RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

Francesco ROMAGNOLI
Doctoral Program in Environmental Science

MODEL FOR SUSTAINABLE BIOENERGY PRODUCTION AND USE

Summary of thesis

Riga 2012

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This study is proposed for attaining the degree of Dr.sc.ing. in Environmental Engineering and will be defended on 27 August 2012 at the faculty of Power and Electrical Engineering, Kronvalda Boulevard 1, Room 21.

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CONFIRMATION STATEMENT

I, the undersigning, hereby confirm that I have developed this dissertation, which is submitted for consideration at Riga Technical University, for attaining the degree of Dr.sc.ing. in Environmental Engineering. This study has not been submitted to any other university or institution for the purpose of attaining scientific degrees.

Francesco Romagnoli …………………………….

Date: ……………………….

The dissertation is written in English and contains: an introduction, five chapters, conclusions, a bibliography, 6 appendix, 61 figures, 36 tables and 162 pages. The bibliography contains 220 references.

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BACKGROUND AND CURRENT SITUATION

Since 1987, when Our Common Future (also known as the Brundtland Report) of the United Nations World Commission on Environment and Development was published, the term ’sustainable development’ has become a crucial concept across the developed world. Sustainable development incorporates three interrelated dimensions: the environmental, economic, and social dimensions. This means that economic development is not based on environmental degradation. In other words, high economic indices go hand in hand with high quality of life.

Consumption of resources, especially energy resources, indicates the limits of the development of our society and economics and thus the limits of our existence. In the current situation, when the peak of fossil fuel will be reached in the nearest future, wider use of renewable energy sources (RES) can serve as a solution that complies with the principles of sustainable development and benefits both the environmental and economic as well as social dimensions. At the same time, wider use of renewable energy sources should not cause adverse effects on ecosystems or biodiversity, nor should it focus on “non-food” energy crops for the production of 2nd and 3rd generation biofuels.

The European Union (EU) has long been one of the leading actors fighting climate change in the international forum. Renewable energy in line with energy efficiency is an integral part of European energy and climate policy. With its 20-20-20 targets, implemented in EU Directive 2009/28/EC, the European Union has committed to reducing greenhouse gas (GHG) emissions to at least 20% below 1990 levels, to increasing the share of RES to 20% of EU energy consumption, and to reducing primary energy use by 20% by 2020. The EU member states are undertaking various national and EU level policies and measures to reach the outlined targets, all of which are implemented in the National Renewable Energy Action Plan (NREAP) of the EU Member States (MSs). Based on these facts, an increase in the bioenergy sector in all its different production routes is foreseeable in the very near future.

Latvia is also undertaking and developing different measures to be implemented within NREAP in order to reach the set target of 40% of final energy consumption offset by the use of renewable energy resources. Even though Latvia presents the second highest share of RES in the European Union (around 35%), important long-term improvements must nevertheless be planned that focus not only on the main energy sectors but also target the environmental, social, and economic aspects in an expanded evaluation. Moreover, Latvia presents a particular situation in which an increase in natural gas imports has been detected in the past years, which is apparently in contradiction with the set targets of EU Directive 2009/28/EC and against sustainable criteria.

Undoubtedly, a transition to an environmentally sound direction in the energy sector is difficult but not impossible. Correct implementation of the best “green policy strategy" is necessary to achieve this goal. In fact, the basic concepts of sustainability related to the green energy market are well known, but the operational aspects and the methodology needed to implement them in the context of policy making and planning are still to be determined. Nevertheless, it is necessary that the development of the most suitable and sustainable strategy requires clear and feasible evaluation tools adopting a global and holistic frame within the transition to a green energy based system. Therefore, a comprehensive analysis in a wider perspective is necessary in order to embrace a global assessment involving the environmental, economic, and social effects of a certain policy framework.

Energy planning and the related environmental impact assessment must be interconnected in order to correctly promote and stimulate the production and use of renewable sources within the bioenergy sector. In light of this fact, an integrated approach involving the use of a typical energy planning modelling tool (such as system dynamics modelling) and cradle-to-grave impact assessment methods (for example, Life Cycle Assessment) may represent a suitable comprehensive analytical tool.

OBJECTIVES

The general objective of this dissertation is related to the development of an analytic tool for the evaluation of the environmental, social, and economic performances of various types of bioenergy routes and bioenergy technologies. The tool is oriented to the energy planning sector in light of EU Directive 2009/28/EC in order to evaluate the effects of various policy measures implemented in the National Renewable Energy Action Plan (NREAP) of the EU Member States.

To reach this objective the following specific objectives have been set:

1. analysis of the environmental performance and sustainability of various types of bioenergy routes within the use of different types of bioenergy technologies in a "cradle-to-grave approach" using the Life Cycle Assessment (LCA) methodology;
2. development of an integrated methodology merging the LCA approach and white box modelling through a system dynamics approach;
3. analysis of the implementation of various policy measures (from the EU Member State NREAPs) based on non-linear structures of complex systems;
4. evaluation of the impact of the Emission Trading Scheme (ETS) as a mechanism to reduce fossil-based energy resources;
5. development of a white box model using the system dynamics modelling methodology to evaluate the effects of policy strategies and the ETS mechanism undergoing the sustainability of national renewable energy sources;

6. validation of the proposed system dynamics method as applied to the case of boiler houses within the Latvian district heating system.

RESEARCH METHODOLOGY

The research methodology is based on two interconnected modelling parts. The first part is related to the use of LCA modelling for the evaluation of the whole environmental performance under specific impact categories. The methodology includes all the main phases foreseen by ISO Standard 14044 and the sensitivity analysis under various bioenergy scenarios. The second part is related to the implementation of the theory of system dynamics, including the final model validation and analysis results using the specific environmental data output of the LCA modelling (i.e. emission factor).

The combination of the above-mentioned methodology is applied to studying forecasts of primary energy consumption within the Latvian district heating system and its sustainable development.

Data has been collected from various sources: the European Commission, the Central Statistical Bureau of Latvia, Latvian energy experts, specific databases (i.e. ecoinvent 2.1), wood energy experts, and forest experts.

SCIENTIFIC SIGNIFICANCE

The analytic approach developed and proposed in this thesis is related to the integration of an energy planning tool using white box modelling (system dynamics modelling) with Life Cycle Assessment (LCA). The scientific significance of the thesis is based on the following aspects:

1. use of an LCA-based analysis for various bioenergy systems in order to evaluate the reduction potentials of alternative bioenergy technologies concerning pollutant emissions and greenhouse gases (GHG);
2. implementation of a system dynamics model for the analysis of policy strategy and the EU ETS mechanism implementation within the target set for the share of renewable energies in the EU;
3. proposal of a tool for the evaluation of the reliability of green investment for operators participating in the ETS;
4. development of an integrated methodology for the evaluation of sustainability and forecasts of primary energy consumption.

PRACTICAL SIGNIFICANCE

The practical significance of the present thesis can be addressed to different target groups at different levels, particularly:

- the governmental level – the results from this thesis are useful for evaluating the effects of support schemes on bioenergy development in Latvia. The results also provide a forecast of primary energy consumption and the installed capacity in regard to the district heating system;

- the energy sector (investors and operators) – the proposed system dynamics model quantifies the effects of the implementation of certain policy mechanisms providing trends for the short and long term in regard to the share of the use of renewable energy sources;
- the environmental level – the proposed methodology focuses on the optimization and reduction of the emissions undergoing sustainable development criteria;
- the scientific level – an integration of LCA methodology and the system dynamics approach is proposed in order to analyze and study issues pertaining to the integration of bioenergy routes within the whole energy sector;the scheme proposed within the model can be further exploited at the European scale by involving other types of policy instruments and bioenergy routes not yet investigated at this step of research.

APPROBATION

Methodologies, advancement of the work and results of this dissertation have been thoroughly documented and discussed:

1. Romagnoli F., Barisa A., Blumberga A., Blumberga D., Dzene I., Rošā M., Rochas C., Policy strategy effects for a sustainable improve of a wood-based energy structure in Latvia: an integrated dynamic model of the district heating system // Proceedings of the 20th European Biomass Conference and Exhibition, Italy, Milan, 18-22 June, 2012.
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STRUCTURE OF THE THESIS

The dissertation is written in English and contains: an introduction, five chapters, conclusions, a bibliography, five annexes, 61 figures, 36 tables and 162 pages. The bibliography contains 220 references.

1. METHODOLOGY

In light of a foreseeable development to a green and renewably sound energy strategy, the choice of the best policy scenarios is important in order to strengthen this transition. Figure 1.1 illustrates that implementation of a sustainable and green energy society in the future is affected by policy strategies and their implementation by policy makers.

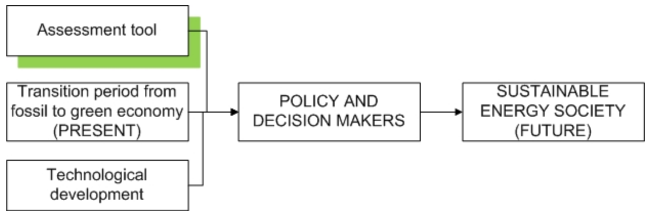

Fig. 1.1. Scheme of dependency of the assessment tool and the development of a green society

Policy decisions must be supported by a rational background based mainly on various types of theoretical and forecasting tools that can consequently limit and restrain a wider range of policy strategies. The target of a green energy based society is associated with the implementation of energy technologies that result in environmental benefits (lowering the environmental impact) and sustainability (maintaining of a certain system function for future generations).

The key aspect in allowing a transition to a green energy based society and reinforcing a sustainable future is to strengthen the most suitable and sustainable policy strategy (see Figure 1.2). In the following chapters the policy tools and key expectations for a transition to a green energy society are discussed.

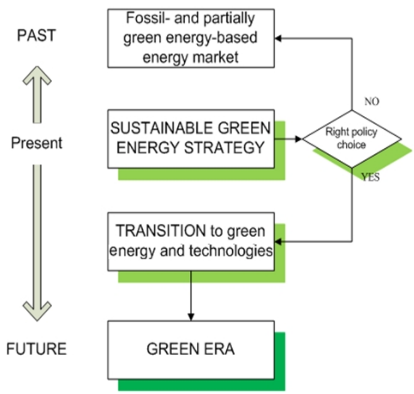

Fig. 1.2. Transition to a green society

A green energy system can be reflected at different levels and on a different space-time scale. Development in the direction of a "Green Era" is a long-term process that involves not only economic and policy activities but also a broader interconnection with other important pillars such as land use, population growth, material and energy flows, and human interaction and behaviour regarding the fulfilment of sustainable development.

In light of this fact, what follows is a proposal of an algorithm of a modelling tool that has been developed in order to evaluate the strength and effects of certain policy scenarios on an environmentally sound direction based on the development of the use of renewable energy sources. The main outcomes of the methodology proposed are based on a long term perspective. This means that, in light of a foreseeable increase in the energy consumption offset by a relative increase in energy sources, it could be possible to evaluate the beneficial effects of a policy strategy to balance the energy shortages in a sustainable and environmentally sound direction.

2. LCA MODELLING: EVALUATION TOOL FOR BIOENERGY PRODUCTION AND USE

In the thesis three LCA case studies are proposed for three different types of bioenergy routes: LCA for the use of biodiesel in an off-road vehicle in Latvian conditions, LCA for the production of biogas from algae substrate in Italian and Latvian conditions (data and information from the project BioWALK4Biofuels©), and LCA for the production of thermal energy in a boiler house supplied with wood fuels (chips, logs, pellets).

The object of the work of all the LCAs has been developed through their sequential phases: goal and scope, boundary definition, setting of the functional unit and the definition of the inventory data for the whole system, impact assessment evaluation, and analysis of results according to ISO standard 14040-44.

The software used for the modelling is Simapro version 7.3.2, following the ISO 14040-44 standard recommendations. The Life Cycle Impact Assessment implemented within all the proposed studies is IMPACT 2002+.

The goal and scope of the LCA studies is to evaluate the potential environmental impacts of various renewable energy sources.

2.1 LCA model for biodiesel production in a Latvian context

The sustainability criteria of the EU Renewable Energy Directive (2009/28/EC) state that in Latvia rapeseed methyl ester (RME), also named as biodiesel, are supposed to be one of the most valuable possibilities to attain this goal. The aim of this part of the research is to understand and model the environmental performance of biodiesel produced from rapeseed under Latvian conditions. Firstly, the energy crops have been studied by assessing their levels of biodiesel productivity. Secondly, the current Latvian climatic conditions and cultivation parameters have been taken into account. In conclusion, a comparison with the impacts of fossil based diesel has been conducted.

2.1.1 *Definition of goal and scope*

The aim of this study is to perform a full comparative LCA of the production and use of biodiesel, providing a comparison with the corresponding fossil fuel for Latvian conditions, in order to investigate its environmental benefit.

The main aims to be reached during the analysis are outlined: demonstration that biodiesel has a positive energy balance and is a renewable source (study of the energy ratio between the renewable energy output produced and the amount of non-renewable energy spent for the production); savings of greenhouse gas emissions; use of LCA to evaluate the life cycle environmental burdens of a biodiesel (BD) system fuelling the investigated vehicle with pure BD from rapeseed oil; identification of the hot spots in the system; and recommendations.

The functional unit to which all emissions and consumption in this assessment have been reported is a pick-up car/vehicle covering a distance of 100km off-road (unpaved road). The relevant environmental mid-point impact categories studied are non-carcinogenic effects, respiratory effects, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy. Results at the end-point impact categories are also proposed in reference to human health, eco-system quality, climate change, and primary resources.

2.1.2 *System boundaries*

The following four stages have been considered per energy crop for the simulation: soil preparation and cultivation (including nursery of the seeds); rapeseed oil production (including refinery); biodiesel production (including refinery); and final end use (see Fig. 2.1).

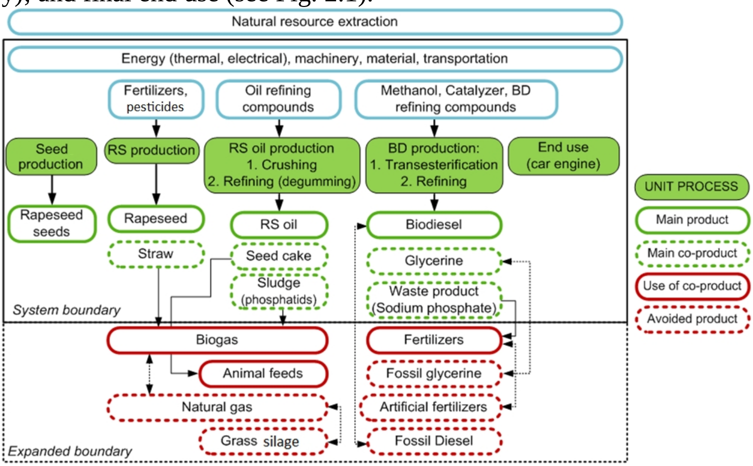

Fig. 2.1. LCA for biodiesel model and boundary

2.1.3 Description and inventory of unit processes

The gathering of data on rapeseed cultivation and biodiesel production has been based on international conditions and local Latvian sources. Other types of data have been collected from the Ecoinvent 2.1 database and GEMIS. As can be seen in the model, it has been assumed that the straw is used for the production of biogas, the seed cake is used for the production of animal feeds, and the waste products (e.g. sodium phosphates) are used as fertilizers. The model foresees the co-production of glycerine in the process. The use of these waste products and co-products is fundamental to increasing the environmental benefits of the whole process because they displace the production of other products (natural gas, grass silage, artificial fertilizer, fossil glycerine).

2.1.4 LCA results

The biodiesel LCA model takes into account the avoided products. A negative value represents an environmental benefit. If this is compared with the model that does not include avoided products, it becomes evident how strong the effect of reusing waste and/or co-products is. One can also see how, for the model considering fossil based diesel, almost 80% of the total impact is related to the non-renewable energy source used (see Fig. 2.2).

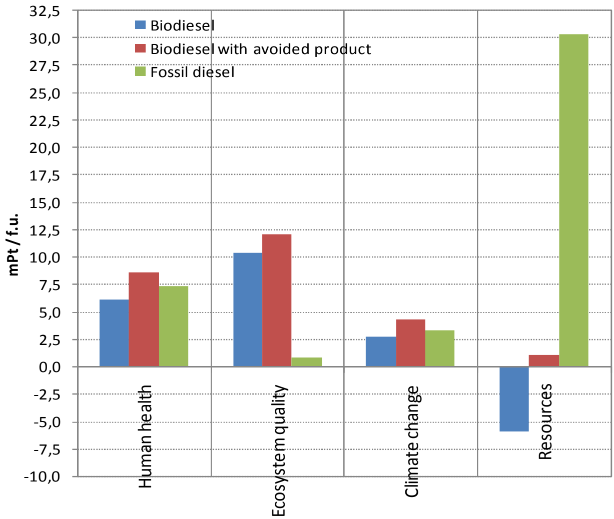

Fig. 2.2. Endpoint impact categories per functional unit for biodiesel production (f.u.) [mPt/f.u.]

To initialize a benchmarking analysis, an energy balance should be performed along with the implementation of the LCA. Table 2.1 presents the indicator E_i defined as the ratio of the total energy used for fuel production (in terms of non-renewable sources) and biodiesel fuel energy (in terms of calorific value). A ratio lower than 1 is meaningful of a process in which the renewable peculiarities have a greater efficiency.

Table 2.1
Energy indicator

LCA scenario	E_i
Biodiesel	- 0.18
Biodiesel (without allocation)	0.14
Other sources	$-1.34 < E_i < 0.64$

where:
$E_i = MJ_{in} / MJ_{out}$ = energy indicator;
MJ_{in} = global non-renewable sources spent within the model [MJ];
MJ_{out} = biodiesel energy (specific heating value – 37.7 MJ/kg).

The results of the LCA show:

- biodiesel is a renewable energy source using the energy indicator E_i presented as the benchmark (lower than 1);
- the use of biodiesel reduces the consumption of non-renewable energy;
- the effects of biodiesel on the environment are roughly 38% less than for fossil diesel. By taking into consideration the avoided product, the percentage increases to 67%;
- for the climate change and human health impact categories, the role of the use of waste and co-products is fundamental in order to have an environmental load lower than foreseen in the fossil based LCA model;
- the impact of fossil diesel on ecosystem quality is almost negligible, if referenced to the biodiesel models. This is related to the use of fertilizers and pesticides and their impact on arable land;
- the global warming impact category demonstrates how fundamental the role of avoided products is to the overall reduction of the CO2 equivalent in biodiesel production. In fact, the model demonstrates an only 15% reduction compared to the fossil fuel based reference system if avoided products are not taken into account as opposed to 36% when these products are included.

2.2 LCA model for biogas production from algae substrate

Currently, the production of biogas is principally carried out through anaerobic fermentation of (mixed) cereal crops, but in terms of substrates more research is needed in order to gather all possible bio-resources. Hence, the need for further exploration of new feedstock sources is a fundamental issue for improvement related to the know-how of second and third generation biofuel technology development.

Algae is one of the possible feedstocks for the production of biomass to be used in anaerobic digestion processes for the production of biogas.

The aim of this LCA is to carry out an environmental assessment of the use of biogas from algae and manure as a biofuel for heat and electricity production in a cogeneration unit (40kW) adopted for Italian and Latvian conditions. The analysis is also performed in light of a comparison with a similar biogas production system based only on agricultural substrate and a fossil fuel based scenario in which natural gas is supplied to the cogeneration unit.

2.2.1 Definition of goal and scope

The goal and scope of the LCA study is to evaluate the potential environmental impacts of the use of marine macroalgae (or seaweed) as feedstock for the production of biogas and its use in a cogeneration unit. The study foresees the identification and quantification of the major environmental impacts (hot spots).

The evaluation is also carried out through a comparison with a natural gas based system using the same functional unit.

As mentioned previously, the analysis is carried out for two proposed conditions: an Italian condition (in which the use of poultry manure is included – base scenario 1) and a Latvian condition (in which the use of waste water from a waste water treatment plant is included – base scenario 2).

2.2.2 System boundaries

The function of the system is to generate thermal and electrical energy. The functional unit chosen to represent the system is defined as the total energy produced in the plant during one year equal to 1,1 TJ_{el} and 2,2 TJ_{th}. The amount of algae necessary to guarantee this production phase has been set to a level of 1729 t/year (wet algae mass) for base scenario 1 and 803 t/year (wet algae mass) for the base scenario 2.

In regard to base scenario 1, the location of the system (Augusta, Italy) is located in southern Europe in the Mediterranean region, and the Italian energy mix for electricity (medium voltage) has been chosen from the Simapro database. The site assumed for base scenario 2 is the WWTP “Daugavgrīva” in the Baltic Sea region, and the EU-27 energy mix for electricity (medium voltage) has been chosen from the Simapro database.

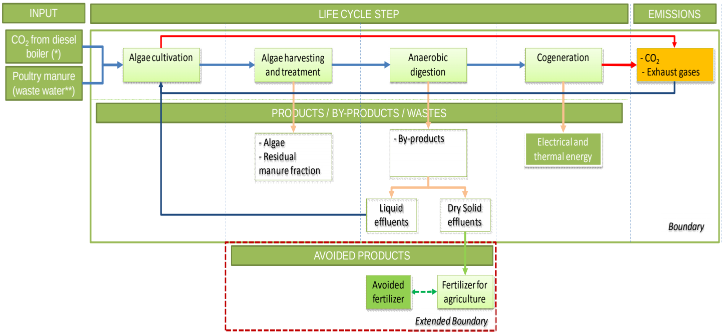

Fig. 2.3. Schematic representation of the system boundary of the production processes for base scenario 1 and scenario 2

Both systems include the macroalgae cultivation phase, harvesting and treatment, 2-stage anaerobic fermentation units, biogas consumption in a cogeneration unit as well as by-product management expressed in terms of boundary expansions. Transportation is not shown in these schemes but is taken into account for all the production stages (see Fig. 2.3).

2.2.3 Description and inventory of unit processes

The different stages of the whole process chain have been taken into account in the following steps in order to analyze their contribution towards different impacts:

- algae cultivation – all input and output related to the production of algae biomass, also including the environmental benefits;
- cogeneration unit, represented by the emissions from combustion in the CHP unit;
- energy inflows – all the energy inflows required for all the unit processes in the production chain are taken into account;
- co-products management that takes into account the environmental benefit of the use of co-products in the extended boundary (e.g. reuse of liquid diegestate in ponds and use of the solid fraction as fertilizers);
- materials – all the components necessary for the building up of the plant;
- transportation.

2.2.4 LCA results

The results show that the potentially most negative effects (not considering the benefits) are related to the human health category for scenario 1 (70% of the whole impact) and climate change for scenario 2 (75% of the whole impact) – see Fig. 2.4.

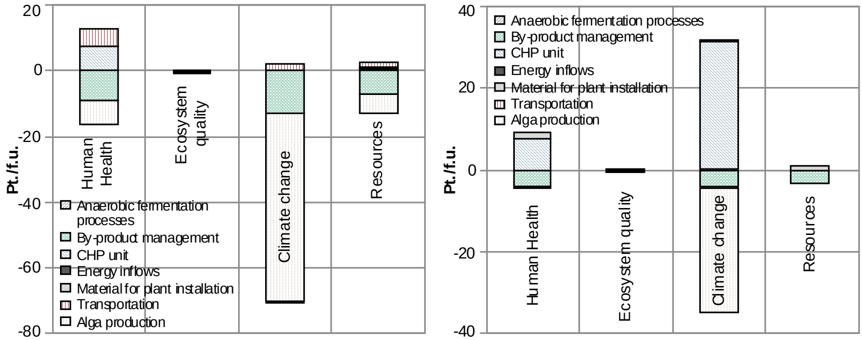

Fig. 2.4. Impact assessment for endpoint categories (e.g. ecoprofile) [Pt/f.u.] – base scenario 1 and base scenario 2

For both scenarios this is directly connected to the emissions from the cogeneration unit not reintegrated in the system. This can thus be considered the main "hot spot" for both models. The difference between the two scenarios can be explained by stressing the fact that for scenario 2 the emissions from the CHP unit can only be reintegrated into the system for the algae growing during the period from May to October. Cogeneration is the most undesirable process from the environmental point of view (65% of the total impact for scenario 1 and 92% for scenario 2), followed by transportation (30% for scenario 1) and materials needed for building up the plant (6% for scenario 2).

The human health category has a gain of environmental benefits due to the use of the co-products as fertilizer and the CO2 fixation in the algae biomass for both scenarios. The biggest environmental benefit is associated with climate change, in which the process of algae cultivation and management of co-products accounts for a value of 82% and 18%, respectively, of the total benefit for scenario 1 and for 88% and 12% of the total benefit for scenario 2.

The main environmental benefits are related to the use of by-products (around 29% of the total benefit for scenario 1 and 26% for scenario 2) and algae cultivation (around 71% of the total benefits for scenario 1 and 74% for scenario 2). To initialize a benchmarking analysis, an energy balance should be performed along with the implementation of the LCA. Table 2.2 presents the indicator E_i.

Table 2.2
Energy indicator

LCA Scenario	**E_i**
Base scenario 1	0.06*
Base scenario 2	0.13*
Other studies	$0.10 < E_i < 0.48$

where:
MJ_{in} = global non renewable sources spent within the model [MJ];
MJ_{out} = biogas energy (specific heating value – 23 MJ/m3);
$E_i = MJ_{in} / MJ_{out}$ = energy indicator.

Sensitivity analyses have been conducted to assess the effects of the variation of key input parameters and assumptions on the results of the impact categories of the study for only base scenario 2. The sensitivity analysis, executed for the mean water temperature (relevant for algae cultivation), shows that a variation of 4.5% (approximately 1°C less) during the months of biomass production produces a negative environmental impact change equal to 6%. This means that the system is not sensitive to changes in temperature even if the value is slightly lower than a value rather close to the change in sensitivity. Other sensitivity analyses should involve transportation assumption, biogas yield, co-product management, and the electricity grid-mix used.

The results of the LCA show that:

- macroalgae can be considered a renewable source (based on the energy indicator lower than 1 and for the LCA eco-profile compared with the reference natural gas based system);
- important and substantial GHG reductions can be achieved with macroalgae, but they always involve significant uncertainties;
- macroalgae can be considered sustainable in regard to the use of local sources. Further and integrated analysis is needed in order to understand the potential use of local sources and the demand on the local market;
- the main environmental issues related to the sustainability of the process are related to: area occupied by the system, local availability of nutrients (in fact, nitrogen based nutrients are a limited local resource), combination and interaction with other marine species, gaseous emissions, and harvesting sediment disturbance;
- other environmental aspects are related to: use of local species that will not contaminate the local ecosystem, risks of the spread of a monoculture ecosystem (spread of disease), and increase in eutrophication risk due to the amount of algae.

2.3 LCA model for the production of thermal energy from wood based boiler houses

Forests cover 55% of the total land area of Latvia, which is 2% more than one decade ago. In this light, forests can be considered an important source of raw material for the production of energy, although the increase of woody biomass for energy purposes must simultaneously face sustainability criteria. The aim of this LCA study is the evaluation and comparison of the environmental impacts of wood based and natural gas based boiler houses in district heating systems through an LCA methodology.

2.3.1 *Definition of goal and scope*

The goal and scope of the LCA study has been addressed to evaluate the potential environmental impacts of the use of wood based fuels for the production of thermal energy in various boiler house systems. The study foresees the identification and quantification of the major environmental impacts (hot spots). The evaluation is also carried out through a comparison with a natural gas based system using the same functional unit.

The interpretation of the results is intended to provide a quantification of the benefits of the use of woody biomass as renewable energy and the strength of the negative aspects. The function of the system is to generate thermal energy; therefore, the functional unit chosen to represent the system is defined as 1 MWh of thermal energy produced in one year in the reference boiler house using three types of wood fuels: chips logs, and pellets.

Depending on boiler house efficiencies, the types of woody biomass used, the moisture content foreseen, and the harvesting method, the amount of biomass necessary for each system has been determined. All the impact assessment results and the different scenarios are compared based on this functional unit.

2.3.2 *System boundaries*

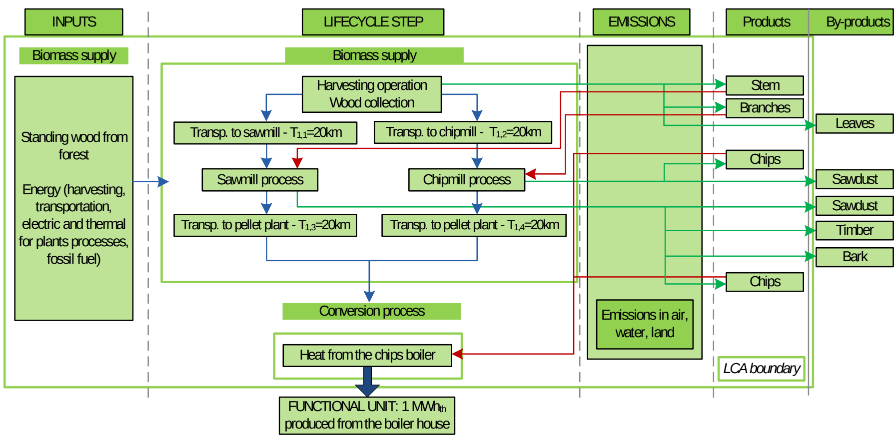

Fig. 2.5. LCA system boundary for scenario BS1

The scenarios analyzed are: a boiler house system based on the use of wood chips (base scenario 1, or BS1, see Fig. 2.5), a boiler house system based on the use of wood logs (base scenario 2, or BS2), a boiler house system based on the use of wood pellets (base scenario 3, or BS3), and a boiler house system based on the use of natural gas (reference scenario 4, or RS4 – the reference system for the comparison of results).

The LCA scheme for BS1 is reported in Figure 2.5. All the other reference scenarios are reported in the dissertation manuscript.

2.3.3 Description and inventory of unit processes

For the scenario based on wood fuels, the operations begin with the harvest at the forest stand and end with the energy conversion at the heating plant (including ash disposal). Trees are felled with a cutter machine (harvester-forwarder). The main products of the felling are stems with bark, wood residues, branches, and leaves. All the machines in the forest use fossil fuel (diesel).

Depending on the scenario, stems and other wood residues are transported directly by the harvester-forwarder to the forest processing point. From this point the wood products are transported by lorries with a maximum capacity of 32 tonnes (EURO 3 emission type) to the sawmill or chipmill for further processing, and likewise for pellet production. In the case of base scenario 2, wood products are sent directly from the forest processing point to the final boiler house, where they are combusted.

Transportation distance is considered a sensitive parameter because it is difficult to assign a fixed average value to a system due to changes in the supply system depending on the choice of wood fuel supplier. Sensitivity analyses are therefore kept in the scope of the study.

2.3.4 LCA results

Figure 2.6. provides a comparative graph of wood fuel based scenarios versus a natural gas based scenario at the endpoint damage categories: resources, climate change, ecosystem quality, and human health. Results are expressed in points (Pt) per functional unit.

The environmental burden of the scenario using natural gas presents higher impacts in terms of resource use and climate change that alone cover more than 90% of the total impact. This is basically due to the high use of fossil based fuels as non-renewable sources. When compared with the analyzed biomass based fuels, however, the natural gas scenario presents a lower impact in regard to ecosystem quality and human health. This behaviour can be explained by a higher impact on ecosystem quality in the biomass scenarios due to higher land use and greater loss of biodiversity. The higher impact of the biomass based scenarios on human health can be explained by the lower emissions during final combustion in terms of non-greenhouse gas emissions in specific volatiles (i.e. VOC), SOx, and NOx. Among the wood fuels, the wood log scenario presents the least impact and the wood pellet scenario presents the greatest impact. This is due mainly to the fact that BS2 foresees a shorter supply chain with a relatively lower use of non-renewable fuels.

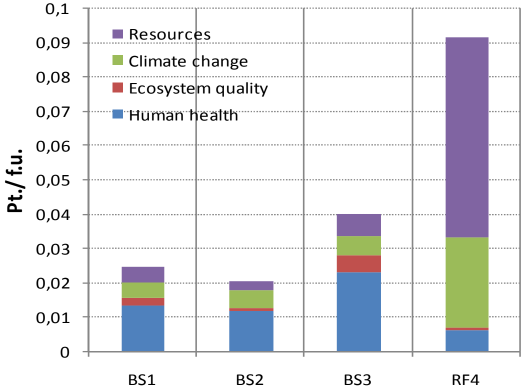

Fig. 2.6. Comparison of the three base scenarios (BS1, BS2, BS3) and the reference scenario (RF4)

The results of this LCA study show the real impact of the scenarios observed within a cradle-to-grave approach evaluating the biomass based fuel life cycle for the thermal energy production system of a Latvian boiler house. A comparison to the reference system based on natural gas was also performed due to the high proportion of this fuel in the thermal energy production system in Latvia.

Since attention is mainly focused on the real impacts of the systems analyzed, the use of the woody biomass within the analyzed scenarios has been considered in a more conservative way without avoiding the same amount of thermal energy produced in a reference natural gas based scenario typical of the LCA substitution based methods. The results show the interdisciplinary nature and complexity of a forest based energy system reflecting how the choice of a specific territorial environment, local climate conditions, and forestry practices as well as the type of final energy conversion technologies affects the full results from a cradle-to-grave aspect. In comparing biomass scenarios to the reference scenario based on natural gas it is observed that natural gas presents a twofold greater environmental impact than wood pellets (base scenario 3), which is the wood fuel based scenario with the greatest impact.

The most environmentally burdened category for all the biomass scenarios (1-3) is human health, which constitutes over 50% of the overall impact for each wood based scenario. This is due to the specific composition of the emissions, primarily particulate matter, released during the end-use of the fuel. In the natural gas scenario, however, impact on human health constitutes less than 10% of the whole impact. Base scenario 1 has the least impact in the climate change category, which is a matter of concern for the study. For this scenario the full environmental impact is distributed across all its life cycle stages (32% for the production phase, 35% for transportation, and 33% in the end-use phase). These aspects provide more flexibility for the use of this wood fuel becoming an interesting sustainable option for energy production.

When compared to other wood fuel scenarios, the weak point of wood logs (base scenario 2) is in the climate change category. Although their impact is released mostly in the end-use stage (49%), wood logs rank second in climate change impact after wood pellets.

2.4 Common aspects of the proposed LCAs

The three LCA studies highlight the complexity of the evaluation of environmental performances through a cradle-to-grave methodology. These aspects are reflected in a not unique quantification of the impact related to a specific bioenergy route basically related to the high number of variables that are involved. The determination of the environmental performances is difficult in light of the different combinations possible: the choice of feedstock, the type of conversion routes, the choice of fuels, the scale of the technology used, transportation distances due to differing productivity yields, end-use technological solutions, and the choice of impact method selected.

Concerning the environmental sustainability of the bioenergy chains, it can be concluded that all life cycle phases within the choice of the foreground and background LCA systems (i.e. practically the definition of the primary and secondary sub-systems) must be carefully taken into account and defined because overall sustainability can be related not to a specific phase but a combination of phases. It has been pointed out that bioenergy does not necessarily mean sustainable energy, because through a cradle-to-grave study the final environmental performances cannot be beneficial within the sustainability criteria.

From the above-mentioned it is foreseeable that LCA results and outcomes will be of primary importance as support for public and private stakeholders and decision makers in evaluating the real benefits of a certain bionergy and biotechnology choice within a decisional policy context. In fact, LCA methodology can play an important role in the improvement of eco-efficiency for a faster diffusion of bioenergy in the whole energy market. The choice of promoting a certain bioenergy route is not separated from the social and economic consequences.

Hence, the use of LCA modelling interconnected with the use of the classical energy planning tools described in the first chapter is advisable in favour of a hybrid type of energy planning tool. This conclusion is in fact the main starting point for the use of a white-box energy planning modelling (like system dynamics methodology) supported by environmental aspects from the LCA methodology.

3. SYSTEM DYNAMICS: EVALUATION TOOL FOR IMPLEMENTING BIOENERGY POLICY INSTRUMENTS

This section of the thesis implements the use of system dynamics (SD) modelling. A real case regarding the effects on the structure of the Latvian district heating sector of proposed policy instruments intended to speed up the use of renewable energy is developed. The model also investigates the EU Emission Trading Scheme (ETS) mechanism and the effects of the whole system regarding sustainability criteria.

The overall aims of the system dynamics model are:

- to look for policy alternatives and mechanisms that could lead Latvia to the implementation of its renewable energy policy goals in transferring from natural gas based to wood fuel based district heating systems;
- to evaluate the impact of this transfer in terms of sustainability of forest resources.

The development of the Latvian district heating system is analyzed under the influence of three policy instruments and the ETS mechanism further discussed. A separate part of the model is dedicated to the evaluation of the sustainability of the analyzed system focused on the forest resource. In fact, the outcomes of the model would demonstrate that under the criteria of sustainable use and management of forest-based biomass it is possible to offset the increase in wood fuel demand in district heating systems arising from RES supporting policies.

The main structure of the model is formed by two flows of two main energy sources that are used in the production of district heat in Latvia: wood fuel (chips, pellets, and logs) and natural gas. The distribution of each fuel is regulated by the central stocks of the “installed capacities” that represent the capacity demanded for the production of a certain amount of heat energy. The model focuses on the use of boiler houses within the district heating system and it has been assumed that the reference total installed capacity for boiler houses within district heating systems in Latvia is 4 GW (see Fig. 3.1.). This value has been kept constant over time in the model. The variable parameter is the sharing of three types of wood fuels and natural gas.

Both wood fuel and natural gas flows are divided into subflows. The wood fuel flow is divided into three subflows characterizing wood logs, wood chips, and wood pellets. The natural gas flow is divided into two subflows indicating natural gas operators that participate in the EU Emission Trading System (ETS) and those that do not (non ETS), with an initial share of 70% and 30% respectively.

The initial value of each stock represents the existing situation in fuel distribution and depends on the total heat energy produced (8000 GWh) taking into account 2000 hours of heating per year. The initial shares are reported in Figure 3.1.

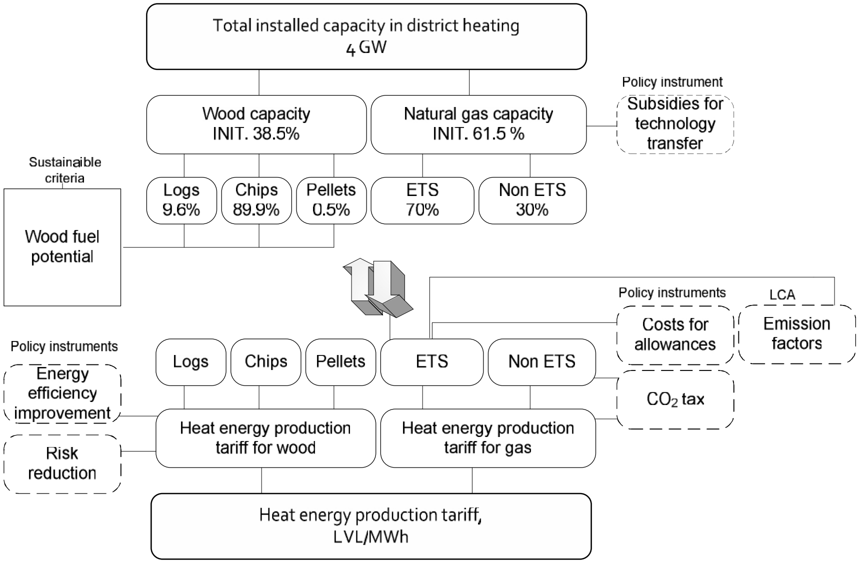

Fig. 3.1. Structure of the model

It has been assumed that the main indicator identifying the fuel structure in the district heating is the capacity of installations that use either fossil fuel or renewable energy sources to produce heat energy (in terms of installed capacity). Therefore, the central elements of the model are identified as stocks representing the installed capacity of wood fuel technologies (using three types of wood based fuels: chips, pellets, and logs) and the installed capacity of natural gas technologies. The capacity of installed facilities is influenced by two factors: investments and depreciation of the equipment over time. Each of the installed capacity stocks is therefore linked to two flows: in-flow and out-flow (see Fig. 3.2). The total amount of installed capacity has been assumed constant over time (4GW).

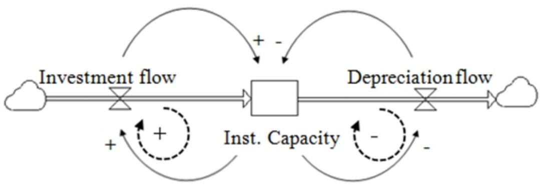

Figure 3.2. Stock flow diagram representing the relationship between the total capacity of installations and investment and depreciation flows

The larger the capacity, the larger the investment flow becomes (a positive reinforcing loop takes place). However, the larger the capacity, the larger the depreciation flow becomes, thereby decreasing the stock of the installed capacity (a negative counteractive loop takes place). This is the way the nodal part of the model works. The model calculates the heat tariff for the production of thermal energy.

The energy production tariffs for each type of wood fuel installed capacity are calculated by taking into account the contributions of: fuel costs (based on wood fuel price, boiler house efficiency, and net calorific value), fixed costs (based on operational and maintenance costs), investment costs (based on initial capital costs and internal interest rate), the risk factor (decreasing when experiences are cumulated due to the implementation of the policy measure), and the cost decrease due to selling ETS quotas for a natural gas operator switching to wood fuel.

The installed capacity is influenced by the heat energy production tariffs, which depend on factors like the price and quality of the fuel, the technology investment and maintenance costs, and efficiency. The heat energy production tariff (LVL/MWh) can be analyzed within the proposed system dynamics model according to the following formulas described for wood fuel based installations and natural gas based installations respectively:

$$T_i = \frac{C_i^{wood}}{Q_i \cdot \eta_i} + C_K^O + \frac{C_i^{cap} \cdot 10^3}{T_{H,i}} \cdot (i + \frac{1}{\tau_i^{ref}}) + R - \left(C_{quotas} - C_i^{invest}\right) \qquad (1)$$

where:

T_i = wood fuel heat energy tariff, *LVL/MWh*;
C_i^{wood} = wood based fuel price, *LVL/t*;
C_i^{cap} = capital costs, *LVL/MW*;
C_K^O = operational and maintenance costs, *LVL/MWh*;
$T_{H,i}$= time of the heating season, *h/year*;
η_i = wood based installation efficiency;
τ_i^{ref} = economic life time, *year (initial value 20 years)*;
Q_i = net calorific value of wood based fuel, *MWh/t*;
i = yearly interest rate, *%/year = 9%*;
R = risk factor, *LVL/MWh (initial value = 12.9 LVL MWh)*;
C_{quotas} = income from selling emission quotas for switching to wood based technology, *LVL/MWh*;
C_i^{invest} = extra cost for investment in natural gas operators switching to wood based technology, *LVL/MWh*.

$$T_j = \frac{C_{NG}^{j}}{Q_j \cdot \eta_{NG}} + C_{NG}^{O} + \frac{C_{NG}^{cap} \cdot 10^3}{T_{H,j}} \cdot \left(i + \frac{1}{\tau_{NG}^{ref}}\right) + C_{CO2,j} \quad (2)$$

where:

$T_{H,j}$ = natural gas heat energy tariff, *LVL/MWh*;
$C_{NG}{}^{j}$ = natural gas fuel price, *LVL/1000* $m_{st}{}^{3}$;
$C_{NG}{}^{cap}$ = capital costs, *LVL/MW*;
$C_{NG}{}^{O}$ = operational and maintenance costs, *LVL/MWh*;
η_{NG} = natural gas based installation efficiency;
$\tau_{NG}{}^{ref}$ = economic life time, *year (initial value 20 years)*;
Q_j= net calorific value of natural gas, *Mwh/t*;
i = yearly interest rate,*%/year = 9%*;
$C_{CO2,j}$ = CO_2 taxation *LVL/MWh* (for non ETS operators), CO_2 allowances purchases, *LVL/MWh* (for ETS operators).

The investment fraction, which in the model is directly linked to the heat production tariff for each installed capacity, is an element that represents the distribution of investments and depends on a factor α, also called the logistic function – "logit" (between the value zero and 1) – characterizing the decision makers' choice between natural gas and wood fuel. The investment fraction is represented by the formula:

$$I_i^S = \frac{e^{-\alpha \cdot T_i}}{e^{-\alpha \cdot T_1} + e^{-\alpha \cdot T_2} + ... + e^{-\alpha \cdot T_{i-1}} + e^{-\alpha \cdot T_i}} \quad (3)$$

where:

I_i^S = share of the investment for single installed capacity (wood pellets, wood logs, wood chips, natural gas within ETS and natural gas outside of ETS);
α = coefficient of the choice of decision makers = 0.2;
T_i = fuel tariffs (for wood and natural gas based energy production), *LVL/MWh*.

The impacts of four different policy instruments have been analyzed within the proposed system dynamics model as well as combinations thereof. The following policy instruments were considered for a total of 16 scenarios analyzed:

- Subsidies – a policy instrument that provides subsidies for district heat producers for the replacement of natural gas installations with wood fuel boilers (defined as P_S tool).
- Risk reduction – a policy instrument that comprises an initial short-term campaign to compensate risks related to the use of wood fuel. The aim of this policy instrument is to encourage the public to choose wood-fired

technologies. It indicates marketing or support measures to initiate the process of disseminating positive experiences of wood fuel use due to information flow (defined as P_R tool).

- Efficiency improvement – a policy instrument that includes measures to improve the efficiency of wood fuel use (defined as P_η tool).
- Emission Trading and CO_2 taxation – a policy instrument that works based on the “polluter pays” principle. Natural gas operators that participate in the emission trading system can buy emission allowances, while natural gas operators that do not participate in the emission trading system pay the CO_2 tax (defined as P_{ETS} tool).

Specifically, the effect of the implementation of the ETS scheme is incorporated in the model based on the assumption that district heating operators will transfer from natural gas to wood-fired installations when costs for emission allowances become higher than investment costs in GHG emission reduction measures. In this case GHG reduction measures are considered as a transition to wood fuel technologies in terms of “green investments”.

The following algorithm (Fig. 3.3) has been implemented within the SD model in order to define when it is convenient for natural gas operators within the ETS to implement an investment for switching to wood based technology:

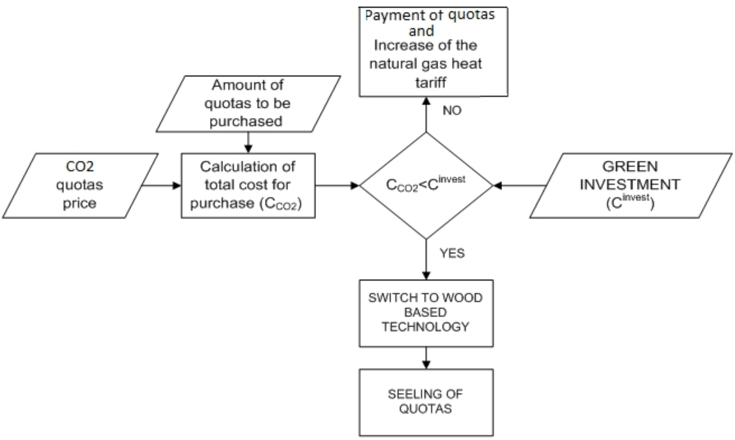

Fig. 3.3. ETS algorithm

The mechanism has been implemented in the model with the following specific model scheme (see Fig. 3.4).

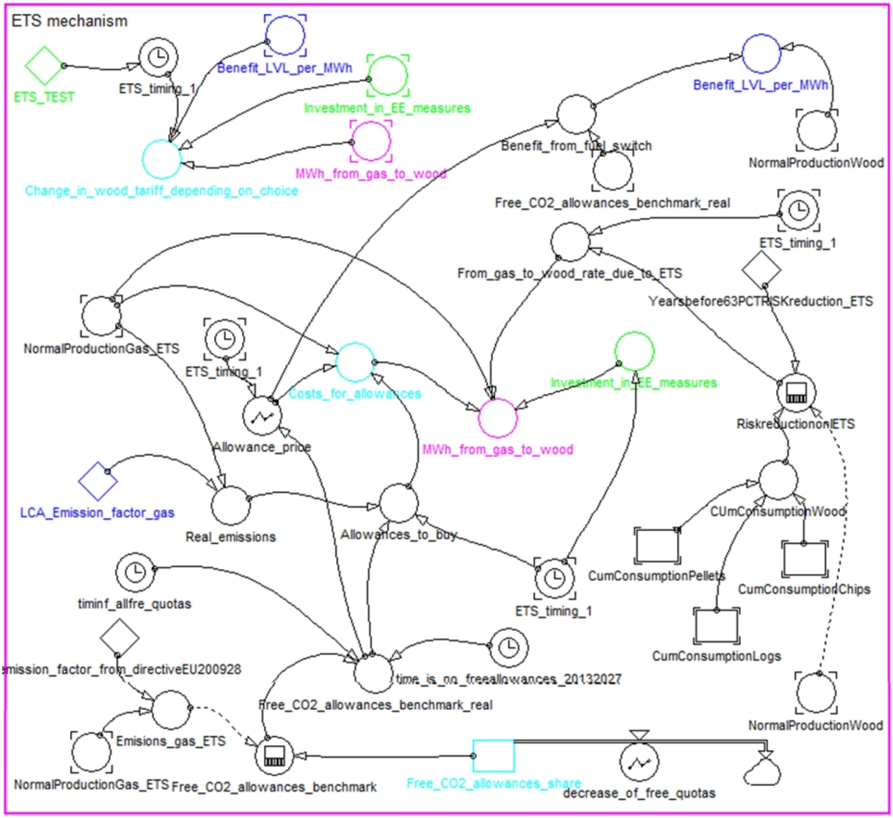

Fig. 3.4. Casual loop diagram for the ETS scheme

The issue of the possible negative impact on sustainability of local forest resources in the case of increased use of wood fuel is one of the arguments of adherents to natural gas.

Considering the actuality of the topic, the proposed system dynamics model includes a module for a forest sustainability evaluation. The model calculates the amount of wood fuel available for energy production taking into account annual forest planting, growing, cutting, and ageing (see Fig. 3.5).

In order to calculate the potential use of the forest resources available for energy purposes, it is assumed a yearly maximum allocation of harvesting volume for the total stock of adult forest in Latvia is equal to 2%. This value is in respect to the criteria of sustainable forest management. The forest planting factor (initially assumed equal to 1.6% of the total forest stock) is a sensitive and important parameter in order to guarantee the sustainability of the wood based energy resource sector.

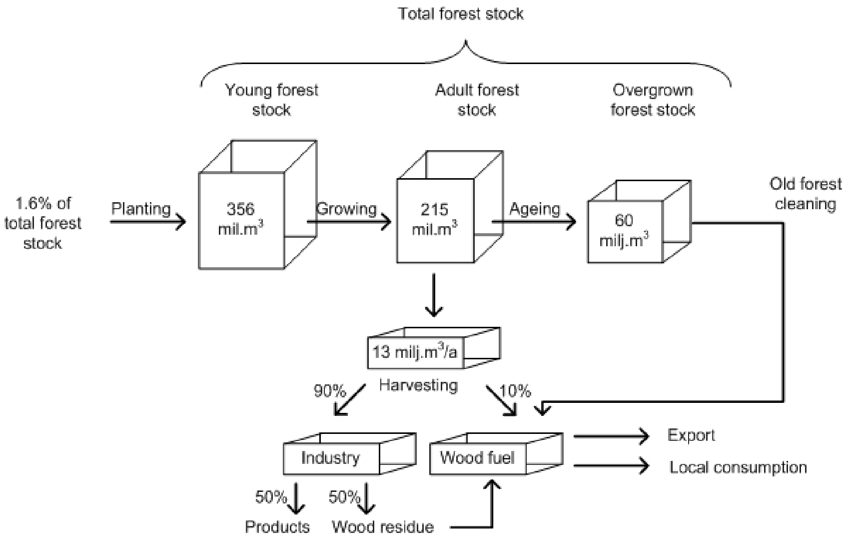

Fig. 3.5. Structure of the wood fuel potential calculation module

The total stock of wood fuel consists of three incoming wood material flows from: forest processing, wood processing, and harvesting and management of the overgrown forest.

Figure 3.6 shows the part of the model regarding forest dynamics.

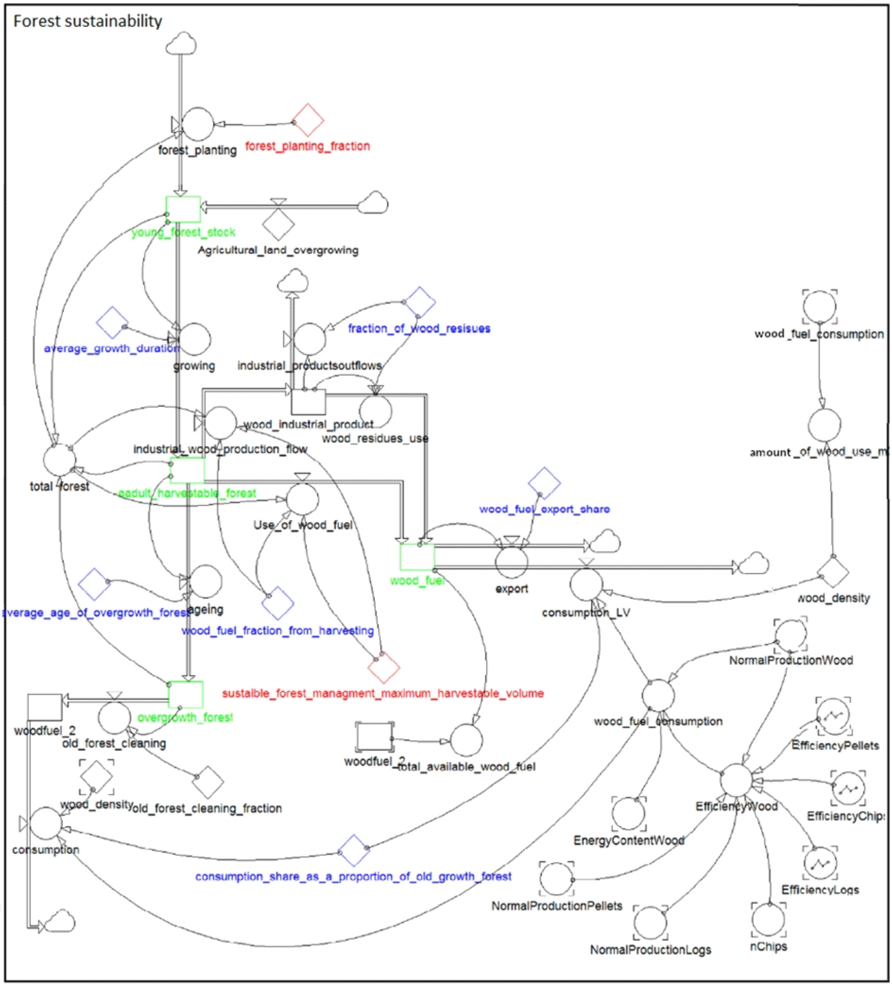

Fig. 3.6. Forest sustainability model

4. RESULTS AND MODEL APPROBATION OF THE USE OF RENEWABLE SOURCES IN THE LATVIAN DISTRICT HEATING SYSTEM

The analyzed scenarios, in regard to the proposed applied case for the evaluation of a set of policy measures within the Latvian district heating system focused on the heat produced by boiler houses, are described in the following table (Table 4.1), in which all the possible combinations of the proposed policy instruments are summarized. A total of 16 scenarios have been analyzed, beginning with the base scenario (also known as “business-as-usual”, in which none of the policy tools are implemented) and ending with the implementation of all possible policy measures in scenario 16 (also known as the “fast green” scenario). When the policy instruments P_S, P_R, P_η, and P_{ETS} are implemented, they present a value equal to 1.

Table 4.1
Policy instruments

Scenarios	Policy instrument			
	P_S	P_R	P_η	P_{ETS}
1. Base scenario (“business-as-usual”) – no implementation of policy instruments ***(BS1)***	0	0	0	0
2. Only subsidies measures	1	0	0	0
3. Only risk reduction measures trough information campaigns ***(C1_best)***	0	1	0	0
4. Only improvement of energy efficiency measures of wood based technology	0	0	1	0
5. Only emission trading mechanism ***(C1_ETS)***	0	0	0	1
6. Combination 1 of the policy instruments – ***(C2_best)***	1	1	0	0
7. Combination 2 of the policy instruments	1	0	1	0
.... i-esim Combination of the policy instruments	...	...	...	..
16. All policy instruments implemented (“fast green”) ***(C4_all)***	1	1	1	1

In order to harmonize the explanation of the results, attention has focused mainly on a comparison of the base scenario (*BS1*), the scenario with the strongest effect regarding the installed capacity of wood fuel in district heating systems related to the implementation of only one instrument (*C1_best*), the scenario related to the implementation of only the ETS mechanism (*C1_ETS*), the scenario with the minimum combination of policy instruments that allows the best results to be achieved (*C2_best*), and the scenario in which all the policy measures have been implemented (*C4_all*).

Moreover, important aspects related to the validation of the model and sensitivity analyses have been involved and presented in detail in the full dissertation thesis. Specifically, these have included: changes in the price distribution of allowances in the market, changes in the CO_2 taxation system, changes in “green investment” within the ETS, unpredicted sharp decreases in natural gas prices, and parameter changes within the sustainable management of the forest resource.

4.1 Scenario BS1

This scenario defines the situation resulting when none of the policy measures proposed to increase the proportion of wood fuel use are implemented. This means no grants are subsidized to replace natural gas heating equipment with wood heating equipment and no information campaigns are implemented with a consequently higher risk of investment and exploitation of wood technology. Simultaneously, no action towards strategic improvements in the energy efficiency of the wood based plant is proposed. Figure 4.1 shows that over a period of 40 years a natural increase in wood fuel use is observed.

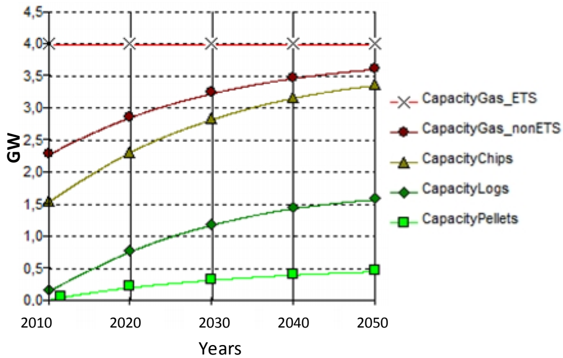

Fig. 4.1. Base scenario *BS1* – structure of the installed capacities for the primary energy mix for the district heating system

4.2 Scenario C1_ETS

Within this scenario the effects of the implementation of the ETS scheme are evaluated. The model shows no strong effects in terms of a higher share of wood based capacity compared to the BS1 scenario (see Fig. 4.2.a).

Figure 4.2.b shows the effect on the heat tariff for this scenario. Two effects have occurred: an increase in the wood tariff for ETS operators compared to those not participating in the ETS scheme, and also a small decrease (beginning in the year 2016). These two effects are consequences of the model part that regulates the ETS mechanism (see Fig.3.3).

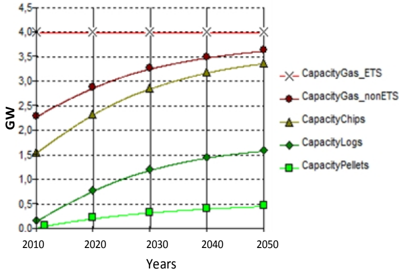

Fig. 4.2.a. Scenario *C1_ETS*

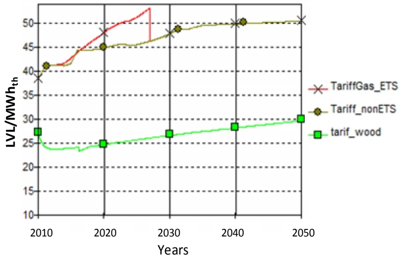

Fig. 4.2.b. Scenario *C1_ETS* – energy tariffs

The heat tariffs for ETS operators during the period of implementation of the third phase of the ETS mechanism (2013-2020 with an extension till 2027) increase more than those for non-ETS operators. This trend is regulated by the cost for ETS operators to purchase CO_2 quotas (an S-shape increase depending on the scarcity of free quotas in the market) and by CO_2 taxation for non-ETS operators that in the assumptions always presents values lower than the price of allowances. The decrease in the wood tariff seen in the year 2017 is justifiable according to the scheme presented in Formula 2, in which a beneficial effect on the whole wood tariff is allocated due to those operators who decided to invest in wood based technology. This mechanism occurs only when the cost for "green" investment is lower than the cost of quotas purchase (see Fig. 4.3).

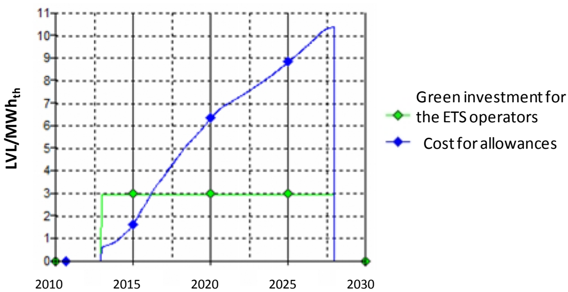

Fig. 4.3. Investment costs of GHG reduction measures compared to costs for allowances

Figure 4.4 shows the graph of the theoretical emissions – related to the installed heat produced by the ETS operators over time – and the free quotas benchmark calculated according to the emission factors defined in the LCA model for production of thermal energy from wood based boiler houses. The difference between the two trends brings to the calculation the total cost for the amount of

CO_2 quotas that the natural gas operator should purchase and consequently evaluates whether a green investment is reliable for the ETS operator. The previous figure represents a good tool to evaluate whether making a green investment for transfer to wood fuel based technology is reliable.

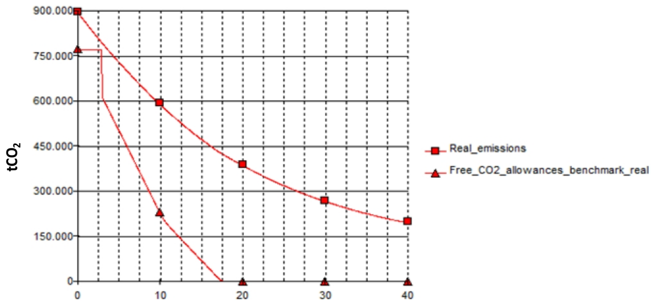

Fig. 4.4. CO_2 allowances benchmark compared to real emissions for *C1_ETS* scenario

4.3 Scenario C4_all

Figure 4.5 shows the results of the implementation of all four policy measures (P_S, P_R, $P_{|}$, P_{ETS}). The scenario resembles the results presented for the *C2_best* scenario, but from the year 2023 an increase in the share of the installed wood fuel capacity is detected when compared to the *C2_best* scenario. In comparison to the *B2_best* scenario, the share of wood pellets does not show any decrease but instead a constant increase to an asymptotic value. Within this scenario the portion of use of wood fuel allocated to wood chips is the most prominent over time but the increase of wood log use shows the strongest increase over the years. In approximately 15 years it registers 90% of use of wood fuel primary energy within the district heating system in regard to heat generation from boiler houses.

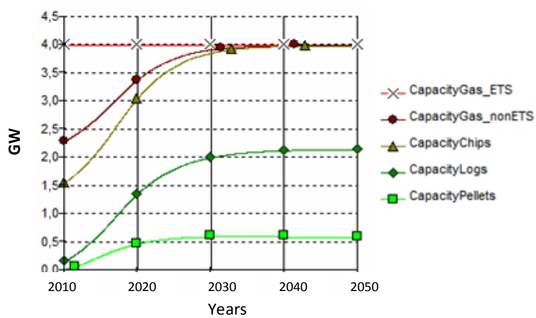

Fig. 4.5. Scenario *C4_all*

All 16 scenarios present not-linear behaviours and the share of wood based fuels by 2050 are in the range of 82-100% (see Appendix of the thesis).

4.4 Sustainability of the forest resource

The results of the modelling show that at the existing rates of forest harvesting and new forest planting according to the sustainable management of forests (see Chapter 5 of the dissertation thesis), the total amount of forest stock in Latvia will have a slow decreasing tendency with an asymptotic final value over time.

4.5 Model validation

A historical behaviour matching test has been conducted based on relevant historical data in regard to the share of the primary energy mix in the district heating sector (i.e. natural gas and wood fuels in the form of wood chips, logs, and pellets) from the year 2000 to 2010. This has also taken into account the price for each fuel source according to the historical trend.

In the following figure (Fig. 4.6) the simulated data are compared with the historical data. As can be seen, given the fluctuations in the prices of the fuel sources (natural gas and wood fuels in the form of chips, logs, and pellets) and the initial share of fuel use in the year 2000, the results of the simulated primary energy share seem to match the historical data in a reasonable confidence.

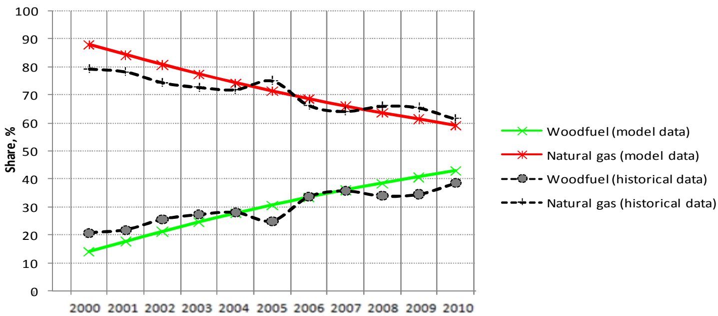

Fig. 4.6. Historical and simulated data for the historical behavior matching test

CONCLUSIONS

1. The doctoral dissertation proposes an integrated approach based on the evaluation of the potential impact assessment of various bioenergy routes through LCA methodology, and the implementation of policy measures and mechanisms to improve the use of bioenergy technologies despite a phasing-out of the fossil based production chain with the use of system dynamics modelling.

2. Within this integrated approach LCA is used as an analytical tool that is able to grasp the complexity of the system and the mutual system dependencies in the bioenergy sector and also as an evaluation tool aimed at studying the sustainability of the bioenergy chains and the net benefit from fossil fuel substitution. Meanwhile, the implementation of system dynamics modelling provides a good tool for forecasting energy developments and trends depending on a set policy frame.
3. The LCA analyses performed show the reduction potentials of alternative bioenergy technologies concerning GHG and other types of pollutant emissions compared to the fossil fuel based alternative. All the proposed LCAs show higher environmental performances compared to the fossil based reference scenario. Specifically, the LCA scenario concerning the use of macroalgae as a substrate for the production of biogas provides a total beneficial environmental burden (i.e. negative value of the whole impact).
4. In the second part of the thesis a system dynamics model for analyzing the effects of policy tools and the EU Emission Trading System on the Latvian fuel mix in district heating systems has been developed for a investigation period of 40 years (2010-2050).
5. The model has been applied to the Latvian district heating system in reference to the heat produced from boiler houses. The aim of the model is to evaluate the primary energy mix within the sector and discover which policy instrument can play a prominent role in the switch to wood based fuels. The model implements the main carbon footprint from the LCA in regard to the use of wood fuel versus natural gas for thermal energy production carried out during this thesis.
6. The policy instruments have been implemented in terms of: i) subsidies for the replacement of natural gas installations with wood fuel based technology, ii) promoting and improving the dissemination of best practices and campaigns for the use of wood based fuels decreasing risk perception, and iii) supporting measures for the improvement of existing wood fuel installations. Moreover, the ETS scheme and a CO_2 taxation frame have been implemented as policy instruments that work based on the “polluter pays” principle.
7. The results of the simulation within the proposed system dynamics model show that the greatest impact in the fuel structure of the Latvian district heating system in order to increase the share of fuel wood based operators comes from a combination of at least two policy tools. Specifically, these are state subsidies for promoting the development of wood based technologies in the market and solutions that act to guarantee a risk reduction perception for investors.
8. The proposed system dynamics model pays attention to the sustainability of wood fuel resources in respect to the increase in wood fuel consumption due

to the implementation of policy measures. Based on the model assumptions with the existing rates of forest exploitation and new forest planting, it is possible to fully offset wood fuel consumption in district heating systems in Latvia. This is verified in the scenario in which all the policies are implemented, thereby maximizing the effect of the potential wood fuel exploitation.

9. It has been demonstrated that the analysis of bioenergy technologies is a very complex task involving technological, economic, ecological, and societal parameters. The method developed in the thesis represents a supporting tool that can significantly increase the understanding of bioenergy technologies within a certain policy frame. The use of an integrated approach aimed at merging LCA methodology and system dynamics modelling has proven to be a reliable and valuable tool for the comparison of various technologies implemented in a wider frame in which the effects of various policy strategies are implemented.

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MODEL FOR SUSTAINABLE BIOENERGY PRODUCTION AND USE

Summary of Thesis

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