop at some point, although this depends on the raw material and geographical area. Resource restriction will not necessarily lead to decline in bio based industrial output, if sustainability is maintained and new bio based raw materials are invented and taken into usage (e.g. algae). It is worth noticing that if bio based raw materials start replacing fossil based raw materials in large scale and the exploitation of fossil raw materials decrease, this could slow down the increase of fossil raw material prices and slow down the transition.

Natural resource depletion also relates to food. At some point, when bio economy grows, the biomass supply limits are confronted and then bio based industries may start competing with food industry, which may cause increase in food prices. Increasing food prices may, for example, lead to social unrest, e.g. protests against bio-economy.

The amount of raw materials changes through regeneration and utilization.

$$\frac{d}{dt}Raw\ material_x = Regeneration_x - Raw\ material\ utilization_x \tag{29}$$

Regeneration for fossil raw materials is zero, and the regeneration of bio raw materials depend on the regeneration rate and the amount of raw materials. Used lookup tables are presented in Figure 5-8.

$$Regeneration_f = 0 \tag{30}$$

$$Regeneration_b = Regeneration\ rate_b * Raw\ material_b \tag{31}$$

$$Regeneration\ rate_b = Regeneration\ rate\ LOOKUP\left(\frac{Raw\ material_b}{Raw\ material\ INIT_b}\right) \tag{32}$$

Raw material utilization depends on the production and technological development (how much raw materials are used per goods).

$$Raw\ material\ utilization_x = Produced\ Goods_x * Raw\ material\ needed\ for\ production_x \tag{33}$$

$$Raw\ material\ availability_x = Raw\ material\ availability\ LOOKUP_x\left(\frac{Raw\ material_x}{Raw\ material\ INIT_x}\right) \tag{34}$$

$$\begin{matrix} Effect\ of\ resources \\ on\ variable\ costs \end{matrix}_x = Effect\ on\ costs\ LOOKUP(Raw\ material\ availability_x) \tag{35}$$

$$\begin{aligned} Produced\ goods_x = {} & Effect\ of\ markup\ \%\ on\ production_x * \ Capacity_x \\ & * \ Production\ per\ capacity \end{aligned} \tag{36}$$

Technological development decreases the needed amount of raw materials for production. Technological development depends on knowhow and the sensitivity parameter θ.

$$\begin{matrix} Raw\ material\ needed \\ for\ production \end{matrix}_x = \frac{Raw\ material\ needed\ for\ production\ REF}{Technological\ development{:}\ Needed\ raw\ material} \tag{37}$$

$$Technological\ development_x = Technological\ development\ REF * \left(\frac{Knowhow_x}{Knowhow\ REF_x}\right)^{\theta} \tag{38}$$

Markup affects the production. The lower the markup, the less is produced.

$$\begin{matrix} Effect\ of\ markup\ \% \\ on\ production \end{matrix}_x = \begin{aligned} & MAX(0, MIN(1, 1 + Expected\ markup\ \%_x \\ & - Desired\ markup\ \%)) \end{aligned} \tag{39}$$

$$Expected\ markup\ \%_x = \frac{Price_x - Variable\ Costs\ per\ Produced\ Goods_x}{Variable\ Costs\ per\ Produced\ Goods_x} \tag{40}$$

Variable	Value	Unit	Description
Fossil raw material INIT	3000	$Resource\ Unit$	Initial value for fossil raw materials
Bio raw material INIT	100	$Resource\ Unit$	Initial value for bio raw materials
Desired markup %	0.25	Dmnl	Desired markup percentage
θ	0.2	Dmnl	Sensitivity of technological development

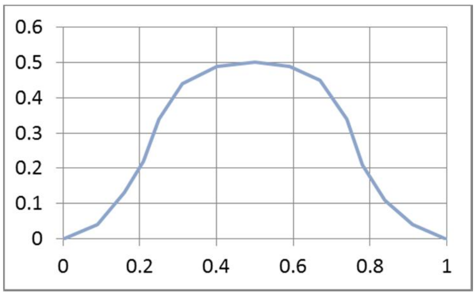

Figure 5. Regeneration rate LOOKUP

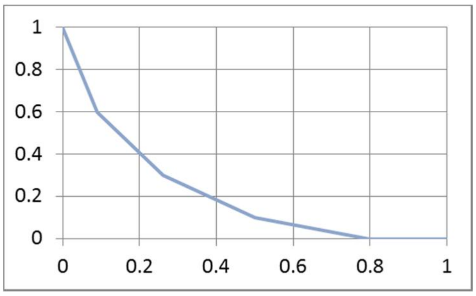

Figure 6. Effect on costs LOOKUP

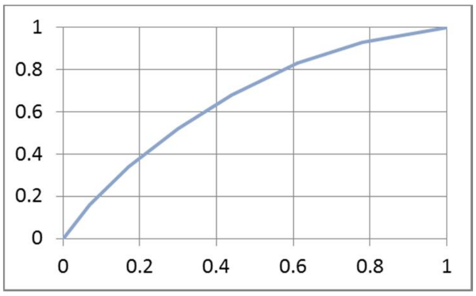

Figure 7. Fossil raw material availability LOOKUP

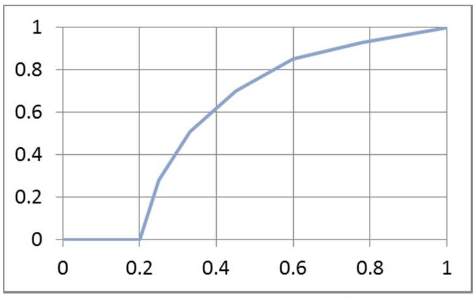

Figure 8. Bio raw material availability LOOKUP

2.4 Emissions

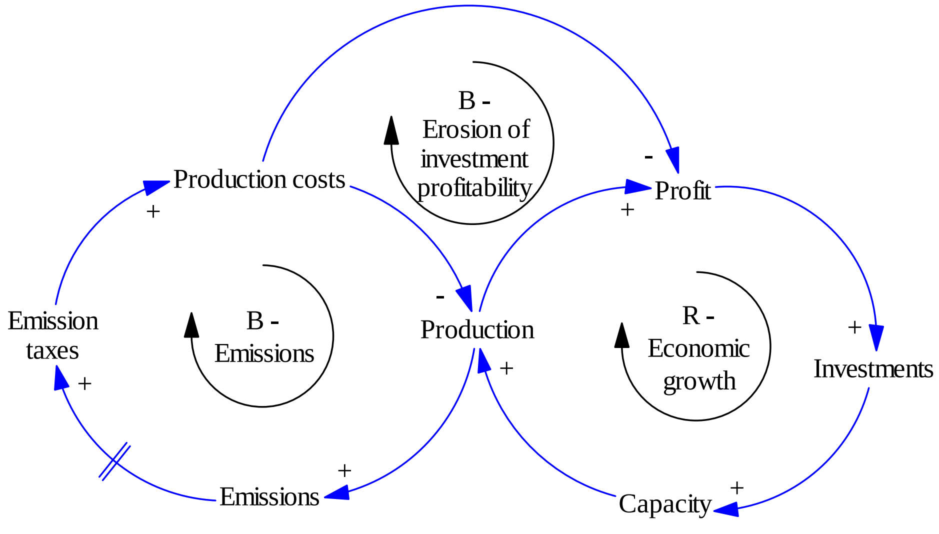

Figure 9: Emissions, economic growth, and erosion of investment profitability

The political goal to reduce emissions and prevent disturbances in ecosystem shapes the bio economy discussion. EU (and other international) agreements call for emission reductions in greenhouse gases, and the long-term goal is zero. In the model emissions include CO2 emissions, ozone layer destruction, environmental problems, bio-diversity decline etc. Bio-economy is seen less polluting than fossil economy; especially it is expected to be a solution for CO2 emissions. However, this is not always the case and bio-economy may also cause the same or different problems, e.g. decline in bio-diversity and deforestation. An example of this is the first generation biofuels, which are blamed for causing destruction of forests in developing countries and competing with food production. Therefore the bio industrial output does not decrease the impact of industrial output on the environment (decreases in some place, but causes other problems in other places). Thus the impact of bio-economy on the environment depends largely on the maturity of new bio innovations. Regardless of the bio-economy problems the EU has set demanding goals for greenhouse gas reductions, as already discussed, and the emission restrictions are going to restrict fossil economy harder. In the short-term the *Emissions* loop may be the most important feedback loop restricting fossil economy, as raw material depletion has not caused dramatic increase in raw material prices.

Emissions loop is a balancing feedback loop limiting the economic growth. The basic idea of these loops is the same for fossil and bio-economy. However, in case of bio-economy these loops are significantly weaker, in best case non-existent, because bio production is assumed to cause less emission than fossil production. The long delays in this loop can cause two kinds of behaviour: 1) Delays are taken into consideration and actions are taken beforehand, and therefore an acceptable level of emissions is reached and maintained. 2) Restrictions are set late because of the delays, and an overshoot in emissions is observed. When considering greenhouse gas emissions, this is the current state of the system, e.g. CO2 emissions are too high and they are needed to decrease, or at least stabilized at the current level. Emission restrictions will increase the costs of raw material utilization, and therefore they may decrease the profitability of investments, and therefore kick back on the economy.

Fossil economy can also decrease the emissions with new innovations, which would reduce the need for change. This kind of incremental maturation of the old system can slow down (or even stop) the transition to bio-economy. Relevant technologies could be, for example, CCP (carbon capture and storage), which could decrease the emissions of fossil based industrial output significantly, and therefore keep the utilization of fossil raw material acceptable.

The amount of emissions changes through emitting and decay of emissions.

$$\frac{d}{dt} Emissions = Emissions\ emitted_x - Decay\ of\ emissions_x \tag{41}$$

Emissions emitted depend on the usage of resources and the share of carbon free technology.

$$Emissions\ emitted = Emissions\ per\ used\ resource * Raw\ material\ depletion_f * (1 - "Carbon\ free\ technology\ \%") \tag{42}$$

$$Decay\ of\ emissions = \frac{Emissions}{Average\ lifetime\ of\ emissions} \tag{43}$$

Environmental pressure and therefore environmental taxes depend on the emissions emitted per year and the amount of emissions in the environment.

$$Environmental\ pressure = DELAY3\ (Emissions\ , Environmental\ pressure\ delay\ ) * Effect\ of\ Emissions\ on\ Environmental\ Pressure \tag{44}$$

$$Tax\ per\ Emission\ Unit = Environmental\ pressure * Tax\ per\ Emission\ Unit\ REF \tag{45}$$

$$Environmental\ taxes = DELAY1I(\frac{Emissions\ emitted * Tax\ per\ Emission\ Unit}{Raw\ material\ utilization_x}, 1{,}0)) \tag{46}$$

Variable	Value	Unit	Description
$Emissions\ per\ used\ resource$	0.01	$\frac{Emission\ Unit}{Resource\ Unit}$	Emission units emitted per used resource unit.
$Average\ lifetime\ of\ emissions$	20	$Year$	Average lifetime of emissions in

			the environment.
$Effect\ of\ Emissions\ on\ Environmental\ Pressure$	1	$\frac{Dmnl}{Emission\ Unit}$	Effect of emissions on environmental pressure.
$Environmental\ pressure\ delay$	15	$Year$	Time that takes for the political system to react to environmental pressure.
$Tax\ per\ Emission\ Unit\ REF$	10	$\frac{€}{Emission\ Unit}$	How much every emissions unit is taxed.

3 Simulations

Base case and 14 different scenarios are simulated and analysed. The purpose of the simulations is to understand possible behavioural modes the system is capable of producing. Used parameter values are presented in Table 1. *Starting year of policies* indicate the year policies are taking place. Default value is year 2012. A blank cell means that the value is kept the same as in the base scenario. Notation * means relative value, i.e. if default value is 1 and policy value is 2, then the policy value is twofold the default value. *Target growth %* determines how fast the capital stock is wanted to grow. Emission tax determines how much emitted emissions are taxed. *Risk vs profit* determines is which one of risk and profit is more emphasised. Raw material default initial values are set so high that they are not restricting the utilization of raw materials. *Carbon free technology* parameter determines how fast the carbon free technology is taken into usage.

Table 1. Parameters that are changed in the simulations. "Starting year of policies" indicate the year policies are taking place. Default value is year 2012. A blank cell means that the value is kept the same as in the base scenario. Notation * means relative value, i.e. if default value is 1 and policy value is 2, then the policy value is twofold the default value.

	Starting year of policies	Target growth %	Emission tax	Risk vs profit	Bio raw material INIT	Fossil raw material INIT	Carbon free technology
Base case	2012	1.5	0	0.7	1*	1*	1*
P1	-	-	10	-	-	-	-
P2	-	-	10	0.5	-	-	-
P3	-	-	10	0.5	-	-	0
P4	-	-	10	0.5	-	-	2
P5	-	-0.5	10	-	-	-	-
P6	-	3.5	10	-	-	-	-
P7	-	-	17	-	-	-	-
P8	-	-	18	-	-	-	-
P9	-	-	19	-	-	-	-
P9-2	-	-	19	-	-	-	2
P10	-	-	-	-	-	0.2	-
P11	-	-	12	-	-	0.2	2
P12	-	-	-	0.4	-	0.2	2
P13	-	-	12	0.4	-	0.2	2

Base case values are not to be treated as true values, because the point of the simulations are not to make predictions but to show how the feedback loops are causing different behaviour. For instance, *Risk vs profit* is set to 0.7 because the interviewees said that the risk taking ability is generally low, and therefore the parameter is set to emphasize lower risk at profit seeking's expense. The scenarios P1 – P13 should always be compared to the base case.

3.1 Base case, P1, P2, P3, and P4

In the base case the total capacity is increasing 1.5% per year and nothing is restricting the positive feedback loop of economic growth. The profits are rising and risk is getting smaller because of maturing technology. The share of bio-economy is growing steadily, but slowly, and the growth of emitted emissions is stopped. From the total economy's point of view this is a desirable outcome, however, this does not satisfy the EU emission restrictions. Different policies, see Table 1, to reach the EU goals are studied in scenarios P1 – P13. The goals in these simulations are to ensure economic growth (growth of total capacity) and environmental sustainability (sustainability of raw materials and decrease of emissions).

In scenarios P1, P2, P3, and P4, see figures 12-17, *Emission tax* is set to 10 and *Risk vs profit* and *Carbon free technology* parameters are altered. Already implementing emission tax, scenario P1, is able to increase the share of bio-economy and decrease emissions with only minor effect on total capacity, because the emission tax affects profits, and therefore channels investments into bio-economy. In scenario P2 the risk taking ablitity is increased a bit, which causes minor improvements. In the scenario P3 the development of carbon free technologies is set to zero and in P4 doubled. In P3 the share of bio-economy is growing rapidly, however, this alone cannot decrease the amount of emissions, it can only stop the growth. In scenario P4 the development of carbon free technology causes the amount of emitted emissions to decrease significantly. On the other hand, this causes the share of bio-economy to stay a bit lower than in scenario P1, because the impact of emission taxes is lower, and therefore keeping the fossil economy more profitable.

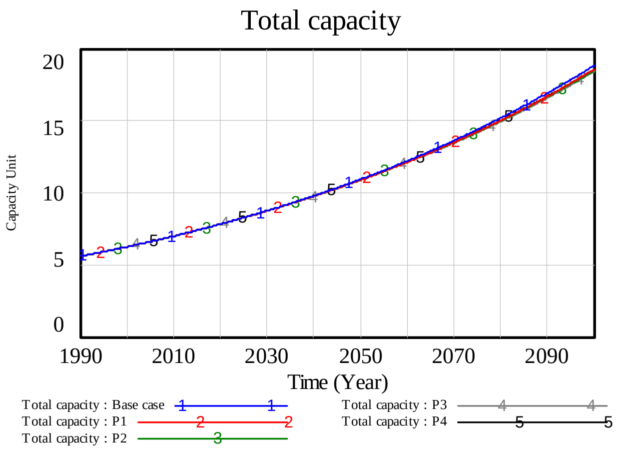

Figure 10. Total capacity.

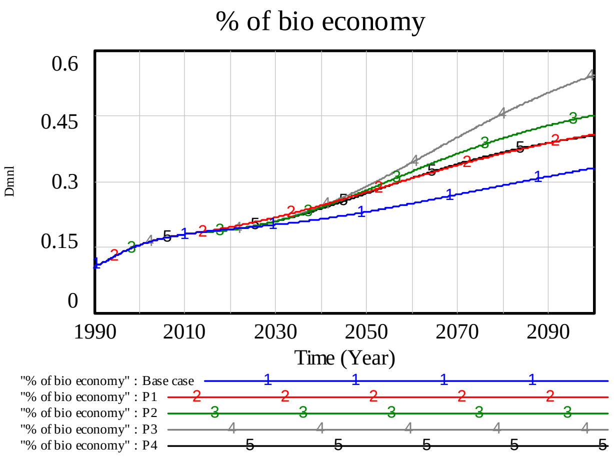

Figure 11. Share of bio-economy.

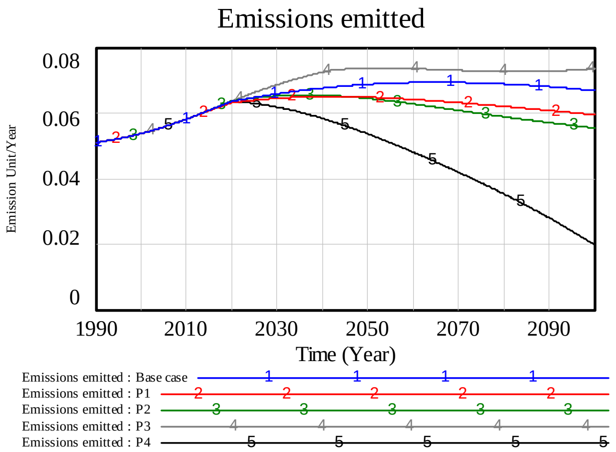

Figure 12. Emissions emitted.

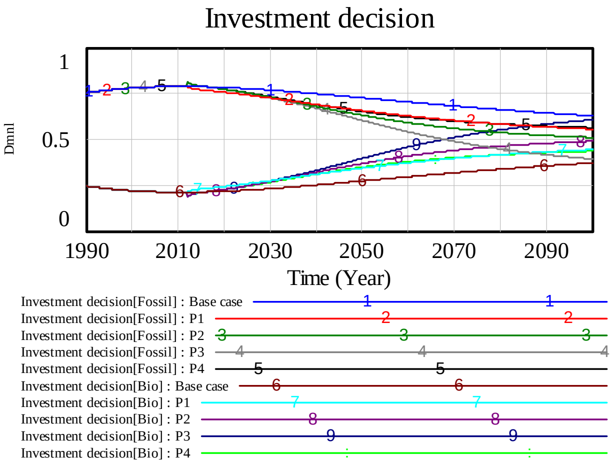

Figure 13. Investment decision.

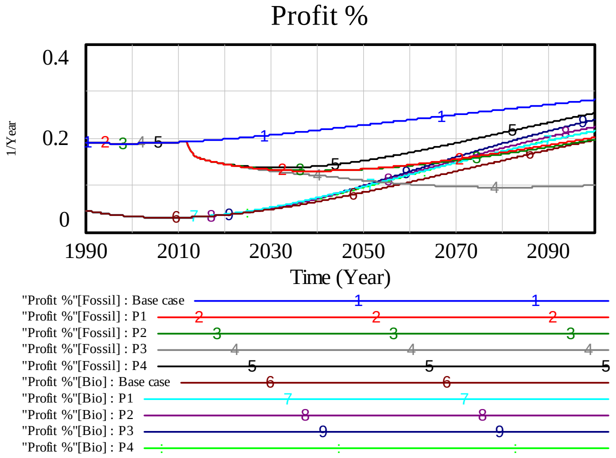

Figure 14. Profit percentage.

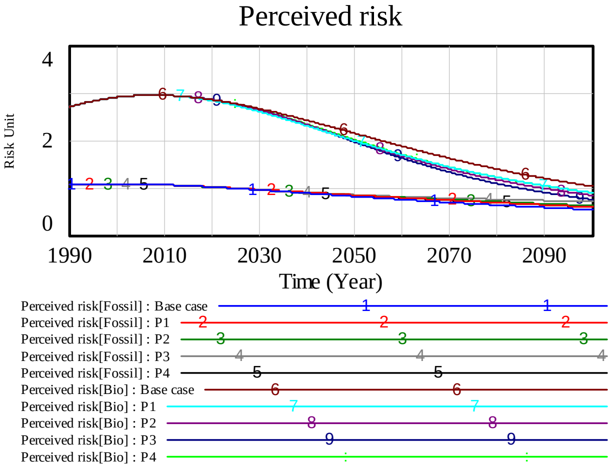

Figure 15. Perceived risk

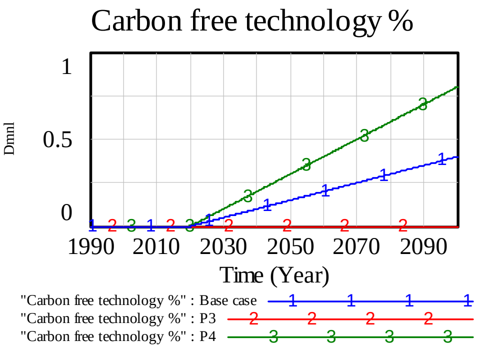

Figure 16. Share of carbon free technology of fossil economy. Bio-economy is assumed to be carbon free.

3.2 Base case, P1, P5, and P6

Scenarios P5 and P6, see figures 19 – 22, present the effect of growth. The increase in target growth affects the share of bio-economy positively, although not on emissions because of the rapid growth of fossil economy too. The interesting thing here is the effect of small negative growth on the share of bio-economy, which will not grow because the positive feedback loops supporting bio-economy do not activate. Especially the lack of *Learning by doing* and *Learning by investing* loops affecting the knowhow, and therefore perceived risk and profitability, have a large impact.

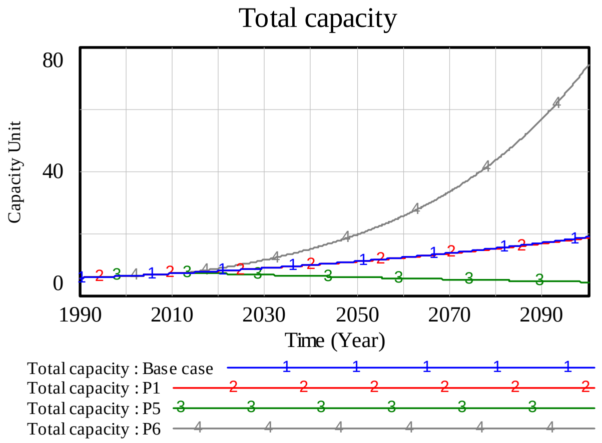

Figure 17. Total capacity.

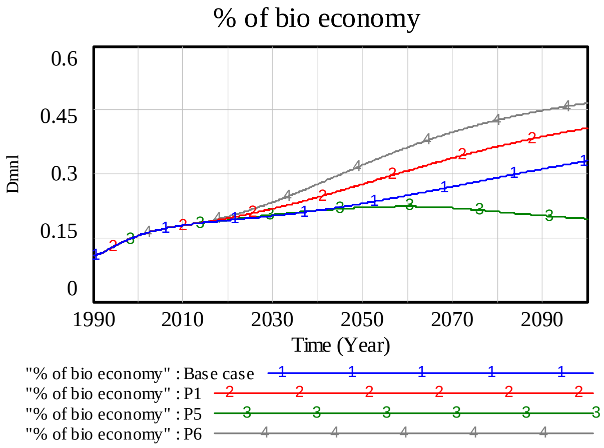

Figure 18. Share of bio-economy.

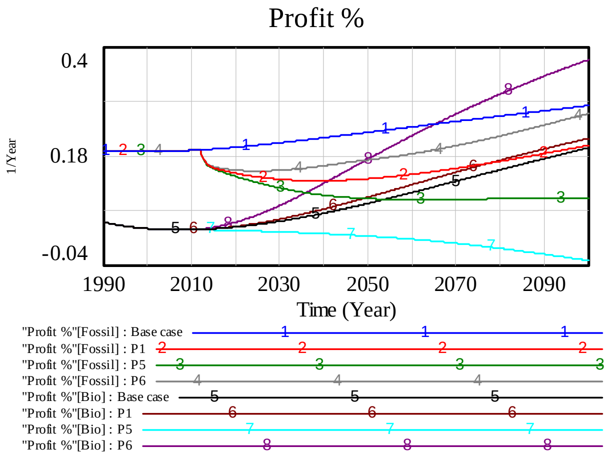

Figure 19. Profit percentage.

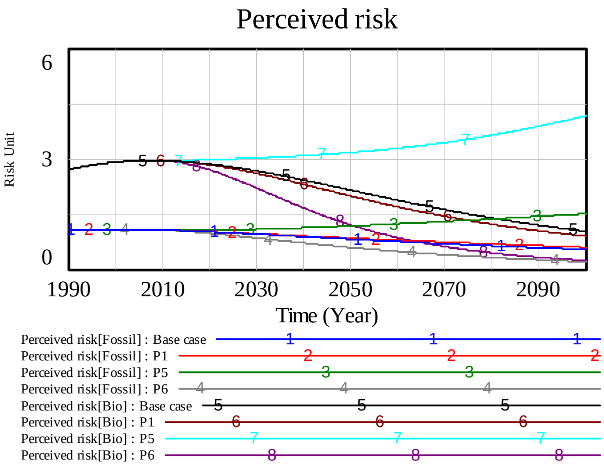

Figure 20. Perceived risk.

3.3 Base case, P7, P8, P9, and P9-2

Scenarios P7, P8, P9, and P9-2, see figures 23 – 26, illustrate the effect of too strict emission taxes, which can cause decline in the economy. Policy P7 decreases significantly emissions, but it has almost no effect on total capacity and bio-economy share of the total economy is high. However, when emissions taxes are increased slightly, the effects are remarkable on total capacity and the share of bio-economy. Strict emission taxes affects profits, which will be negative in policy P9, and therefore causing decrease in new investments, and therefore also a decrease in total capacity. In Policy P9-2 carbon free technology diffusion is twice as rapid as in base case, and therefore causing earlier investments into bio-economy, which is able to make bio-economy strong enough to keep growing when fossil economy starts to decline.

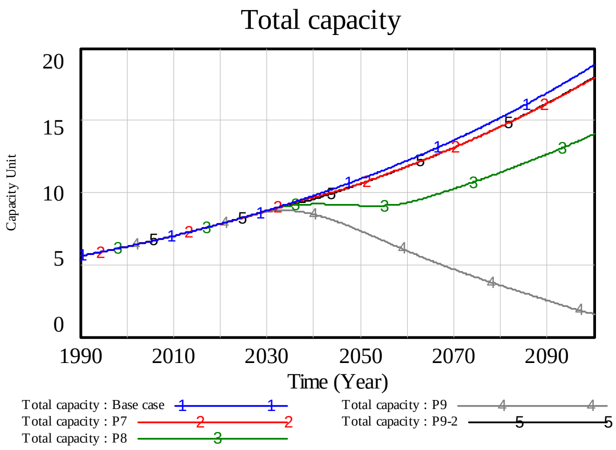

Figure 21. Total capacity

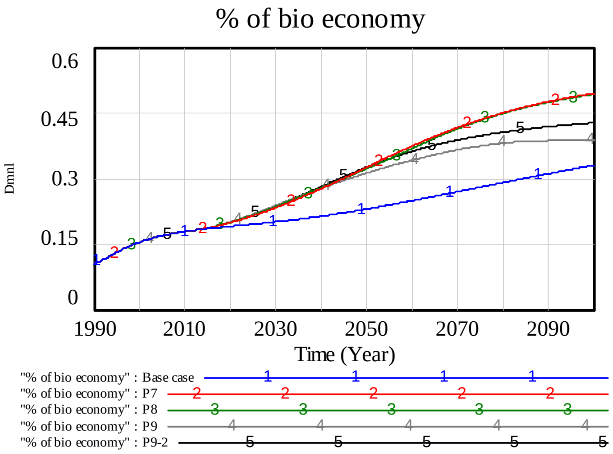

Figure 22. Share of bio economy

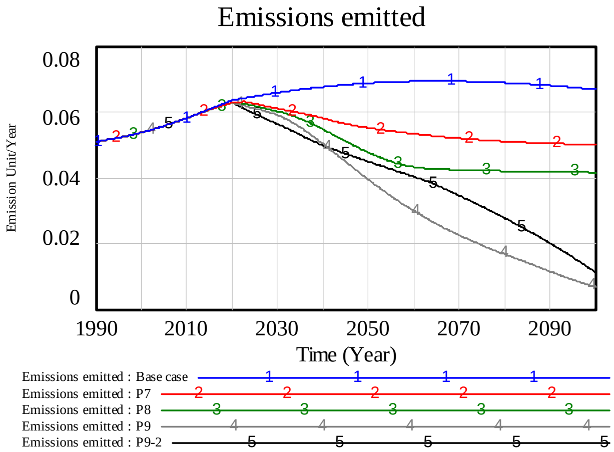

Figure 23. Emissions emitted

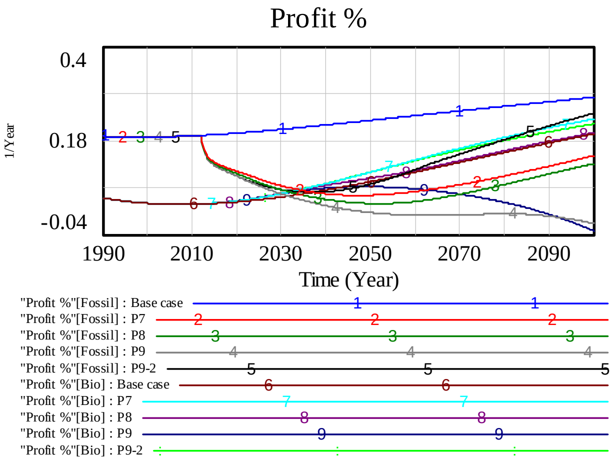

Figure 24. Profit percentage

3.4 Base case, P10, P11, P12, and P13

Scenarios P10, P11, P12, and P13, see figures 27 – 30, illustrate the effect of raw material depletion. In most of the scenarios initial value of raw material is so high that the raw material depletion loop does not affect the results. In scenarios P10 - P13 the amount of fossil raw materials is decreased to a level where the utilization of raw materials affects the raw material price significantly. In scenarios P10, P11, and P12 the result is collapse in fossil and bio capacity. In scenario P13, however, the growth is maintained by bio-economy. This is a joint effect of several factors. For instance in scenario P12 emissions taxes are not implemented, but in P13 they are. This causes sooner transition to bio-economy, which becomes strong enough to survive when fossil economy collapses.

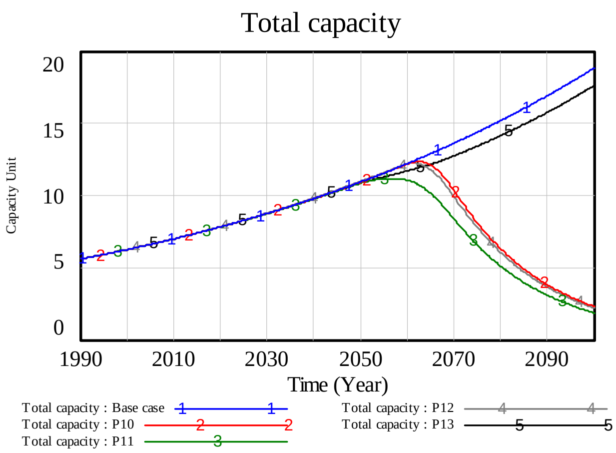

Figure 25. Total capacity.

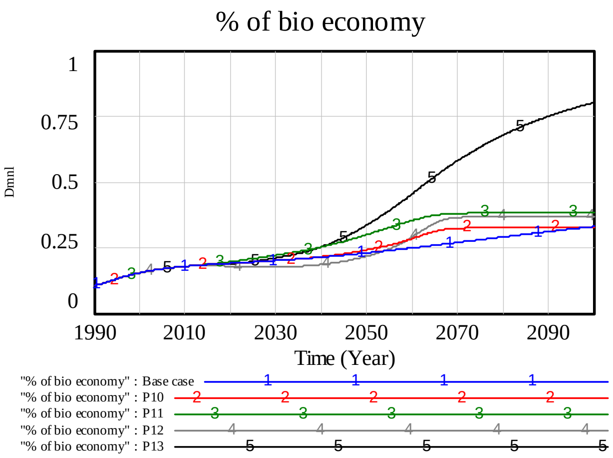

Figure 26. Share of bio-economy.

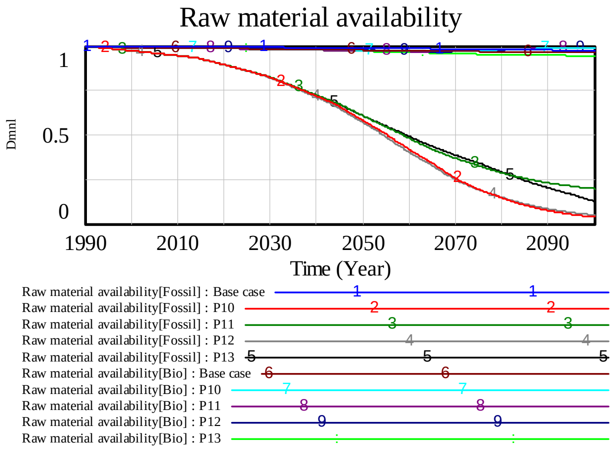

Figure 27. Raw material availability.

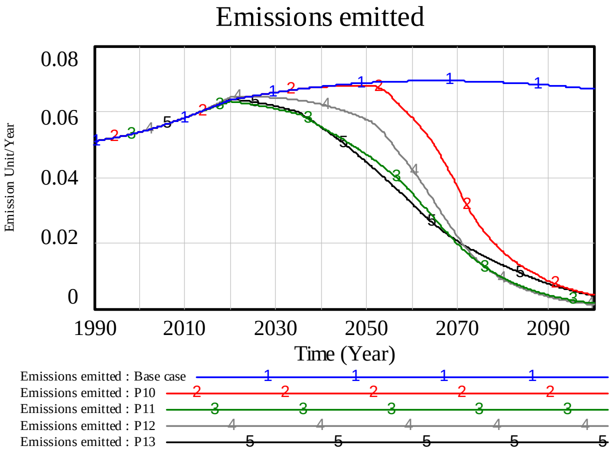

Figure 28. Emissions emitted.

4 Discussion

The consequences of global economic growth has been studied from system dynamics point of view for decades (Forrester 1971; D. H. Meadows et al. 1972; D. H. Meadows et al. 1992; Randers 2000; D. H. Meadows et al. 2004; Randers 2012; Turner 2008) and most of the debate has concentrated on exponential growth. One conclusion from these studies is that one of the main reasons causing the future problems is exponential growth, i.e. exponential growth of population, industrial output, food production, pollution, and consumption of non-renewable resources etc. These studies address that if no actions are taken towards sustainable world, then the system will kick back when the carrying capacity is exceeded and decline or a collapse will be seen sooner or later. The same possible overshoot and collapse behaviour is seen in the simulations presented in this paper, if resources are set low enough or strict emission taxes are implemented. The transition from fossil to bio-economy does not change the fundamental constraint of limited resources fighting against exponential growth, as seen in the simulations. However, the target percentile growth is observed to affect the system also in other ways; for instance, in the case of a small negative growth bio-economy has difficulties againts fossil economy, because the lack of profits to be invested in bio-economy. On the other hand, bio-economy cannot be sustainable in long-term if exponential growth of physical production is maintained, and therefore the transition from fossil to bio-economy should be a transition to a new paradigm where not only raw materials are changed, but also on a broader sense the dominant way of thinking is changed too, i.e. the growth should come somewhere else than from the growth of raw material utilization. Thus sustainability is seen very important when talking about bio-economy. For instance, Asveld et al. (2011) emphasize sustainability and mention that there are many ecological and social restrictions biomass production is facing, e.g. shortage of fertile land, deforestation. Gustafsson et al. (2011) on the other hand underline that sustainability has three dimensions (environmental, social, and economic), which are mutually dependent, and therefore forgetting one might harm the others. This is what the simulations presented in this paper also suggest; how different parts of the system interact should be taken into account in the analysis, otherwise sub optimization may cause harm to the overall system. This means that, for example, too strict emission taxes may harm the overall system in long-term.

At the moment, discourse and stakeholder analysis are ready, and the first version of system dynamics model is created. Example simulations have been carried out and the model structure and the simulations have been used as conversation enablers. The results are encouraging, as the model enables structured analysis and discussions about this complex system. However, a complementary workshop would be ideal after the interviews, but this is planned for the autumn as well as a secondary round of interviews to validate the developed model structure. Next steps include better validation of the model as well as connecting system dynamics model and stakeholder analysis in order to analyse more deeply does the salient stakeholders have power to change the system behaviour from the systems perspective.

Simulation results reveal that if too strict emission restrictions are implemented, then there is a possibility of collapse. Also, if raw materials are exploited, there is a possibility of collapse. However, as the simulations reveal, in either case there are policies to decrease the possibility of collapse, and in fact the outcomes may be desirable, as in simulations P4 and P13. The main concern is whether or not the positive feedback loops in bio-economy activate early enough and are strong enough to resist the decrease of fossil economy. Simulations also reveal, that high growth does not make bio-economy share to rise significantly, and the lack of growth may prevent the growth of bio-economy. This suggests that growth is needed, but too high growth rates may hinder the growth of bio-economy.

5 Conclusion

In this paper, a system dynamics model was constructed based on interviews and literature. The analysis revealed several feedback loops affecting the system behaviour. Bio-economy has been studied in recent years a lot; however, this paper contributes on analysing feedback loops and interconnections of fossil and bio-economy, and therefore gathering insight how these two interconnected systems behave dynamically.

Based on the simulations the system is highly complex dynamically as it is conceptually. The system dynamics model has given insight how the two economies are interconnected together and how this affects the system behaviour, e.g. the restrictions directed to fossil based economy may restrict also bio-economy. The model can be used to enhance understanding about the interconnections and dynamics of the system.

Economic growth and learning by doing loops are observed to be powerful feedback loops, and these loops affect the diffusion of bio-economy in several ways. For example, if no restrictions are set to fossil economy (e.g. emission tax, resource depletion), it is very difficult, for bio-economy to overcome fossil economy in near future.

This paper contributed mainly on the dynamic patters the interconnections between fossil and bio economies are able to produce. The interviews revealed that understanding more deeply the interconnections and possible behavioural modes would be beneficial to the policy makers. However, more research is needed to understand all significant feedback loops working in the system.

References

Asveld, L., Van Est, R. & Stemerding, D. eds., 2011. *Getting to the core of the bio-economy: A perspective on the sustainable promise of biomass,*

Bossel, H., 2007. *System Zoo 2 Simulation Models: Climate, Ecosystems, Resources*, Norderstedt, Germany: Books on Demand GmbH.

European Commission, 2012. What is the EU doing about climate change? Available at: http://ec.europa.eu/clima/policies/brief/eu/index_en.htm [Accessed January 7, 2013].

Forrester, J.W., 1971. *World Dynamics*, Wright-Allen Press.

Geels, F.W., 2012. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *Journal of Transport Geography*, 24, pp.471–482.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems. *Research Policy*, 33(6-7), pp.897–920. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0048733304000496 [Accessed October 5, 2012].

Gustafsson, M., Stoor, R. & Tsvetkova, A., 2011. *Sustainable Bio-economy: Potential, Challenges and Opportunities in Finland,*

Kuisma, J., 2011. *Kohti biotaloutta. Biotalous konseptina ja Suomen mahdollisuutena,*

Luoma, P., Vanhanen, J. & Tommila, P., 2011. *Distributed Bio-Based Economy - Driving Sustanable Growth*, Helsinki.

Meadows, D.H. et al., 1972. *Limits to Growth*, Universe Books.

Meadows, D.H., Meadows, D.L. & Randers, Jorgen, 1992. *Beyond the Limits*, Chelsea Green Publishing.

Meadows, D.H., Randers, Jorgen & Meadows, D.L., 2004. *Limits to Growth: The 30-Year Update*, Chelsea Green Publishing.

Randers, Jørgen, 2012. *2052 – A Global Forecast for the Next Forty Years*, Chelsea Green Publishing.

Randers, Jørgen, 2000. From limits to growth to sustainable development or SD (sustainable development) in a SD (system dynamics) perspective. *System Dynamics Review*, 16(3), pp.213–224. Available at: http://doi.wiley.com/10.1002/1099-1727%28200023%2916%3A3%3C213%3A%3AAID-SDR197%3E3.3.CO%3B2-5.

Struben, J. & Sterman, J.D., 2008. Transition challenges for alternative fuel vehicle and transportation systems. *Environment and Planning B: Planning and Design*, 35(6), pp.1070–1097. Available at: http://www.envplan.com/abstract.cgi?id=b33022t [Accessed July 27, 2012].

Turner, G., 2008. A Comparison of the Limits to Growth with Thirty Years of Reality. *Working Paper Series 2008-09,* (June).

Valtioneuvoston kanslia, 2010. *Biotalous Suomessa - arvio kansallisen strategian tarpeesta*, Helsinki.