RIGA TECHNICAL UNIVERSITY
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MODEL FOR SUSTAINABLE BIOENERGY PRODUCTION AND USE

PhD. – Thesis

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ANNOTATION

With its 20-20-20 targets, implemented in the Directive 2009/28/EC, EU has committed to: reduce greenhouse gas (GHG) emissions, to increase the use of Renewable Energy Sources (RES) and increase energy efficiency. On this basis, the development of the bioenergy sector in all its own production routes is foreseeable in the very next future.

Latvia is undertaking and developing different measures to be implemented in the national Renewable Energy Action Plan in order to reach the set target of 40% of final energy consumption offset by the use of renewable energy resources. Nevertheless, important improvements need to be planned in the long-term perspective. This will not only focus on the main energy sectors, but target the environmental, social and economical aspects in an expanded evaluation.

Within the transition to a green energy-based system, it is necessary that the development of the most suitable strategy requires clear and feasible evaluation tools adopting a global and holistic 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 this light, an integrated approach e of a typical energy planning modeling tool - i.e. system dynamics modeling - and cradle-to-grave impact assessment methods - i.e. Life Cycle Assessment (LCA) - may represent a suitable, comprehensive, and analytical tool.

The general objective of this dissertation is the development of an integrated analytical tool for the environmental performance evaluation of different bioenergy routes within several possible “green” policy alternatives.

The main work tasks addressed were to:

1. analyze the environmental performances and sustainability of different types of bioenergy routes using different types of technologies based on Life Cycle Assessment (LCA),
2. definite the integrated analytical tool, involving the:
   a. development of an integrated methodology linking LCA and white box modeling through the system dynamics approach,
   b. analysis of the implementation of different policy measures aimed to increase RES use with a System Dynamic (SD) model. The objective of the model is to represent the casual relationships between the behavior of the complex system of the Latvian district and its underlying structure heating system. The model evaluates the combination of three different policy instruments focusing on encouraging the installation of woodfuel installations in favour of those using natural gas,
   c. evaluation of the impact of the Emission Trading Scheme (ETS) as a mechanism to reduce the use of fossil fuels-based energy resources within the SD model;
3. validation of the proposed system dynamic model to the Latvian district heating system.

The results of this research can be addressed to different target groups at different levels, in particular: the governmental level, the energy sector (investors and operators) level, the environmental level, and the scientific level.

The schemes proposed within the model can be further exploited at the European scale involving other types of policy instruments and bio-energy routes not investigated at in this step of research.

ANOTĀCIJA

Atjaunojamie energoresursi, līdztekus energoefektivitātes uzlabošanai, ir neatņemama Eiropas enerģētikas un klimata politikas sastāvdaļa. Tās 20-20-20 mērķos, kas noteikti ar 2009/28/EC Direktīvu, ES apņēmusies : samazināt siltumnīcas efekta gāzes (SEG) emisijas, palielināt atjaunojamo energoresursu (AER) izmantošanu un energoefektivitāti. Līdz ar to bioenerģijas sektora un visu tās ražošanas veidu attīstība paredzama pavisam tuvā nākotnē.

Arī Latvija ir uzsākusi un turpina attīstīt dažādus pasākumus, kas paredzēti Atjaunojamās Enerģijas Rīcības plānā, lai varētu sasniegt uzstādīto mērķi – nodrošināt 40% no gala enerģijas patēriņa, izmantojot atjaunojamos energoresursus. Neraugoties uz to, ilgtermiņā nepieciešami nozīmīgi uzlabojumi. Turklāt, tie nedrīkst koncentrēties tikai uz galvenajiem enerģētikas sektoriem, paplašinātā novērtēšanā jāpievērš uzmanība arī vides, sociālajiem un ekonomiskajiem aspektiem.

Līdz ar pāreju uz zaļajā enerģijā balstītu sistēmu, piemērotākās stratēģijas izveidošanai jāizmanto skaidri saprotami un ticami novērtēšanas instrumenti, izmantojot vienotu vērtēšanas sistēmu globālā mērogā.

Enerģētikas plānošanai un ar to saistītajam ietekmes uz vidi novērtējumam jābūt savstarpēji vienotiem, lai varētu pareizi sekmēt atjaunojamās enerģijas ražošanu un stimulēt tās izmantošanu bioenerģijas sektorā. Balstoties uz iepriekšminēto, piemērotu, visaptverošu un analītisku rīku varētu dot integrēta pieeja tipiskajam enerģētikas plānošanas modelēšanas instrumentam – t.i. sistēmu dinamikas modelēšanai – un ‘no šūpuļa līdz kapam” (cradle-to-grave) ietekmes novērtēšanas metodei – t.i. Dzīves Cikla analīzei (LCA).

Galvenais šis disertācijas mērķis ir integrēta, analītiska instrumenta izveide, dažādu bioenerģijas veidu ietekmes uz vidi novērtēšanai, dažādu alternatīvu “ zaļo” politiku īstenošanas gadījumos.

Galvenie uzdevumi bija :

1. analizēt dažādu bioenerģijas iegūšanas procesu un tehnoloģiju ietekmi uz vidi un ilgtspējīgu, balstoties uz Dzīves cikla analīzi (LCA);
2. definēt integrētās analīzes rīku, kas ietver:
   a. integrētas metodoloģijas izstrādāšanu, apvienojot Dzīves cikla analīzes pieeju un sistēmu dinamikas - ,, baltās kastes” modelēšanas – pieeju,
   b. dažādu AER izmantošanas veicināšanai domātu politiku īstenošanas rezultātu analīzi izmantojot Sistēmu Dinamikas(SD) modeli. Šī modeļa mērķis ir attēlot nejaušās sakarības starp Latvijas rajona kompleksās sistēmas uzvedību un tā siltumapgādes sistēmas struktūru. Modelis tiek izmantots trīs dažādu politikas instrumentu kombinācijas nevērtēšanai, koncentrējoties uz atbalstu koksnes kurināmā iekārtu uzstādīšanai, aizvietojot iekārtas, kurās izmanto dabasgāzi,
   c. emisijas kvotu tirdzniecības sistēmas (ETS) kā fosilo energoresursu patēriņa samazināšanas mehānisma ietekmes novērtējums;
3. ieteiktās sistēmu dinamikas metodes validācija Latvijas centralizētās apkures sistēmā.

Šī pētījuma rezultāti var tikt attiecināti uz dažādām mērķa grupām dažādos līmeņos, galvenokārt: valdības līmenī, enerģētikas sektora(investori un uzņēmēji) līmenī, vides līmenī, kā arī zinātniskā līmenī.

Modelī piedāvātās shēmas tālāk var tikt izmantotas Eiropas līmenī, iekļaujot citus politikas instrumentus un bioenerģijas ieguves veidus, kas netika apskatīti šajā pētījuma posmā.

ANNOTAZIONE

Relativamente agli obiettivi definiti come “20-20-20” inseriti nella Direttiva 2009/28/EC, la Comunità Europea (CE) si è impegnata nel ridurre le emissioni di gas serra, di aumentare l’utilizzo di energie e fonti rinnovabili e di incrementare l’efficienza energetica. Su tale presupposto è auspicabile un incremento del settore bio-energetico nei suoi vari differenti processi produttivi.

Sullo stesso trend è indirizzato lo sviluppo di diverse strategie energetiche in Lettonia da attuare all’interno del piano nazionale per le energie rinnovabili al fine di raggiungere l’obiettivo prefissato di 40% di utilizzo di energie rinnovabili nel consumo lordo di energia finale. Ulteriori miglioramenti devono essere comunque pianificati per strategie di sviluppo a lungo termine mirate non strettamente all’aspetto energetico, ma concertando su una più larga visione dove aspetti ambientali, sociali ed econimici non ne possono essere disgiunti.

La scelta della più corretta e giusta strategia necessita di strumenti chiari, implementabili ed utilizzabili al fine di poter garantire il passaggio ad un sistema basato sulla “green-ecomony” e conseguentemente sulle rinnovabili.

La pianificazione energetica e la valutazione di impatto ambientale non possono pertanto essere disgiunte al fine di promuovere e stimolare l’utilizzo delle fonti rinnovabili nel settore bio-energetico. Ciò significa che, un approccio integrato relativamente all’utilizzo di modellazioni e strumenti di calcolo nel settore della pianificazione energetica (come la modellazione “system dinamics”) e una valutazione ambientale che tenga conto dell’impatto sull’intero ciclo di vita della tecnologia utilizzata (approccio “cradle-to-grave” base della metodologia LCA), rappresenta un corretto e comprensivo strumento analatico di valutazione.

Su tali presupposti l’obiettivo generale di questa tesi di dottorato è indirizzato allo sviluppo di uno strumento analitico mirato sia alla valutazione ambientale di differenti percorsi per la produzione di bio-energia, sia alla valutazione dell’effetto della scelta di differenti alternative politiche, atte a promuovere l’incremento dell’utilizzo delle rinnovabili.

Nello specifico la tesi è stata sviluppata su tre principali tematiche:

1. valutazione dell’impatto ambientale e della sostenibilità di diverse tipologie di bionenergia utilizzando la metodologia LCA;
2. definizione di uno strumento integrato di valutazione includendo:
   a. lo sviluppo di una metodologia collegante l’appproccio LCA e la modellazione “system dinamics” per la pianificazione energetica,
   b. l’analisi dell’effetto a lungo termine di diversi strumenti politici implementati in diverse strategie indirizzate all’incremento delle installazioni termiche a combustibili lignei utilizzando la modellazione “system dynamic”. Nella presente tesi è sata considerata e modellata la struttura del sistema di teleriscaldamento Lettone,
   c. valutazione dell’effetto dell’ “Emission Trading Scheme”, sulla struttura in esame, inteso come meccanismo atto a ridurre l’uso di risorse fossili;
3. validazione dei risultati relativamente al modello proposto per la struttuta del sistema di teleriscaldamento Lettone.

I risultati di questa ricerca possono essere indirizzati a differenti categorie di destinatari e settori: governativo, energetico (sia per investitori e sia per operatori), ambientale e scientifico. Gli schemi proposti nel modello sviluppato potranno essere in seguito utilizzati, con gli opportuni cambiamenti, su scala Europea prevedendo l’utilizzo di ulteriori strumenti e strategie politiche ed ulteriori processi bio-energetici non considerati in questa fase di ricerca.

ACKNOWLEDGEMENT

Paulo Coelho writes important suggestions on climbing mountains “… *choose the mountain you want to climb, find out how to reach the top, learn from someone who has been there before, pay attention to what is around you, keep in mind the objective however the view around is changing, be prepared to go the extra mile, be joyful when you reach the top, make a promise to discover another mountain and tell your story*”.

This thesis represents the example how I reached the top of “my mountain” but where each step along the path has been supported by solid rocks coming from the competence, comprehension, empathy and love of many persons around me.

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TABLE OF CONTENTS

INTRODUCTION

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

The 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 our current situation when the fossil peak will definitely be reached in the near future, wider use of renewable energy sources (RES) can be found as a solution complying with the principles of sustainable development and giving benefit to environmental, economic, as well as social dimensions. At the same time, a wider use of renewable energy sources should not cause adverse effects on ecosystems, biodiversity and the need to 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 the EU Directive 2009/28/EC, has committed to: reduce greenhouse gas (GHG) emissions by at least 20% below 1990 levels; to increase the share of RES to 20% of EU energy consumption, and to reduce primary energy use by 20% by the year 2020. The EU member states are undertaking various national and EU level policies and measures to reach predefined targets, all of them are implemented through the Renewable Energy Action Plan (REAP) of the EU Member States (MSs). Using this as a base, the increased production of the bioenergy sector, in all its own different forms, is foreseeable in the very near future.

Latvia is also undertaking and developing different measures to be implemented in the national REAP to reach the set targets of 40% of final energy consumption offset by the use of renewable energy resources. Since Latvia has the second highest share in the European Union, around 35%, great improvements still need to be planned in a long-term perspective. These must be focused not only on the main energy sectors, but also targeting environmental, social, and economic aspects in an expanded evaluation of the situation. Moreover, Latvia presents a particularly difficult situation where an increase in the import of natural gas has been detected in the last years. This is in contradiction to the set targets of the EU Directive 2009/28/EC and against the criteria for sustainability.

Undoubtedly, the transition to an environmentally sound direction in the energy sector is difficult, but not impossible. Achieving this challenge will need the correct implementation of the best “green policy strategy”. In fact, the basic concepts of sustainability related to the green-energy market are well known, but the operational aspects and the methodology to implement them in the context of policy making and planning are not yet determined. Nevertheless, it is necessary that the development of the most suitable 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 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 this light, an integrated approach to the use of typical energy planning modelling tools - i.e. system dynamics modelling - and cradle-to-grave impact assessment methods - and Life Cycle Assessment (LCA) - may represent a suitable comprehensive analytical tool.

The general objective of this dissertation is related to the development of an analytical tool for the evaluation of the environmental, social, and economic performances of different types of bioenergy sources and bioenergy technologies. The tool is oriented to the energy planning sector, and specifically Directive 2009/28/EC. The tool will evaluate the effects of different policy measures implemented in National Renewable Energy Action Plan (NREAP) of the European Union (EU) Member States (MSs).

To reach this objective the following objectives have been set:

1. Analyse the environmental performances and sustainability of different 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. Develop an integrated methodology merging LCA approach and white box modelling through the system dynamics approach;
3. Analyse the implementation of different policy measures, from the EU MSs NREAPs, based on non-linear structures of complex systems;
4. Evaluate the impact of the Emission Trading Scheme (ETS) as a mechanism to reduce fossil-based energy resources;
5. Develop 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. Perform a case study of the Boiler Houses of the Latvian District heating system to validate the proposed system dynamic method.

The research methodology is based on two interconnected model parts.

The first part is related to the use of the LCA model for the evaluation of the whole environmental performance under specific impact categories. The methodology included all the main phases laid out by the ISO Standard 14044 and the sensitivity analysis under different 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 a specific environmental data output of the LCA model.

The combination of the previously mentioned methodology is applied to the study of forecasting the primary energy consumption within the Latvian District heating system and its sustainable development.

Data has been collected from different sources: EU commission, Latvian Statistical Bureau, Latvian energy experts, specific database (i.e. Ecoinvent 2.1) Wood energy experts and forest experts.

The analytical approach developed and proposed in this thesis is related to the integration of an energy-plan using white box modelling (system dynamics modelling) with Life Cycle Assessment (LCA). The scientific significance of the thesis pertains to the following aspects:

1. Use of an LCA-based analysis for different 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 a policy strategy and EU ETS mechanism implementation within the target set for the share of renewable energies in the EU;
3. Proposing a tool for the evaluation of reliability of green investment for operators participating in the ETS;
4. Developing an integrated methodology for the evaluation of the sustainability and forecasting of primary energy consumption.

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

- Governmental level; the results from this thesis are useful for evaluating the effects of support schemes for bioenergy development in Latvia. At the same time, the results provide a forecast for the primary energy consumption and the installed capacity in regard to the District heating system;
- Energy sector (investors and operators); the system dynamics model proposed quantify the effects of the implementation of certain policy mechanisms providing trends for short and long terms in regard to the share of the use of renewable energy sources;
- Environmental level: the methodology proposed is focused on the optimization and reduction of the emission when assessed by the sustainable development criteria;
- Scientific level: a wider and interconnected integration of LCA methodology and system dynamics approach can be developed in order to analyse and study problems oriented to the integration of the bioenergy routes within the whole energy sector.
- The scheme proposed within the model can be further exploited at the European scale involving other types of policy instruments and bioenergy routes which were not investigated at this stage of the research.

1 LITERATURE REVIEW

1.1 Bioenergy conversion processes routes

Bioenergy is seen as one of the most favourable options to mitigate greenhouse gas (GHG) emissions and replace fossil fuels. This is evident in Europe where the Directive 2009/28/EC ratified the main guidelines in regard to renewable energy and where bio-energy, is a highly promoted sector. As it is well-known [1] biomass is one of the main sources for the production of bioenergy.

The main features and aspects of biomass can be summarized by the following:

- easier storage and transportation, if compared to other renewable sources (like wind and solar) that generate electrical power with the need of an instantaneous consumption and connection to the main grid;
- with respect to other ways for production of renewable energies that use free resources (e.g. wind, sun, geothermal heat, wave) biomass has a market cost, this represents a share of around 50-90% [2] of the total production cost of the bioenergy system. The fluctuations and the range of the variation of price [3] in each national market have different effects on the way that biomass is used for energy production [3]. The only exception is made by the use of waste and residues that have essentially no costs;
- the need of at least one conversion step in order to transform raw biomass into bioenergy evaluable as products and/or services. Biomass can be considered a chemical energy carrier. Solar energy is converted through photosynthesis in the growing mass of a plant. Basically, in this process the fixation of the carbon dioxide and the storage of chemical energy in the chemical bonds of the molecule constituents occur. This energy can be released through direct combustion with the generation of heat, and after further transformation processes into electrical power (if an engine or turbine are used) or combined heat and power (if cogeneration unit are used). The embodied chemical energy can also be converted into different intermediate chemical and energy products. The final biomass product can be found on the market under a different “status”: solid (chips, pellets, charcoal, etc.), liquid (biodiesel, bioethanol, etc.) or gaseous (biogas, synthesis gas, hydrogen, etc.). The final end use of this product can vary between two different applications: power production purposes and transportation (even if the transportation sector could be included in the previous category as mechanical energy);
- a wide range of variation in nature of the biomass feedstock, this feature is different when compared to the other renewable energy resources. In this light, also a variation of the specific technologies that use biomass has to be taken into account and developed.

1.1.1 Definition of the bioenergy system

The preliminary key-plan of the available technologies for bioenergy production is shown in Figure 1.1, and involves both the commercial and novel energy carrier types from modern biomass. The available energy products in the market are based on sugar crops (e.g. sugarcane and beets), starch crops (maize, wheat, cereals etc.), and oil crops (rapeseed, sunflower, soy etc.) as feedstock to produce bioenergy.

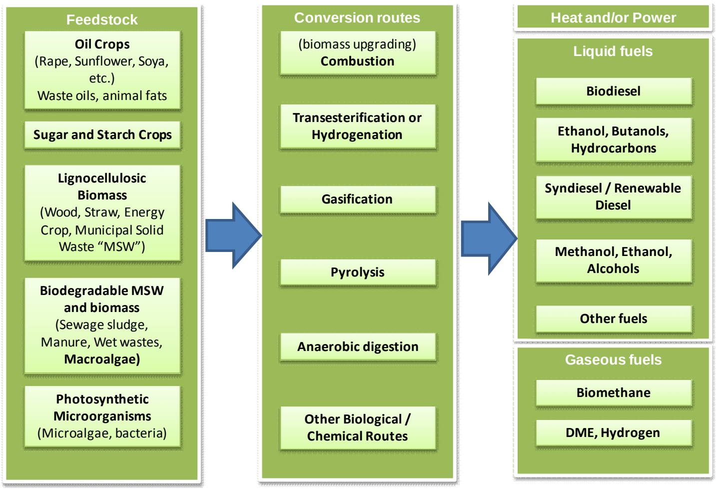


Fig. 1.1. Schematic view of the bioenergy systems (readapted from [2])

Nowadays, bioenergy production is also in connection with the use of residues from the:

- industrial forest sector;
- pulping industry;
- municipal wastes (dry and wet);
- sewage sludge (from waste water treatment plants);
- other types of organic wet wastes from different sectors (e.g. manure substrate for biogas production).

In this light, it is already understood that the use and re-use (including recycling) of these wastes and residues instead of leaving them unused or untreated, can have a bigger impact on climate [2].

Therefore, since a wide range of raw biomass feedstock exists in nature, many possible bioenergy routes as well as a variety of possible end usages are possible. A bioenergy scheme or route can be defined as sequential conversion steps in which raw biomass feedstock is transformed into final energy products (heat, electricity or biofuel in transportation sector).

The main commercial bioenergy routes begin with the principal feedstock such as forest or agriculture based crops and waste streams (e.g. industrial, commercial or municipal) also including the production of by-products. These routes end with the final production of electricity or heat from biomass (direct or combined production), biogas and liquid biofuels (e.g. ethanol from sugarcane or corn or similar crops and biodiesel from oilseed crops) for the transportation sector.

1.1.1.1 First, second and third generation biofuels: different types of feedstock

The use of different feedstock can also be described in relation to the final biofuel generated. In reference to Figure1.2 biofuels can be generically classified as primary and secondary biofuels.

The main distinction is in regard to the form of use: primary biofuels are used in an unprocessed form where basically combustion is used as the main conversion process for the production of heating. The main feedstock of the first type of biofuel is basically lignocellulosic biomass (e.g. wood, straw, energy crops). On the other hand, secondary biofuels can be described as a direct or indirect transformation of the primary biofuels including a processing of the original feedstock. This is the case in the production of biodiesel and bioethanol processed from the original feedstock coming from oil and energy crops.

The final application of the secondary biofuels can be found in transportation and various industrial processes. Therefore, secondary biofuels can be divided into three types of classes: the first, second and third generation biofuels. This distinction is principally based on the type of raw material and technology used during the production processes (see Figure 1.2).

Biofuels can originate from different sectors: forest, agricultural, fishery, or municipal wastes, and also involve by-products and wastes derived from the agro-industry.

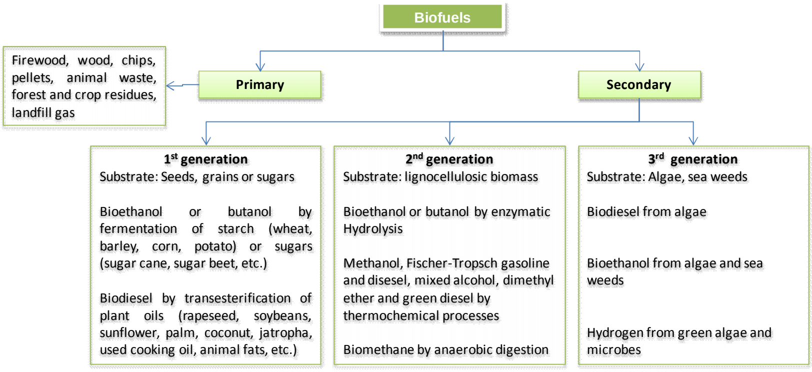


Fig. 1.2. Classification of biofuels [4]

A higher efficiency for the production of electricity and heat is associated to the second-generation feedstock and the relative conversion processes [5]. At the same time, they provide a wider range of alcohols, liquid hydrocarbon fuels, ethers, chemical products and polymers (bio-based materials) within the biorefineries [5].

The production of hydrocarbon fuels starts from sugar and starch crops, the product range can offset the fossil based system for gasoline, diesel, and jet fuel. Both improved first-generation crops and second generation plants related to local and specific geographic sites have the peculiarity to provide a wide range of energy products maximizing the outputs of end products per unit of feedstock [5].

In the following sections each generation type of biofuel is described in detail.

1.1.1.2 First-generation liquid biofuels

The feedstock of the first-generation liquid biofuels is sugars [6], grains or seeds [7, 8] in reference to oil and energy crops. The most well-known first-generation biofuels are bio-ethanol and biodiesel.

The first generation liquid biofuels are produced by sugar fermentation from crop plants and starch-based kernels [9] and from transesterification processes from the production of biodiesel from oil crops.

Bioethanol is produced from biological matter with high contents of sugars through the fermentation carried out with special enzymes produced from yeast [4]. Initially, the sugar of the feedstock is separated, and then the fermentation, using yeast to convert the glucose into ethanol occurs. The wheatear concentration reaches the necessary level through distillation and dehydration (hydrated or anhydrous ethanol), the obtained bio-ethanol can then be directly used or blended with fossil fuels.

When the raw materials are matter rich in starches (e.g. grains), usually hydrolysis is used for converting the starches into glucose.

Biodiesel is basically produced from oil crops produced from the vegetable oils of plants. It is possible to produce fatty acids (methyl or ethyl Ester: so-called biodiesel) and glycerine as by-products through the use of catalyzers (alkaline, acid or enzymatic, eg NaOH and KOH) and alcohol (eg. ethanol or methanol) within the transesterification process. [4] .

First-generation fuel technologies are well developed and the production of large amounts is already present in a number of countries. However, the conflict with the food supply is a sustainable, ethic and viable issue [10] which is yet solved.

1.1.1.3 Second-generation liquid biofuels

The second-generation liquid biofuels can be produced from biological or thermochemical processes from agricultural and lignocellulosic biomass feedstock. The base raw materials are bio-residues from food crops or from the whole biomass of a plant. The second-generation biofuels use non-edible feedstock, consequently the competition with food crops, as it is for the first-generation biofuels, has decreased.

The feedstock used within the production processes can be found among lignocellulosic biomass (wood residues, straw) or biodegradable wastes (manure, wet wastes). With reference to a unit land area, the use of “wastes” increases the total environmental efficiency of the production processes and the amount of the raw material of the considered land that can be allocated for producing biofuels. Practically, this can be considered as an increase of the land use efficiency compared to first generation biofuels. For the majority of second-generation biofuels, the characteristics of feedstock may be considered a possibility for lowering fuel costs and to bring important energy and environmental benefits[11]. Nevertheless, second-generation biofuel at this stage needs more advance processing (including equipment) and a larger amount of initial investment per unit of production. Consequently, a larger-scale facility is mandatory to decrease and contain the total capital cost.

Basically, a few second-generation biofuels such as ethanol and butanol are produced through biochemical processes, all other second-generation fuels are involved in thermochemical processes.

A wide number of second-generation fuels, through thermochemical processes, are produced commercially from fossil fuels: refined Fischer-Tropsch liquids (FTL), methanol, and dimethyl ether (DME). Pyrolysis oil (from pyrolysis processes) is considered as unrefined fuel and needs a more complex and important refining before it can be used as a fuel for vehicles [4].

1.1.1.4 Third-generation liquid biofuels

As has been previously described, bioenergy resources in connection to first-generation biofuels bring the negative effects in terms of strong strains and conflicts with the world food markets, as well as other problems that can be identified in relation to the lowering of water resources (in relation to the crop cultivation) and contributing to deforestation [4]. This can also be seen in regard to the second-generation biofuels where the raw material originates in lignocellulosic bio-residues, from the agricultural and forest sectors. In this light, using a non-food crop such as feedstock decreases the strong environmental load of the first type of biofuels. However, the discussion over competing land use or required land use changes is still an open question [12].

Therefore, on the basis of the current scientific knowledge and technology projections, third-generation biofuels specifically derived from microbes and microalgae are considered to be a viable alternative energy resource that is free of the major drawbacks associated with first and second-generation biofuels.

Biofuel from microbes. Recent studies have shown that species such as yeast, fungi and microalgae can be potentially used for biodiesel production. This is mainly related to the biosynthesis processes of these microbial species that allow for the storage of large amounts of fatty acids [13] in their biomass.

The studies of Huang et al [14] and Zhu et al. [15] have reported studies on microbial oil production from waste rice straw and production of microbial biofuel from waste molasses for biodiesel production.

Biofuel from algae. Algae represents one of the most ancient life-forms [16] that are possible to be found in different ecosystems, in several varieties, and in a wide range of environmental conditions [17]. They are primitive plants and have chlorophyll as their primary photosynthetic pigment [18, 19].

Under natural growth conditions, phototrophic algae absorb sunlight, and assimilate carbon dioxide from the air and nutrients from the aquatic habitats [12]. Production of algae as a feedstock for second and third generation biofuel has been the subject of research in this last decade in the light of the need to focus on 'non-food' energy crops [20-23].

This is mainly related to their higher growth rate than terrestrial plants. In fact, if compared with second generation biofuels, algal fuels have a higher yield: they can produce 30–100 times more energy per hectare compared to terrestrial crops.

Algae are the fastest growing plants in the world, and about 50% of their weight is oil. This means that many algae are rich in oil which can be converted to biodiesel [18, 21] .

The algal organisms are photosynthetic macroalgae or microalgae growing in aquatic environments. Macroalgae are classified into three broad groups based on their pigmentation: (1) brown seaweed (Phaeophyceae); (2) red seaweed (Rhodophyceae) and (3) green seaweed (Chlorophyceae) [24].

The three most important classes of microalgae in terms of abundance are the diatoms (Bacillariophyceae), the green algae (Chlorophyceae), and the golden algae (Chrysophyceae).

Macroalage can be cultivated mainly in open or covered ponds. Microalgae can be cultivated in open or covered ponds and/or closed photobioreactors (tubular, flat plate or other designs).

Producing microalgae biomass is generally more expensive than growing crops, but the production yield per unit of area yield is 7 to 31 times greater than the next best crop. Algae biomass has a photosynthetic efficiency higher (6– 8%, on average) than that of terrestrial (1.8–2.2%, on average). This enhances the CO_2 fixation and leads to higher biomass production [20, 22, 25].

The pond culture of algae presents the advantage of assimilating carbon dioxide emitted by external industrial sources (e.g. electricity plant), using wastewater that may supply the amount of required nutrients. Hence, the direct use of CO_2 is becoming a large factor for increasing the daily growth rate of algae [20, 25]. Not only external sources are needed to feed CO_2 into the algae growth media, [26, 27] but this is also possible in the form of soluble carbonates such as Na_2CO_3 and $NaHCO_3$ [28]. That means that algae present a capability to transform the negative eutrophication potential effects into a benefit for algae growth.

Hence, if used as an interface between biowaste and energy production, macroalgae allows direct utilization of biowaste and, at the same time transforms negative environmental externalities into positive ones [21, 29]. Consequently, the ability of algae to fix CO_2 has been proposed as a method of removing CO_2 from flue gases from power plants, and thus can be used to reduce the emission of greenhouse gases (GHG).

1.1.2 Bionenergy routes: conversion processes

The development of several conversion technologies is necessary for the adaptation of the different features and characteristics of the feedstock (e.g. physics and chemical characterization) to the final end use [30].

Some routes basically do not foresee intermediate conversion processes, consequently they can be considered as straightforward routes (e.g. direct combustion of forest or wood industrial residues for heat production). Others need pre-treatment and upgrading before the conversion (e.g. wood pellet, liquid biofuels for transportation). Upgrading technologies for biomass feedstock (e.g. pelletisation, briquettisation, or wood chips drying) intend to direct the attention to a more convenient and sustainable use of the biomass in the conversion process. In fact, converting raw biomass into more dense energy carriers optimizes the steps of the transport, storage and finds a more suitable end use [2].

In Figure 1.3, a general overview of all the routes starting from the main biomass feedstock and including both the final end use and the type of generation of feedstock is provided. From Figure 1.3 it is possible to see that six main classes of conversion routes can be identified:

1. Thermo-mechanical conversion: specificly should be considered more as an upgrading technology of the biomass where through the use of external thermo-mechanical sources (e.g. steam for pelletization) the bulk raw material is made denser for a more energy-efficient carrier for further direct combustion.

2. Thermo-chemical conversion, by which biomass goes through chemical degradation induced by high temperature. The main thermochemical conversion processes are combustion, gasification, pyrolysis, torrefaction and drying. They diverge in their temperature ranges, heating rate and content of oxygen present in the reaction. The following describes these processes in more detail.

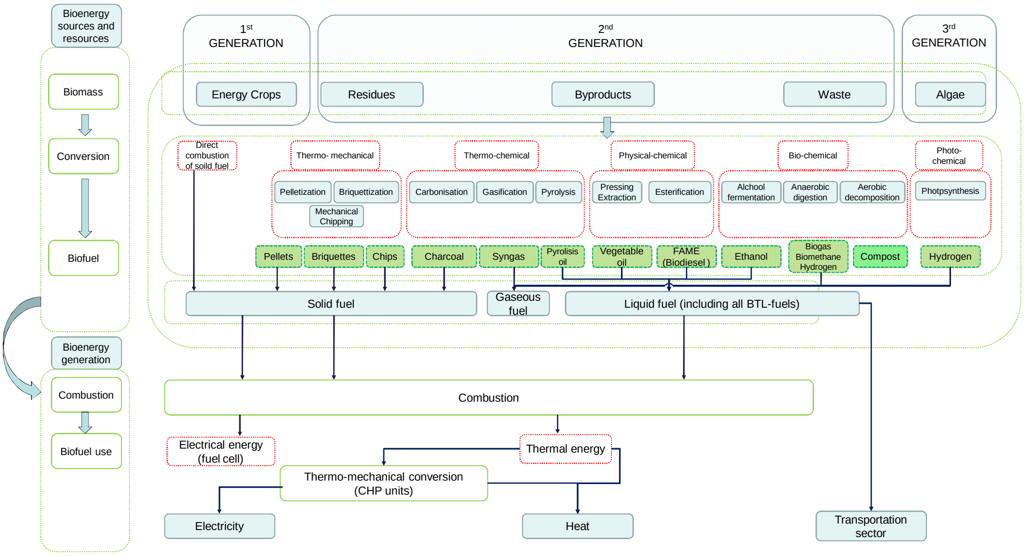


Fig. 1.3. Schematic view of the wide variety of bioenergy routes

Combustion. During combustion the biomass is burned in the presence of air. Theoretically, it can be defined as a complete oxidation of fuel. This is the worldwide process to obtain heat, mechanical power or electricity by converting the chemical energy stored in biomass. The direct use of biomass to produce heat by combustion is an inefficient way of utilizing its energy. The combustion of biomass produces exhaust gases in a temperature of 800–1000 °C [31].

Gasification. Gasification is the conversion of biomass into a combustible gas mixture (also called syngas), by the partial oxidation of biomass at high temperatures, typically in the range of 800–900 °C. It can also be defined as the thermal degradation (devolatilization) with a controlled amount of the oxidation agent (air, oxygen and/or steam) [32]. Within the term gasification, char oxidations are also included. The processes are focused on maximizing the gas mix production, this is different from pyrolysis that is usually optimized with respect to maximum char or tar yield [32] . The gas mix is mostly CO, CO_2, H_2O, H_2 and CH_4 [33] .

Through synthesis, the gas produced can be directly utilized as a fuel for gas turbines and gas engines. Many gasification methods are available for producing fuel gas. In reference to cost, complexity and efficiency of the used technology, circulated fluidized bed gasifiers are more suitable for large-scale fuel gas production [34].

Pyrolysis. Pyrolis is the conversion of biomass to liquid, solid and gaseous fractions by heating the biomass in total absence of air at around 500 °C temperature. The main products are low molecular weight gas products, pyrolysis produces a liquid product called bio-oil (the tar of the thermal degradation), which is the basis of several processes for the development of the various energy fuels and chemicals, and bio-char. In addition, CO and CO_2 can be formed [31, 35].

Torrefaction. It is a high-efficiency thermal process in the range of 200-300°C by which biomass (usually wood) is chemically upgraded into a dry product. Torrefaction is basically the removal of oxygen from biomass which aims to produce a fuel with increased energy density by decomposing the reactive hemicellulose fraction.

Consequently, torrefied biomass is a high quality solid biofuel [36], it has a high energy density and is hydrophobic, this is a good characteristic concerning the issues of transportation over long distances, and outside storage without losses in its calorific value.

Torrefied biomass can also be palletized to further reduce its handling and transportation costs. Torrefied pellets are expected to be even more cost competitive than traditional pellets [31].

Drying. It is the thermal process where the moisture contained in the biomass evaporates. The range of temperature is always under 100°C. Since evaporation uses energy released from the combustion processes this affects the temperature in the combustion chamber (decrease) with an effect to the efficiency of the whole combustion process.

3. Physical-chemical conversion is addressed to the production of liquid fuels (biodiesel or vegetable oil) from energy crop (rapeseed, soybean, Jatropha, etc.) by oil extraction that is basically the raw material for the production of liquid biofuels using transesterification processes.

The main physical-chemical processes are transesterification and hydrogenation [37] that are described below.

Transesterification. It is the process in which alcohols in the presence of a catalyst (acid or base) start to react with triglycerides contained in vegetable oils or animal fats. The result of the process is the forming of an alkyl ester and a raw-glycerine as a by-product.

Before transesterification, the needed vegetable oil is extracted from seeds through mechanical crushing or by the help of chemical solvents. The “bio-diesel” is the fatty acid alkyl esters that can be blended with petroleum-based diesel fuel due to common physical and chemical properties [18]. The protein-rich residue, also known as seed-cake, is typically used for animal feed or as fertilizer [2].

The hydrogenation. It is applied on vegetable oil, animal fats or recycled oils; in the presence of a catalyst to bring about the production of a renewable fuel (biodiesel). Also, this hydrocarbons compound can be blended with different shares of fossil-based diesel.

The process causes the reaction of vegetable oil or animal fats with H_2 together with the presence of a catalyst [2, 5]. Hydrogenated biofuels presents a high cetane number, a low sulphur content and high viscosity [38].

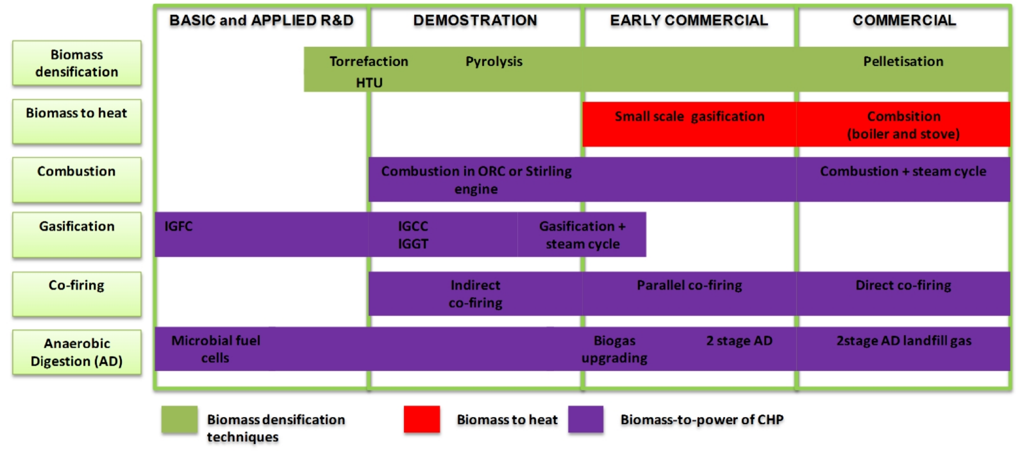
4. Bio-chemical conversion uses living micro-organisms (enzymes, bacteria) to decompose the feedstock leading to the production of liquid and gaseous fuels. There are several biological routes, the main conversion mechanisms are: fermentation from lignocellulosic (grass, wood, etc.), starch (corn/maize, wheat, etc.), sugar (e.g. sugar-cane, sugar-beet, etc.) feedstock and anaerobic digestion mostly from wet biomass obtained from agricultural biowastes and/or different types of manures. Hereafter, the anaerobic digestion is described in detail.

Anaerobic digestion. It is characterized by the breakdown of organic compounds. Practically, it is an anaerobic microbiological decomposition [39]. Feedstocks can also be provided by agricultural biowastes (such as animal manure, leafy plant materials, solid and liquid wastes, or food waste streams). The reactions are carried out by microorganisms in the total absence of oxygen. The product is biogas, a gas mixture on which methane (50 to 70%) and CO_2 are prevalent [39]. Within the process, the solid fraction is fed into a closed container or digester. In this place, the biodegradation occurs in the presence of methanogenic bacteria and under anaerobic conditions with the production of methane-rich biogas and effluent (solids and liquids). The final use of biogas is wide: it can be used for cooking and heating, utilized (after upgrading) in the transportation sector, or used in low-pressure gas turbines, or steam turbines for electrical energy production. The upgraded biogas (85 to 90% methane) can also be injected in the natural gas grid. The residue from anaerobic digestion both solid and liquid can be used as an organic fertilizer or processed further for the production of pellets [5].

5. Bio photo-chemical routes are more recent trends of the branch of biochemical conversion (e.g. hydrogen production using algae), which require the action of sunlight to drive the photopsysnthesis processes that drive the production phase [18].

1.1.3 Biomass for heat and electricity applications

Figure 1.4 points out the different stages of the conversion technology related to their application on the market.



HTU = hydrothermal upgrading, ORC = Organic Rankine Cycle, IGFC = Integrated Gasification Fuel Cell, IGCC = Integrated Gasification Combined Cycle (CC)/ Gas Turbine (GT).

Fig. 1.4. Development status of the main technologies to upgrade biomass and/or to convert it into heat and/or power (readapted from [2])

Traditionally, the energy use of biomass is used for heat production. As it has been evaluated, the route biomass-to-heat is commercially-oriented and cost-competitive, although the economic evaluation would be in relation to the specific bioenergy context and dependent on the different changes in the cost of fossil alternatives. This behaviour is mainly related to the characteristic of the combustion process to be considered; nevertheless, it is a straightforward and well-understood process. A wide range of existing commercial technologies adapted to the characteristics of biomass and the scale of the application can be found in the market.

For a more energy efficient use of the biomass resource, modern, large-scale heat applications are often combined with electricity production in combined heat and power (CHP) systems [40].

Today, biomass-based district heating provides a significant share of the heating requirements in some countries (e.g. northern European countries).

The main bioenergy system related to combustion processes can be divided into three groups: domestic systems, district heating and cooling, industrial systems.

1.1.3.1 Domestic systems

Even though biomass combustion represents the most ancient method to provide heating, it is the most problematic heating fuel to burn in a clean and efficient way. If typical residential wood based facilities are taken into account, the combustion processes depend on an important amount of particulate, carbon monoxide and other exhausted gases. This is even in comparison to a fossil-based system [32] (not taking into account the whole "life-cycle" of the final end use). In this light, modern appliances start to focus on this developmental direction. Producers address their attention to the reduction of undesirable emissions. The consequence is the increasing popularity of pellet boilers. These facilities present an efficiency close to 90% wheatear, the vast majority of traditional domestic biomass (e.g. cooking stoves found mostly in developing countries) have a lower efficiency, around 5-30% [41].

The main view of the design phase is related to the challenging investigation on batch-fired heating systems in order to provide a controlled heat output over time. At the same time, an alternative method is developing mainly related to heat accumulation in high thermal mass systems (stoves) or separated heat storage tanks [32].

In this type of system, nominal thermal capacity is always under 100kW.

1.1.3.2 District heating and Industrial systems

Nowadays biomass-based district heating provides a significant share of the heating requirements in some countries (e.g. northern European countries) [2, 42, 43]. Although it is mature technology, from an economical point of view, biomass-based district heating depends on a number of complex techno-economical parameters that can affect the overall economic efficiency of the system (operational and investment costs related to the logistical optimization and the physical parameter of the wood fuel supplied). The high cost of new heat distribution networks and the difficulty of guaranteeing high overall efficiency are key issues where precise analyses are required. Interest in district cooling systems (especially in combination with heat and electricity production, i.e. tri-generation) is on the rise. This could provide an efficient way of providing cooling services and improve the economic viability of biomass schemes through the enhanced utilisation of plants and infrastructure.

At the same time, an increase of boilers in the range if 0.5-10 MW_{th} are detectable in industries that present a large heat consumption and have a large availability of biomass residues at their disposal site [2]. The industrial sector is potentially a large market for biomass heating, but it requires adequate solutions that meet the technical requirements of a wider range of industries (e.g. in terms of heating temperatures and flue gas quality).

The following combustion technology can be found for industrial combustion plants and/or district heating systems: fixed bed combustion, fluidized bed combustion, and pulverized combustion.

Gasification technology could suit several possible applications in various market segments mainly due to its high versatility. Its use of different types of feedstock with high conversion efficiency to fuel gas and the direct use for heat or power applications or upgrading to syngas demonstrate its diversity.

Gasification offers higher overall conversion efficiencies if compared to combustion-based routes and mostly if in combination with a power-generation facility. This is more evident for medium- and small-scale plants (maximum 10 MWe) where the gasification systems could be easily coupled with gas engines, and where steam-based systems can bring significant disadvantages and expenses related to the plant scale [2] .

Pertaining to larger scales (>30 MWe), the gasification based systems are coupled with combined gas and steam turbines, providing a positive solution in terms of efficiency benefit if compared to combustion. Nevertheless, these plants require more accurate and skilled operations when compared to combustion plants, and their efficiency and reliability still need to be fully established since this is related to the “learning” period of the plant performance.

Gasification can also co-produce a range of end-products, such as heat and electricity, together with liquid fuels and possible other products in biorefineries. These concepts are at the pilot plant level.

Liquid biofuels from biomass present higher production costs than solid biomass used for heat and power, and that solid biomass (not processed) is less costly than pre-processed types (for pellet production). At the same time, this last type presents higher logistical costs. Therefore, this explains the reason why both types of solid biomass markets are developed. Technologies that have had successful results at a large scale (such as combustion for electricity generation) cannot be directly applied to the small-scale in a cost-effective manner because of economies of scale. Therefore, there is a need to identify effective alternative technologies for the commercial stage (e.g. ORC and Stirling engine, see Figure 1.4) [5].

In this light, the intermediate liquid fuel from pyrolysis processes starts to be used as fuel for heating and power and co-firing applications mainly in relation to its transportable peculiarity. This liquid tar is under investigation for stationary power and for upgrading to transport fuel [5].

Biomass gasification is related to industrial applications, CHP and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improved in efficiency over time. Several European countries are developing digestion systems using a mixture of solid biomass, municipal waste, and manures while producing either electricity or high-quality methane. At the smallest scales, the primary use of biomass is for lighting, heating and cooking.

Many bioenergy chains end with a cogeneration unit in their systems where the heat generated can be considered a byproduct of the power generation and used for different uses, such as the production of steam for heating plant requirements. Efficiency has a wide range, from 60% to approximately 90% in some cases [44].

Technologies available for high-temperature/high-pressure steam generation using biomass as a fuel make it possible to operate at higher levels of energy efficiency and generate more electricity than what the plant required. This is the case for the sugarcane bagasse in the sugar mill and the black liquor for the pulp and paper industry. Cogeneration-based district heating in Nordic and European countries is very popular [5].

Also in this case, due to economies of scale, small-scale plants CHP (<150 kW installed capacity) usually provide heat and electricity at higher production costs than larger systems do, even if variation due to local aspects can lead to variations of this trends [43].

Nowadays, different technologies exist, or are in the developmental phase, for the production of electricity from biomass. Co-combustion (also called co-firing) in coal-based power plants is the most cost effective use of biomass for power generation. Biomass combustion plants, including Municipal solid waste (MSW) combustion plants, are also in operation, and many are industrial or district heating CHP facilities. In the case of sludges, liquids and wet organic materials, anaerobic digestion is currently the recommended solution for producing electricity and/or heat from biomass. Nevertheless, its economic case reveals a sensitive problem in regard to the feedstock cost that is not always low. All of these technologies are well established and commercially available (see Figure 1.4).

There are few examples of commercial biomass gasification plants, consequently at this stage, the implementation of this technology is affected by its sensitive economic case and complexity. From a long-term perspective gasification promises a larger penetration in the market in the light of the foreseeable cost-effective improvements, favourable economics at both a small and large-scale, and lower emissions compared with other biomass-based power generation options. Other technologies (such as Organic Rankine Cycle and Stirling engines) are currently in the demonstration stage and could prove economically viable in a range of small-scale applications, especially for CHP (See Figure 1.4).

1.1.3.3 Biomass for biofuel for transport applications

In the transport sector, bioethanol from starch and sugar crops and biodiesel from oil crops and residual oils and fats (basically first generation biofuels) are strongly in use in several countries. Since the production costs of current biofuels vary significantly depending on the feedstock used, also the share at the national market is widely different [1, 5].

Pertaining to topics mainly related to sustainable land use, the potential for the further improvement of first generation technology is still high. From the other side, facing social and environmental challenges (mainly food vs. fuels) and possible indirect land use change would increase the price of the raw material.

While these risks can be smoothed through regulation and sustainability criteria, technology development is also advancing for next generation fuels that focus on non-food biomass (e.g. lignocellulosic feedstock such as organic waste, forestry residues, high yielding woody or grass energy crops and algae). The use of these feedstock for second and third generation biofuel production would significantly decrease the potential impact on land use with global greenhouse gas emission descries in comparison to some first generation biofuels. As previously mentioned, second generation technology, mainly using lignocellulosic feedstock for the production of ethanol, synthetic diesel and aviation fuels, are still immature and need further development and investment to demonstrate a reliable operation at a commercial scale and to achieve cost reductions through scale-up and replication practices. The same aspects are related to third generation biofuel using algae or biomass feedstock. The current level of activity in the area indicates that these routes are likely to become commercial over the next decade. Future generations of biofuels, such as oils produced from algae, are at the applied R&D stage, and require considerable development before they can become competitive contributors to energy markets

The goal for second and third generation technology is therefore to produce sustainable, low cost biofuels from a broad range of resources that do not compete with food production and that have significantly lower GHG emissions than first generation biofuels.

In conclusion, further developments of bioenergy technologies are needed mainly to improve the efficiency, reliability and sustainability of the bioenergy chains. In the heat sector, improvement would lead to cleaner and more possible systems in connection to higher quality fuel supplies. In the electricity sector, the development of smaller and more cost-effective electricity or CHP systems could better fulfil local resource availability, decreasing the economic load. In the transport sector, improvements could lead to higher quality and more sustainable biofuels.

Bioenergy production may increasingly occur in biorefineries where transport biofuels, power, heat, chemicals and other marketable products could all be co-produced from a mix of biomass feedstock. The link between producing energy and other materials deserves further attention both technically and commercially.

1.1.4 Latvian biofuel production trends

Latvian energy supply is characterized by a strong dependence on energy imports, and the highest share of renewable energy in the entire European Union. The latter consists of approximately one third of the total energy consumption. Imported energy sources account for roughly two thirds of Latvia’s total energy consumption. Except for peat, which can be found in approximately 10% of its soil, Latvia has no fossil resources for energy production worth mentioning. Natural gas, oil products and coal are mainly imported from Russia.

However, renewable energy sources are substantial. Forests cover approximately 55% of Latvia’s territory, making biomass the largest domestic resource currently used in heat generation. Hydropower is already the biggest contributor to electricity generation, and still has some unused potential. Wind power has gained importance in recent years and has good potential, as wind is abundant. This is particularly the case along the coast, where, in addition, the transmission network is particularly well-developed.

Latvia can meet about 70% of its electricity demand domestically, mainly with CHP-plants, wind turbines and hydroelectric facilities. The latter two are subject to natural variations in water and wind availability. Therefore, large shares of imported electricity are needed. Many of these imports had come from the Lithuanian nuclear power plant Ignalina, which was shut down in 2009. This situation creates further challenges for the Latvian electricity supply sector and represents a real opportunity for the exploitation of renewable energy sources within the country.

For 2010, the EU-Directive 2001/77/EC set a target of 49.3% of gross electricity consumption to consist of renewable sources, and a 5.75% biofuel-use is obligatory, according to the Directive 2003/30/EC, in the same period.

The target for renewable energy, as a share of final consumption, is 40% by 2020 according to the EU-Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The same directive demands a minimum of 10% of renewable energy in transport.

National commitments include biofuel targets of 10% by 2016 and 15% by 2020, 8% of electricity produced in biomass-run CHP-plants, as well as the above mentioned 49.3% target for 2010 segmented into different generation technologies [18].

1.1.5 Sustainability of bionenergy routes

As previously mentioned, Bioenergy represents one of the key elements within the execution of the RES Directive, as well aswithin the National Renewable Energy Action Plan (NREAP) of each EU Member State. Also from the EU overview about NREAP implementation, the importance of the bionergy sector within the overall EU economy in all its energy sectors emerges. Within this trend, biomass is recognized as one of the main contributors to a reduction in GHG emissions, without lacking in energy security and rural diversification and development [1, 45].

At the same time, for a holistic approach to the reduction of GHG emissions, social and economic factors have to be taken into account for future bioenergy developments.

From the previous description of the bionergy routes, it is evident how these present a composite framework that involves different scales for the bionenergy production and different target groups in an interdisciplinary system.

Lucia Elghali et al. (2007) [45] highlight how the supply chain related to bionergy production routes involves different actors, ranging from biomass growers until regulatory institutions.

Connected with this, the whole bionergy system is sensitive to delay in the planning approval stage, and missing support from public authorities and stakeholders. On the other hand, the reduction of GHG is a primary issue for each EU member State, as well as topics related to increase the income of its inhabitants, job creation and regional development. This should be seen as a base support for the development of any new bioenergy plant [46].

According to Mitchell at al. [47], the criteria for sustainable development can be summarized as providing:

- economic viability and a fiscal framework, in order to supply a strong base;
- environmental reliability, related to the performance in order to prioritize low carbon dioxide emissions throughout the whole bioenergy system;
- social acceptability, a bioenergy based system should not generate any negative social impacts.

More specifically, according to [45] the key topics related to the development of a sustainable bioenergy system, it has to include:

- environmental impacts throughout the full fuel cycle;
- use of biomass as a way to reduce GHG emissions for different energy sectors;
- guarantee of security and stability of bioenergy supply chains;
- more competitiveness and security of the bioenergy chains through innovation;
- implementation of bioenergy at different scales and in different sectors;
- a favourable acceptance and assessment of social impacts for the development of the bioenergy systems;
- the implementation of policy measures in order to promote bioenergy.

Related to these aspects, the choice of a correct method to evaluate the level of sustainability within a certain bioenergy system [48] with the use of certain technology is important [45].

Elghali's paper [45] reports a methodology to establish a level of sustainability of different bioenergy routes where the main framework is seeking to assess the impacts and benefits of a certain bioenergy system while considering the LCA methodology.

Other studies highlight the discussion concerning the sustainability of the bioenergy system [49-53]. In particular, for a bioenergy system based on the direct conversion of biomass, the flows (in- and out-) from a certain system may directly affect the whole environmental performance. Since (as already mentioned) bioenergy routes are complex and interdisciplinary systems based on industrial processes (depending on human decisions and control) and agri-forestry based systems (not fully controllable by human choice) make the system analysis more complicated.

According to A. Cowie et al. [54] the beneficial effect of some first generation biofuel systems can be reduced if indirect emissions associated with the main chain processes of crop production are considered. Similarly for other biofuel systems, such as oil palm, the greatest greenhouse benefits due to efficient high-yielding production systems are redefined, if the effects of indirect impacts such as deforestation are accounted for. Other factors like direct or indirect land use change in biodiversity can negatively affect the net beneficial effect of the bioenergy system.

In the same article, recommendations for improving the sustainability of bioenergy are suggested to:

- improve use of existing biomass resources, oriented to wood and agricultural residues;
- recognize competing needs for land resources, land is a limited resource: restricting the contribution of bioenergy can bring shortages on the mitigation of climate change while the expansion of bioenergy may create undesired side-effects (desertification, lack of carbon pool, loss in biodiversity);
- acknowledge the impact of indirect land use change, emissions from indirect land-use change presents a difficulty to be quantified (difficult to isolate the impact related to biofuels);
- look for synergistic land use solutions in an interdisciplinary consensus (food vs. energy);
- use biomass efficiently to deliver the services required, for example if biomass is a more efficient source for power;
- develop effective policy and operational guidelines to improve the sustainability of bioenergy in different governmental sectors aiming to improve the sustainability in the bioenergy industrial sector;
- consider the full life cycle impacts, a holistic cradle-to grave approach has to be accounted for, in order to evaluate the environmental performances in a wider spectrum (considering type of resources, production system, end-use and final disposal). LCA is one of the most useful tools in this direction;
- allow for a flexible definition of sustainability and adaption to local problems;
- facilitate international trade in sustainable bioenergy to allow its potential to be realized, sustainability must involve each level of the supply chain;
- implement solutions at a scale relevant to the situation;
- learn from existing examples;
- improve understanding of bioenergy.

1.1.6 The sustainability of forestry biomass

Different studies on bioenergy supply have shown that biomass can be one of the principle sources of energy production, and consequently bioenergy technology is expanding worldwide [55].

As it is reported by UNECE/FAO, 2009 [56] the most sensitive environmental issues within the use of biomass, as a renewable source involve the risks related to an intensive large scale use and a globally-sourced supply of biomass for the EU production of bioenergy.

The implementation of the bioenergy scenarios involves assumptions at a global, national, and local scale. The Renewable Energy Directive has set new targets to be achieved by 2020 (i.e. reduction of GHG emissions by 20%; 20% share for renewable energy; improvement of energy efficiency by 20%) [57].

In this context, the European Environment Agency (EEA) calculated that environmentally, bioenergy could reduce the baseline GHG emissions for 2030 emissions by around 11–13% [58]

When a global bioenergy/biofuel scheme is arising worldwide several aspects and issues are developed. These are mainly related to impacts in terms of sustainability and environmental-impact lowering. For example, loss of biodiversity [59], food vs. energy crops [60], resource management and access, calculation of GHG emissions from direct and indirect land use change [61] and insufficient policy support mechanisms [55, 62].

Bioenergy, due to its complexity, needs close management and harmonization among institutions. They must be able to correctly operate in this field, and evaluate different production routes and alternatives while also evaluating the pros and cons of the endeavour in terms of competing demand for land and water for agriculture.

The European Renewable Energy Directive 2009/28/EC sustains measures addressed to deal with the risks for sustainability within the rising markets of biofuels and solid biomass [63].

The European Union Commission admitted that the risks related to the sustainability of domestic biomass production from wastes and agricultural and forestry residues are currently low [64], if no land use change occurred.

Moreover, the Commission highlighted that when agricultural residues are used, the GHG savings of European feedstock are high, and generally above 80% savings compared to the fossil alternative, in this way GHG savings are higher compared with liquid biofuels. This difference, in the case of pelletization is that the process is less energy-intensive than the processes required to make transport biofuels [64].

As well, the Commission stressed that the possible risk related to an increase of the demand for forestry or agricultural residues could cause a reduction of carbon in the soil [64].

The Commission reported that the limitation of sustainability-certified forestry is that it needs a more strict control in the context of higher demands for biomass for bioenergy purposes [65]. Due to the relatively higher sustainability risks for forestry biomass, the Commission states that it will monitor progress in this sector addressing the attention on national sustainability with specific assessment schemes. It will also evaluate barriers against the bioenergy sector [65].

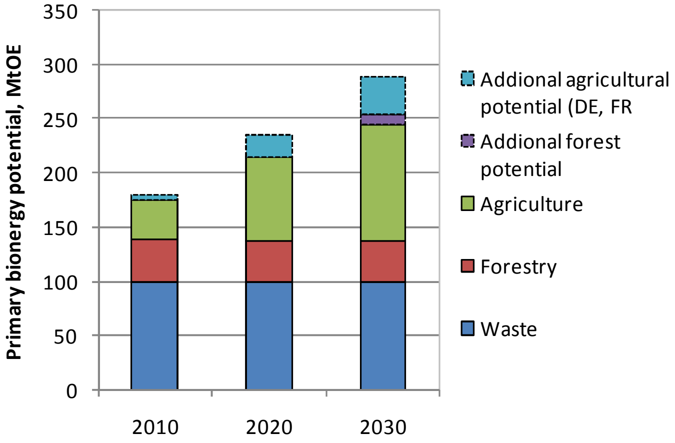


Fig. 1.5. Primary bioenergy potential in the EU-25 [55]

Figure 1.5 reports the primary bioenergy potential in the EU-25 from an environmentally-compatible perspective [55]. The agricultural potential comprises specific bioenergy crops and cuttings from grassland, and was calculated for the EU-25 without Cyprus, Luxembourg and Malta. The forestry potential is based on residues from fallings and complementary fallings.

For pellets, only 1% of the wood fibers goes into energy production [66] even if an increase of the European wood-pellet market has been noticed.

In the study of UNECE/FAO [56] it is reported that globally the area of forest certified for sustainable forest management is increasing worldwide with an increase of approximately 40% in respect to the level of 2007.

For forestry energy species with high rates of biomass productivity there is the risk connected to the management of the water resources that can affect the plantation in terms of environmentally sustainable land management if for example not enough natural water from rainfall is guaranteed [67].

The last aspect is related to removing the biomass. In fact, when removing high biomass volumes from land, the risk of soil nutrient depletion has occurred.

1.2 Bioenergy planning

The planning of the bioenergy sector started after the last oil crisis [68]. In fact, together with the investigation of different types of new energy sources, able to offset the energy demand, the interests concerning the investigation of energy forecasting and a more organized energy planning started to increase. This aspect was supported by a development of IT technology, specifically in the development of hardware and software tools.

The preliminary models were economically oriented, basically intended to investigate the optimization of different bioenergy supply systems

Within the increase of the need of energy planning, the first models were addressed to the analysis of forecasting related to the study of energy demand in connection with the bioenergy supply system. This occurred more at the national and international scale.

With the start of the development of energy decentralization and energy markets, local and regional planning increased their importance with a consequent development of regional or local evaluation tools.

Within this last decade, energy planning started to be a fundamental tool for the implementation of national goals and local actions in respect to sustainable thinking.

Recently, together with the development of local and regional energy issues, the consciousness to face environmental problems connected to the development of a specific energy system received a strong boost. The consequence of this is to focus attention in a more holistic analysis within the implementation of energy models. In fact, the development of energetic-, environmental- , economical-based models has looked not only on improvements and optimizations of energy consumptions and cost, but also to the evaluation of the environmental performances within an implementation of a certain model [69].

In the light of an interdisciplinary analysis, the ‘weighing’ of the problems has become one of the factors within the model simulation than can greatly affect the final results depending on their objectiveness within the evaluation process. At the same time, a powerful holistic tool has started to be developed. This is the Life Cycle Assessment [70, 71] where a “cradle-to-grave” approach is proposed. This takes into account all the steps within a certain analysed system from the extraction of raw material until the final disposal. This method though comes up short in the evaluation of social aspects within the model. This has become more evident recently in the light of the development of a sustainable economy [72].

Finally, different types of methodology implemented in several models have started to develop with the results to provide a wide range of possibility to be chosen within the implementation of a specific energy plan.

E. F. Dzenajavicien et al. [68] report a summary table reporting the specific characteristics, restrictions, applications, strengths and weaknesses of different planning methods.

In regard to the variety of models applied in energy sector planning, a more specific section is needed.

1.2.1 Evaluation tools for bioenergy planning models

Models in energy sector planning are present in a large range. As previously mentioned, the main feature within their use for policy makers and stakeholders is related to the forecasting and projective aspects within the study of certain policy strategies or the implantation of a specific energy technology. A well-known tool is MARKAL (Market Allocation model). This is a linear programming model where the economy is a system with different flows among the single processes (monetary and physical) [73].

Basically the following characterization and general differentiations can be provided:

- “Black box” models, divided in “Bottom-up” and “Top-down” models (and hybrid),
- “White box” models.

Specifically, the “black box” or correlation model is principally based on data and is focused on forecasting issues. They can be considered valid if there is a good match of the model’s output with reference to a real database, for example, regression models [74].

The main challenge in “black-box” modelling is the choice of the reference system, variables for reference trend, shift in reference system, interaction among saving effects, interaction among saving effect and other effects and energy quantities.

“Black box” models are divided into “bottom-up” and “top-down” models. As mentioned by A. Blumberga et al. 2012 [74] the “top-down” models can be used for an aggregated level by comparing findings to the historical database of national energy consumption based on the macro-economic and social relationships. They are classified as econometric and technological models. The first type are based on energy use in relationship to a specific parameter (e.g. income, fuel prices, and GDP), in order to relate the energy sector and economic output. The second ones include other factors that influence energy use (e.g. technological progress, saturation effect, structural change).

The main disadvantages of “top-down” models can be associated to a lack of details on current and future technological options since they are focused on the macroeconomic trends observed in the past that might not be correctly related to the present. This is particularly evident in cases of economic recession or climate change.

A “Top-down” method is the ODEX indices used in Europe made by 26 separate indicators for the end-use sectors i.e. industry, households and transportation [75, 76], and the decomposition analysis where analysis is based on total energy consumption and GDP.

The “bottom-up” models provide the immediate and direct impacts of a specific energy policy, while the top-down assesses general equilibrium effect over a longer time.

The “bottom-up” models are used for a disaggregated level; therefore, a detailed database of empirical data is needed. A well-known “bottom-up” method is the MURE simulation tool used at the EU-level [77]. Within the tool, the impacts of different past energy efficiency policy measures in EU member states are determined. In some cases, both “bottom-up” and top-down methods are combined into hybrid models, for example in the case of the Canadian model CHREM. The model consists of both statistics and building physical modules [78].

Some authors suggest to merge both methods into hybrid models [74].

The “white box” modelling tools, like System Dynamics, (described in more detail in the next chapter) are graphical modelling tools that are specifically designed to guarantee a more clear and defined way of the relationships between the underlying systems structure and the resulting systems behaviour over time.

Data quality and availability are always key aspects for all modelling exercises. The lack of data, or data gaps, does not impact the validity of “white box” System Dynamics models as much as it would affect the quality of projections generated with “black box” econometric and optimization models. Barlas [79] provides an excellent explanation of the reason for why the availability of data is not crucial to create good System Dynamics models, but he also states that the validation of System Dynamics models has to be carried out rigorously, both for structural (where an additional set of tests is needed relative to econometrics and optimization) and behavioural validation.

Every methodology, as well as its applications, has strengths and weaknesses. These depend on the specific characteristics of the methodology and on the issues being analysed.

1.2.2 Merging bottom-up and top-down models

The “bottom-up” model can be considered an engineering model which addresses its attention to the interactions among a large amount of energy technologies that builds up a specific energy system of a certain economy. At the same time, they are a tool for assessing the macroeconomic costs of CO_2 abatement and its economy.

The “top-down” models are basically macroeconomic models that give attention to the effect on prices of the supply–demand interactions. Within this aspect, as well as the evaluation of the costs of CO_2 abatement, economy-based feedbacks are included.

According to I. Sue Wing [80] “*Hybrid climate policy simulations have sought to bridge the gap between bottom-up engineering and top-down macroeconomic models by integrating the former’s energy technology detail into the latter’s macroeconomic framework*”. In the previous report, it is stated that the complexity of the hybrid models rely on the difficulty of interconnecting sources of economic and engineering data.

From the literature, this attempt has not been fully investigated. The complexity probably has to do with the difficulty to involve technical specific databases which include both macroeconomic data with engineering specification. This affects the robustness of the validation of hybrid models [80].

1.2.3 EU climate energy policy

The first step in the light of a full EU climate Energy policy started in 1997 when the EU Council decided to adopt the White Paper for a Community Strategy and Action Plan [81]. In this act, attention was given to the reduction on the dependence of fossil-based energy with the promotion of RES, parallel to the feedback effect on CO_2 reduction and job creation.

By 2000, the EU ratified the Green Paper “Towards a European strategy for the security of energy supply” [82] stressing the fact that the EU energy supply dependence could rise up to only 70% of the Union’s energy requirements if no measures are undertaken.

In 2004, the concepts of environmental items and “sustainable development” in relation to energy supply systems in terms of security designed and comfort of the citizen, while respecting and looking towards sustainable development, were introduced [83].

An important year was 2007, when the EU decided to implement the outcomes of the Kyoto protocol assuming the ambitious targets to reach a 20% share of RES in the total EU energy consumption by 2020 and a 10% share of biofuels used within the transportation sector [84].

In 2009, the EU tried to harmonize the implementation of the strategic energy planning in order to meet the new targets. In this way, a comprehensive framework for the promotion of the use of all RES was stated. The proposal was mainly acting on all EU Member States in respect to the single national targets with the aim of a sustainable bioenergy system (for use and production) avoiding biomass conflicts.

A crucial moment for energy and climate change in EU policy was in 2008, when in January the European Commission endorsed the Energy and Climate Change Package 2013–2020. Basically, the proposal is practically oriented in order to implement more constructive energy action plans to positively face climate change and promote renewable energy sources. This package was based on 4 main structures for the building of the EU legislation:

- a directive regarding RES promotion,
- a directive addressed to improve the emission trading system in the EU,
- a directive oriented on Carbon Capture and Storage (CCS),
- a decision on promoting the sharing of efforts.

In light of that, the following directives were adopted.

1.2.3.1 Directive on the promotion of the use of energy from renewable sources (Directive 2009/28/EC)

Each national target is set in this Directive:

1. overall share of energy from renewable sources in the gross final consumption of energy,
2. a share of energy from renewable sources in the transport sector.

In the Annex I of Directive 2009/28/EC [57], compulsory national targets for the share of energy from renewable resources by 2020 are set.

The main objectives of the Directive are:

1. mandatory national overall targets and measures for the use of energy from renewable sources(see Figure 1.6). These targets are referenced to consistently reaching a minimum target of 20% of energy from RES in the EU's gross final consumption of energy by 2020;

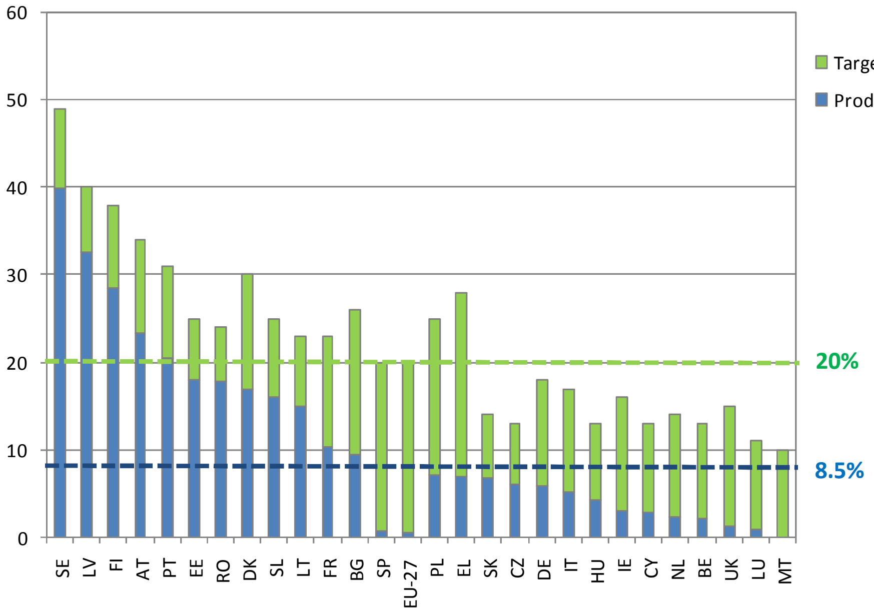


Fig. 1.6. Share of Renewable energies in EU in 2020 (readapted from [57])

2. definition of the trajectory towards 2020; in order to monitor the progress of renewable energy sharing specific planned periodical reference figures have been implemented;

3. definition of action sharing; the application of support schemes, and measures of cooperation between different Member States has been proposed in order to guarantee the achievement of the mandatory levels for the RES;
4. definition of the sectoral breakdown; the EU needs to increase the share of electricity from renewable energy sources from 16% in 2006 to over 30% and transport by 2020. This is at least 10% of biofuels in the transport sector in each Member state concerning the final consumption of energy in transport;
5. definition of National Renewable Energy Action Plans.

In reference to article 4 of the EU Directive 2009/28/EC each Member State shall propose a National Renewable Energy Action Plan (NREAP). Within the compilation of the NREAP, each EU state members should:

1. specify the way and strategy how to reach the 2020 RES targets (basically consisting of the definition of the trajectories for the fixed share of RES within gross energy consumption),
2. distinguish the sector of transport, electricity and heating and cooling,
3. evaluate the potential effects of different policy instruments oriented to energy efficiency,
4. define the technology planning oriented to the fulfilment of the RES targets,
5. specify the policy strategy (measures and reforms) in order to tackle the main barriers to RES development.

In the following a description of the relevant directives will take place and after, an overview of the EU figures based on the analysis of the measure implemented in each NREAP member will be reported. Moreover, a special section will be dedicated to the Latvian NREAP.

1.2.3.2 Directive on the on the energy performance of buildings (Directive 2010/31/EU)

In 2010, the reformulation of the 2002 Directive (2002/91/EC) on energy performance of buildings was ratified in order to increase the energy performance requirements in order to prioritize energy efficiency improvements in buildings and reducing the gap among Member States [85].

According to the directive, each Member State has to set different targets than the others. These are in relation to: defining the requirements to the energy performance, increasing the number of nearly zero-energy buildings, implementing an energy certification system, performing system inspections, and prioritizing a decentralized energy supply system based on RES.

1.2.3.3 Electricity Directive concerning common rules for the internal market in electricity (2009/72/EC)

This directive aims to provide a structured framework for the whole electricity system in all unit components: generation, transmission, distribution and supply. In the light of the endorsed directive, the EU foresees an improvement and integration of the competiveness within the electricity markets [86].

In light of this directive, the distribution system operator will have the role to prioritize the installations addressed to the use of RES (or waste) or Combined Heat and Power units.

1.2.4 EU energy figures: an overview of NREAP from EU member states

As mentioned in Annex I of Directive 2009/28/EC, a compilation of the NREAP must be included. These are composed of two important parts: Part A, where the national overall targets for the share of energy from renewable sources for the year 2020 are reported, and Part B, where the paths for making the trajectories for each Member State are defined.

Within the NREAPs all the projections for gross final energy consumption in the period 2010 – 2020 are reported below.

Table 1.1 shows the total amount of the gross final energy consumption and their trajectory from 2005 until 2020. The main prevalent sector over time is the Heating and Cooling sector, with a value that ranges from 49% (2005) to 46% (2020).

Table 1.1.

Share in the total gross final consumption for all demand sector for the EU27 [87]

	2005	**2010**	**2015**	**2020**
Electricity [%]	23.9	24.8	25.7	26.7
Heating and cooling [%]	49.3	47.7	46.7	45.8
Transport [%]	26.7	27.5	27.6	27.4

In the next table, table 1.2, the contribution from RES for all the EU27 Member States is reported. The heating and cooling sector represents the prevalent one attesting to its value share of 45% by 2020.

Table 1.2.

Share in the total gross final consumption demand from RES for all sectors of the EU27[87]

	2005	**2010**	**2015**	**2020**
Electricity [%]	41.2	39.9	41.8	41.8
Heating and cooling [%]	54.9	49.2	46.5	45.2
Transport [%]	3.9	10.9	11.7	13.0

From Table 1.3 it can be seen that in the year 2020, the overall share of renewables in the NREAP scenario is slightly bigger than the EU-27 target of 20% renewable energy in the year 2020, as it arrives at 21.7%. Table 1.3 also presents the share of renewables in transport according to the directive, where a value of 10.3% is reported hence reaching the 10% required from the RES Directive.

Table 1.3.

Overall RES share for all sectors of the EU27 [87]

	2005	**2010**	**2015**	**2020**
Electricity [%]	15.3	19.4	26.0	33.9
Heating and cooling [%]	9.9	12.5	15.9	21.4
Transport [%]	1.3	4.8	6.8	10.3
Total [%]	**8.9**	**12.1**	**16.0**	**21.7**

It is evident how the electricity sector and the heating and cooling sector have to practically double their share value, while the transport sector has to increase it by 8 times.

From the previous tables, it was as well possible to realize how the targets demanded by the RES directive are slightly different from that ones’ implemented within NREAPs. The following picture presents this discrepancy. As it is possible to see Spain, Hungary and Germany present higher values of the share of RES by 2020 respectively with increases of 13.5%, 13% and 8% in reference to the planned share in the Directive.

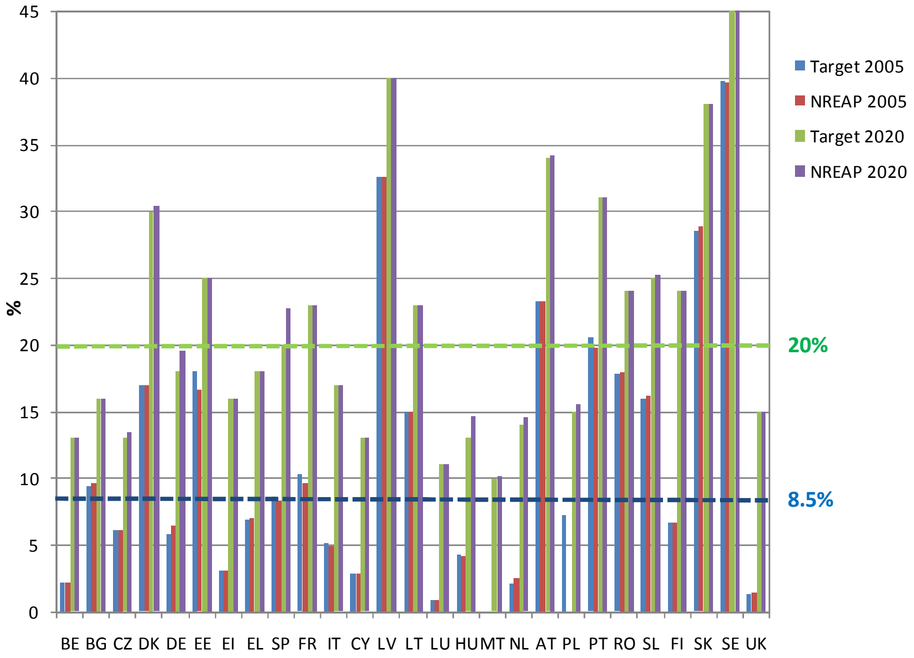


Fig.1.7. RES share according to ANNEX 1 of RES Directive and according to the NREAP document [57, 87]

1.2.5 EU emission trading scheme

The most important EU mechanism based on a "cap-and-trade" system of allowances for emitting carbon dioxide [88] is the EU emission trading scheme (ETS). In a cap-and-trade scheme an institutional body defines a limit (or cap) in reference to the amount of a pollutant that can be emitted. Within this mechanism, the "cap" is the full amount of emission allowances available for a certain year that determines the maximum amount of emissions possible defined by a central authority. This is normally a governmental body.

The first EU ETS was ratified in 2005 and was set up in the light of the Kyoto protocol "Clean Development Mechanism (CDM)" and "Joint Implementation (JI)" criteria.

Basically, there was a decision to establish a price for each tonne of carbon emitted forcing the cost of emissions to address investments to low-carbon technologies with a favourable effect to stimulate the business community in finding innovative and reliable ways to tackle climate change within the reduction of the global GHG emissions.

The EU ratified the EU Directive 2003/87/EU where the main framework of the mechanism is defined.

The EU ETS foresees 3 phases of implementation (trading periods):

- phase 1 – January 2005 – December 2007. The intended targets are to: define the carbon price, promote the free trade of emissions in the EU, and establish the necessary infrastructure for monitoring, reporting and verifying the actual emissions from the businesses covered by the scheme. It can be considered a sort of pilot phase, according to the directive "*each Member State shall decide upon the total quantity of allowances it will allocate for that period*". In the first trading period, from 2005 to 2007, the scheme covered CO_2 emissions from high-emitting installations in the power and heat generation industry and in selected energy-intensive industrial sectors: combustion plants, oil refineries, coke ovens, iron and steel plants and factories making cement, glass, lime, bricks, ceramics, pulp and paper.

- phase 2 – January 2008 – December 2012. It is the period during which the EU and its Member States must fulfil their emission targets in the light of the ratified protocol providing a national allocation plan.
- phase 3 – January 2013 – December 2020. It is the period for boosting long-term investment in emission reductions in order to deal with the reduction targets by 2020. In this period, the real EU-wide cap based on the number of emission allowances (that will decrease annually) is implemented [89]. The allocation of allowances will be based on harmonized rules and an auctioning system that will be the main frame for the allocation method. During phase 3, generally, the cap will decrease each year by 1.74% of the average annual total quantity of allowances issued during phase 2. Within this period a unique EU-wide cap of allowances will replace the current system of 27 national caps implemented through National Allocation Plans (NAPs).

The mechanism related to the allowances is strictly related to the cap that generates scarcity of free allowances over time within the market. On the other hand, operators that keep their emissions below the level of their allowances can sell their savings according to the market price based on a supply-demand mechanism.

Within phase 3 small installations (i.e. with emission less than 25 thous. tCO_2 and installed capacity of maximum 20 MW) foresees the exclusion from the ETS, since they generate only around 3% of total CO_2 emissions [90]. Nevertheless, Member States need to implement substitution measures in order to guarantee the equivalent CO_2 emission reduction.

The power generation sector has to purchase its allowances from 2013; nevertheless, Member States will have the option of derogating from this rule temporarily for existing power plants (i.e. 70% allowances for free by 2012 going progressively to zero in 2020).

Installations implementing the capture, transport, and geological storage of greenhouse gases will have to buy their allowances as well, but not for those stored.

For other sectors there will be a progressive transition to auctioning, starting with a 20% share of allowances auctioned in 2013 and rising to 70% by 2020 with the target to reach full auctioning by 2027.

Each EU ETS operator needs a permit from its competent authority for emissions of all six GHGs implemented by the Kyoto Protocol. It is mandatory that the operator be able to monitor and report the emissions of the plant. A permit defines the requirements of emission monitoring and reporting differently from the allowances which represent the unit within the trade mechanism. The report must be on a yearly time scale. The EU has defined a set of monitoring and reporting guidelines to be followed.

Therefore, the expected results within this mechanism are related to encourage the CO_2 reduction through measures that prioritize the switch to low carbon technology and fuels increasing investment in this area.

For the power sector, the “quantification” of a price on CO_2 emissions will increase the competitiveness of low carbon fuels. The directive is attributed to the combustion of biomass leaving a zero value of emission. Therefore, no allowances must be bought to offset emissions related to the combustion of biomass. This consequently increases the potential to use a biomass-based energy system. On the other hand, price has not been appropriate to motivate companies to invest in low carbon technologies on a large scale [91].

A crucial point within the bioenergy sector is in respect to the fossil-fuel based system and concerns the price at which CO_2 is sold. In IEA bionergy Task 38 report [92], it is figured out that the price of 40 €/tCO_2 is necessary for a favourable price for a biomass plant to be competitive with a coal plant.

To combat this problem, [91] different ranges of the CO_2 auctioned are provided within different CHP plants to be competitive when compared to a coal-based one. Finland has the lowest range around 15-23 €/tCO_2.

Another problematic aspect of this scheme is giving the companies the ability to report their emissions. This has led to a situation where companies over report their emissions. This will give the possibility to gain allocation without any significant investments in energy efficiency.

Moreover, a possible lack of market scarcity – which the cap should have as a precondition for a market creation – can occur due to overshooting the offer in respect to the demand allowances.

1.2.6 Policy instruments for the promotion of bioenergy

As mentioned in the IEA World Energy Outlook 2011 Factsheet [93] the role of policy schemes in supporting the growth of renewable energy is fundamental.

In this context, the EU set the "20-20-20" goals which firstly aims to reduce greenhouse gas emissions by 20% in comparison to the year 1990; secondly, it aims to ensure 20% of end used energy to be provided by renewable sources; and thirdly, reduce the utilization of the primary energy by 20% [94].This plan also includes requirements which the EU member states have ratified.

From the NREAP policy strategies of the EU State Members, it is possible to identify the following four main policy instruments [95]:

- subsidies,
- tax incentives (tax exemptions, reductions and tax refunds);
- financial support (i.e. Low interest loans) and;
- feed-in tariffs.

In this way, according to Dzene I. [96], the main policy tools implemented in Directive 2009/28/EC and consequently within the NREAP can be summarized as:

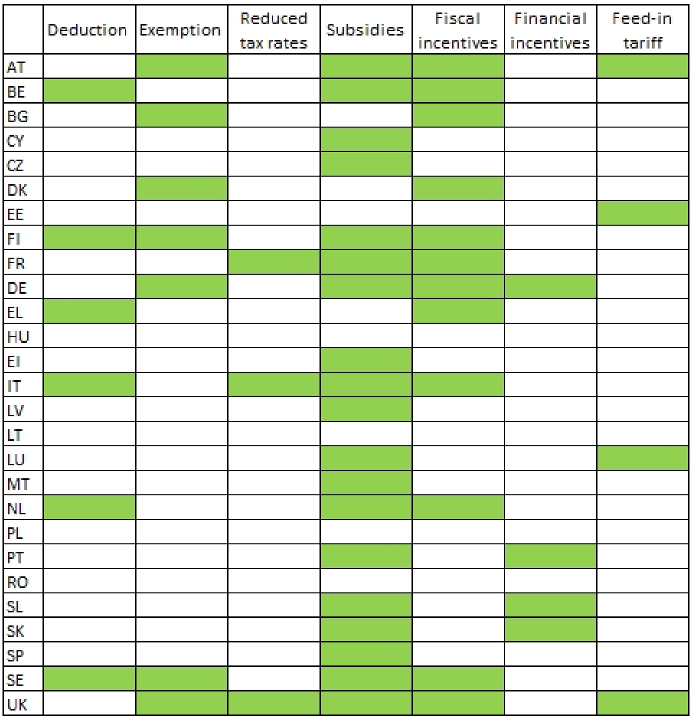
- Green Certificates;
- Investment aid;
- Tax incentives (Tax Exemptions, Tax Reductions and Tax Refunds);
- Renewable Energy Obligation Support Scheme;
- Direct Support Scheme, including price):
  - feed-in tariff,
  - premium payment.

Table 1.4 summarizes the renewable energy measures mainly used in all the EU Member States [1, 95, 97] in regard to the promotion of RES for the heating and cooling system.

From the previous table it can be observed that the way how policy measures have been implemented by MSs is different. In the following section, a small overview of each policy instrument is described.

Table 1.4.

Summary of the policy measures to promote RES in the Heating and Cooling sector



	Deduction	Exemption	Reduced tax rates	Subsidies	Fiscal incentives	Financial incentives	Feed-in tariff
AT		🟩		🟩	🟩		🟩
BE	🟩			🟩	🟩		
BG		🟩			🟩		
CY				🟩			
CZ				🟩			
DK		🟩			🟩		
EE							🟩
FI	🟩	🟩		🟩	🟩		
FR			🟩	🟩	🟩		
DE		🟩		🟩	🟩	🟩	
EL	🟩				🟩		
HU							
EI				🟩			
IT	🟩		🟩	🟩	🟩		
LV				🟩			
LT							
LU				🟩			🟩
MT				🟩			
NL	🟩			🟩	🟩		
PL							
PT				🟩		🟩	
RO							
SL				🟩		🟩	
SK				🟩		🟩	
SP				🟩			
SE	🟩	🟩		🟩	🟩		
UK		🟩	🟩	🟩	🟩		🟩

1.2.6.1 Subsidies

The instrument of subsidies to promote biomass supply within the heating system is widely applied in the EU-27.

The technologies most commonly granted through public subsidies in the EU-27 are based on biomass, solar-thermal and geothermal [95]. Normally, the entity of the subsidy is fixed depending on each institutional government in terms of percentage of the total cost of the investment with a maximum cap.

The reason why subsidies are the most widely used instrument employed by MSs is that they rely on the direct stimulation given by this type of incentive for the implementation of specific technology capital intensive measures directly acting on the reduction of the costs of the whole investment.

In reference to the heating supply system subsidies, they can be seen as an easy way to promote RES due to their application scheme (i.e. easiness of calculation of subsidy percentage of the total cost of the investment) chosen among public or private beneficiaries.

Subsidies present the disadvantage to be strictly related to resources allocated to each national budget. This limits the number of projects that can be granted.

1.2.6.2 Tax incentives

As previously described, these are related to tax deduction, tax exemption and tax refund. The meaning of the incentives is to make the energy generated from RES more profitable than that generated by other fossil-based energy sources.

Tax deduction can involve different target groups. In EU Member States deductions are related to investments on Renewable Energy (RE) equipment, with different supporting schemes that affect the maximal deductible percentage within the personal income tax or within the fiscal profit.

The tax deduction can also include tax rebates, an instrument mainly used to stimulate the adoption in the market of renewable technology directly at the consumers level [95].

Tax Exemptions prioritize different types of actions, among them: solar heating plant exemptions from energy tax (Denmark), RES exemptions from the tax on heating (Finland), and bioenergy-, solid waste- and peat-based energy uses (Sweden).

Also, in Austria, biomass fuels for heating are considered exempted from fossil fuel taxes, and similarly in Germany.

By promoting a price increase for the fossil-based fuels, tax exemptions can play a crucial role.

Reduced tax rates. A reduction of the tax rate is much more commonly used for the promotion of RES [95], only 3 MSs (France, Italy and the United Kingdome) implemented this instrument for heating and cooling systems.

1.2.6.3 Financial support

Financial support measures are also instruments used to promote RES. In relation to the heating and cooling sector the implementation is not so common within the MSs (Cansino et al., 2010). Based on that, only four MSs (Germany, Portugal, Slovak Republic and Republic of Slovenia) decided to implement reduced-interest rates on loans to support systems based on RES within the heating and cooling sector.

On the other hand, it should be mentioned that a probable increase of this mechanism is foreseeable. In Germany, an interest loan at a low level has been offered since 2007 in order to fund solid biomass and solar thermal plants for heating and cooling [95].

1.2.6.4 Feed-in tariffs

Feed-in tariffs (FITs) is another type of support within the implementation of renewable energy technology-based in the energy market. From Chiung-Wen Hsu [98] this is even defined as the *“more effective than alternative support schemes in promoting renewable energy technologies schemes than in promoting (RETs)”.*

Until 2009, FITs were used in 20 Member States but mainly to support electricity production from renewable energy sources [99]. Feed-in tariffs are granted to operators that can be eligible to produce renewable electricity from their electricity plant that is later fed into the grid. The specific feed-in tariffs granted to producers are managed and decided by each government. Basically, FITs are defined with a total price per unit of electricity paid to the producers (i.e. €/kWh). However, the FIT can also be considered as the total amount per kWh received by an independent producer of renewable electricity [100].The cost for the grid operator is included within the tariff price FITs support scheme and, theoretically, foresees a longer time period for financial stability for possible investors [101]. The major benefit of FITs is that private independent producers receive a long-term, minimum guaranteed price for the electricity they generate. For this reason, FITs can provide a certain degree of financial reliability for the producers of renewable electricity.

This mechanism is well-introduced in Germany, Denmark and Spain, where the rapid development of wind, biomass and solar energy has taken place in the latest years.

The basic financial argument in favour of this system is that the FIT value should guarantee the investment costs within a reasonable payback time.

In the case of the heating and cooling sector, feed-in tariffs are used in only a few countries (Austria, Estonia, Luxemburg and the UK).

1.2.6.5 Tendering

The use of tendering, for the announcement of the provision through an order of a fixed amount of electricity from a certain technology source, should ensure the choice of the cheapest offer. For example, Denmark has recently decided to implement a tendering procedure for the development of wind projects.

1.2.6.6 Benchmarking

Benchmarking processes started with the base idea of being a tool for the evaluation, judging and improvement of performances and efficiency in the industrial sector. The base of benchmarking is in the determination of the so-called “Solomon index”, where the comparison of large processes (in term of costs, production efficiency, maintenance, and energy consumption) are provided as a tool in order to evaluate installations in a more economical way. The terms benchmarking and emission benchmarks can be explained as a comparison of performances with respect to GHG emissions against peers (benchmarking) and predefined values for the specific emissions for a certain activity (emission benchmarks). These can be classified by products, fuel, and technology [102].

In other words, emission benchmarks can be considered as quantitative indicators (or emission factors) applied to a unit of energy produced in terms of gCO_2/MWh (or similar).

According to EU regulations, benchmarks are established through a consultation among relevant stakeholders, including the sectors and sub-sectors concerned. The information necessary for setting the benchmarks, installation data on the production, emissions and energy use, was collected in February 2009 from different industry associations, Member States, publicly and commercially available sources and through a survey asking installations to participate [103].

Benchmarks can be calculated in different ways (i.e. average assessment from historical figures or forecasts), and in a different “domaine” (i.e. time and space horizon) and for different space scales (local, regional, national). The choice of the calculation method affects the final results.

According to Dzene [96] benchmarks evaluation of combustion plants are related to the following main parameters:

1. the input energy,
2. the installed capacity,
3. the energy generated (MWh of electricity, MWh of thermal energy, MWh of electricity and heat in a cogeneration cycle).

If the benchmark is calculated by the input energy, the calculation cannot take into account the energy efficiency indicators, as well as the production of the type of product.

The EU directive suggests calculating benchmarks for products rather than for inputs. In this way, the GHG reductions and energy efficiency savings can be maximized within each production process of the sector or the sub-sector concerned.

In the heating supply sector benchmarking can be considered a good method since it provides a tool for supply heating operators to compare standard, low-efficient and advanced technology solutions while substantially promoting and incentivizing the energy efficiency measures in the light of the achievement of the benchmarking index.

The implementation of the benchmarking methodology, within the revised EU ETS and RES Directive can be considered a tool to promote incentives for enterprises to reduce emissions in the most economically reliable manner, to promote better efficiency in respect to carbon-based emissions and to promote innovative methodology and approaches to reduce emissions.

1.2.7 NREAP in Latvia

In reference to the last NREAP [104] Latvia’s target according to Directive 2009/28/EC, is to increase the use of RES from 32.6% of gross final energy consumption in 2005 to 40% in 2020.

According to this document, Latvia’s RES main targets can be summarized as:

- increasing the share of renewable energy in total gross final energy consumption (GFEC) up to 40% by 2020 focused on the use of local energy sources without any supplementary mechanisms provided for the Directive 2009/28/EC;
- increasing of the share of renewable energy in the transport sector up to **10%** of gross final energy consumption by 2020.

Independently from the planned energy efficiency measures, GFEC foresees an increase of 11% by 2020 compared with 2008.

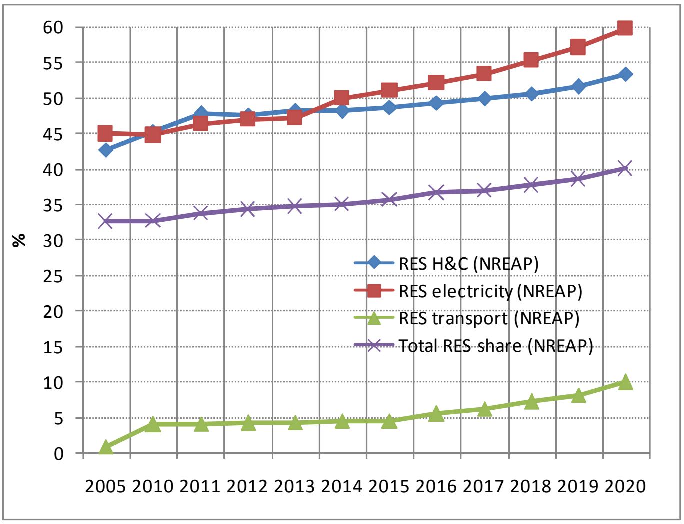


Fig.1.8. National 2020 target and estimated trajectory from renewable energy sources in gross final consumption based on the Latvian NREAP [%]

Figure 1.8 defines the trajectories for reaching the EU ratified targets in regards to the share of RES of GFEC and the developments within each energy sector in Latvia.

Specifically, for the electricity sector the share of GFEC increases from 44.9% in 2005 to 59.8% in 2020, for the heating and cooling sector the share increases from 42.7% to 53.4%, while for the transport sector the share is attested at 0.9% in 2005 and 10% in 2020. The whole total share of RES by 2020 is defined equal to 40%.

1.3 LCA methodology: overview

In recent years, the concept of Life Cycle Thinking has become essential in order to evaluate the environmental impact of a product or service. This approach considers the entire production chain and identifies which improvements and innovations can be made to it [30, 105, 106].

By the evaluation of the supply of raw materials, their production, use and end of life in the same global view offers a wide potential optimization for many products and/or processes. This makes it possible to manufacture products, that are closely integrated both with the production system in the region and with consumption uses and habits, to provide a strong scope for real improvements in a more environmentally sound direction [30]. The supply of raw materials close to the production site or an end-of-life that maximizes collection and recovery of waste are fundamental elements of continuous improvement within the scope of sustainability.

In light of Life Cycle Thinking, the Life Cycle Assessment (LCA) is the main tool to implement this strategy. LCA is then an objective method for evaluating and quantifying the energy and the environmental consequences and the potential impacts associated with a product/process/activity throughout its entire life cycle, from the acquisition of raw materials until its end of life (the “from cradle-to-grave” approach). Within this technique, all phases of a production process are considered related and interdependent, making it possible to evaluate the cumulative environmental impacts.

Therefore, LCA is a widely used approach that enables the energy requirements, GHG balance and other environmental impacts to be calculated. From this point of view LCA appears as a really good tool useful for both the science sector and the policy sector since it is a computational methodology. The LCA approach can be recommended as an appropriate way of determining whether alternative fuels provide benefits over the fossil fuels they replace in reference to the requirements stated by the RES Directive.

In this context the strengths of the LCA are that it:

- enables users to avoid a partial optimization of the whole analysed product system focusing only on a few processes,
- makes it possibile to make comparisons of different scenarios,
- has an effective engineering accounting perspective, useful to understand the optimization of a system and in relation to potential evaluations of optimization changes,
- is multidisciplinary and that it takes into account the impact on the natural environment from different impact perspectives.

Nevertheless, in relation to bioenergy studies, the outcomes from the LCA procedure can lead to misleading interpretations. This has led to an internal controversy that has had the consequence of opening a debate in the scientific literature and media [107].

1.3.1 Applications of LCA

LCA has different fields of application that lead to the achievement of the following main objectives:

- providing a picture, as complete as possible, of the interactions of an activity with the environment;
- identification of the major environmental impacts and the life-cycle stages contributing to these impacts;
- comparing the environmental impacts of alternative products, processes or activities;
- contribution to the understanding of the overall and interdependent nature of the environmental consequences of human activities;
- providing decision makers with information on the environmental effects of these activities and identify opportunities for improvements.

The use of LCA in the private sector varies, depending on a large extent to where a given company is situated in the product chain and on the key driver for the LCA activity, e.g. legislation or market competition. For business teams, the LCA tool should be used to understand the environmental issues associated with upstream and downstream processes as well as on-site processes. This understanding can be used for continuous improvement in reducing the impacts throughout the supply chain.

The integration of environmental aspects in strategic business planning is becoming a hot topic in the agenda of many companies. There are several motivating factors behind the decision to integrate environmental issues, many of which are interrelated:

- consumer demands;
- compliance with legislation;
- community needs for environmental improvement;

- security of supply;
- product and market opportunities.

Some basic product strategies in relation to environmental performance and market potential can be seen in Figure 1.9.

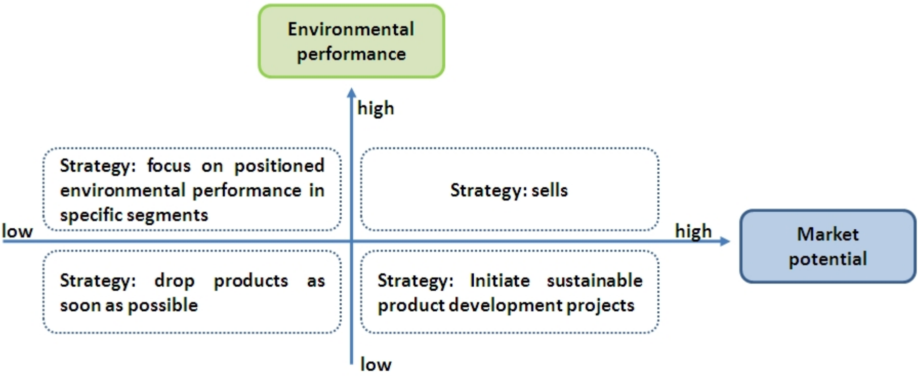


Fig. 1.9. Basic product strategies in relation to environmental performance and market potentials [108]

Acceptable environmental performance is changing from being a necessary characteristic of many products to being a strong positioning tool in the market [108]. Life Cycle Approach can be used both in relation to existing products and to identify market segments to be opened for environmentally sound products.

LCA information and results can provide decision makers and stakeholders an understanding of the environmental pros and cons of their products and services and/or the application of different types of environmental management scenarios. In fact, many business managers are not educated in environmental items (e.g. ecology, environmental modelling) and in this situation the LCA approach can be utilized.

Hence, the evolution of LCA has come out and will probably take on more importance in the fields of:

- internal industrial use in product development and improvement;
- internal strategic planning and policy decision support in industry;
- external industrial use for marketing purposes;
- governmental policy making in the areas of eco-labelling, green procurement and waste management opportunities.

1.3.2 ISO STANDARDS 14040:2006 and 14044:2006

Nowadays, the target of ‘‘sustainable development’’ requires a well-defined methodology in order to quantify and compare the environmental impacts of providing goods and services to society. Every product has its own life, starting with the design/development phase, passing throughout the resource extraction phase, production phase, use/consumption phase, and finally end-of-life activities (including collection/ sorting, reuse, recycling, waste disposal).

All activities can be expressed as cause-effect interactions (e.g. production, use) or feedback interactions (e.g. reuse, recycling) and all of these processes among a product’s life result in quantitative environmental impacts due to key factors such as consumption of materials and/or energy, emissions of substances into the natural environment, and other environmental exchanges [71].

Life Cycle Assessment (LCA) methodology can be defined as a framework for evaluating and assessing the environmental impacts in accordance to the life cycle of a product on the basis of certain types of impact categories chosen for the best understanding of the system impact.

Therefore, LCA evaluates the role of specific elements of a product system to establish its environmental impact. The implementation varies depending on the adoption pattern and on the precision that needs to be achieved.

The International Organization of Standardization (ISO) has also provided very a relevant input to the process of defining an LCA. According to ISO 14040 [109], LCA is:
"A technique for assessing the environmental aspect and potential impacts associated with a product by: compiling an inventory of relevant inputs and outputs of a product system, [e]valuating the potential environmental impacts associated with those inputs and outputs, [and i]nterpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. LCA studies environmental aspects and potential impacts through the product's life cycle (from cradle-to-grave) from raw material acquisition to production, use, and final disposal".

An overview of the LCA methodology can be summarized in the following Figure 1.10.

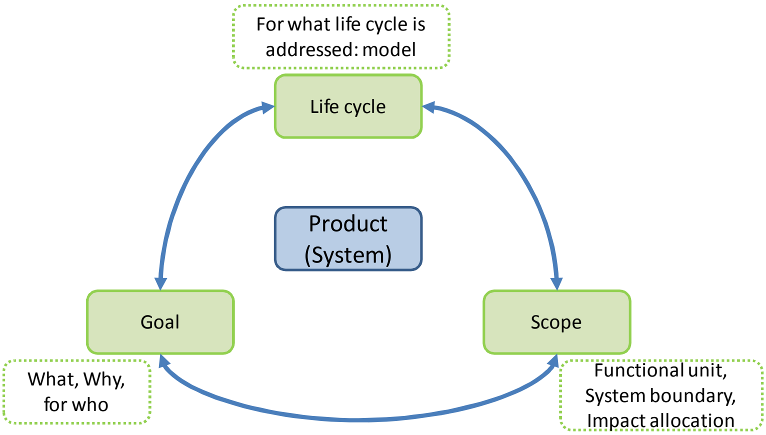


Fig. 1.10. LCA interdependent scheme

As one can see, there is a mutual interaction among all the main phases of the methodology with the consequence to bring structural changes in the case of a change to only one phase.

The methodology is standardized within the ISO 14040 and ISO 14044 [110, 111] that does not provide a strict specification on how the methodology should be integrated for each phase, but a framework within which these elements can be developed and used. The main steps of the ISO Standard 14040-44 can be summarized in the next Figure 1.11.

As one can see, the framework for LCA includes the steps of: goals and scope, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA) and Life Cycle Interpretation.

Due to the constraints on resources and/or data availability, industrial companies usually perform an analysis based on simplified LCA approaches or they simply apply the general principles of Life Cycle Thinking to certain aspects of the production system [112].

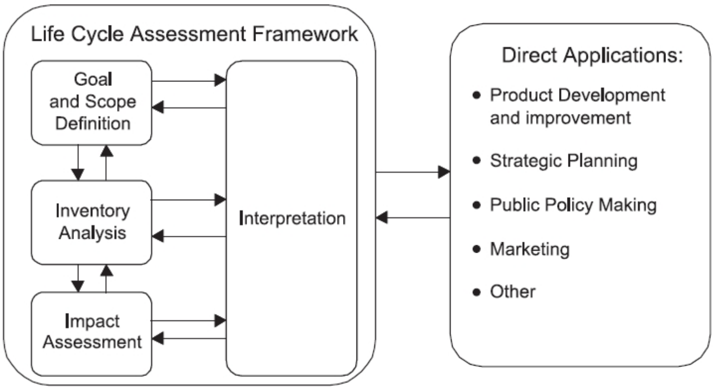


Fig. 1.11. The phases of a Life Cycle Assessment [71]

Basically two main types of LCA can be defined: attributional (also defined as descriptive, retrospective) and consequential (also defined as change-oriented, prospective). The Attributional LCA (ALCA) has been defined as a method "*to describe the environmentally relevant physical flows of a past, current, or potential future product system*" [113]. It can be used to describe GHG emissions of each product manufactured or service produced in the economy at a given point of time. In contrast, the Consequential LCA (CLCA) can be defined as a "*method that aims to describe how environmentally relevant physical flows would have been or would be changed in response to possible decisions that would have not or would be made* [113]". The ALCA reflects the system as it is whereas the CLCA attempts to respond to the 'What if' question. Most bioenergy system LCAs are designated as attributional to the defined process system boundaries. Consequently, LCAs analyse bioenergy systems beyond these boundaries, in the context of the economic interactions, chains of events and the effect in bioenergy production and use, and effects of policies or other initiatives that increase bioenergy production and use. LCAs can then investigate systemic responses to bioenergy expansion (e.g., how the food system changes if increasing volumes of cereals are used as biofuel feedstock or how petroleum markets respond if increased biofuels production results in reduced petroleum demand) [113].

1.3.2.1 Goal and Scope Definition

The goal and scope is the phase in which the LCA product system in terms of the system boundaries (temporal, geographical and technological) and functional unit is defined and described. Hence, at this stage the initial choices which determine the working plan of the entire LCA are made. The definition of the goal and scope itself is a critical part of LCA modelling due to its strong influence on the final result of the study.

In the goal, the definition has to be clearly stated. The aim and objective of the study specify the intended use of the results, the reason of the study (e.g. commissioner and/or proposer) and the target audience to address the result of the study.

1.3.2.2 Inventory

The inventory phase is the fundamental core of an LCA.

Life Cycle Inventory (LCI) is the phase in which the amounts of inflows and outflows of the overall systems in terms of materials, resources, energy, waste flows and emissions attributable to a product's life cycle are estimated and evaluated [71].

The processes within the life cycle involve all the associated material and energy flows and the total inputs and outputs from, and to, the natural environment.

This final result is a product system model and an inventory of environmental exchanges related to the functional unit. In other words, the final result of the inventory analysis is an inventory table.

1.3.2.3 Impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in which the results of the inventory analysis are further processed and translated in terms of potential environmental impacts.

Hence, the result of the LCIA is an evaluation of a product life cycle, based on the chosen functional unit, in terms of several impact categories such as global warming, acidification, eutrophication, land use, etc. also called mid-point category analysis; and, in some cases, the results are expressed in an aggregated way such as years of human life lost (e.g. DALY – Disability Adjusted Life Years), CO_2 equivalent, potential of an animal species to disappear (e.g. PDF - Potentially Disappeared Fraction) also called end point. According to the ISO 14042 and 14044 the mandatory steps are listed below (see Figure 1.12).

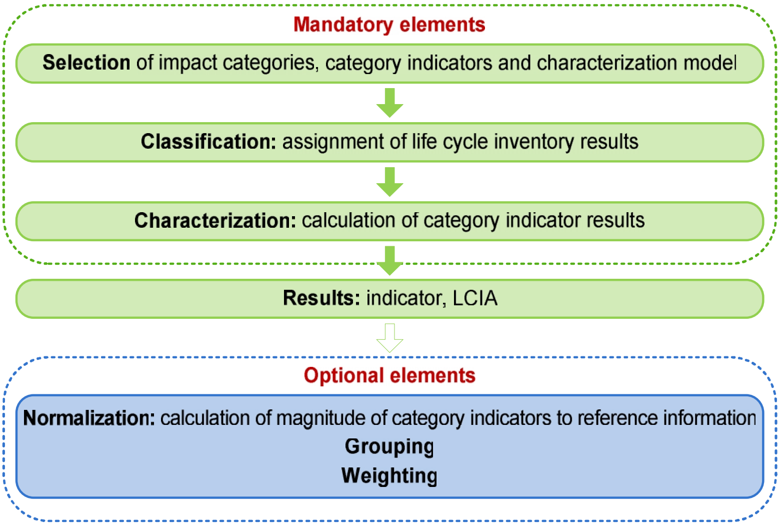


Fig. 1.12. LCA elements [111]

As one can see from Figure 1.12 from the ISO 14042-44 methodology in addition to the mandatory steps of impact assessment, there are some optional elements to help the interpretation of the results.

1.3.3 Bioenergy routes: a “cradle-to-grave” approach with LCA methodology

With a foreseeable increase of the use of biomass for energy purposes related to the real evaluation and validity of the whole bioenergy systems as a choice to reduce greenhouse gas emissions and dependence on fossil fuels have started to increase.

In this light, a methodology is fundamental in order to provide a comparison between the bio-system and the corresponding depleted fossil-based system.

This evaluation should be mainly addressed to the following crucial factors that are the base for the bioenergy scientific research:

- feedstock;
- production process;
- scale of production;
- utilization.

The analysis of the crucial factors should answer the following key issues:

- sustainability;
- surplus production of food in developed countries;
- agricultural subsidies and trade barriers;

- large-scale production, industry concentration;
- low efficiency of small-scale production;
- consistent biofuel standards;
- a global biofuel market (for a large-scale production);

In this direction the evaluation of the environmental impacts along the whole life cycle of a bioenergy system results in a difficult and time-consuming task in order to quantify the real benefit since environmental impacts such as ecotoxicity, eutrophication or biodiversity are usually higher for a bioenergy system than for a fossil-based system. Moreover, the negative effects of the bio-system are more evident if carbon and biodiversity loss due to direct and indirect land transformation are considered in the full life cycle of biofuels [114].

The use of Life Cycle Assessment (LCA) as a methodology capable to show these environmental and energy performances in different bioenergy systems and within the fossil based scenarios is appropriate.

LCA is a well-known tool for analyzing environmental impacts at a wide perspective ("cradle-to-gate") with reference to a certain energy system.

Within this methodology, it is possible to assess the complete bioenergy system production chains until the final end usage in order to ensure, together with the energy delivered, the relative carbon savings. A global interest is rising in relation to a sustainable assessment protocol for the bioenergy sector: this interest coincides well with LCA methodology [114].

The most critical aspect of Life Cycles on bioenergy systems is related to their variability depending on several aspects: feedstock type, location, production of by-products, process technology and the way the fuel is used [115].

As LCA studies have mentioned, LCAs provide a standardized and "holistic" tool to compare renewable and fossil-based technologies.

In the sector of energy technology the majority of the available literature is based on attributional LCAs, which investigate the environmental impacts associated with the average product or technology lifecycle. A key limitation is that changes in the energy system that might result from the decision to install additional renewable capacity are excluded.

The main aspect related to the importance of the implementation of an LCA within the analysis of a bioenergy system is its holistic approach; this allows an objective and more realistic evaluation of the whole system. If we are looking to a general bioenergy system, it is possible to identify the same main components that characterize all the bioenergy routes. This can be summarized in terms of the growth of the required biomass, land needed, harvesting, processing, transportation, and final use.

Two types of approaches can be distinguished. These depend on the type of the final use (e.g. thermal, electric or combined energy production, or use in the transportation sector), the Well-to-Tank (WtT) or Tank-to-Well approaches, while also considering the final step at the stage of the fuel station (if the final use is the transportation sector) or at the transport stage of use.

During all these processes, the whole impacts, but as well the environmental benefits, are collected.

Based on the previously mentioned steps, an example of a flow scheme for the use of biofuel within a vehicle is reported in Figure 1.13.

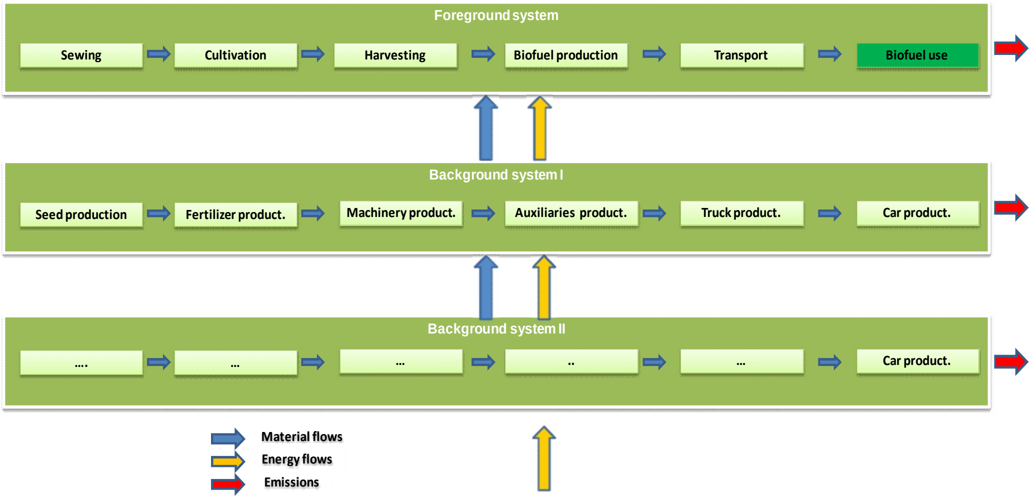


Fig. 1.13. A schematic flow diagram of material flows, energy flows and pollutant emissions in the biofuel production chain [114]

As it can be seen from Figure 1.13, all the inflows (material and energy) are accounted for, as well as all the emissions associated to a single unit process. The background system represented in the picture is defined until the second order processes; however, this choice should be clarified during the definition of the boundary variables.

In this way, it is foreseeable to use an LCA-based approach as a tool to stakeholders in order to evaluate the environmental feasibility and performance of a certain bioenergy system. Consequently, this brings a use of the LCA for technological planning and optimization of a certain technological policy choice.

On the other hand, LCA methodology alone cannot conceive of a whole bioenergy system that all the stakeholders would agree on.

1.3.4 LCA for renewable energy technologies and a driver of a more sustainable system

Due to the previously mentioned phases, the implementation of a regulation ensuring governments a sufficient mitigation of climate change, and consequently a decrease and avoidance of unacceptable and justifiable negative effects in a bioenergy system, the evaluation and the proposal of sustainability requirements (e.g. restriction for liquid transport fuels within the Directive 2009/28/EC) is fundamental.

In term of sustainability, the environmental, economic, and social effects vary importantly between the final products of a certain bioenergy route, and depend on many factors (see section 3.2).

Consequently, the sustainability assessment depends not only on the interpretation of a certain benchmarking system based on a predefined criteria or indicators, but also on the type of methodology used for the evaluation (e.g. top-down and/or bottom-up [68]).

The bioenergy routes, as previously reported, are complex and interdisciplinary systems depending on human decisions and agro-forestry management. Total human control is then impossible within the management of the programme. Therefore, proponents of the Life Cycle Assessment (LCA) have started to increase its use as an analytical tool providing a comprehensive and objective view of the environmental balance useful for the evaluation of the sustainability of the bioenergy system.

In the study by F. Cherubini and A.H. Strømman [116] the importance of the use of LCA for sustainability is highlighted, but at the same time different assumptions within the methodological approach are evident. This can lead to a situation where the results of an LCA can lead to misleading conclusions if compared to other results. In the paper by G.A. Blengini et al. [117] the important outcomes to be carried out for a significant and meaningful LCA for a bioenergy system are described. The goal and scope must be clearly defined, input data and inventory results have to be made available and a mathematical manipulation should be possible, the final LCA has to be a representation of a complex combination of a specific territorial context (i.e. local climate conditions, local agri-forestry practices, adoption of the energy conversion technologies, disposal of residues).

The main evaluation of the bioenergy system is related to the study and analysis of the fundamental inventories (i.e. agricultural activities, energy production, transportation, management of wastes and residuals) and their comparison of energy performances among renewable and non-renewable systems.

As reported by Schlamadinger et al. [118] the structure of an LCA is a proper tool to study the bioenergy system since it represents a methodological approach to standardize the comparison of the GHG balances of different bioenergy systems with those using a fossil-based reference system. Schlamadinger highlights that a detailed definition of the system boundaries, and other operating items included within the system are needed in order to have a final optimization of the whole system from the GHG perspective. Buratti and Fantozzi [119] propose a new approach for an impact assessment through LCA by providing a more reliable tool based on real data for the biomass cultivation step.

Cherubini [49] proposes the crucial aspect related to bioenergy GHG balances in relation to mere energy production (electricity and heat) and biofuels for transportation: in this analysis a global overview is provided with a comparison in reference to fossil-based systems.

In the paper of Valente et al. [120], a study of alpine forest wood-fuel chain through an LCA analysis is reported. Specifically, the study assesses the integration of the harvest of logging residues with the harvesting of conventional wood products. The aim of the paper focuses on three main sustainability criteria: global warming potential (GWP) impact category, costs, and direct employment potential. The case study proposed by Valente et. al. demonstrates that mountain forests are a viable source of wood fuel, which can be exploited without generating excessive impacts.

In light of the previous overview, it is evident how an LCA might represent a methodology to provide comparative analysis and reliable data to inform both governments and industry about the potential impact of a specific supply chain system in terms of energy and GHG savings. In this context, it is as well evident that an LCA can be used as a tool for the optimization of bioenergy sustainability.

Nevertheless, the LCA contains uncertainties mainly related to its own methodological approaches that can affect the final results and conclusions. This leads to the situation where there are unclear aspects concerning the issue in relation to the evaluation of the impacts from land use change.

As it is, for the energy-crop growing and the sustainability assessments, it is important for the assessment of the impact to be of the whole supply chain [121].

1.3.5 LCA on forestry-based biomass

In this chapter a short overview concerning the LCA studies on forestry based biomass production is provided.

Generally, different studies present results about the production of biomass from forestry operations. In particular Berg and Lindholm [122] present results concerning the technology systems in Sweden while in the paper of Athanassiadis [123] forest operations are compared in order to find those with less emissions and end use of energy for logging operation.

Primary energy and long transportation distance in Finland are proposed by Karjalainen and Asikainen [124]. In the study conducted by Berg and Karjalainen [125] a comparison of the GHG emissions of forest operations in Sweden and Finland is proposed.

The outcomes of González-García et al. [126] are related to a comparison of two case studies from Sweden and Spain concerning the environmental impact evaluation of forest production and supply of pulpwood.

In the paper by Valente et al. [120] the whole analysis of an LCA for the evaluation of environmental and socio-economic impacts in relation to wood energy on Italian Alps is proposed.

1.3.6 Positive aspects and weak points of LCA

LCA appears as an effective tool which is useful for both the science sector and the policy sector since it has a computational methodology. The LCA approach can be suggested as an appropriate way of determining whether alternative fuels provide benefits over the fossil fuels they replace. This is in reference to the requirements posed by the 2009/28/EC Directive.

In this context the strengths of the LCA are that it:

- enables operators to avoid a partial optimization of the whole analysed product system, focusing only on a few processes;
- is possible to make comparisons of different scenarios through the methodology of the LCA itself;
- is an engineering accounting tool useful to understand the optimization of a system and the evaluations of potential changes;
- is a multidisciplinary tool that takes into account the impact on the natural environment and the people connected to and affected by the impact [127].

The main weak points and limitations can be summarized in that [128]:

- an holistic approach that can be gained only by simplifying the aspects of the whole life cycle;
- the LCA is typically a steady-state, rather than a dynamic approach. Even if a lot of developments have addressed this direction, such as future technological developments, they can be somehow taken into account in LCA studies;
- the LCA often does not include market mechanisms or secondary effects on technological development;
- mainly the LCA regards all processes as linear, both in the economy and in the environment;
- the LCA focuses on the environmental aspects of products, and not on the economic, social and other aspects;
- a limitation can be found in the availability of data, often the use of a database is implemented;
- the environmental impacts are often described as "potential impacts" because they are not specified in time and space and are always linked to a pre-defined functional unit.

In this light, it seems foreseeable and applicable that the possibilities to integrate the LCA system in a wider context while taking into account not only environmental impacts but also social and monetary impacts within the society is necessary. In the same way, the possibility of studying non-linear impact interactions can be considered. The System Dynamic thinking described in the next chapter could be an effective tool to be used as an interface within the analysis of a real impact of certain bioenergy routes in reference to environmental, social and monetary spheres.

1.4 System Dynamics modelling: a tool for the evaluation of complex policy systems

System Dynamics (SD) is a methodology whose algorithms can be implemented in a computer simulation. This is suitable for fast structuring and solving complex problems [129]. Another source [130] defines system dynamics as a method for analysing dynamic structures of complex systems. If summarizing, it can be said that system dynamics is a method for studying the dynamic development of complex systems that helps to solve complex problems.

The theory of system dynamics is based on the analysis of the relationship between the "behaviour" of a system and its underlying structure [131]. In order to carry out a consistent model solution, the analysis of the structure of the system provides a better understanding regarding the reasons of a certain behaviour shown by the system.

The system dynamics modelling technique combines both the possibility of the human mind to identify important relationships between parts of the system and the possibility of a computer to visualize consequences of the dynamic interactions of these relationships by processing large quantities of information in a relatively short time [132].

A system dynamics model is a simplified reproduction of the real system that focuses on the main aspects to explain the behaviour of a system. In other words, system dynamics models show how the behaviour of a system changes according to the interaction of the elements it contains [133, 134].

System dynamics thinking was proposed for the first time in the mid-fifties by a professor at the Massachusetts Institute of Technology: Jay Wright Forrester [135]. He developed a system dynamics approach as a tool for managers of large companies to solve the problems they met. Initially, the calculations of the structure of the stock-flow feedback simulations were done manually; later Forrester and his working group extended the use of system dynamics by creating formal computer models implementing these calculations.

The first system dynamics computer modelling language "SIMPLE" (Simulation of Industrial Management Problems with Lots of Equations) was created by Richard Bennett in 1958. In 1959 Phyllis Fox and Alexander Pugh improved "SIMPLE" and created the first version of "DYNAMO" model (DYNAmic MOdels), a language of system dynamics that became a standard in the field for the next 30 years.

Throughout the fifties and sixties system dynamics was a tool for solving problems associated with the management of organizations. The book "Urban Dynamics" offered the first important system dynamics model that was not relevant to business activities, but analysed the interaction between the policy of the city and its development.

The Second significant non-business use of system dynamics was the socioeconomic model "WORLD1" that described important relationships between the population, industrial production and pollution, stores of resources and food. The aim of the model was mainly addressed to explain and find out necessary changes in policies in order to guide the global system towards sustainable development in the future. Later on, improved versions of "WORLD1" were developed, and these models began the use of SD as a tool for energy planning and policy analysis.

As it has been mentioned, black-box models are divided in bottom-up and top-down models. In this context SD modelling, including the white-box modelling tools, can be considered the quintessential representative of top-down modelling [136].

Within the modelling and simulation associated with "white box" tools (like System Dynamics), it is possible to make transparent cause-and-effect relationships in complex, dynamic systems with delays, feedbacks and non-linear behaviours. The structural elements of this type of modelling are: stocks related to the principle of accumulation (i.e. the characterization of the accumulation of flows into stocks, thus forming a dynamic structure of the system), flows (regulating the stock as in- or out-flows) and auxiliary variables (i.e. parameters and constants). In other words, a stock is an element that represents the environment surrounding the decision-maker in each feedback loop, and serves as storage for material or nonmaterial valuables. A *flow* is an element that represents the decisions, actions, or changes, and serves as a tool used to transmit information to or from a stock [137, 138].

The explicit structure of System Dynamics modelling represents a good interdisciplinary tool enabling the sharing of information among stakeholders, experts, policy makers, and the public audience as well [74]. Recent global developments, mostly "black box" methods, do not effectively support integrated long-term planning exercises.

Cross-sectoral relations enable the analysis of a wider spectrum of policy implementation carrying out the identification of potential secondary effects or the long-term crucial aspects for future development.

The use of system dynamics modelling involves the following main steps [139]:

- *model formulation*, prior to the definition of the problem under study– i.e. purpose, goal and type of model, nature of the problem, expected behaviours;
- *the principal dynamic hypothesis*, i.e. definition of the main stock and flows within the system and the related feedback loops;
- *model simulation* within specific software (i.e. STELLA, Powersim, iThink), where the variables under study are identified and the model is implemented in a dynamic modelling software;
- *model analysis and validation*, where the confidence and robustness of the model is tested and the implementation of different policy strategies is conducted.

1.5 Integration of dynamic modelling and LCA

As previously mentioned, LCA is a good tool to analyse the environmental performances and burdens of a certain product or service along with their whole life-cycle in a "cradle-to-grave" approach (e.g. from raw material extraction until final disposal, including the intermediate processes such as manufacturing, distribution, and use). In this light, it can be considered a good tool to evaluate the environmental benefits of different types of bioenergy routes, based on environmental indicator comparisons, while respecting the use of those based on fossil fuels.

At the same time it has also been mentioned how LCA is typically a steady-state, rather than a dynamic approach, LCA often does not include any market mechanisms or secondary effects on technological development, and that with only an LCA it is difficult to optimize a system from the environmental and economic points of views.

Moreover, within the increasing of the environmental footprint the manufacturing processes and the whole back-ground systems (i.e. supply chains) it has started to become more sustainable in the aspects of economic viability, environmental, and social impacts.

In this light, the idea of integrating the framework of the dynamic modelling the LCA methodology for an interdisciplinary design facing with economic, social and environment-sound aspects has started to be developed in the last decade.

Ei Sandi New et al. [140] propose an approach integrating LCA indicators and dynamic modelling for green energy supply chain design and operation. Within Ei Sandi New's study, specific environmental indicators are merged into a dynamic model of a green supply chain. In this way, the sustainability of different designs and operational decisions can be fully assessed in a more holistic way, taking into account not only the environmental aspect but as well other parameters as profit and customer satisfaction. The basic idea of Ei Sandi New et al. integrates different aspects: the processes of the supply chain analysed, the engineering aspects and data and the practices for the improvement of the environmental performances and economic viability.

Zulfiqar Ali-Quershi [141] stresses the attention on the need to have a top-down approach and make a post manufacturing environmental audit and consequently and demand that this aspect be in an LCA based evaluation methodology.

Zulfiqar Ali-Quershi (2010) also proposes a more “functionally-oriented” method based on the setting of specific principles that can provide a design valuable attribute.

Within the doctoral thesis of Alexander Röder [142] the aspect of the integration among a bioenergy planning tool and the LCA within the evaluation of powertrains and fuel is investigated. Specifically, the author proposes a method where the LCA data of the analysed technologies are bridged into a MARKAL model with the results of successful energy planning. Röder has proven that the idea of approaching LCA methodology and an energy planning model is a useful and complete tool to compare different technology within different bioenergy routes stressing the fact that a large margin for improvement still exists.

2 METHODOLOGY

In the light of a foreseeable development to a green and renewable sound energy strategy the choice of the best policy scenarios is important in order to strengthen this transition. Figure 2.1 illustrates that the implementation of a sustainable and green energy society in the future is affected by policy strategies and their implementation by policymakers.

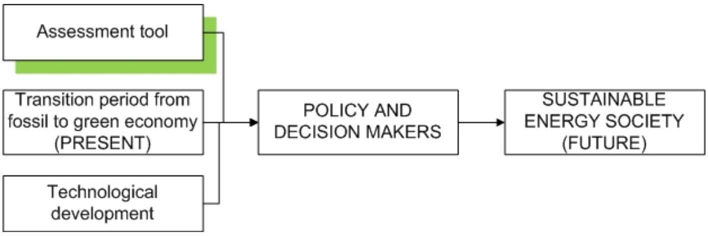


Fig. 2.1. Scheme of dependency of assessment tool with the development of a green society [143]

Policy decisions have to be supported by a rational background. This is mainly based on different types of theoretical and forecasting tools that consequently can limit and restrain a wider range of policy strategies.

The target of a green energy-based society is associated with the implementation of energy technology that brings beneficial environmental effects (lowering the environmental impact) and sustainability (maintaining a certain system function for future generations).

It is primarily the key aspect of strengthening the most suitable policy strategy in order to allow the transition to a green energy based society and reinforce a sustainable future (see Figure 2.2). In the following chapters, the policy tools and key expectations for the transition to a green energy society are discussed.

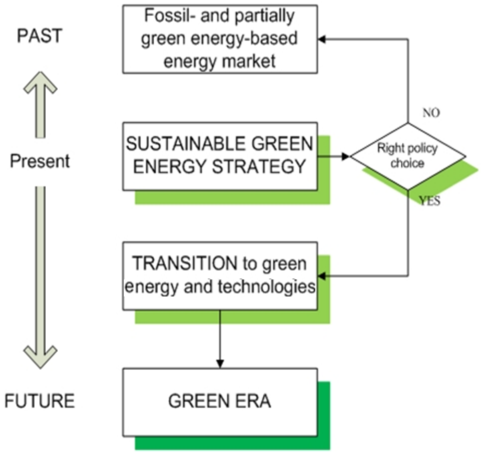


Fig. 2.2. Transition to green society [143]

A green energy system can be reflected at different scale levels and in different space-time scales. The development in the direction of a "Green Era" is a long-term process that involves not only economical, policy activities but also a wider interconnection with other important pillars such as land use, population growth, material and energy flows and humans interaction and behaviour in the light of a fulfilment of the sustainable development criteria [144]

As described in Chapter 1, within the implementation of the policy strategy within a top-down framework, it is essential that the policy mechanism be used to speed the transition to a sustainable and green-based society. On the other hand, an integrated bottom-up evaluation tool is necessary to have a holistic approach valid also for the regional-local scale and not only national.

As mentioned before, since different processes in different spheres of society (e.g. economic, political, social, and environmental) affects the transition to a green-era system dynamics, methodology represents a good frame in order to model a complex system with indirect linear cause-effects interactions.

In this light, within a system dynamics modelling it can be possible to obtain a potential impact of different policy alternatives within certain system relationships.

The LCA is a well-known tool for analysing environmental impacts on a wide perspective (using the cradle-to-grave approach) with reference to a product system and the related environmental and eventual economic impacts. One of the most important limitations is the application of LCA as an input for strategic decision-making from an environmental perspective. It limits the inclusion of cost and investment considerations [112]. This means that in regard to effects related to environmental aspects, the LCA is an effective tool in order to measure the human burden on a specific ecosystem [112]. Within this manuscript, a methodological structure to facilitate the evaluation of certain policy scenarios integrating the concept of the system dynamic approach with the environmental assessment related to the outcomes from an LCA-based system is proposed.

In light of that, the following proposes an algorithm of a modelling tool which has been developed in order to evaluate the strengths and the effects of certain policy scenarios to 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, the predictable increase in the consumption of energy is 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 [145].

As it is represented in Figure 2.3 the algorithm is made by three main modules or parts:

- the initial data entry from the evaluation of the environmental performances of different environmental technologies, the most suitable technology and the most beneficial bioenergy routes can be selected and the main outcomes and results in terms of environmental impact and emission factors are implemented in the next step of the methodology;
- the system dynamic model of the whole system, in fact the computational core of the whole algorithm (white-box modelling), where the structure of the model is modified depending on the choice of the policy scenario;
- evaluation of effectiveness of a certain policy strategy prior to implementation at a decisional level taking into account the sustainable criteria.

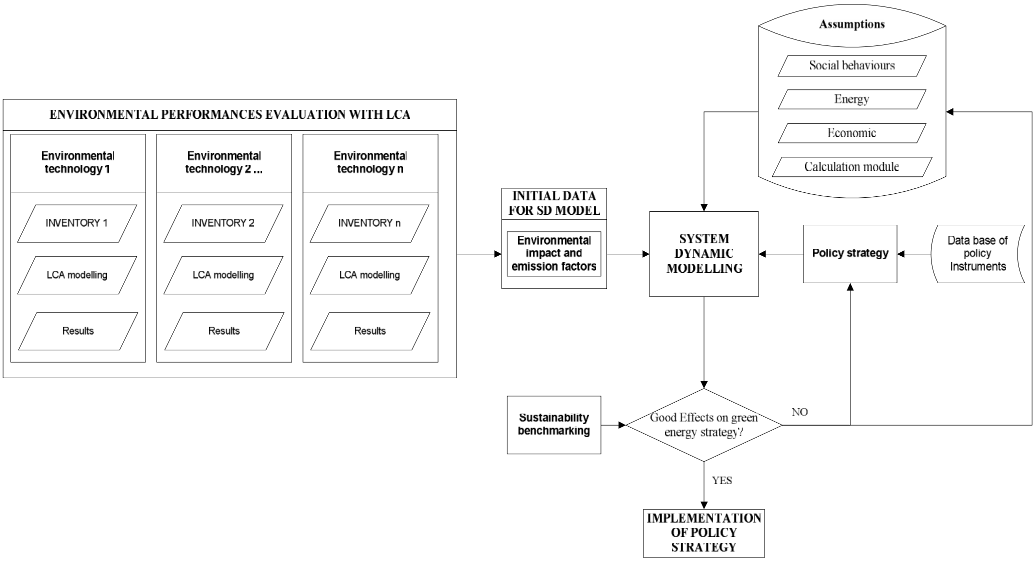


Fig. 2.3. Algorithm of an integrated methodology for the evaluation of policy strategy effects

The algorithm proposed as a base for the modelling tool is innovative in its integrated aspect. In fact, through the implementation of an interdisciplinary approach the main factors and considerations related to the development of sustainable and green energy oriented technology utilization are taken into account. More specifically this involves:

- social aspects in terms of social benefits (within the module of the system dynamic model);
- environmental aspects: evaluation of environmental impacts (within the module of the LCA);
- technical aspects: development of innovative technologies, the increase of energy efficiency (within both modules of the of the system dynamic and LCA);
- economic aspects: lowering costs of investments, operation and maintenance, as well as biofuels price and tariffs, (within the module of the system dynamic model) and;
- commercial aspects, e.g. incentives, information dissemination and communication (within the module of the system dynamic model).

The algorithm has been implemented in a real model focusing on the evaluation of those policy scenarios that will most affect the transition to a renewable energy based economy. The development is applied to the Latvian context with the objectives of:

- evaluating if the renewable energy targets set by the RES Directive [57] will be fulfilled;
- strengthening the policy strategies that will be favourable in this direction.

In the following chapters, applied cases where the proposed methodology is implemented are discussed. In Chapter 3, the environmental outcomes from the application of the LCA methodology in respect to three different types of bioenergy routes associated with different types of biofuel generation are reported. In Chapter 4 white-box modelling, through the use of the system dynamics approach, is proposed and implemented in a case study of the Latvian District heating system for promoting the use of non-renewable energies within it. In Chapter 5, the results of the proposed specific model are presented, discussed and validated.

3 LCA MODELING: EVALUATION TOOL FOR BIOENERGY PRODUCTION AND USE

As previously mentioned, biomass is a source of renewable energy. At the European and world level countries are following and proposing strategies and opportunities in order to decrease the level of GHG by using their own climate change framework. Hence, in the very near future, a strong increase of biomass consumption is expected. In this light, the "Biomass Action Plan" [146] of the EU Commission fixed the targets of 75 mtoe (3140 PJ) for the heating sector to be reached by 2010 from a level of 48 (2097 PJ) in reference to the year 2003. Moreover, the Directive for Renewable Energy (2009/28/EC) [57] fixed the level of sharing of renewable energy resources for 2020. That presents an ambitious strategy assigning an important role to the increase of renewable energy production and energy efficiency.

This behaviour is also related to the positive aspects and advantages related to the use of biomass in respect to a fossil based energy source. For example, there is *''less energy dependence, promotion of regional economic structures and provision of alternative sources of income for farmers''* [146].

Latvia, as a member state of the European Union (EU), has undertaken obligations to collaborate in the implementation of the EU energy policy and, consequently, within the 2009/28/EC Directive [57]. According to that, Latvia has to reach a 40% share of renewable energy resources in final consumption by year 2020. In this context, the main objectives of the Latvian energy policy are to ensure sustainable accessibility of necessary energy resources and have a secure supply in order to have faster economic growth and improve the quality of life, to ensure environmental quality retention and to meet the objectives set by the Kyoto protocol, the RES Directive and the Latvian Climate Change Program.

In this chapter, three LCA case studies are proposed for three different types of bioenergy routes:

- LCA for use of biodiesel in an off-road vehicle in Latvian conditions [147];
- LCA for production of biogas from algae substrate in Italian and Latvian conditions (data and info from project BioWALK4Biofules©) [148];
- LCAs for a production of thermal energy in a boiler-house supplied by wood-fuels (chips, logs, pellets).

All the LCAs in this work have 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 the ISO standard 14040-44 as defined in Chapter 1.

The software used for the modelling is Simapro version 7.3.2 [149]. The Simapro software is especially created for building life cycle models of products and services.

The impact assessment IMPACT 2002+ [150] has been chosen within the modelling and evaluation steps.

The impact assessment method IMPACT 2002+ (see Figure 3.1) foresees a methodology where a combined midpoint/damage-oriented approach interconnects all the life cycle inventory results through 14 midpoint categories (human toxicity, respiratory effects, terrestrial ecotoxicity, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial acidification/nutrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy, mineral extraction) and weighted four damage categories or end-point categories (human health, ecosystem quality, climate change, and resources).

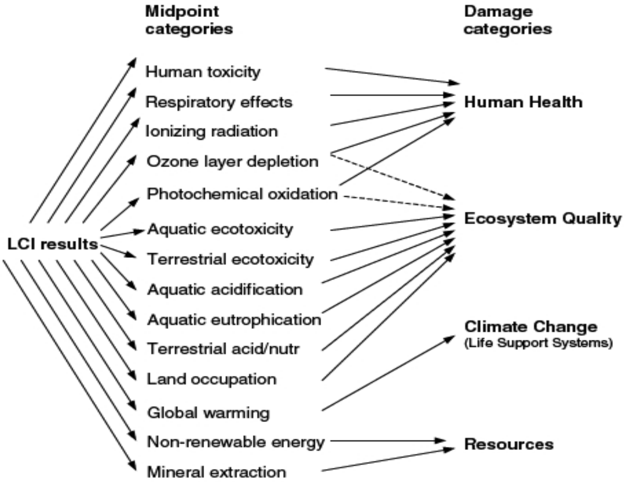


Fig. 3.1. Overall scheme of the IMPACT 2002+ framework, linking LCI results via the midpoint categories to damage categories, based on Jolliet [150]

In the IMPACT 2002+ the damage category is expressed in the unit measures presented in Table 3.1. In the same table, the normalized values expressed in Point (i.e. the average damage in Western Europe per person and year) are reported.

Table 3.1.

Normalization references for the four damage categories for Western Europe [150]

Damage categories	**Normalization factor**	**Unit**
Human Health	0.0071	DALY/point
Ecosystem Quality	13700	PDF·m^2·yr/point
Climate Change	9950	kg CO_2 /point
Resources	152000	MJ/point

Within the three case studies, the results are presented at the end-point impact category and mid-point category stages.

3.1 Biodiesel production in the Latvian context

To all Member States, the European Commission has indicated that the use of transport biofuels must reach the level of 5.75% in 2010. In Latvia, rapeseed methyl ester (RME) is generally supposed to be one of the most valuable possibilities to attain this goal [18].

As investments grow, it is important to evaluate the environmental impacts of this production and to highlight the main sources of these impacts.

Nowadays, the share of biofuels in the transport sector in Latvia is given a value of 0.3% (around 75% biodiesel and 25% bioethanol). Biofuel production in Latvia doubled in the last two years: the total biodiesel production is approximately 64 ktonne/year (year 2009) [18].

In this chapter, the environmental performance of biodiesel produced by rapeseeds under the local Latvian conditions is modelled. 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.

The system boundaries include rapeseed cultivation, oil extraction and processing, biodiesel production and final use. The system has been expanded to take into account the valorisation of by-products in the substitution of natural gas production (from fermentation of straw in the cultivation process), animal feed (rapeseed meal also called seed-cake) or chemicals (glycerine). The functional unit was the transportation over a distance of 100 km by a compact pickup truck in off-roads conditions.

This study shows that the environmental benefits from biodiesel have better results, compared to conventional diesel. The valorisation of by-products leads to considerable environmental improvements. Concerning global warming environmental impacts, the valorisation of the by-product is fundamental in order to have a level lower than that one of conventional diesel.

The results lead to the conclusion that it is feasible to successfully increase the environmental and sustainable efficiency of the Latvian biodiesel production model. The use of the LCA methodology is a fundamental tool in the foreseeable future to enhance Latvian biodiesel production.

3.1.1 Latvian biofuel production trends

The Latvian energy supply is characterized by a strong dependence on energy imports and the highest share of renewable energy in the entire European Union. The latter consists of approximately one third of the total energy consumption. Imported energy sources account for roughly two thirds of Latvia's total energy consumption. Except for peat, which can be found in approximately 10% of its soil, Latvia has no fossil resources for energy production worth mentioning. Natural gas, oil products and coal are mainly imported from Russia [18].

However, renewable energy sources are substantial. Forests cover approximately 55% [18] of Latvia's territory, making biomass the largest domestic resource currently used in heat generation. Hydropower is already the biggest contributor to electricity generation, and still has unused potential. Wind power has gained importance in recent years and has high potential, as wind is abundant. This is particularly the case along the coast, where, in addition, the transmission network is particularly well-developed.

Latvia can meet about 70% of its electricity demand domestically, mainly with CHP-plants, wind turbines and hydroelectric facilities. The latter two are subject to natural variations in water and wind availability. Therefore, large shares of imported electricity are needed. Many of these imports had come from the Lithuanian nuclear power plant Ignalina, which was shut down in 2009. This situation creates further challenges for the Latvian electricity supply sector and represents a real opportunity for the exploitation of renewable energy sources within the country.

By 2010, the EU-Directive 2001/77/EC sets a target of 49.3% of gross electricity consumption to consist of renewable sources, and a 5.75% biofuel-use is obligatory, according to the Directive 2003/30/EC, in the same period [18].

The target for renewable energy, as a share of final consumption, is 40% by 2020 according to the EU-Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The same directive demands a minimum of 10% of renewable energy in transport.

National commitments include biofuel targets of 10% by 2016 and 15% by 2020, 8% of electricity produced in biomass-run CHP-plants, as well as the above mentioned 49.3% target for 2010 segmented into different generation technologies.

In relation to the use of biofuel in the transportation sector the figures show a value of 0.2% despite the 5.75% required by the EU Directive [151].

3.1.2 Life cycle definition

Biofuel sustainability has been widely debated. Nevertheless, political decisions are being made, economic investment is on course and environmental and social impacts are taking place [152, 153].

Evaluating the sustainability of human activities, involves a comparison between the environmental status resulting from the activity and the natural or desired status [153]. A favourable comparison, in the case of biofuel production, would ideally agree with the following aspects:

- the fuel should supply an amount of energy superior to that required to produce it;
- the long-term feedstock supply should be guaranteed, in order to assure long-term biofuel;
- supply to the market, which depends on the sustainability of the underlying activities;
- the emission of unwanted substances to the environment should be less than those that would result from the use of a fossil fuel to obtain the same amount of energy;
- land use should not compromise food production, nor respect for the balance of the ecosystem.

Due to their comparable physical properties, biodiesel and fossil-based diesel can be used for conventional diesel engines [154-156]. Thus, the primary concern of this study is the question as to whether or not the production of biodiesel is comparable to the production of fossil diesel from an environmental point of view, taking into account all stages of the life cycle of these two products.

Biodiesel production from rapeseed in Latvia has been investigated in three scenarios for this LCA study. These include a model based on the existing Latvian biodiesel production, not including the avoided products coming from the use of the co-products and/or waste from production, a second model which considered the avoided products and the comparable LCA model for a fossil-based diesel production and final use in Latvia.

The potential environmental benefits and/or damages and ascertaining the environmental optimum of biodiesel production in the Latvian condition will be identified.

3.1.3 Goal and scope definition

The development of the biofuels industry in Europe has led to numerous environmental studies [157-159].

Therefore, the aim of this study is to perform a full comparative Life Cycle Assessment 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 last step will be the identification of the main sources of the environmental impacts, and the proposition of improvements of the environmental performances.

In the following, the main aims to be reached during the analysis are outlined:

- demonstrate that biodiesel has a positive energy balance and it is a renewable source (study of the energy ratio among the renewable energy output produced and the amount of non-renewable energy spent for the production);
- savings of greenhouse gas (GHG) emissions;
- use of LCA to evaluate the life cycle environmental burdens of a biodiesel (BD) system use (B100) from rapeseed oil;
- identify the hot spots of the system and make recommendations.

The functional unit to which all emissions and consumptions in this assessment have been reported is a pick-up truck (Toyota Hilux) covering 100 off-road (unpaved road) kilometres. Even if biofuels are generally used as additives, results will be presented for cars working with pure biofuels as mixing with fossil fuels could have an influence on the conclusions of the comparison, and the aim is to determine which biofuel offers the highest environmental benefit [18, 160].

The relevant environmental mid-point impact categories studied are: non-carcinogens effects, respiratory effects, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy.

3.1.4 Life cycle inventory and system boundaries

For the simplification of the simulation, the following four stages have been considered per energy crop:

- soil preparation and cultivation (including nursery of the seeds);
- rapeseed oil production (including oil refinery);
- biodiesel production (including biodiesel refinery),
- final end use (see Fig. 3.2).

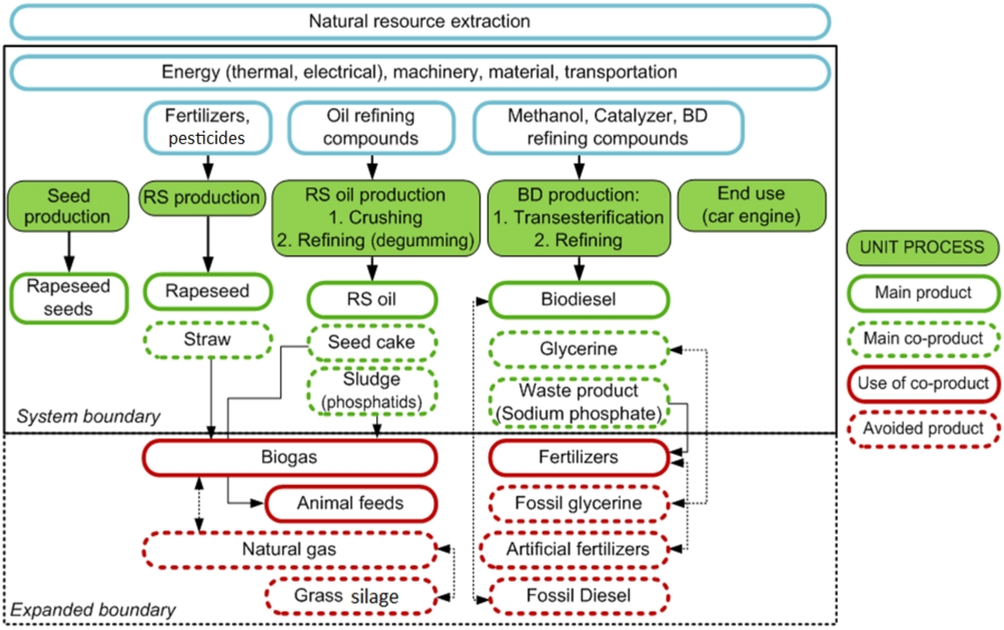


Fig. 3.2. LCA model and boundary: scheme implemented in the Simapro software also considering the expanded boundaries. The main inflows and outflows in the model in terms of material/product, as well as the avoided products, are reported.

As evident in the model, it has been assumed that the straw is used for the production of biogas, the seed cake for production of animal feeds, and waste products (e.g. sodium phosphates) as fertilizers. The model foresees the co-production of glycerine in the process. The use of these wastes and co-products is fundamental to increase the environmental benefits of the whole process, as they displace the production of other products (natural gas, grass silage, artificial fertilizer, and fossil glycerine).

Data gathering on rapeseed cultivation and biodiesel production has been based on international conditions, and local Latvian sources (see Tables 3.2 and 3.3).

Other types of data have been collected from the Ecoinvent 2.1 database [161] (included in the Simapro 7.3.2 software and from GEMIS [149, 162, 163].

The production (or nursery) of the seeds needed to produce the future rapeseed culture is the preliminary step, the data entered into the model is directly extracted from the Ecoinvent 2.1 database [161].

The culture of rapeseed is the first real step in the production of biofuel. The production of the fertilizers (N, P, K) and the pesticides, soil/water/ground emissions, the consumptions and emissions of the tractors (fertilizing, tillage, sowing, harvesting, transport) and the valorisation of by-products, like rapeseed straw, substituting fertilizers (also in terms of N, P, K) or producing biogas have been taken into account.

The next step is the conversion of the feedstock to biofuel. After drying the rapeseed grains, oil is extracted in two steps, involving a mechanical extraction followed by an extraction with an organic solvent. Two products are generated: oil, and rapeseed meal (or seed-cake), rich in proteins and easily integrated in the rations of animal feed. The extracted oil is then refined, and finally reacts with methanol to produce rapeseed methyl ester and glycerine, which is purified and used in the chemical industry.

Table 3.2.

Inflows and outflow in the model [18]

FLOWS	**Cultivation**	**RS oil production**	**BD production**
Land [ha]	-0.97		
Seeds [kg]	-3.39		
N fertilizer [kg]	-49.44		
P fertilizer [kg]	-12.80		
K fertilizer [kg]	-60.35		
S fertilizer [kg]	-84.34		
Pesticides [kg]	-1.95		
Leaf fertile.[kg]	-7.46		
Straw [t]	5.82		
Rapeseeds [t]	3.10	-3.10	
Rapeseed cake [t]		2.01	
H_3PO_4 (deg.) [t]		0.00	
NaOH (deg.) [t]		-0.02	
Citric acid (deg.) [t]		-0.0003	
Rapeseeds oil [t]		1.05	-1.05
Methanol [t]			-0.11
KOH (trans.) [t]			-0.01
H_2SO_4 (trans.) [t]			-0.01
NaOH (glyc.) [t]			-0.02
H_3PO_4 (refin.) [t]			-0.0011
Gliceryn [t]			0.11
Biodiesel (RME) [t]			1.00

The exhaust emissions and fuel consumption of the vehicle used for this study have been calculated on the basis of fossil fuel vehicles. The energetic contents of the biofuels are different from those of the corresponding fossil fuels and consumption, expressed in kg/km, is also different. In the study, the amounts of 16.5 kg/km in regard to a car fuelled by biodiesel and 18.0 kg/km for a car totally fuelled by diesel have been taken into account.

As it belongs to the natural cycle of carbon, carbon based emission (CO_2 and CO) emitted by the combustion of the biofuels does not contribute to global warming and is subsequently not taken into account in the model. Using biodiesel leads to an increase of the emissions of nitrogen oxides, a decrease of the emissions particulates (PM) and hydrocarbon [164] – see Figure 3.3.

Table 3.3.

Energy and non-renewable fuel requirements [18]

ENERGY and NON RENEWABLE FUELS	**Cultivation**	**RS oil production**	**BD production**
Electricity [kWh/biodiesel tonne]			203.35
Thermal energy [MJ/ biodiesel tonne]			2737
Diesel [tonne/biodiesel tonne]			0.07*
Machinery [tractor/ha]	0.0009		
Boiler efficiency [15 MW boiler house]		90%	90%

In our study, in reference to a diesel engine in an off-road pick-up truck type [24], the following coefficients have been used:

- NO_X = 0.312 g/km – increase of 10% in respect to a diesel engine;
- PM = 0.039g/km – decrease of 45%.

The complete Life Cycle Inventory has been established using Simapro 7.2 databases. By-products have been taken into account with energetic or mass allocation. Environmental credits (avoided impacts of the production of equivalent products) for the substitution to other products, like animal feed or chemical products, have been calculated. As no data were available for some of the by-products, an assumption has been made to calculate equivalencies with products described in the Simapro databases.

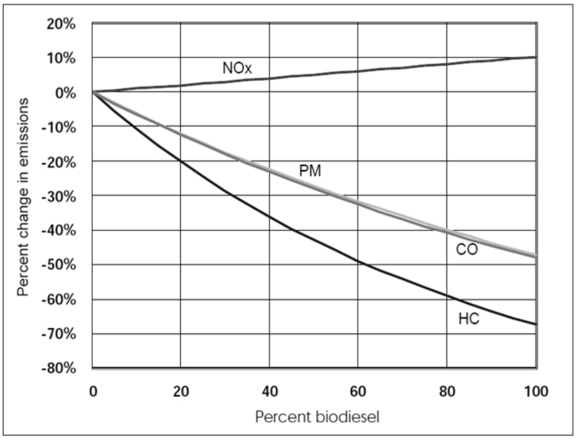


Fig. 3.3. Percentage emission change of a biodiesel engine vs a fossil- based diesel engine [164]

The glycerin at the end of the production process was assumed to be a substitute for the chemical glycerin produced by hydrolysis of epichlorohydrin (from the Ecoinvent 2.1 database).

The system boundaries include biodiesel production (rapeseed cultivation and processing for biofuel, extraction and refining of fossil fuels), but also the final use of the fuel and the valorisation of its different by-products. Table 3.4 reports the assumptions for the transport distances.

It is considered in the model that the plant is unable to produce the rapeseed oil needed for the required diesel production. Consequently, a model has been calculated that 2/3 of the oil is obtained from an imported oil mix, not from the plant's production.

The system foresees the use of two boiler house systems (around 15 MW total capacity) which are supplied by fossil diesel. The emissions related to the use of fossil diesel for the needs of thermal energy required from the plant processes have been taken directly from the Ecoinvent 2.1 database. The total amount of the thermal energy in the whole production processes was equal to 2737 MJ/tonne biodiesel.

The main assumptions, also taken into account for the model, were:

- 25-year biodiesel plant technical lifetime;
- Use of straw for biogas production;
- Use of average EU electricity mix (EU25);
- Transportation distances estimation based on the data in Table 3.4.

The production of biogas from 1 straw has been calculated at the relation of: 0.38 m^3 biogas =1 kg straw [165]. The amount of artificial fertilizers displaced has been calculated at: 1 kg of slurry = 0.15kg NKP fertilizers [153].

Table 3.4.

Transportation assumptions

Material	**Unit process**	**From**	**Distance [km]**	**Way of transport**
Seeds	Cultivation	UK (50%), FR (50%)	1270, 1750	40 t truck
Fertilizers	Cultivation	GER	1400	40 t truck
Pesticides	Cultivation	GER	1400	40 t truck
Tractor	Cultivation	SWE	400	Medium size cargo, 89000 t
Rapeseed	RS oil production	LV (35%), LT (35%), BY (15%), KZ (15%)	150, 300, 600, 1000	40 t truck
Oil mix	BD production	RU (60%), BY (40%)	500, 600	40 t truck
Methanol	BD production	RU	500	40 t truck

The relative amount of the displaced natural gas has been calculated with respect to the ratios of the values of the two low heating values (LHV), using the following data:

- Biogas LHV = 23.3 MJ/m^3 [163],
- Natural gas LHV = 35.1 MJ/m^3 [163].

This corresponds to an overall avoided amount of natural gas equal to 1514 m^3.

3.1.5 LCA results

Six mid-point categories were analysed, with four end-point categories. The characterization and weighted results are presented in terms of mPt. The biodiesel results concern the implementation and the exclusion of the avoided products in the model. Subsequently, a final comparison with the fossil diesel LCA is performed.

In Figure 3.4, it is possible to understand the main impact category that presents the strongest environmental load.

The biodiesel LCA model, that takes into account the avoided products, shows a negative value that represents an environmental benefit. If this is compared with the model without avoided products, it becomes evident how strong the effect of reusing waste and/or co-products is (approximately a fivefold increase). 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.

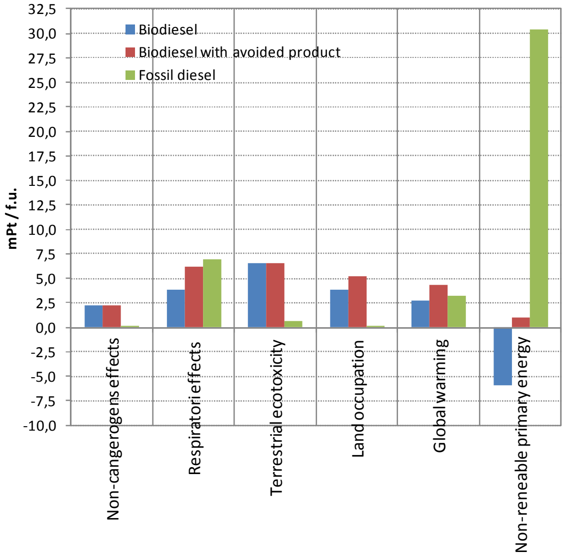


Fig. 3.4. Midpoint impact categories per functional unit (f.u.) [mPt/f.u.]

Mainly due to the use of fertilizers, pesticides and arable land the LCAs for the biodiesel present higher impacts in relation to the land use and ecotoxicity impact category. By giving attention to the global warming impact category, the fundamental degree in which the avoided products are relevant in the overall reduction of the CO_2 equivalent in biodiesel production becomes evident. The model in fact demonstrates only 15% reduction in respect to the fossil-based reference system, if avoidances are not taken into account, against 36% when these are included.

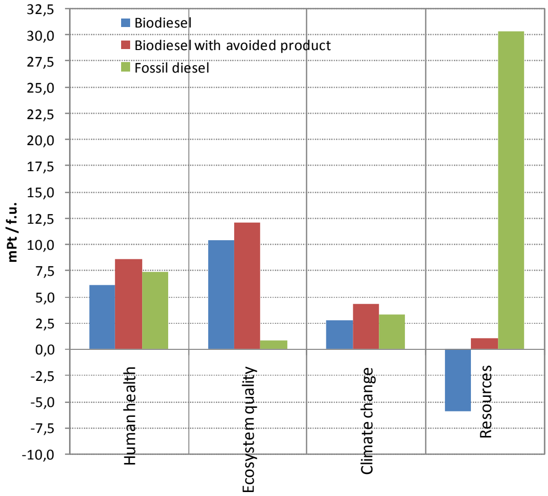


Fig. 3.5. Endpoint impact categories per functional unit (f.u.) [mPt/f.u.]

In Figure 3.5, the same results, but in terms of the end-point categories are presented. These are human health, ecotoxicity quality, climate change, and use of resources.

The results confirm what has already been highlighted in the mid-point category analysis:

- for 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 the one foreseen in the fossil-based LCA model;

- the impact on the ecosystem quality for the fossil diesel is almost negligible, in reference to those of the biodiesel models. This is related to the effects of the use of fertilizers, pesticides and the impact on arable land.

Figure 3.5 and Figure 3.6 clearly show the reduction in terms of total environmental impact. The driving force for this reduction is the use of the co-products of the biodiesel production.

Without including any use of the waste or co-products, the decrease is in fact around 38%. By including the avoided products and their benefits, the total decrease reaches 67%.

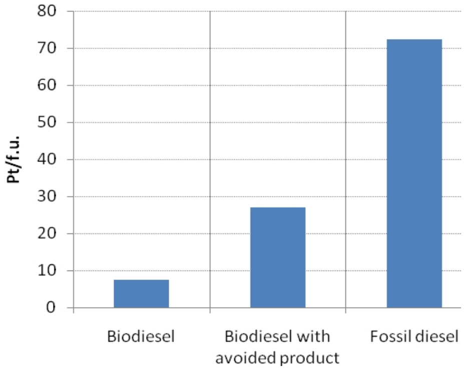


Fig. 3.6. Single score eco-profile [mPt/f.u.]

As it can be seen from the previous figure, the biodiesel scenario generates a whole burden approximately 10 times lower than that of the referenced fossil-based scenario. Nevertheless, the whole impact does not provide a global beneficial effect (i.e. negative value) this means that optimization can be foreseen mostly in reference to the supply system of the inflow materials (rapeseed and extra oil mix provided from external sources).

In order to initialize a benchmarking analysis, an energy balance should be performed, along with the implementation of the LCA. Table 3.5 presents the indicator E_i.

The energy indicator E_i is 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).

This process will make it possible to evaluate the theoretical strength and level of the renewable processes. A ratio lower than 1 is meaningful, when the renewable peculiarities have a greater efficiency.

Table 3.5.

Energy indicator

LCA	**E_i**
Biodiesel	- 0.18
Biodiesel (without allocation)	0.14
Other sources [18]	$-1.34 < E_i < 0.64$

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).
In our analysis, the values are in line with those found in the literature.

The results lead to the conclusion that it is feasible to successfully increase the environmental and sustainable efficiency of the analysed Latvian biodiesel production model.

Specifically, the work concludes that for the Latvian conditions:

- Biodiesel is a renewable energy source using the energy indicator E_i presented as the benchmark (lower than 1);
- It has been shown that using biodiesel reduces the consumption of non-renewable energy;
- Biodiesel effects on the environment are roughly 38% less than for fossil diesel. By taking into consideration the avoided product, the percentage increases to 67%;
- For 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 it is foreseen in the fossil based LCA model;
- The environmental burden related to the ecosystem quality impact category related to fossil diesel is almost negligible, if referenced to the biodiesel models. This is related to the use of fertilizers and pesticides and their impact on the arable land;
- The global warming impact category demonstrates how fundamental the role of the avoided products to the overall reduction of the CO_2 equivalent in the biodiesel production is.
- The biodiesel scenario generates a whole burden approximately 10 times lower than that one of the referenced fossil-based scenario. Nevertheless, the whole impact does not provide a global beneficial effect (i.e. negative value) this means that optimization can be foreseen mostly for the raw material supply chain and in-flow materials.

3.2 Biogas production from algae substrate

The allocation of two-thirds of the global CO_2 emitted is related to two main sectors: power generation and transport [166]. The electricity and heat productions are the main reasons of CO_2 emissions (41% of the CO_2 emissions in the world [93]), where 80% is related to the use of non-renewable sources (oil, natural gas, coal and peat).

In the same way, it is also known that natural fossil reserves are rapidly decreasing even if it is not well-known when and how they will be definitively exhausted [167, 168].

From Chapter 1, one is reminded that biomass can be considered a real flexible and versatile resource usable in different applications (heat and electricity production, and the transport sector), results are clear that further research is needed to develop this path. In this light, a future demand of biomass is estimated to grow during the very near future [169]. If applied to a wider bioenergy context, biomass will play an increasing and primary role in the whole energy system particularly in reference to savings of greenhouse gas emissions, sustainability, energy security and rural/agricultural development.

Nevertheless, much more attention should be driven to the sustainability related to the cultivation of energy crops: competition for land food crops and land use change has to be avoided.

The Food and Agriculture Organisation [170] underlined the need to focus on ‘non-food’ energy crops for the production of 2nd and 3rd generation biofuels.

In this scenario, the Directive 2009/28/EC has highlighted that biogas is one of the most promising substitutes for fossil-based energy [171, 172].

Biogas production has increased over the last period. Currently, the production of biogas is principally carried out through anaerobic fermentation of (mixed) cereal crops but still in terms of substrates. More research is needed in order to gather all possible bio-resources. Hence, the need to further explore new feedstock sources for biogas is a fundamental issue and the improvement of the know-how about second generation biofuel technology production is the natural consequence.

One possible feedstock for the production of biomass is algae (both: macro and micro algae, see Chapter 1).

Algae biomass has a photosynthetic efficiency higher (6– 8%, on average) than that of terrestrial (1.8–2.2%, on average). This enhances a higher CO_2 fixation affording a higher biomass production [25]. Algae biomass is easily adaptable to grow in different conditions, either in fresh or marine waters, and in a wide range of pH [25].

The cultivation of algae in open ponds presents the advantage of assimilating carbon dioxide emitted by external industrial sources, using wastewater or other types of biowastes that may supply the proper amount of required nutrients [20, 173, 174].

The direct use of CO_2 is becoming a large factor for increasing the daily growing rate of algae [20, 173]. That means if used as an interface between biowaste and energy production, macro- and micro-algae present a capability to transform negative environmental impacts, into benefits for algae growth. In this way, negative environmental externalities are transformed into positive ones.

A Life Cycle Assessment (LCA) is fundamental in order to optimize the overall process from the environmental point of view, addressing the attention on the environmental "hot spots" of the process.

In this part, a transformation system that couples the anaerobic digestion of raw algae with algae cultivation is investigated. The beneficial effects can be focused on the recirculation of the liquid fraction of the digestate toward the algal ponds, onto the significant amount of fertilizers recycling the solid digestate fraction, and the use of external sources of CO_2 within algae growth.

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 on a cogeneration unit (40kW) adopted for Italian and Latvian conditions. The analysis will also be performed in the light of a comparison with a similar biogas production system based only on agricultural substrate and a fossil fuel-based scenario where natural gas is supplied to the cogeneration unit. The biogas production from algae is referenced to the pilot plant in Augusta (Italy), implemented within the framework of the FP7 project BioWALK4biofuels [148].

The results gained in the study are useful for decision makers in the sphere of energy planning and research fields. Moreover, the final intention of this study is to identify environmental indicators and a benchmarking threshold within the specific technology analysed.

3.2.1 Algae technology description

Nowadays, the global amount of biomass produced per year provides about 14% of the global energy needs [41]. In this light, it is evident that there is a strong contribution that is given by biomass to the whole world economy, [175], and how biomass represents one of the most available and abundant renewable resources that can be addressed for the production of biogas.

Biomass of marine macro-algae represents a good feedstock for production of second and third generation biofuels; the main algae peculiarities can be summarized as: higher photosynthetic efficiency, approximately twice that of terrestrial plants (energetic crops) traditionally used for the production of 1st generation biofuels [173], consequent higher capability of CO_2 absorption within the bio-fixation processes in respect to terrestrial plants [174], greater efficiency in the absorption of nitrogen-, phosphate-based compounds during the growing phase, a higher growing rate than other terrestrial plants, no-land needs during the cultivation phase (if cultivated in open ponds on the surface) and no conflict with crops for food production (if the small amount of algae for specific algae-based food is excluded) [174]. If compared with micro-algae, the harvesting methodology for macro-algae requires a higher amount of energy within the whole process [173]. In fact, it is necessary to apply a centrifugation of the growing media in order to isolate the unicellular algae useful for the next plant phases.

In this context, the utilization of biowaste can be seen as an excellent use for feeding algae growing ponds and ideally, to fully meet a plant’s energy supply through renewable energy sources.

The feeding of the algae ponds can be conducted with different types of nutrients, among them animal litters (e.g. manure), sludge from waste water treatment plants (WWTP) and/or industrial purified water. Nevertheless, the way how the nutrients can be collected is an important issue mainly in relation to sustainability and the optimization of the whole system process.

The use of algae biomass within a scaled-up and automated plant production system seems foreseeable in the near future. In fact, if used within the fermentation process for the production of biogas the limited extension of cultivation (in comparison with terrestrial energy crops), the limitation of machineries usage for harvesting and transportation will be favourable items for the spreading of such a novel type of algae-based technology.

In this context, an LCA methodology to an experimental pilot plant has been conducted in order to evaluate the environmental feasibility performances of the whole system [148]. Two types of technological scenarios have been implemented: one for Italian conditions (using manure as a nutrient for algae feeding) and the second for Latvian conditions (using waste water from WWTP).

It should be reminded that this study represents only an initial predictive assessment of a biogas plant from anaerobic digestion within an intensive cultivation of macro-algae since the pilot plants analysed have not yet been achieved. This means that to better evaluate the environmental performances of the whole system, more data after the start-up of the pilot plant are required.

The analysed technology for the production of biogas from marine macro-algae is based on two different scenarios: the first in reference to Italian conditions (using poultry manure as inoculums, called base scenario 1) and the second in reference to Latvian conditions (using waste water from Riga Waste Water Treatment plant “Daugavgrīva”, called base scenario 2). In the following part, the principal technological system that is shared by the types of scenarios will be described. The basic plant scheme is that one designed for the production of biogas obtained in the plant located in Augusta, and included in the pilot project BioWALK4Biofuels[148]. Figure 3.7 shows a 3D overview of the whole system; from this view it is possible to understand the main parts that characterized the pilot plant and its extension. The area (around 670m^2) where the pilot plant will be located with its main components (anaerobic digesters, manure/biomass homogenisation tank, big bag for algae harvesting, screw conveyor from the manure storage, de-nitrification reactor, biogas up-grading cryogenic unit, the adsorption column, the biogas storage, the cogeneration unit) is shown in dark yellow. The anchoring point to stabilize the ponds, through the use of steel ropes, the system against the sea weave motion (courtesy from [148, 176], can be seen in the red circles.

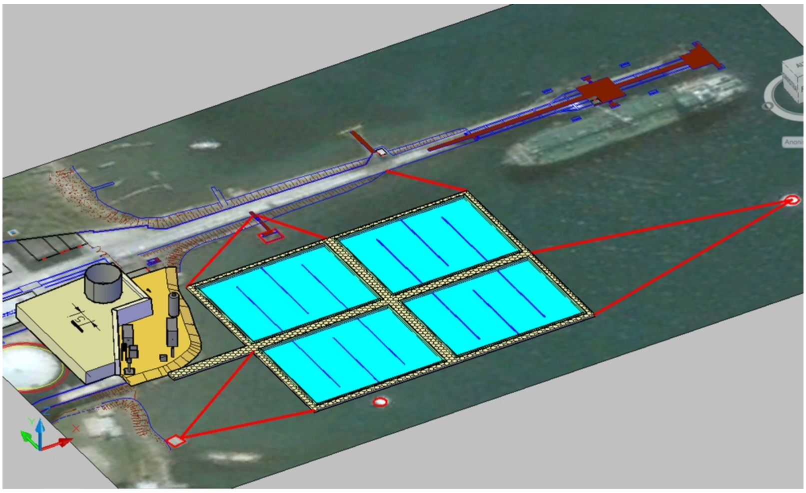


Fig. 3.7. 3D view of the pilot plant

The main parts of the pilot plant can be summarized as: nutrient supply system for algae (poultry manure for Italian conditions, waste water from WWTP for Latvian conditions), CO_2 supply system (from external industrial source and from combustion in the 40kW CHP unit), algae cultivation, algae harvesting, anaerobic digestion and a 40 kW CHP unit. The other two parts are foreseen within the final implementation of the pilot plant: the installation of an algae protoplast incubator (in order to provide the initial algae biomass and [177] to increase the growing rate yield of the algae), and the implementation of a cryogenic technology for a cost-efficient liquid biogas transformation in order to produce biomethane destined to be used as an energy carrier for transportation purposes. At this stage of research, the last two steps have been excluded.

Once the most suitable local algae have been chosen the growth processes are ensured by providing four open ponds. The appropriate conditions are described in the next chapters. The specific conditions of the growing media within the ponds mainly depend on: temperature of cultivation, solar irradiation, photoperiod, amount of $CO_{2,}$ and the supplied amount of nutrients. In the cultivation, strict controls implemented in a developed monitoring system are assured in reference to several parameters (e.g. pH, nitrogen compounds, phosphates).

In this phase, water from the sea and fresh water is filled-in in order to compensate the losses due to the harvesting of the biomass (sea water) and the evaporation effects (fresh water). In order to control the cultivation process the open ponds are separated from the surrounding waters with a special membrane made of Ethylene Propylene Diene Monomer (EPDM) rubber.

Algae need carbon (in the form of CO_2) and nutrients for optimal growth. It has been demonstrated that an artificial increase of the concentration of CO_2 in the growth media (e.g. from industrial external sources) increases the algae growth rates by a factor of 1.2-1.8 [20].

Initially, there is supposed to be a preliminary amount of algal biomass (taken from the protoplast incubator, not taken into account in the LCA model) in the ponds: 100kg for the Italian scenario and 200kg for the Latvian scenario [178]. When the biomass reaches the level necessary, the planned biogas is harvested.

In the system, a part of the nutrients are re-circulated directly from the biodigestor and a part is supplied directly from sludge of the WWTP process. CO_2 is reused from the exhaust gases of the combustion processes of the cogeneration unit and from an external source related to industrial processes (only for the Italian scenario). This is a supply to the ponds, through a piping system, that allows the creation of moderate turbulence in the ponds preventing the thermal and nutrients stratification and guaranteeing the correct media mixing, the correct light exposure, and bigger availability of nutrients to the growing algae.

The harvesting system is performed by the use of the particular textile “big-bag” prior transporting the solution of pond water and algae biomass . The bag allows the water filtration to retain the whole biomass that can be collected in the bottom by opening a valve. The algae biomass needs to be clean with fresh water since salinity affects efficiency during the digestion processes. The resulting water will be reintegrated into the system [176].

The harvested algae biomass from the open ponds is pumped in a hydrocyclone for the removal of sand (or directly sends the harvested algae to storage in the case that waste water is used). This removal process is necessary to avoid damages to the stirred hydrolysis and acidification reactors.

In the next step, the prepared algal biomass together with manure or sludge (from the WWTP) is pumped into the anaerobic digester for biogas generation.

Generally, the direct use of biowaste in biodigestors is problematic due to the heterogeneity of the compound and the high nitrogen content (e.g. in poultry manure). As it could be for the case of poultry manure (or waste water from WWTP) this causes problems in the fermentation process, so the introduction of a biomass mixing tank and a homogenization tank is required in order to have a homogenous mixture within the biodigestors.

The Anaerobic Digestion (AD) system is based on a two-stage bioreactor type. In this system, the hydrolysis and acidification steps are separated from the methanization processes in two different bio-reactors. After the first digestion stage, the effluents are clarified: the solid part is then recycled to complete the hydrolysis, while the liquid part will pass through the second phase for methanization. The outflows from the digestion phase are then separated. The solid part is removed from the liquid, in order to obtain fertilizers. The liquid fraction is reused in the system in the open ponds for algae growing. This is a good way how to use the co-products of the biogas production with an increase of the total environmental benefit of the plant.

The acidification phase is completed in the first anaerobic digester at 38° C. In the second phase of the anaerobic digestion, associated to the methanization, a patented rotor (“Archimedes Rotors” © [179]) is used to maintain a high concentration of bacterial methanogenic flora and optimize the stripping of biogas.

In the final stage, the biogas is used to feed the cogeneration unit where electrical and thermal energy are produced.

In reference to what was described above, the main system flows are:

- protoplasts from incubators for the production of the initial algal biomass (not considered in the LCA);
- sea water and fresh water to respectively compensate the biomass harvested and the water evaporation;
- poultry manure or sludge - used for algae growth in order to provide the right amount of nutrients necessary for the process;
- CO_2 (together with exhaust gases) used to increase the algae growth;
- heat and electricity from the co-generator;
- digestate from the anaerobic digestion:
    - dry fraction to be used for fertilizers production;
    - liquid fraction of residual to be re-used as input in the algae growth ponds.

The energy demand (both thermal and electrical) necessary for the plant is supposed to be provided by the CHP unit.

3.2.2 Goal and scope, system boundary and data inventory

The goal and scope of the LCA study will be addressed to evaluate the potential environmental impacts of the use of macroalgae 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 previously reported, the analysis is carried out for two proposed conditions: an Italian condition (where the use of poultry manure is included – base scenario 1) and a Latvian condition (where the use of waste water from WWTP is included - base scenario 2).

The outcomes focus on clarifying how marine macroalgae is a potential eligible biogas feedstock contributing to the environmental optimization of the growing phase and the conversion processes.

The substitution method has been used for the accounting of by-products. It consists in an expansion of the system boundaries in order to take into account the impacts generated by the by-products.

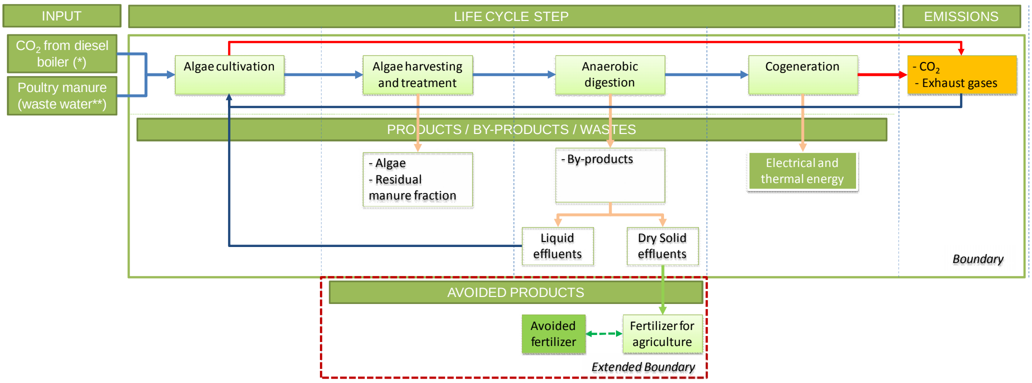
The inventory is based on figures derived from academic resources, research, and technical information from experts. When no data were available the Ecoinvent database [161], found in the Simapro software, was used.

The function of the system is to generate thermal and electrical energy. The functional unit chosen to represent the system was defined as the total energy produced in one year in the plant equal to 1,1 TJ_{el} and 2,2 TJ_{th} [173, 174, 180].

The amount of algae necessary to guarantee this production phase has been set to a level of 1729 t/year [173, 174, 180] for base scenario 1 and 803 t/year for base scenario 2 [20].

Regardingbase scenario 1, the location of the system (Augusta – Italy) is located in southern Europe in the Mediterranean area, and the Italian energy mix for electricity (Medium voltage) has been chosen from the Simapro database. The database also chose an EU-27 energy mix for electricity (Medium voltage) for base scenario 2 which is in the Baltic Sea region, in the territory of the WWTP “Daugavgrīva”. Consequently, both scenarios have Medium voltage. Figure 3.8 shows the flow scheme of the analysed systems. As it can be seen, both systems include the macroalage cultivation phase, harvesting and treatment, 2-stage anaerobic fermentation, the biogas consumption in a cogeneration unit as well as the by-product management expressed in terms of boundary expansions. In these schemes transportation modes are not shown, but are taken into account for in all the unit processes (see Table 3.6).

Since residues from by-products - that occurred during the pre-treatment and fermentation processes – still have a nutritional factor, a beneficial credit has been applied for fertilizer use in the agricultural sector. This means that a certain amount of fertilizers can be avoided since it could be replaced by the by-products of the biogas production as presented in Figure 3.8. It schematically represents the boundary system of the production processes for base scenario 1 and base scenario 2. The boxes represent unit processes, the outflow materials (products, by-products and wastes), the emissions and the avoided products. The dash dotted green arrow represents the displaced process. The dashed red lines represent the extended system boundary.



(*) only for scenario 1, (**) only for scenario 2

Fig. 3.8. Boundary system of the production processes for BS 1 and BS 2

The energy costs and environmental loads of certain capital equipment (buildings, roads) as well as the production of the protoplast were excluded. The impact for the plant construction has been taken into account, with a lifespan of 25 years. Basically, only the inputs and outputs directly associated with the production and use of biogas were identified and quantified. Impacts such as noise and odours were excluded in this study because there are no characterization methods to assess these impacts.

In this study, for both base scenarios, primary data were collected to quantify the operational inputs and outputs associated with each biogas production chain [173, 174, 180], while secondary data from published literature and reports were used to characterize various background processes. Where no other data were available, the Ecoinvent database – included in Simapro – was used.

Operational data for biogas production and the two-stage biogas production plant were obtained from experts related to the project in reference. Calculations, on the basis of the project partner’s information [148], were carried out in relation to the yearly production of the algae biomass [176]. Moreover, useful expert opinions were used in relation to the characterization of the WWTP sludge and manure.

The key data for the biogas pathways are shown in Table 3.6, 3.7, and 3.8. Trying to minimize uncertainties about the data quality, all primary data were checked and compared with the recent and represented current technologies in order to understand if they were outside the normal range for similar products or processes. At this stage, the data could be considered of sufficient quality.

Table 3.6.

General inventory data of plant project [21, 173, 174, 180, 181]

Parameter	**Base scenario 1**	**Base scenario 2**
Geographic setting	Europe (Italy)	Europe (Latvia)
Theoretical amount of biogas produced at plant regime level	40m^3/h	40m^3/h
Total volume of the ponds	3000 m^3	3000 m^3
CO_2 from cogeneration unit	292 t/year	311 t/year
CO_2 from external sources	511 t/year	-
Average monthly water temperature	See Figure 3.9	See Figure 3.9
CH_4 content in biogas	60%	68%

Table 3.7.

Specific inventory data of manure and sludge [21, 173, 174, 180, 181]

Parameter	**Base scenario 1**	**Base scenario 2**
Type of integrative substrate	Local poultry manure	WWTP “Daugavgrīva” sludge
Dry mass of total solids	20%	23%
Volatile solids (of total dry mass)	78 %	68%
Chemical composition of integrative substrate	$NH4^+$ = 6.35 g/kg; NOx = 0.112; PO_x = 9.0 g/kg	NO_3 = 20 mg/g $_{TS}$*; NH_4 = 46 mg/g $_{TS}$*; PO_4 = 26 mg/g $_{TS}$*
Theoretical biogas yield	0.350 m^3/kg $_{VS}$**	0.412 m^3/kg $_{VS}$**

* g $_{TS}$ – g of total solids

** kg $_{VS}$ – kg of volatile solids

Table 3.8.

Specific inventory data of algae [21, 173, 174, 180, 181]

Parameter	**Base scenario 1**	**Base scenario 1**
Type of algae used	*Ulva prolifera*	*Ulva prolifera*
Theoretical period of algae growth	See Figure 3.9	See Figure 3.9
Average algal daily production	4,7 t/day (fresh weight)	2,2 t/day (fresh weight)
Algae cultivation duration	10 days	10 days
Algae daily growth rate (DGR), natural condition	Depending on temp. (see Figure 3.9)	Depending on temp. (see Figure 3.9)
Increase of the DGR due to additional CO_2	20%	21%
Dissolved Organic Compounds (DOP) and Particulated Organic Compounds (POC)	%C = 5% of the dry weight	%C = 5% of the dry weight
Amount of CO_2 in solution sea water	0,09 g/l	0,09 g/l
Amount of CO_2 absorbed in the process of algal biomass growing	511 t/year (Carbon contained in the algal biomass equal to 30%)	300 kg/year (Carbon contained in the algal biomass equal to 30%)
Dry mass of total mass	20%	20%
Volatile solids (of dry mass)	78%	78%
Theoretical biomethane yield	0,275 l_{CH4}/g $_{VS}$ *	0,275 l_{CH4}/g $_{VS}$ *
Absorbed nutrients per day by algae	NO_3= 20 mg/g $_{TS}$ ** NH_4 = 100mg/g $_{TS}$ ** PO_4 = 25 mg/g $_{TS}$ **	NO_3= 20 mg/g $_{TS}$** NH_4 = 100mg/g $_{TS}$ ** PO_4 = 25 mg/g $_{TS}$ **

* g $_{VS}$ – g of volatile solids

** g $_{TS}$ – g of total solids

As it can be seen from Table 3.9 the pond area and the internal walls are made in Ethylene Propylene Diene Monomer (EPDM) rubber, while the walking docks are made in high-density polyethylene (*HDPE*) and aluminium.

Table 3.9.
Life cycle inventory of materials used. All the data input considers a lifespan of 25 years and is adapted to the reference to one year of activity [20, 21, 173, 174, 180, 181]

Material	**Base scenario 1**	**Base scenario 2**	**Used in:**
AISI 304 Steel	109 kg/year	118 kg/year	Poultry manure treatment system (supply system of sludge/manure, Archimede Rotor, Fans, Pumps, algae separation grids)
HDPE	1030 kg/year	1030 kg/year	Walking docks, Archimede Rotor
EPDM	296 kg/year	296 kg/year	Internal ponds walls
Aluminum	132 kg/year	132 kg/year	Walking docks
Lubricating oil	116 kg/year	116.0 kg/year	CHP unit

The following tables, 3.10 and 3.11, report the assumptions for the transportation of material in terms of type and distance and the energy resources required.

Table 3.10.
Life cycle inventory of transportation. All the data input considers a lifespan of 25 years and is adapted to refer to one year's activity [20, 21, 173, 174, 180, 181]

Parameter	**Base scenario 1**		**Base scenario 2**		
	Way	**Distance**	**Way**	**Distance**	**Used in:**
Transport	railway	2.5 tkm	railway	2.5 tkm	Poultry manure treatment system
	sea	685 tkm	railway	685 tkm	Anaerobic digesters
	railway	1.75 tkm	railway	5.5 tkm	Pumps
	railway	25 tkm	railway	45 tkm	Algae separation grids
	railway	80 tkm	railway	110 tkm	Archimede Rotor ©
	sea	1970 tkm	road	1290 tkm	Ponds (Walking docks in HDPE and internal pond walls in EPDM)
	road	5 tkm	road	16 tkm	Fans
	road	165 tkm	-	-	Manure
	road	640 tkm	road	640 tkm	Dry digestate transportation

Table 3.11.
Life cycle inventory of energy used [20, 21, 173, 174, 180, 181]

Parameter	**Base scenario 1**	**Base scenario 2**	
	Data	**Data**	**Used in:**
Electric energy (medium voltage – EU27 mix)	3 MWh_{el}/year	6.4 MWh_{el}/year	Manure treatments/sludge processing
	11.9 MWh_{el}/year	-	Manure injection system
	23.8 MWh_{el}/year	23.8 MWh_{el}/year	Manure/sludge pumping system
	56 MWh_{el}/year	26 MWh_{el}/year	CO_2 supply system
	28 MWh_{el}/year	11.9 MWh_{el}/year	Water pumping system
	16 MWh_{el}/year	6.8 MWh_{el}/year	Algae's separation system
	8 MWh_{el}/year	8.0 MWh_{el}/year	Anaerobic digestion
	4.6 MWh_{el}/year	4.6 MWh_{el}/year	Cogeneration (electric)
Thermal energy	184 GJ_{th}/year	184 GJ_{th}/year	Anaerobic digestion

The study has assumed the manure requirements are supplied to the system by a small truck with a distance travelled equal to 50 km/day with 50% capacity.

3.2.2.1 General results for the inventory of algae growth

Algae growth depends on several parameters where water temperature and the external adding of CO_2 are only two of a wider range that involves: water aeration, water salinity, density of the biomass in the pond and effect of the nutrient added.

The production yield of biogas depends on the algal biomass that the cultivation can provide. This is related to the daily growth rate (DGR) that can be calculated from the resulting increase in the algal biomass in fresh weight, and expressed as a percentage of growth per day. The resulting formula is reported as follows [182].

$$DGR = [(W_t/W_o)^{1/t} - 1] \times 100 \tag{3.1}$$

where:

DGR (daily growth rate) is the daily growth rate in fresh weight per day,

W_o is the initial weight at time “zero”,

W_t is the weight after t days.

The algae growing phase is dependent on the temperature of water of the growing medium [182-184] and consequently, the seasonal variation of temperature can affect the global biomass production yield. Data for the average water temperature has been taken from project partners for base scenario 1 [185] and the Latvian metrology centre [186] for base scenario 2.

In order to calculate DGR (dependent on water temperature),the following formula for Ulva Prolifera is used[182]:

$$DGR = -0.234T^2 + 10.134T - 64.647 \tag{3.2}$$

where:

T = temperature of the water medium.

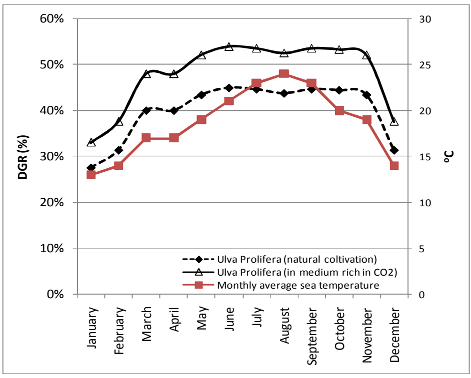


Fig. 3.9a. Ulva prolifera daily growth rate and average water temperature in Italian conditions

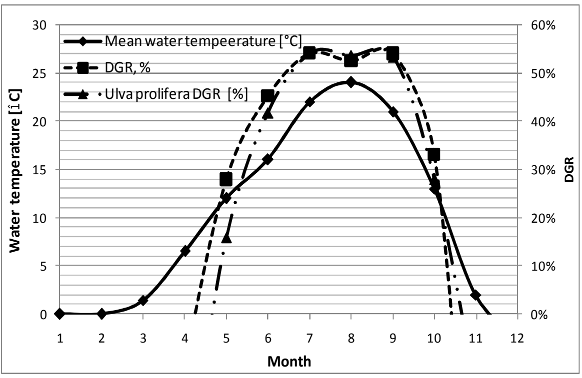


Fig. 3.9b. Ulva prolifera daily growth rate and average water temperature in Latvian conditions

In Figure 3.9a-b the average water temperature conditions for the two scenarios is shown. For the Italian conditions, temperatures vary from a value of 14°C, during winter time until a value of approximately 24°C during summer time, while for the Latvian condition temperatures vary from a zero value, during winter time, until a value of approximately 23°C during summer time (in fact a suitable temperature for the natural growth of algae). It is important to remember that a temperature higher than 30°C can be critical for Ulva prolifera growing.

As can be seen in figures 3.9a-b for both scenarios a maximum of 54% can be reached during July and September (for higher range temperature). It should be mentioned that in natural conditions salinity of the Baltic Sea water is around 6‰ [187, 188]; however, for the *Ulva prolifera* growth salinity level needs to be 25-36‰. Nevertheless, at this stage of the research, it has been decided to use a preliminary stage of the environmental analysis through the LCA methodology and use the same value reference for both conditions.

Using formula 1 makes it possible to understand that the cultivation period - and consequently the harvesting period - for algae in Latvian conditions can be achieved from May until October. This means that the production of biogas will be coupled with the algae biomass digestion within this period only.

It is also important to mention that at the moment of the research; only natural conditions of sun light (which influences the water temperature) are considered, in order to avoid additional energy consumption.

As said before, nutrients for algae growth in both scenarios are supplied by poultry manure or sludge. In order to guarantee algae growth for the whole year approximately 1200 t/year of poultry manure and 770 t of sludge (see table 3.12) are needed. The necessary amount of sludge has been calculated based on the sludge chemical composition and algae fixation capacity (see Table 3.12).

In order to obtain the highest possible growth rate, additional CO_2 is added. The theoretical maximum amount of CO_2 that can be fixed has been calculated by the methodology proposed in the following where CO_2 not absorbed within the ponds is also evaluated. The results obtained are presented in Table 3.12.

Table 3.12.

Life inflows and outflows of algae growth process [20, 21, 173, 174, 180, 181]

Base scenario 1			Base scenario 2		
Harvested algal biomass [t/year]	Used sludge for algae growth [t/year]	CO_2 fixed [t/year]	Harvested algal biomass [t/year]	Used sludge for algae growth [t/year]	CO_2 fixed [t/year]
1729	1203	449	803	770	295

For scenario 2, during the months when algae cannot be harvested there is no fixation of CO_2 and consequently no benefits from the absorption of CO_2.

3.2.2.2 Mass balance of the CO2 sent to the open ponds

It is fundamental to know the amount of the inlet CO_2 in ponds ($CO2_{in}$) responsible for the algae biomass growth ($CO2_{BM}$), the part dissolved in the water ($CO2_{wat}$), the part released in the atmosphere from the water surface of the open ponds ($CO2_{rel}$), and the dissolved organic carbon and particulate organic carbon biomass ($CO2_{D.P.}$).

All these parameters can be summarized in the following equation that expresses the mass equivalence of the inlet CO_2:

$$CO2_{in} = CO2_{rel} + CO2_{BM} + CO2_{D.P.} + CO2_{wat} \tag{3.3}$$

In this equation:

$CO2_{in}$ = inlet CO_2 in the open ponds,
$CO2_{rel}$ = part of the CO_2 released in the open ponds from the water surface,
$CO2_{BM}$ = part of the CO_2 responsible for the algae biomass growing,
$CO2_{wat}$ = CO_2 dissolved in the open ponds,
$CO2_{D.P.}$ = $CO2_{DOC}$ + $CO2_{POC}$,

where:
DOC = dissolved organic carbon,
POC = particulate organic carbon.

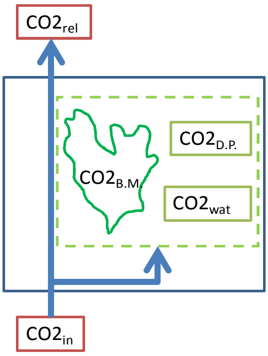


Fig. 3.10. CO_2 mass balance

Figure 3.10 is a visualization of the equation. The amount of daily CO_2 provided to the open ponds ($CO2_{in}$) can be known from the inventory initial data.

The amount of CO_2 transformed in algae filamentous biomass ($CO2_{BM}$) can be calculated in this way [178]: once the amount of algae biomass produced is known (in accordance with the DGR chosen) and the percentage of the carbon contained in the algal biomass is also known (in first instance equal to 30% of the dry weight [21] it is possible to know the amount of CO_2 by a simple proportion between the two molecular weights (it is assumed that all carbon in the CO_2 is responsible for the creation of the algal carbon content) and after multiplying with the carbon content in the dry weight of the algal biomass:

$$CO2_{BM} = BiomassDryweight \cdot \%C \cdot 44/12 \tag{3.4}$$

In this formula, the Biomass Dry weight is assumed equal to 20% of the total algal biomass according to Table 1.

The amount of CO2 dissolved in the water of the ponds needs to be studied in more detail, when the research was being conducted, the assumption chosen was to assign the outlet water from the ponds a value of CO2 equal to the same typically present in seawater. The value of 0.09 gCO2/l has then been chosen [21]. If the total hourly water recirculation rate is known, together with the working hours of the system, it is possible to evaluate the parameter CO2wat. The final calculation is described below:

$$CO2_{wat} = CO_2 \text{ in the sea water} \cdot \text{hourly water recirculation} \cdot \text{working hours} \tag{3.5}$$

where:

CO_2 in the sea water = 0.09 kg/m^3,
hourly water recirculation = 15.0 m^3/h,
working hours = 12 h.

The part of the dissolved organic carbon (DOC) and particulate organic compounds (POC). Regarding this, a total value equal to 5% of the dry weight is assigned [21].

The last factor of the CO_2 release out of the open pond is calculated by equation 1, only subtracting all the other amounts of CO_2 previously calculated.

3.2.2.3 General results of biogas generation

The amount of biogas produced is dependent on the algal biomass. For the base scenario 2 during the period from November until April, only sludge biomass is used for biogas production since it is not theoretically possible to cultivate algae during this period (see Table 3.13.).

Table 3.13.

Biogas produced for base scenario 1 and 2 [20, 178]

	Poultry manure [t/month]		**Algal biomass [t/month]**		**CH$_4$ from algae [m^3/month]**		**CH$_4$ from sludge [m^3/month]**		**CH$_4$ in total [m^3/month]**		**Biogas in total, [m^3/month]**	
	1	2	1	2	1	2	1	2	1	2	1	2
J	25	231.1	37	0	1583	0	503	2752	2086	2752	3476	4047
F	49	208.7	71	0	2998	0	969	4727	3967	4727	6612	6951
M	114	231.1	164	0	6886	0	2278	8659	9164	8659	15273	12734
A	110	223.6	158	0	6656	0	2202	9792	8858	9792	14764	14400
M	124	210.9	178	13.18	7496	555.1	2484	9237	9981	9792	16634	14400
J	124	125.4	178	94.35	7496	3974	2484	5492	9981	9466	16634	13920
J	124	6.4	178	225.87	7496	9513.5	2484	279	9981	9792	16634	14400
A	124	13	178	218.99	7496	9224.1	2484	568	9981	9792	16634	14400
	120	16.5	172	215.33	7246	9069.6	2401	722	9648	9792	16080	14400
O	129	189.7	184	35.19	7746	1482.3	2567	8310	10313	9792	17189	14400
N	124	223.6	178	0	7496	0	2484	8925	9981	8925	16634	13125
D	36	231.1	52	0	2221	0	718	3545	2938	3545	4897	5213
Tot	***1203***	***1910.98***	***1729***	***802.91***	***72817***	***33818***	***24060***	***63007***	***96877***	***96826***	***161462***	***142391***

The bigger amount of biogas needed for scenario 1 is motivated by the fact that a different share of biomethane in the biogas mix has been used for the two different scenarios: 60% for scenario 1 and 68% for scenario 2.

In Figures 3.11a and 3.11b, the dark columns represent the biomethane generated from algal biomass, and the white the biomethane from manure or sludge biomass.

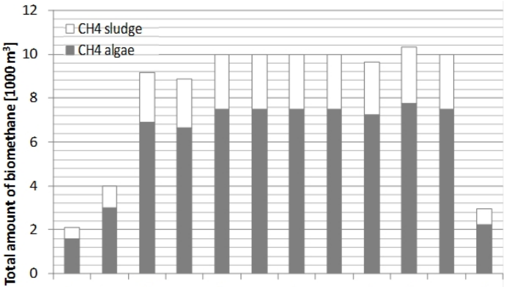


Fig. 3.11a. Amount of biomethane in the biogas mix generated from Ulva Prolifera and sludge throughout the year [1000 m^3] – scenario 1

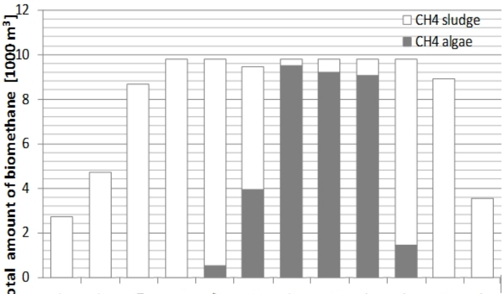


Fig. 3.11b. Amount of biomethane in the biogas mix generated from Ulva Prolifera and sludge throughout the year [1000 m^3] – scenario 2

From Figures 3.11a and 3.11b, it is possible to understand that the share of the biomethane produced from the digestion of the algal biomass is equal to 75% for scenario 1 and 35% for scenario 2. This difference, if attributable to the use of the algae biomass for scenario 2, is limited only to the period from May to October.

3.2.2.4 Co-product allocation

The substitution method according to the boundary expansion has been applied to this study for both scenarios.

The residues from by-products still have a nutritional factor that can be considered as a beneficial credit if used as fertilizers in the agricultural sector. Table 3.14 and 3.15 show that the parameters have been used to account for the emissions avoided which are related to the use of manure (solid and liquid fraction) for production of biogas and the emissions avoided from the use of the solid and liquid digestate as a fertilizer expressed in nutritional factors.

Table 3.14.

Avoided emissions from field use of manure for the production of biogas in reference to the functional unit [189, 190]

Compounds	Amount [g/f.u.]	Fraction
CH_4	10.14	solid
NH_3	48.08	solid
N_2O	43.22	solid
CH_4	49.51	liquid
NH_3	240.95	liquid
N_2O	59.46	liquid

Table 3.15.

Avoided amount of fertilizers using solid digestate as fertilizers – referenced to one kg of digestate [189, 190]

Compounds	Amount [g/kg]	Fraction
N_{tot}	3.9	solid
P	4.5	solid
N_{tot}	3.4	liquid
P	0.6	liquid

A share of 90% of liquid fraction and 10% of solid has been used for the total daily amount digestate. Only the solid fraction has been taken into account as a fertilizer in the agricultural sector. In fact, the liquid part is re-used within the cultivation process.

3.2.3 *Impact assessment: sources and stages*

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

- algae cultivation, all input and outputs related to the production of the 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 related to all the unit processes on the production chain that are taken into account,
- co-product management, that takes into account the environmental benefit from the use of the co-products in the extended boundary (e.g. reuse of the liquid digestate in the ponds and the use of the solid fraction as fertilizers),
- materials, all the components necessary for the building up of the plant,
- transportation.

For scenarios 1 and 2 the outcomes at the endpoint category are presented in terms of Pt/functional unit (f.u.).

The following figures, 3.12a and 3.12b, compare base scenarios 1 and 2. As it can be seen, the most potentially negative effects (not considering the benefits) are related to the human health category for scenario 1 (70% of the whole impact) and to climate change for scenario 2 (75% of the whole impact).

For both scenarios, this is directly connected to the emissions from the cogeneration unit not reintegrated in the system. This can be considered the main "hot spot" for both models. The difference within the 2 scenarios can be explained, stressing the fact that for scenario 2 only during the period from May to October the emissions from the CHP unit can be reintegrated into the system for growing algae.

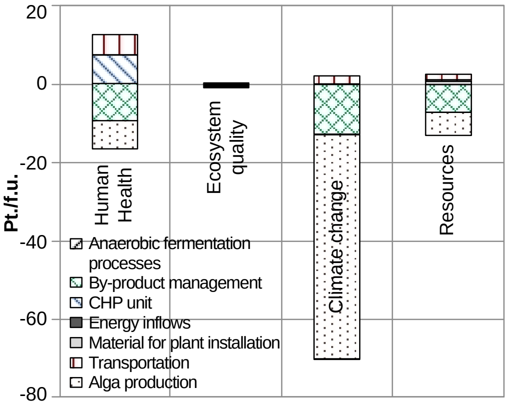


Fig. 3.12a. Impact assessment at endpoint categories (e.g. ecoprofile) [Pt/f.u.] – base scenario 1

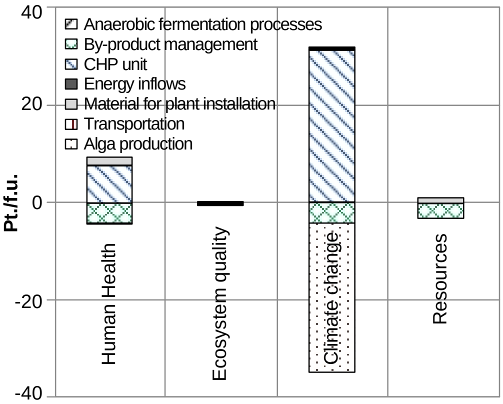


Fig. 3.12b. Impact assessment at endpoint categories (e.g. ecoprofile) [Pt/f.u.] – base scenario 2

From figures 3.12a and 3.12b it is also possible to understand that the cogeneration process is the most undesirable one 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 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 a fertilizer and to the CO_2 fixation in the algae biomass for both scenarios. The results of this category in terms of net impact (environmental load less benefits) are a value of -3.5 Pt for scenario 1 and a value of 5.2 Pt for scenario 2. So, due to the photosynthesis process of the algae, the damage driven by the cogeneration processes can be fully recovered for scenario 1 and decreased by 50% for scenario 2.

In the referenced figures 3.12a and 3.12b one can see a low impact given by the energy used (thermal and electrical), since the energy demanded is, at the end of model, re-used within all the production processes.

The biggest environmental benefit is associated to climate change, where the process of the algae cultivation and management of the co-product accounts for a value of 82% and 18% respectively. The total benefit for scenario 1, 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).

The total net impact (summing up all the impact categories) of the algal biogas system throughout the life cycle is equal to –81.5 Pt for scenario 1 and 1.02 Pt for scenario 2. This means that the whole process shows a total environmental beneficial effect for scenario 1 differently from scenario 2 where a "real impact" (bigger than zero) occurs. As mentioned before, the big difference among the two scenarios is attributable to the different amount of CO_2 absorbed in the system associated with algae cultivation. Nevertheless, the total environmental effect has to be compared with the scenario that takes into account the use of natural gas in the CHP unit. In fact, this is the real goal of the study addressed - to understand the real environmental feasibility of the technology analysed.

3.2.4 Comparisons with other studies: biogas from generic agricultural biowaste and a natural gas-based system

The base scenario has been compared with two other scenarios, which have equal functional units. In the analysed cases, the comparisons have been carried out among different types of gas used in the same cogeneration unit. More specifically, these are: natural gas and biogas from agricultural biowaste feedstock. The LCAs in comparison have been extrapolated directly from the Simapro database; within the scheme of the agricultural scenario, any benefits from the use of the by-products have not been taken into account.

As it is clearly shown in Figures 3.13a-b and 3.13a-b the base scenarios provide a lower environmental net impact.

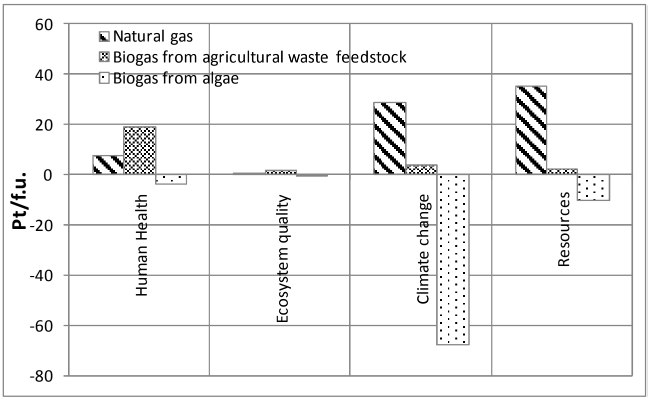


Fig. 3.13a. Comparison of base scenario 1, agricultural feedstock and natural gas scenarios [Pt/f.u.]

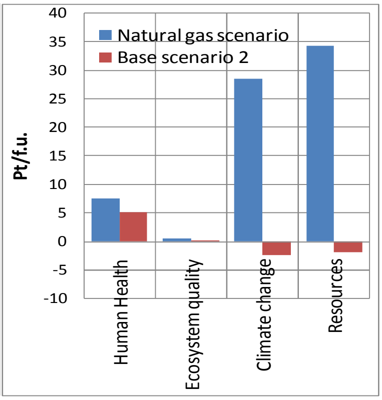


Fig. 3.13b. Comparison of base scenario 2 and natural gas scenarios [Pt/f.u.]

From the previous figures, the scenarios related to the use of natural gas the strongest environmental load is given by the use of non-renewable sources that accounts for 50% of the total impact followed by the climate change impact that accounts for 30%.

For all biogas scenarios, the ecosystem quality impacts present a higher value than the natural gas scenarios; this aspect is mainly connected to the use of pesticides and the effect of global eutrophication.

Also, for the human health impact category, related to the use of agricultural bio-wastes the impact is higher than the natural gas. This behaviour is connected to the strong effect of the exhaust gases in relation to human toxicity and respiratory effects.

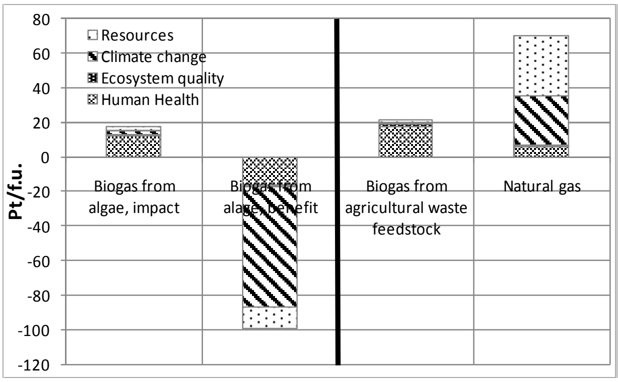


Fig. 3.14a. Single score comparison: scenario 1, agricultural feedstock and natural gas scenarios [Pt/f.u.]

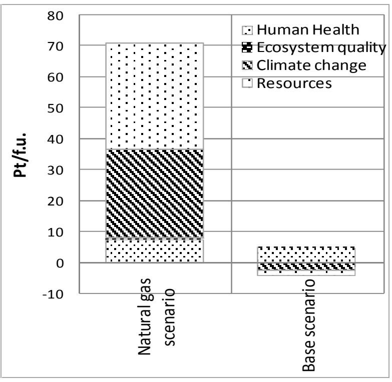


Fig. 3.14b**.** Single score comparison: scenario and natural gas scenario [Pt/f.u.]

The comparison of the algae base scenario 1 and 2 with a similar biogas production using agricultural wastes shows a similarity in terms of the total impact, and in terms of the main impact category which is human health. For both cases, this potential impact accounts for a share of approximately 80%. Nevertheless, the algae based scenario accounts for a reduction of 18% (22Pt against 18Pt) with respect to the agricultural scenario; this can be attributed to the use of pesticides during the production of biomass for the anaerobic digestion.

The results show that the biogas base scenario using algae, has a lower impact than the natural gas and agricultural bio-wastes scenarios (Figure 3.14a and 3.14b).

3.2.5 Energy performances

The energy balance carried out in this research can be considered as the first start for a benchmarking analysis. In light of that, the following table presents the indicator $E_{i,}$ defined as the ratio of the total energy used for fuel production (in terms of non-renewable sources) and the biogas energy (in terms of calorific value).

At the same time, this process will be possible to evaluate the strength and the level of the theoretical renewable processes since a great deal of the ratio is lower than one, the processes then have more efficient renewable peculiarities.

Table 3.16.

Energy indicator

Scenarios	$\mathbf{E_i}$
Base scenario 1	0.06*
Base scenario 2	0.13*
Other studies [191, 192]	$0.10 < E_i < 0.48$

*without avoided products

where:

MJ_{in} = global non-renewable sources spent within the model [MJ];
MJ_{out} = biogas energy (specific heating value – 23 MJ/m^3) [163];.
$E_i = MJ_{in}/ MJ_{out}$ = energy indicator.

3.2.6 Sensitivity analysis

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 elasticity method (i.e., the ratio of the change in the results to the change in data input [193] was used to perform this task. At this stage, the sensitivity analyses were performed for the CHP efficiency factor, and the average water temperature. Moreover, a sensitivity analysis for the choice of the impact assessment method (comparison with CML method [128]) has also been evaluated.

The elasticity method states that the model is sensitive to a certain parameter variation, if the ratio of the change in the results to the change in data is bigger than 1.

When the efficiency of the CHP (initially equal to 90%) is decreased by a factor of 9% (according to Lanche [190]) the results of the analysis show an increase of the environmental burden of 10%. According to the elasticity factor this means that the model is slightly sensitive to changes to the efficiency value.

The sensitivity analysis, executed for the water mean temperature (relevant for algae cultivation), shows that a variation of 5%, (around 1°C) during the biomass production months produces a negative environmental impact change equal to 4.5%. This means that the system is not sensitive to changes in temperature; even if the value is slightly lower than one, but rather close to change concerning sensitivity. Other sensitivity analyses should involve: transportation assumption, the biogas yield, the co-product management, and the electricity grid-mix used. At this stage, these evaluations have not been considered.

The sensitivity analysis on the choice of another impact assessment method (CML compare to IMPACT 2002+) - carried at the mid-point stage - shows only evident changes in the respiratory inorganic impact category.

3.2.7 Limitations of the study

It must be underlined that the research carried out in regard to the biogas production system using macro-algae is a prospective LCA of a non-existing plant. Consequently, the production systems described in this study should not be considered as fixed, and can be subject to important modifications. Indeed, technologies used for growing and harvesting algae are based on initial assumptions that can be improved in the future. Therefore, the aim of this study is to identify the main bottlenecks of a biogas production process from algae, and to compare them with the advantages and the drawbacks of mature technology for biogas production with a reference to a natural gas-based system.

At the same time, the direction of the study is also to find the most suitable algae in relation to the local condition. This should be further investigated.

Further analyses are required based on the evaluation of the changes in results within a variation of data in the model. This evaluation should be evaluated in connection to:

- change of the average water temperature in connection with the algae DGR;
- change of the evaluation of the DGR formula used;
- change in the emissions for the combustion processes within the CHP unit;
- change in the assumptions for the transportation distances;
- choice of a different type of algae.

3.2.8 Comments on results

Among the LCA models not yet implemented, macro-algae based on technology has been taken into account concerning different aspects; one of the main aspects is related to the GHG balance. This part is essential in order to quantify the correct amount of GHG flows for the evaluation of the carbon neutral cycle of the whole system.

For this reason during the data collection for the implementation of the LCI, attention was given to the following aspects:

- CO_2 absorbed from seawater in the ponds;
- CO_2 sequestered and fixed in the algae biomass;
- the beneficial effect of the use of exhaust gases within the algae growing system;

- the beneficial effect of the use of nutrients from biowaste (in this specific case manure and sludge from WWTP)
- the use of non-renewable fuel within the whole system;
- the use of equipment or machineries;
- the use of materials (in terms of inflows and outflows);
- direct emission of gases directly connected to potential global warming.

During the building-up of the LCI, several assumptions have been provided. This has mainly involved:

- the choice of the algae and the related growing parameters (e.g. DGR, water temperatures, carbon fixed in algae biomass, required amount of supplied CO_2, nutrient absorption factors, dry mass percentage);
- the choice of the specific conditions of the growing media within the ponds like: the dissolved amount of CO_2 in the water ponds, Dissolved Organic Compounds (DOP) and Particulated Organic Compounds (POC). Factors such as solar irradiation, photoperiod and water evaporation from the water pond surface have been considered constant over time;
- the choice of the biogas production yield;
- the choice of the transportation schemes.

The assumptions have made increases in the uncertainties of the whole system, but at the same time provide results for the evaluation of beneficial environmental effects like:

- the evaluation of the algae growth to increase the CO_2 sequestration,
- the identification of the "hot spots" with the corresponding minimization of the use of non-renewable fuels into the system.

3.2.9 LCA study discussion and conclusions

The main overall conclusions from the results of the model analysed are:

- Due to the system performance, the human health category is influenced the most in scenario 1, while the climate change category is influenced the most in scenario 2. From the net impact perspectives (taking into account the environmental benefits) the human health category is providing the highest burden for both scenarios.
- The cogeneration process is the most damaging one, but algae cultivation is the most environmentally beneficial element of the system for both base scenarios.
- For scenario 1 the use of algal biomass for biogas production gives 18% environmental performance improvements (not considering benefits) in comparison with the agricultural bio-waste scenario and four times improvements in comparison with natural gas.
- The main environmental benefits come from the by-products used (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).
- The biggest environmental benefit is associated to climate change, where the process of the algae cultivation and management of the co-product accounts for a value of 82% and 18% of the total benefits for scenario 1, and for 88% and 12% of the total benefits for scenario 2.
- The base scenario 1 is totally environmentally feasible (net impact lower than zero). The base scenario 2 does not present values of net impact lower than zero, nevertheless if compared with the natural gas based scenario the impact is 70 times lower.
- For scenario 2, the results are slightly sensitive to change in the CHP unit efficiency.

As an overview of the main outcomes from the previous results, it can be summarized that:

- macro-algae can be considered a renewable resource (base on the energy indicator lower than 1 and the LCA ecoprofiles),
- with macro-algae, an important and substantial GHG can decrease reductions, but always under significant uncertainties,
- macro-algae can be considered sustainable in terms of the use of local sources. Further and integrated analysis are 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 the:
  - 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;
  - harvesting sediment disturbance – organic matter.
- Other environmental aspects are related to the:
  - use of local species that will not contaminate the local ecosystem;
  - risks of the spreading of a monoculture eco-system (spreading of disease);
  - Eutrophication risks due to the amount of algae can increase;
  - Environmental benefits of integration with aquaculture.

A fundamental question to point out is related to the comparison among inshore and offshore cultivations. The advantages for the 2 types of cultivations can be summarized in the following points:

<u>In-shore cultivations</u>

- The favourable availability of place for cultivation facilitating an easy monitoring of the system and transport (good potential for local stakeholder involvement and investments);
- Potential for synergies with fish farm bioremediation and economics.

<u>Off-shore cultivations</u>

- Offers more space without reflection on “land-use” impact (still has constraints with shipping channels);
- Potential for synergies with fish farm bioremediation and economics.

Disadvantages

<u>In-shore cultivations</u>

- Economic feasibility low if the production, processing, and final use are not at the local scale;
- Need to maintain ground related to fishing activities;
- High uncertainty for up-scaling of the systems.

<u>Off-shore cultivations</u>

- Changeable sea conditions, problems related with tides and currents;
- Economic feasibility low if the production, processing, and final use are not sufficient at the local scale;
- High uncertainty for up-scaling of the system;
- Need to maintain navigation channels and fishing areas;

- Less protection than in-shore and possibility to contaminate the local eco-system.

3.3 Thermal energy production of wood fuel based on Latvian boiler houses

Nowadays, forest lands in Latvia cover 55% of the total land with an increase of 2% over the past decade [194].

In this light, forests can be considered an important source of raw material for the production of energy and decreasing energy dependency. However, the increase of woody biomass for energy purposes has to face the sustainable criteria (i.e. avoiding negative impacts from a more intensive use, offsetting the decrease of the availability of natural resources in a long-term perspective).

On the other hand, the development of biomass as an energy source can be related to emissions dangerous for human health and to the environment in connection to the final combustion step and the whole total supply and disposal system.

For these reasons, the scale of impacts involves local and global levels (regional and national). If attention is focused on the air quality, wood-based combustion has shown relevant contributions for the air pollution in relation to some residential areas of Europe, mainly due to the high level of fine particulates with respect to the fossil-based combustion processes [195-197].

If one considers all the previously mentioned aspects a “cradle-to-grave” approach is relevant for a wider and comprehensive understanding of the benefits (environmental, financial and social) associated to the biomass use.

3.3.1 LCA of biomass combustion: production of thermal energy from wood-based boiler houses

The aim of this LCA study is the evaluation and comparison of the environmental impacts of wood-based and natural gas boiler houses related to the district heating systems. This will be completed by using the LCA methodology, based on site-specific data and information - whenever possible - and data from well-known databases: Ecoinvent [161] and GEMIS [163].

This study has developed an LCA assessment based on a comparison of different scenarios:

- boiler-house system based on the use wood chips (base scenario 1),
- boiler-house system based on the use of wood logs (base scenario 2),
- boiler-house system based on the use of wood pellets (base scenario 3),
- boiler-house system based on the use of natural gas (base scenario 4).

3.3.2 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 within the production of thermal energy in different boiler-house systems. The study foresees the identification and quantification of the major environmental impacts. The evaluation is also carried out through a comparison with a natural gas-based system using the same functional unit.

The interpretation of results is intended to provide a quantification of the beneficial effects from using woody biomass as a renewable energy, and to assess the strength of the negative aspects (i.e. the effect of higher level of fine particulates emitted during the combustion processes).

Since attention is mainly focused on the real impacts of the systems analysed, using a more conservative approach, the use of the woody-biomass within the analysed scenarios has been taken into account. This has been completed without avoiding the same amount of thermal energy produced in reference to the natural-gas based scenario typical of the LCA substitution-based methods. In the same way, a mass allocation has been applied, but not taking into account the potential of by-products and/or wastes (this means again that a boundary extension has not been implemented at this stage).

The inventory is based on figures derived from academic resources, research and technical information from experts [198].

The function of the system is to generate thermal energy; therefore, the functional unit chosen to represent the system was defined as 1 MWh of thermal energy produced in one year in the boiler house.

The amount of biomass necessary to be used within each system has been determined.

3.3.3 Scenarios analysed and system boundaries

The scenarios analysed are located in Latvia. The electrical power mix used within the modeling refers to the Latvian mix (hydropower = 62%, CHP using natural gas = 36%, wind power and biogas = 2%) [199].

The evaluation and quantification of all direct and indirect impacts related to the main processes involved in each scenario have been included in the inventory. The Figures 3.15, 3.16 and 3.17 show the flow schemes of the wood fuel systems. In the LCA schemes, the main unit processes are described in the boxes as life cycle steps. Products, by-products and wastes are reported on the right hand side of the figure. Thinner solid lines represent the out-put materials for each process, thinner dotted lines represent the out-put materials for each process.

The scenarios can be summarized as:

- boiler-house system based on the use of wood-chips – base scenario 1 (BS1),
- boiler-house system based on the use of wood-logs – base scenario 2 (BS2),
- boiler-house system based on the use of wood-pellets – base scenario 3 (BS3),
- boiler-house system based on the use of natural gas – base scenario 4 (RS4) using an alias reference system for the comparison of the results.

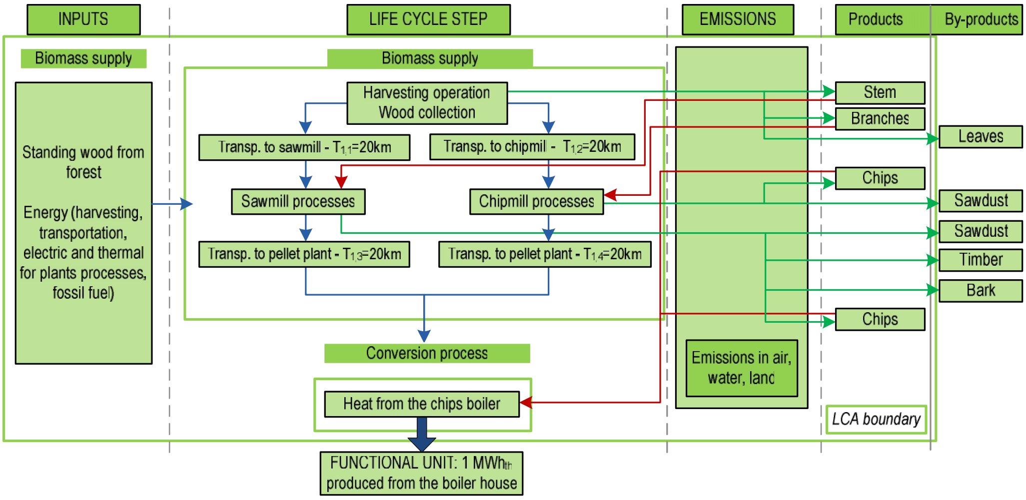


Fig. 3.15. LCA System boundary for scenario BS1

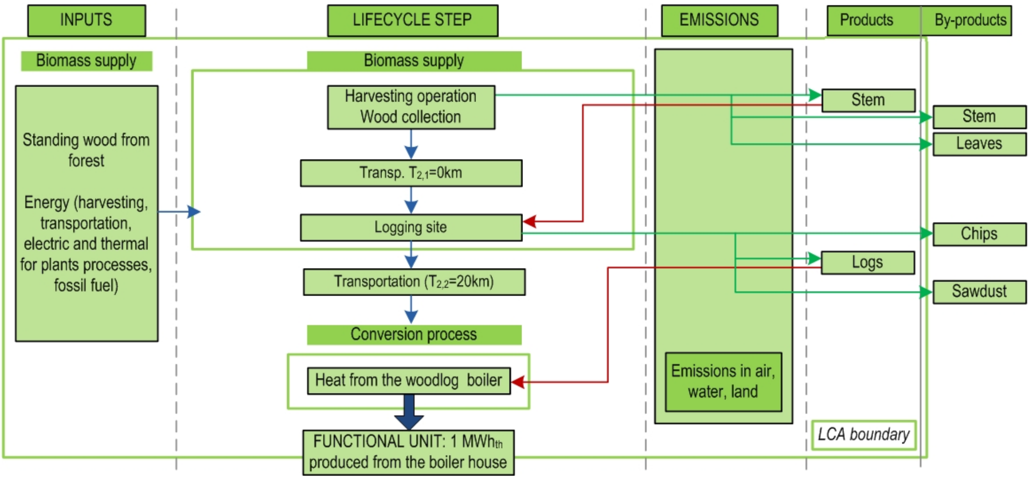


Fig. 3.16. LCA System boundary for scenario BS2

For the scenario based on wood-fuels, the operation starts with the harvesting at the forest stand, and ends with the energy conversion at the heating plant (including the ash disposal). Trees are felled with a cutter machine (harvester-forwarder). The main product from the felling is stems with bark, wood residues, branches and leaves. All the machines in the forest use fossil fuel (diesel).

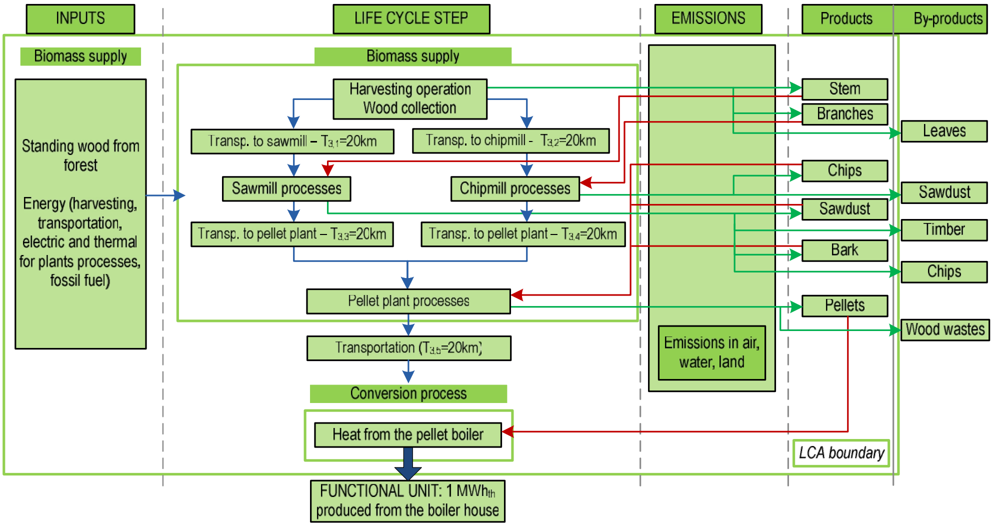


Fig. 3.17. LCA System boundary for scenario BS3

Stems and other wood residues are transported directly by the harvester-forwarder to the forest processing point. From this point, the wood-products are later transported with trucks with a maximum capacity of 32 tonnes (EURO 3 emission type) to the sawmill or to the chipping point in order to be further processed (as it is for pellet production). In base scenario 2, logs are directly sent from the forest processing point to the final boiler house where they are combusted.

It is important to mention that the transportation distance is considered a sensitive parameter, as it is difficult to assign a fixed average value to a system since the supply system is constantly changing. It depends on the choice of the wood-fuels supplier. Therefore, the sensitivity analysis is held within the scope of this study.

3.3.4 Life cycle inventory: hypotheses and data

Reliable data are necessary for quantifying inputs and outputs related to each unit process. Inputs are represented by woody biomass types, transportation distances, productivity, fuel consumption, by-product co-productions, technical life of machineries, and wood processing operations. Outputs are GHG emissions and the direct final production of thermal energy.

The following data has been selected from the Ecoinvent database in the Simapro software:

- forest harvesting felling techniques (mechanized whole tree system),
- fuel consumption for forest machinery (assumed diesel),
- fuel consumption for transportation with lorries (assumed diesel).

Several assumptions related to woody biomass characteristics, conversion factors for the calculation of biomass volume, energy equivalence and energy content were made, and they are summarized in the following where the main emission from the combustion processes are proposed.

The main characteristics of the studied systems are summarized in Table 3.17.

The energy costs and environmental loads of certain capital equipment (buildings, roads) were excluded. The impact from the construction of the plant has been taken into account, with a lifespan of 25 years. Basically, the inputs and outputs directly associated with the production and use of wood fuel and natural gas were identified and quantified. Impacts such as noise and odours were excluded in this study because there are no characterization methods to assess these impacts. The geographical boundary for this study is Latvia and Europe, while taking into account the raw materials production.

Table 3.17.

Characteristics of biomass combustion systems analyzed in the study

Main characteristics of the system			**Characteristics of the fuel**		
Scen.	Boiler house	Efficiency [%]	Type	Moisture content	Net calorific value
1	8 MW plant	85	Wood chips	50% [200]	9.5 MJ/kg [200]
2	2 MW plant	75	Wood logs	50% [201]	9.0 MJ/kg [202]
3	1 MW plant	85	Wood pellets	6-8% [201, 203]	16.5 MJ/kg [201, 203]
4	8 MW plant	90	Natural gas	-	45.0 MJ/kg [163]

In reference to the LCAs boundaries scheme, the following assumption concerning distance has been made.

Table 3.18.

Transportation distances: assumption within the base scenarios

Scenario	**Distances**
BS1	$T_{1.1} = 20$ km $T_{1.2} = 20$ km $T_{1.3} = 20$ km $T_{1.4} = 20$ km
BS2	$T_{2.1} = 0$ km $T_{2.2} = 20$ km
BS3	$T_{3.1} = 0$ km $T_{3.2} = 20$ km $T_{3.3} = 20$ km $T_{3.4} = 20$ km $T_{3.5} = 20$ km

As mentioned the distance is a parameter that requires a substantial sensitivity analysis. In fact, the distances related to the delivery of wood fuel from the production unit processes, including to the end use unit, as well as the distances within the interim processes are further analysed with two other different lengths (50km and 150 km).

In the following tables (3.19, 3.20, and 3.21), the main useful information for allocations within the model are shown:

Table 3.19.

Biomass distribution in a final felling: mass allocation [204]

Products	**Allocations**
Branches	16%
Stems	73%
Leaves	11%

Table 3.20.

Sawmill products produced: mass allocation [204]

Products	**Allocations**
Timber (50% moisture content)	45%
Bark	10%
Sawdust	12%
Chips	33%

Table 3.21.

Resource to produce 1 tonne of pellets in a pelletisation plant [205]

Resource	**Moisture content**	**Amount [t]**
Bark	50%	0.85 t
Sawdust for pellet production	50%	0.55 t
Sawdust for heat production	50%	0.40 t
Other wood residue mix (chips and shavings)	20%	0.30 t
Total	**2.1 t**	

The pellets produced consist of circa 50% bark and 50% sawdust/shavings. The moisture content of the pellets is about 6-8%.

In the next table, Table 3.22, the main assumptions related to woody biomass characteristics, conversion factors for the calculation of biomass volume, and energy content are summarized.

Table 3.22.

Woody biomass characteristics, conversion factors

Standing Woody biomass characteristics		**Data Source**
Density of standing woody biomass (wet basis)	0.9 $t/m^3_{S.V.}$ *	[200]
Moisture content	50%	[200]
Productivity	188 m^3/ha/year	[194]
1 $m^3_{S.V.}$	2.5 $m^3_{L.V.}$**	[194]
1 $m^3_{S.V.}$	1.67 $m^3_{St.V.}$***	

*S.V. = solid wood; ** L.V. = loose volume; *** St.V. = stocked volume.

The natural gas based system has included data from the Ecoinvent 2.1 database. Specifically, this has included:

- place of natural gas extraction: on-shore plant in Russia;
- fossil fuel for extraction, refining and transportation of the natural gas;
- piping system length;
- emission from natural gas combustion.

The energy costs and environmental loads of certain capital equipment (buildings, roads) were excluded. The impact for the plant construction has been taken into account, with a lifespan of 25 years. Basically, only the inputs and outputs directly associated with the production and use of wood-fuel and natural gas were identified and quantified. Impacts such as noise and odours were excluded in this study because there are no characterization methods to assess the related impacts. The geographical boundary for this study is Latvia and Europe while taking into account the production of raw materials.

The following paragraphs present the main data collected and implemented in the LCA model. The steps of the life cycle within scenarios 1, 2, and3 are described.

1. Collection and transport of raw materials. The primary biomass sources considered in all wood fuel-based scenarios was assumed as a natural standing forest wood. It was also assumed that raw material originating in Latvia, would consist of unspecified round wood from 40-60-year rotations [194]. The primary biomass source, when sent to intermediate industrial processes, prior to being usable as wood fuel (e.g. sawmill), presents a multi-output step. Consequently, a mass allocation approach has been applied to the by-products. This is the case of the scenarios based on the use of pellets and chips: in fact, as it has been shown in the schemes of figures 3.15, 3.16, and 3.17 the raw material partly came directly as a primary source from the natural forest and partly as residue from the sawmilling processes.

The distances for the source of raw materials and plants is based on information provided by Latvian boiler-house plant operators [198] and from the technical literature [206, 207]. For the scenarios 1, 2, and 3 the transportation distances from the forest to the consequent processing was assumed equal to 20 km.

For scenario 1, 2, and 3 the transportation has been assumed with 32t capacity trucks. The estimations of the emissions from forestry operations, and the road were taken from the LCA database implemented in the Ecoinvent 2.1 database within the software Simapro 7.3.2. The loading and unloading operations have not been considered, since it is negligible when compared to the forest operations [207].

Since natural conditions were assumed, energy and material consumption for ground preparation, pesticides and herbicides were not included. Potential biomass uptakes were estimated through the evaluation of the average productivity of forest related to the amount of land use within a certain wood productivity [tonne wood/ha].The average wood productivity in the forest was assumed to be equal to 188 m^3/ha/year of biomass [194].

The non-renewable fuel consumption for the harvester-forwarder considered within the study is reported in the next table.

Table 3.23.

Forwarder-harvester non-renewable fuel consumption for 1 tonne of wood [205]

Material	**Amount [kg/t]**
Diesel	4.143
Hydraulic oil	0.0966

Moreover, it has been calculated that the average distance for this machine during the forest felling operation was equal to 1.15km for one tonne of wood.

In the table 3.24, the emission from the use of the harvester-forwarder considered within the study was reported.

Table 3.24.

Emission during the felling [205]

Emissions	**Amount [g/tkm]**
CO_2	1.81E+04
CH_4	1.39E+01
N_2O	5.04E-01
NOx	1.42E+02
SO_2	1.90E+01
PM	1.16E+01
Cd	3.30E-06
Hg	1.37E-05

2. Production. Wood chips for base scenario 1 were supposed to be produced from two sources: the first from forest residues (branches – 50% in mass) and the second from sawmill residues (chips – 50% in mass). The data presented in Figures 3.15, 3.16, and 3.17 and in Table 3.25 were considered estimates for energy and material consumption for the production of a functional unit from wood chips.

Wood logs (base scenario 2) were supposed to be produced from the direct logging of stems. The log spot has been assumed at the forest. In Table 3.25, the main aspects related to the production of logs are summarized.

Table 3.25.

Life cycle inventory from the production steps until final end-use for the base scenarios 1, 2, and 3

		Base scenario		
	Transportation	**BS1 (chips)**	**BS2 (logs)**	**BS3 (pellets)**
	Distances	$T_{1.1}$ = 20 km $T_{1.2}$ = 20 km	$T_{2.1}$ = 0 km $T_{2.2}$ = 20 km	$T_{3.1}$ = 0 km $T_{3.2}$ = 20 km $T_{3.3}$ = 20 km $T_{3.4}$ = 20 km $T_{3.5}$ = 20 km
	Final ash disposal distance	$T_{1.3}$ = 10 km	$T_{2.3}$ = 10 km	$T_{3.6}$ = 10 km
INPUT	**Materials**			
	Raw material chipping mill	Branches = 1.1 t/t_{chips}	-	Branches = 1.1 t/t_{chips}
	Raw material sawmill	Stem = 2.22 t/t_{timber}	-	Stem = 2.22 t/t_{timber}
	Raw material for logging plant	-	Stem = 1.05 t/t_{logs}	-
	Raw material for pelletisation plant	-	-	Bark = 0,85 $t/t_{pellets}$ Sawdust =0,95 $t/t_{pellets}$ Chips/shavings = 0.30 $t/t_{pellets}$
	Woody bio-fuel for boiler house	Wood chips = 1.6 $m^3_{L.V.}$/MWh [198] (50% from chipping mill; 50% from sawmill)	Logs = 0.65 t/MWh	Pellet = 0.250 t/MWh

	Power input			
	Electricity for chipping mill	17.3 kW/ MWh	-	9.4 kW/MWh
	Electricity for sawmill	17.4 kW/ MWh	-	22.5 kW/MWh
	Electricity for pelletisation plant	-	-	60 kW/MWh
	Electricity for boiler house	Assumed negligible	Assumed negligible	Assumed negligible
	Diesel for logging at forest	-	83.9 MJ/kg_{logs}	-
OUTPUT	**Material**			
	Chipping mill	Chips = 1.0 $t/_{branches}$ Sawdust = 0.1$t/t_{branches}$	-	Chips = 0.75t $t/_{branches}$ Sawdust = 0.35 $t/t_{branches}$
	Sawmill	Timber = 1.0 t/t_{timber} Bark = 0.22 t/t_{timber} Sawdust = 0.12 t/t_{timber} Chips/Shavings = 0.74 t/t_{timber}	-	Timber = 1.0 t/t_{timber} Bark = 0.22 t/t_{timber} Sawdust = 0.12 t/t_{timber} Chips/Shavings = 0.74 t/t_{timber}
	Pelletisation plant	-	-	Wood residues = 0.05 $t/t_{pellets}$
	Logging plant	-	Logs = 0.65 t/MWh	-
	Ash amount	1.25 kg/MWh [163]	1.56 kg/MWh [163]	1.36 kg/MWh [163]

Wood pellets (base scenario 3) were supposed to be produced from forest residual chips (branches) and sawmill wood residues. Interim steps such as drying and milling, were considered in order to estimate energy and material consumption for pellet production (Table 3.25). The share of raw material mix needed for pellet production has been proposed according to the study of K.F.A. Damen [205]. The pelletisation process involves several steps. The considered steps for pellet production are: crushing of residues by a coarse hammer mill, drying with air flow with a temperature of 650°C to a moisture content of 6-8%. The final step is cooling and sieving, after which the pellets can be transported to the final end-use destination.

The thermal (steam and hot dry air) requirements in the process are supposed to be supplied by a boiler using sawdust that is accounted for as an extra input of raw material. All the energy and material inputs within each scenario for the wood-fuel unit processes are summarized in Table 3.25.

3. Combustion. In order to evaluate the environmental impacts during the final step of biomass combustion, a review of different emission factors for different combustion boiler houses and various literature sources was performed. Due to the fact of the extreme variability of emissions, depending on chemical and physical properties of biomass, type of technology and operative conditions, the average emission factors for each pollutant and boiler house were identified by using the GEMIS database.

Table 3.26.

Emission factors used in base scenario models, g/MWh [163]

	CO_2	CO	CH_4	N_2O	NO_x	SO_2
Wood logs	0	14120.93	488.80	7.97	271.56	183.90
Wood chips	0	329.99	10.99	2.20	244.43	117.55
Wood pellets	0	248.60	12.43	4.97	298.32	131.93

In the light of the neutrality of wood-fuel carbon, the biogenic CO_2 emission factor is assumed null for base scenarios 1, 2, and 3. This means that the assumed characterization does not ignore differences in the timing of carbon releases and subsequent re-sequestration in growing forests. Burning biomass for energy certainly releases carbon in the form of CO_2 to the atmosphere - in fact, useable energy biomass typically releases more CO_2 than natural gas, oil or coal per unit [208] - but of course this corresponds to the amount of carbon sequestrated from CO_2 in the atmosphere during natural biomass growth. In this study, it is assumed that the lifespan for the wood-fuelled boiler houses and the supply system are durable enough to consider it carbon neutral.

4. Disposal. In all the scenarios, the system included the final disposal of the ashes and the indirect emissions generated from all the different processes involved, assuming a maximum distance of 10 km.

3.3.5 Impact assessment

This part is devoted to describe the results of the environmental impact of the woody-biomass base for the performed systems. Within this section, the whole unit processes for each of the wood fuels (wood logs, wood chips and wood pellets) are investigated and compared with in comparison to a natural gas scenario. In the final part, a sensitivity analysis together with the observations in regard to the energetic aspects of the wood fuels is proposed.

As previously mentioned, the obtained results have been carried out with the use of the IMPACT 2002+ impact assessment methodology. ECOINDICATOR 99 (H) impact assessment methodology has been used to compare the results within the sensitivity analysis for the methodology chosen.

The proposed results only involved an end-point impact category analysis. This was done specifically for: climate change, human health, ecosystem quality and resource impact categories. As mentioned, the resulting units are expressed in points (Pt),

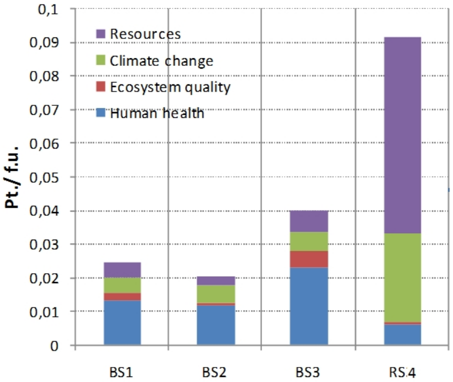


Fig. 3.18. Comparison of the three base scenarios (BS1, BS2, BS3) and the reference scenario (RS4)

Figure 3.18 provides a comparative graph of biomass based scenarios versus natural gas based scenario contributing to the end-point damage categories - resources, climate change, ecosystem quality and human health – shown in points (Pt) per functional unit (f.u.).

The environmental burden of the scenario using natural gas presents much higher impacts in terms of the use of resources and climate change. Those alone cover more than 90% of the total impact. This is basically due to the strong use of fossil-based fuels as non-renewable sources. However, comparing with the analysed biomass-based fuels, a natural gas scenario presents a lower impact concerning the ecosystem quality and human health.

This behavior can be explained because of the higher impact due to the higher land use and higher loss in biodiversity for the ecosystem quality related to the biomass scenarios. For human health, the higher impact for the biomass-based scenarios can be explained through the lower emissions during the final combustion in terms of non-greenhouse gas emissions and specific volatiles (i.e. VOC, SOx and NOx). Moreover, a natural gas operated power plant is more efficient (efficiency ≥ 90% [209]) and "cleaner" (concerning its PM, SOx, NOx emission levels) than the systems using wood fuels [209].

The wood logs scenario presents the least impact, and wood pellets cause the largest impact among the wood fuels. This is mainly related to the shorter supply chain, with a relative lower use of non-renewable fuels (for the harvesting operation, transportation and electricity consumption). Its total burden is 4.5 times lower than that of the natural gas scenario. The main impact category is human heath, as mentioned before, that alone covers approximately 55% of the whole potential impact. In the case of wood logs, the greater impact in the climate change category with respect to the other two biomass scenarios refers to the differences in emission composition related to the quality of the wood fuel, and the lower environmental efficiency of the technology used. In fact, during the combustion processes there is a higher value for GHGs, PM and SO_x.

The full impact of the wood chips scenarios is approximately 25% bigger than that of the wood logs. This is basically due to interim production processes that involve a sawmill and chipping operation. The wood chips scenario presents a lower value for the climate change category in comparison to the two other wood-fuel scenarios. This is due to the assumed allocations that directly affect the electricity use and the emissions, but is also due to it having the most efficient use of the production by-product.

The wood pellet scenario presents the environmental burden of the three wood fuel scenarios, in particular respect to the climate change category due to the energy-consuming preparatory processes (sawmilling, chipping, drying etc).

Table 3.27 represents the results in units according to each end-point category expressed by the original unit measure: DALY, PDF*m2*yr, kg $CO2_{eq}$ an MJ of primary non-renewable energy.

Table 3.27.

Wood log, wood chips and wood pellet comparison at end-point categories

Damage category	**Unit**	**BS1 (logs)**	**BS2 (chips)**	**BS3 (pellets)**	**RS4 (natural gas)**
Human health	DALY	8.3E-05	9.4E-05	1.6E-04	4.2E-05
Ecosystem quality	PDF*m^2*yr	8.83	28.98	67.28	11.53
Climate change	kg CO_{2eq}	53.24	43.72	57.43	262.28
Resources	MJ primary	402.46	706.02	965.21	8809.52

Specifically, if the attention is focused on the carbon foot-print, as it can be considered part of the climate change category, the total amount of emitted kg CO_{2eq} for the biomass scenarios is between 4.5 (pellets) and 6 times (chips) lower when compared to the natural gas reference scenario. Therefore, this analysis shows how the requirement of the sustainability criteria within the RES Directive, where it demanded that biofuels (in order to be considered as such) must offer at least 35% carbon savings compared with the relative fossil fuel, are matched. It is interesting to see how the footprint for chips is lower than for logs: this is due to the fact that the portion of the chips coming from the sawmill. This does not lead to any impact.

Moreover, the results provide important information that can be used as the emission factor within the calculation of the Emission Trading Scheme. In fact, according to the EC directive EU/2011/278 [103] the heat benchmark for natural gas is 0.22 $tCO_{2\,eq}$ /MWh_{th} while for the implemented analysis this value is equal to 0.26 $tCO_{2e\,q}$ /MWh_{th} changing the way how free allowances can be accounted for.

This feature is crucial if the governmental authority decides to implement the use of LCA emission factors within the use of biofuel in the fulfilling of the sustainability criteria [210]. On the other hand, the results from another important aspect is also evident from the fact that in their full life cycle wood fuel is not a zero emission type of resource (as it is considered in the ETS mechanism). This raises an important matter of concern that at the moment is not clearly developed in the ETS Directive.

3.3.6 Sources and stages of impacts

In the following section, a disaggregated analysis of the impact of each unit process is carried out. In each disaggregated unit process, the transportation and specific energy consumption within the unit process considered are included.

Wood fuel preparatory processes were assessed in order to define the contribution of a single process throughout the life cycle of the wood fuels analysed. Figure 3.19 below represents the quantitative results for base scenarios1, 2, and 3.

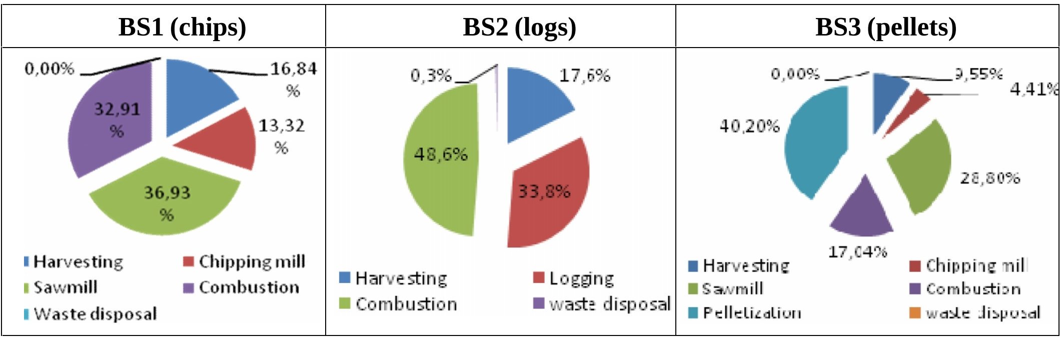


Fig. 3.19. Impact assessment of the unit processes for scenarios BS 1-3

It was found that the most impactful process in wood log life cycle is combustion, where the GHG and other impactful compounds (e.g. NO_x and SO_2) are released to the atmosphere (see Table 3.24).

For wood chips the process that presents the most environmental burden, according to the IMPACT 2002+ assessment methodology, is sawmilling, where electricity and additional heat for biomass drying are required. The combustion at the conversion plant contributes as much as the sawmilling process.

For the wood pellets scenario, the pelletisation process contributes the most to the overall impact expressed in Pt, around 40%. The process deals with the electricity input as wood biomass is dried and pressurized in order to obtain the final wood product in terms of pellet efficiency.

Figure 3.20 presents the shares of production (harvesting, chipping, sawing, pressing, and extraction), transportation (or distribution) and combustion processes for the three biomass fuels and natural gas.

For the natural gas scenario, which includes the extraction and transportation via pipelines to a boiler house, the combustion process still remains the most impactful (about 60% according to IMPACT 2002+ methodology). This is explained by the fossil origin of this fuel, and specifically to the import requirement of non-renewable sources during the extraction.

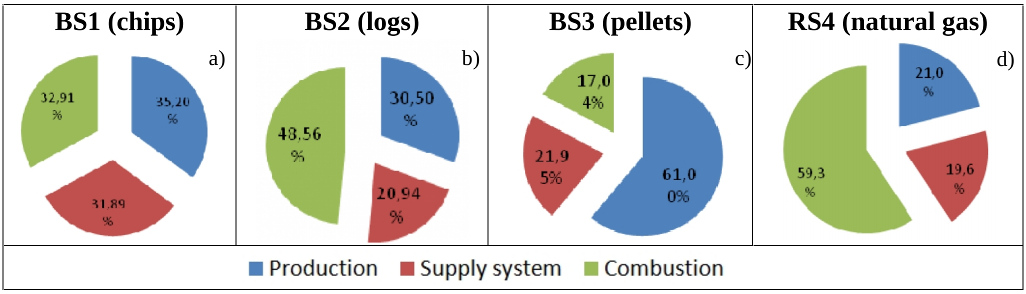


Fig. 3.20. Shares of production, transportation and combustion processes for scenarios BS1-3 and RS4

The most unit processes associated with the highest environmental burden for the wood logs scenario resembles that of natural gas – combustion still has the most substantial value. For pellets, the situation differs: the production process including harvesting, chipping, sawing and pelletization due to the additional energy and resource consumption becomes the most impactful stage of the cycle (61%). Wood chips scenario takes the intermediate position: it is more efficient as fuel than wood logs and its environmental performance is better than that of wood pellets.

3.3.7 Energy performance

Many bioenergy LCA studies include primary energy analysis in their assessment, in order to quantify the possible non-renewable energy savings of the bioenergy system. Different indicators can be used for this purpose, and the energy analysis approach usually evaluates all the energy inputs along the full chain, from agricultural cultivation, transportation, processing and final distribution. In light of that, the following table indicates the energy rate defined as the ratio of the energy produced in respect to the total non-renewable energy used for fuel production (in terms of non-renewable sources). Ranges on biomass for heat and power production are available in Cherubini et al., 2009 [191].

Table 3.28.

Energy ratios for wood fuels and the natural gas scenarios

	BS1	BS2	BS3	RS4
Primary energy Input (non renewable) [MWh]	0.20	0.11	0.27	2.45
Energy Output [MWh]	1.00	1.00	1.00	1.00
Energy rate	5.10	8.95	3.73	0.41

Table 3.28 represents the energy rates for all 4 base scenarios. Input of primary energy considers only the non-renewable energy consumed for the production of a functional unit. Within this analysis, we can understand if the analysed system is renewable (ratio bigger than one) or not (ratio lower than one).

For the production of 1 MWh of thermal energy from wood pellets it is necessary to consume 0,27 MWh of primary non-renewable energy sources throughout pellet life cycle. Wood pellets going through various biomass preparatory processes have the least energy rate among the three biomass fuels observed. More than 1,5 times less non-renewable energy is required throughout the life cycle of wood logs; therefore, its energy ratio is significantly higher (i.e. a value of 8,95). Natural gas, due to its fossil origin, and the environmental impact associated with it, has the least energy rate. This stresses the non-renewability of this energy route.

Building on Table 3.28, it is evident that it is necessary to consume almost 10 times more non-renewable energy to produce 1 functional unit for scenario RS4 than for scenario BS1.

Clearly, the more fossil fuel inputs a certain bioenergy system has, the less energetically desirable it is. As a consequence, some production chains are more desirable than others, depending on the productivity per area of land, the feedstock processing requirements, the energy conversion processes, and the types of by-products used [191].

3.3.8 Carbon neutrality

The main conditions to describe carbon neutrality are: “time conditions”, and “spatial conditions”. The following conditions have to be satisfied for bioenergy based on wood resources from harvesting to be carbon neutral:

- forest growth on the harvested area is included in the system boundaries for the time required for the forest to grow until the size of harvesting (sustainable forest management criteria) - time conditions,
- storage, direct combustion, and change in properties of the wood-based products have no direct connection to the carbon cycle - time conditions,
- the harvesting area included in the system boundaries includes the forest area from which the timber is harvested - spatial conditions,
- the yearly increment of growing is at least equal to harvesting - spatial conditions [208].

Within this study, Latvian forests grow under the criteria of sustainable management [194]. Therefore, the annual increment of the forest exceeds the amount harvested and the carbon neutral condition is met.

3.3.9 Sensitivity analysis

Sensitivity analyses were performed in order to assess the effects of key parameters and assumptions on the results of the study for the base scenarios 1, 2, and 3. Transportation distances and changes in the efficiency of the conversion plant were assessed. This varies the base scenario values of these parameters. The elasticity method (the ratio of the change in the results to the change in the input parameter) was applied for the transportation distance and boiler house efficiency sensitivity evaluation [193]. Within this method, values which are higher than 1.0 in the model are sensitive to the parameter.

The changes in the final impact of all the four end-point categories were referred to the changes in respect to the initial data within the base scenarios.

More specifically, the variation of the following assumptions and/or parameters was investigated:

- change in distance from the forest site until the intermediate production processes (e.g. 50 km, 150 km) and to the final delivering to the boiler house (50 km, 150 km) for the base scenario 1, 2, and 3,
- changes in efficiency of the boiler houses [207],
- sensitivity analysis in respect to a second type of impact assessment at the mid-point category (ECOINDICATOR 99 (H).

It has been assumed that the transportation distance is a variable parameter in this study, since the supply system route changes depending on the supplier location for different reasons (e.g. unit cost of the wood fuel, changes in moisture content, changes in net calorific value) the only method to evaluate the effect of this parameter within the full impact is a sensitivity analysis. The base models of LCAs of the three biomass fuel types comprise transportation between different preparatory processes at 20 km each. In order to perform the sensitivity analysis for this parameter, another range of distances with values of 50 km and 150 km was assumed. This choice of distances is justified with the example of Ludza Boiler house in Latvia that claims to have its suppliers up to 120 km far from the conversion plant.

Figure 3.21 represents the resulting change for all the three biomass fuel types switching the transportation distance to 50 km and 150 km referring to the base scenario (20 km).

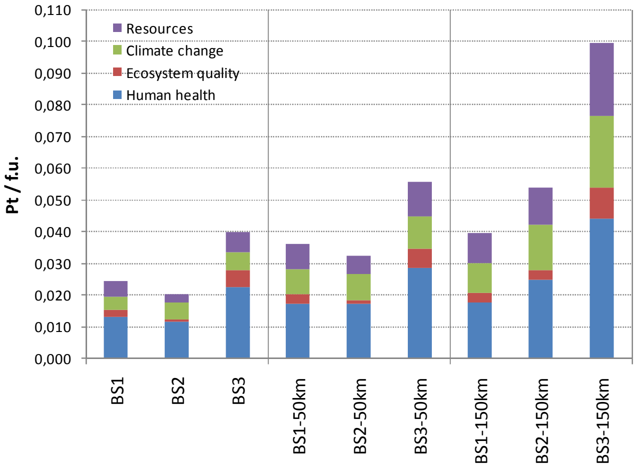


Fig. 3.21. Sensitivity analysis for the transportation distance

The results of the elasticity were between 0.1 and 0.40. This means that changes in distances for the overall pathways for the production of thermal energy does not affect the whole system within the range of distance of the sensitivity; moreover, the energy ratios between the non-renewable energy input and the final energy system output are still lower than 1 indicating the renewability of the systems analysed also for extended distances.

The efficiency of a conversion plant (and of the technology used) is a matter of concern as it determines how rational the usage of a certain fuel type is. The efficiency of a plant affects the amount of fuel needed to produce a certain amount of energy and it also defines the compound and amount of undesirable emissions. In this study, the sensitivity analysis for the efficiency of a conversion plant was performed.

The base scenarios 1, 2, and 3 assume that the conversion plant efficiency is equal to:

- 75%, for the BS2;
- 85%, for BS1 and BS3.

In order to find out if the plant efficiency is a sensitive parameter, the value of efficiency for the boiler house within the BS2 was changed using 65% and 80% as new parameters, while for BS1 and BS3 the efficiency was changed to the values of 75% and 90%. The increasing change in efficiency has been translated in term of the equivalent of extra woody fuel to be supplied to the boiler house and vice versa.

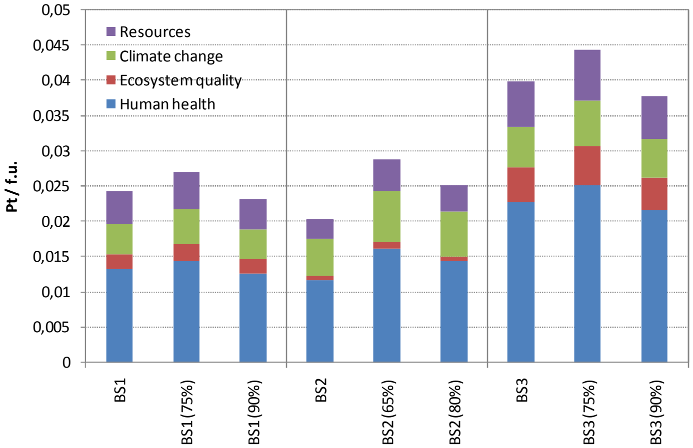


Fig. 3.22. Sensitivity analysis respect changes in efficiency of the plant

As shown in the previous figures (3.21 and 3.22), the model is sensitive only for the scenario BS2 where wood logs are used. This is explained by taking into account that in this scheme the raw material comes directly from the standing wood in the forest. A decrease of the efficiency in the plant is more sensitive than other scenarios where the raw material comes from residues that are not causing any environmental burden accept the one for the increased distance of transportation.

The results of the comparison at the mid-point categories for two impact assessment methodologies – IMPACT 2002+, the one that is used for the base scenario, and ECOINDICATOR 99 (H) – show that the model is not sensible to the choice of the selected impact assessment.

3.3.10 Limitations of the study

In order to evaluate the net impact within the implementation of a wood fuel based boiler house, instead of a natural gas based boiler house, the substitution method should be implemented. This method foresees that the fossil-based system when replaced by the use of woody biomass upstream impacts all the impact categories that should be included in the LCA estimations. Therefore, the real net effect of substitution can be defined as the total amount of the upstream impacts and emissions from the replaced fuels minus the upstream impacts from the use of wood fuels, while biomass is considered carbon neutral. This means that the net impact does not change the environmental load of the supply systems of the models, and moreover, the choice of the replaced fossil-based system affects the final net impact of the whole woody biomass-based LCA. In this study, the scenarios using the substitution method are not included since, as mentioned, attention was addressed to the comparisons of the real environmental burdens.

Concerning general uncertainties within the finalized work, it should be mentioned that several assumptions have been made. These have basically involved items like: the choice of the harvesting technology, the related fuel type and fuel consumption, the choice of the transportation trucks (and consequently their fuel consumption and emissions), the scheme of the transportation distances within the whole supply chain and the choice of the amount of the wood fuel necessary for the production of 1MWh of heat. Of course, different assumptions can strongly affect the final results. In this light, a further analysis of the data used within the inventory is desirable.

Another important issue is related to effect of forest residues, in fact they may have effects in a long-term perspective in relation to the fertility and productivity of the forest soil strictly connected to sustainability items.

Moreover, products such as logs, chips, barks, shavings and wood residues are produced at the same time in the forestry operation. This means that the resource use and emissions can also be allocated with a partial approach, or with a by-product approach [211]. In the first situation, a statistic distribution approach can be used to evaluate the allocated impacts through variables such as mass or costs. In the case of the second approach, the impact allocation is mainly addressed to the main product, while the by-products are not considered. This approach is correct in the case that there is a main product within the share of material. In the analysed cases, all the allocations have been made by a mass allocation considering wood residues as a by-product, and not waste. In fact, there are several studies where it is under discussion if milling and forestry residues can be considered as waste or residues.

3.3.11 Conclusions of the study

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 held due to the high share of this fuel in the thermal energy production system in Latvia.

Since attention is mainly focused on the real impacts of the systems analysed, in a more conservative way, the use of the woody-biomass within the analysed scenarios without avoiding the same amount of thermal energy produced in reference to a natural-gas based scenario typical of the LCA substitution-based methods has been considered.

Three base scenarios assumed for the production of thermal energy using wood chips, logs and pellets (base scenario 1, 2, 3) were analysed and compared with a natural gas based system (reference scenario 4).

The results presented show the complexity of a forest-based energy system reflecting how the choice of a specific territorial environment, local climate conditions and forestry practices, as well the type of final energy conversion technologies, affect the full results in a cradle-to-grave aspect.

Comparing biomass scenarios to the reference scenario based on natural gas, it has been observed that natural gas presents a twofold greater environmental impact than wood pellets (base scenario 3), which is the most impactful among wood fuel based scenarios.

The biggest environmental burden category for all the biomass scenarios (1-3) is human health; it makes up over 50% of the overall impact for each wood-based scenario. This is due to the specific composition of the emission released during the end-use of the fuel, particulate matter (PM) first of all. This is in comparison to the natural gas scenario concerning the human health impact category that makes up less than 10% of the whole impact.

Base scenario 1, where the wood chips based system was implemented, has the least impact concerning the climate change category, which is a matter of interest for this study. For this scenario, the full environmental impact is distributed in all its life cycle stages (32% for the production phase, 35% for transportation and 33% for its end-use phase). These aspects give more flexibility for the use of wood fuel to become a sustainable, interesting option for energy production.

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

Some of the parameters of the systems observed are hard to strictly define; for example, transportation distance. Fuel suppliers may be situated a few kilometres away, or up to a few hundred kilometres away. This is the reason why a sensitivity analysis was held in order to state whether all the parameters chosen are sensitive within the model affecting the final results. Specifically, the effect on transportation distance, boiler house fuel consumption (associated to a different efficiency of the boiler house) and impact assessment methodology were evaluated. It has been shown how transportation distance is not a sensitive parameter for the base scenarios 1, 2, and 3 observed in the defined conditions.

In a cradle-to-grave perspective, in all the base scenarios, between 0.11–0.27 MWh of non-renewable energy is used in order to generate 1MWh of heat. As a final result, the potential in terms of GHG saving in respect to natural gas is encouraging. On the other hand, it is evident how the environmental performance of the whole chain strictly depends on several factors, and the initial assumptions that might change or decrease the expected outcomes. For example, the choice of another fossil-based scenario can change the final GHG savings' reduction.

Further analysis can be focused on a scenario where all the three wood-based fuels are merged into a comprehensive whole in order to better evaluate the optimization of the environmental performances.

Globally, all the scenarios present lower impacts in respect to the fossil based reference scenario in a range from 2 times in the wood pellets scenario until 4.5 times in the wood logs scenario.

4 SYSTEM DYNAMICS: AN EVALUATION TOOL FOR THE IMPLEMENTATION OF BIOENERGY POLICY INSTRUMENTS

This part of the thesis discusses the use of the system dynamics (SD) modelling with the LCA approach as described in the methodology proposed in Chapter 2. Within the SD modelling, the main methodological steps described in Chapter 1 are used. A real case, regarding the effects on the structure of the Latvian district heating sector in respect to the proposed policy instruments and mechanism in order to speed up the use of renewable energy based sources in the district heating systems is developed. The model investigates the implementation of the specific policy instrument, as well as the EU ETS mechanism evaluating the final effects of the whole system in respect to the sustainability criteria.

Latvia has committed to decrease its GHG emissions by 8% in 2012, compared to the 1990 level (Kyoto target) and to increase its share of renewable energy sources in gross energy consumption by up to 40% by 2020 (RES target in line with Directive 2009/28/EC [212]). Current development trends show that annual GHG emissions in Latvia are lower than the respective Kyoto target. . Also the current share of renewables goes in line with the forecasted trend.

Despite the comparatively large share of renewable energy sources in the primary energy balance, its local potential is not fully exploited. The main potential is related to the wider use of forest based sources like logs, pellets, and chips in regional district heating systems. Although several studies have concluded that local wood fuel resources can fully cover district heat energy production needs, around 80% of the district heat in Latvia is produced from imported natural gas resources. The model looks for alternatives how to speed up the transfer from natural gas based heat production systems to locally available biomass resources.

4.1 System dynamic model definition

4.1.1 Problem formulation

Although renewable energy plays an important role in Latvian primary energy consumption [213], in the national energy mix (see Figure 4.1) fossil fuels dominate. The largest fraction is the share of petroleum-based products used in the transport sector. Several incentives have been undertaken at the national level to increase the share of biofuels in the transportation sector, but these have not led to the achievement of the national transport biofuel targets.

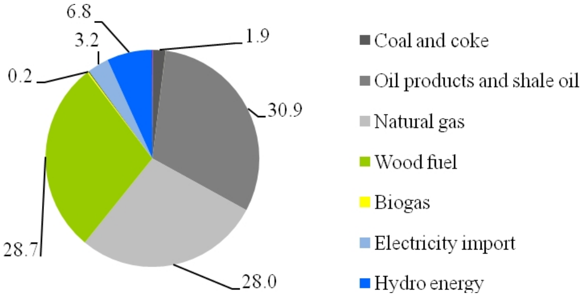


Fig. 4.1. Primary energy consumption in Latvia in 2009 [199]

Another fossil-based fuel, natural gas, together with the wood fuel, shares the second place in the fuel mix. Both natural gas and wood fuel are used in the transformation sector for heat and electric energy production. Natural gas is partly used for combined heat and electricity production in cogeneration plants, and partly for heat production in boiler houses. At the same time, the local wood fuel is used for heat energy production in individual and local heating systems, as well as in district heating systems. In fact, the dominance of fossil fuels is clearly visible directly in the district heat supply systems where the share of imported natural gas (80.0%) is five times larger than the share of locally available woody biomass (15.2%) [199]. At the same time, scientists have estimated that local biomass potential is large enough to fully cover the energy demand in district heating systems.

Historically, the share of RES in the electricity production sector in Latvia has been notable due to large hydro power stations (approximately 60% of the electricity nationally produced). Other electricity production sources are natural gas, biomass and biogas, and wind energy. The remaining part of the needed electricity is imported.

Taking the aforementioned description into account, it is visible that in the district heat production sector there is a significant potential for locally available biomass resources. The trend to gradually move toward wood-based energy sources is also evident from statistics where the evaluation of the energy-balance of the district heating system detects an increase within the share of the use of biomass for the production of thermal energy during the last two decades. A similar aspect is reflected as well in Europe, where the importance of the DH in the EU-27 is evident in comparison to the total share within the total EU heating system. Hence, it is foreseeable that within this sector a more intensive use of RES will be applied with a more extended implementation of subsidies to encourage the substitution of a fossil-based fuel system in favour of RES [95].

Transferring from natural gas to wood fuel does not require sophisticated technological solutions, but gives a range of benefits including a contribution to GHG emission reduction and the achievement of national climate targets, lower heat energy production costs, and the development of new work places.

In light of the Kyoto protocol and RES Directive, Latvia has developed a wide range of policy planning documents in the support of renewable energy. It is foreseeable that thanks to both national and EU level policy measures the use of RES will increase. However, the lack of a common and strong RES-oriented political framework showing a clear and unambiguous way for RES strategy implementation has resulted in a not optimal way of using local available biomass sources. Moreover, the strong import of natural gas is “against” the environmental and economic sustainability.

4.1.2 Aim of the model

The overall aims of the SD model are:

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

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

4.2 Identification and development of the principal dynamic hypothesis

The model represented in this section is based on a previously developed model [137, 138]. The aim of the original system dynamics model was to analyse the effects of three different policy instruments in order to find the best scenarios to move from fossil to renewable energy sources within district heating systems. A detailed description of the base model can also be found in the system dynamic book edited by A. Blumberga [139]. Specifically, the new model presented within this chapter represents an improved system dynamics model that has been created to analyse the effects of the EU ETS including the evaluation of the forest sustainability criteria including the main outcomes (in terms of emission factors) from the implementation of a LCA approach.

Basically, the developments respect the previous model by providing a differentiation of three types of wood fuels (wood chips, wood logs, wood pellets) within the proposed system, and the implementation of the ETS mechanisms and the sustainability evaluation in regard to the potential use of the wood fuel.

As in the first version of the model, it has been assumed that the main indicator identifying the fuel structure in district heating is the capacity of installations that use either fossil fuel or renewable energy sources to produce heat energy. Therefore, the central elements of the model are identified as stocks representing the installed capacity of wood fuel technologies (using three types of woody-based fuels: chips, pellets and logs), and the installed capacity of natural gas technologies.

In the next step, it was assumed that the capacity of installed facilities is influenced by two factors: investments and depreciation of the equipment over time. Therefore, each of the installed capacity stocks were linked with two flows: in-flow and out-flow. The in-flow represents investments aimed to increase the capacity of installed heat energy facilities. The out-flow represents the depreciation of the heat energy facilities, thus reducing the value of the total installed capacity.

Figure 4.2 represents the stock-flow structure using system dynamics modelling elements valid for each type of the installed capacities (three types of woody-biomass and natural gas).

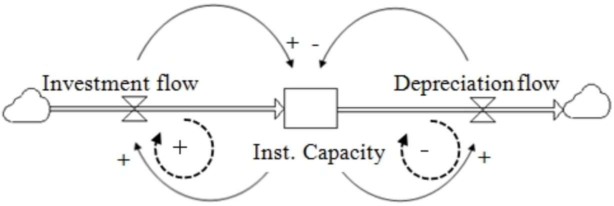


Fig. 4.2. Stock-flow diagram representing the relationship between the total capacity of installations and investment and depreciation flows

The installed capacity stocks are influenced by incoming investment flows and outgoing depreciation flows (or discard flows). The installed capacity of each fuel represents the proportion of a particular fuel in the fuel structure of the district heating system.

The larger the capacity is, the larger the investment flow (a positive reinforcing loop) becomes. But, also, the larger the capacity is, the larger the depreciation flow while in the meantime decreasing the stock of the installed capacity (a negative counteractive loop) becomes. This is the way how the nodal part of the model works.

This type of combination defined a typical S-shape dynamic behaviour that is possible to detect in the final results.

The installed capacity is influenced by the heat energy production tariffs which depend on factors like the price and quality of the fuel, the investment in the type of technology and maintenance costs, and the efficiency. The heat energy production tariff (LVL/MWh) is the second aspect that can be analyzed within the proposed system dynamics model and is explained hereafter.

In order to understand the behaviour of switching to wood fuel technologies over time, the model was based on a dynamic "equilibrium" principle. This means that the entire installed capacity (natural gas and wood fuel facilities together) is assumed constant over time with a value equal to 4GW.

It could also be assumed that the behaviour of the observed system in the model was formed by the interaction of the investment and depreciation flows, and the capacity stock.

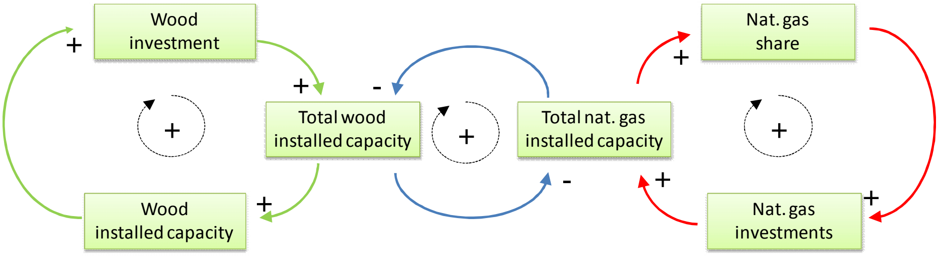


Fig. 4.3. Casual loop diagram of the main structure of the model reference to the total installed capacity

In reference to the previous picture, Figure 4.3, the casual loop on the left side represents the total installed capacity of wood-based fuels. These show that the larger the investments for wood fuels are, the larger the installed capacities and consequently the share of wood-based fuels are. The central loop shows that an increase of the total installed capacity of wood-based facilities led to a decrease in the total installed capacity of natural gas installations. This was done to guarantee the constant production of thermal energy over time (base assumption). This central reinforcing loop is the main reason connected to the explanation of the tendency of the wood fuel technology to naturally increase over time.

According to Directive 2009/29/EC [63] energy producers (excluding operators that utilize renewable energy sources) with the installed capacity exceeding 20 MW are obliged to participate in EU ETS. The rest of the operators pay the CO_2 tax for their calculated or measured emissions according to the methodology proposed by the directive. Specifically, within the model, this environmental parameter has been calculated using the carbon footprint (in terms of kg of $CO_{2\ eq}$ emitted from the whole thermal production system) directly from the specific LCAs made for the evaluation of the whole impact of the district heating system proposed in Chapter 3.

Thus, another factor influencing the heat energy production tariff for natural gas installations is the additional costs related to environmental pollution. The evaluation of the emission trading effect on the fuel mix is based on the hypothesis that natural gas operators participating in EU ETS will be willing to implement GHG emission saving measures (transfer to wood fuel) in case the costs for allowances will exceed the investment costs in GHG emission reduction measures.

The results of the original system dynamics model indicated that by applying particular policy instruments, it was possible to increase the share of wood fuel in district heat supply systems from 15% in 2010 to almost 100% in 2035. In the case of such a significant increase on wood fuel consumption, the influence on the sustainability of local forest resources should be taken into account. For this reason, the system dynamics model includes a part describing the structure of local wood fuel resources.

4.3 Model formulation and simulation

The simulation of the behaviour of the system is done by the system dynamics modelling software Powersim Constructor 2.5; this is a graphical programming language.

4.3.1 Model structure and elements

The general structure of the system dynamics model is illustrated in Figure 4.4. The complete system dynamic model is reported in Figure 4.5 and in Appendix.

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. Those energy sources are wood fuels (three types of options: chips, logs and pellets) and natural gas. As it can be seen in the model from figures 4.4 and 4.5, 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. This value has remained constant over time. The variable parameter is the sharing of three types of wood fuels and natural gas. The initial share of wood fuel (reference to the year 2010) is 38.5% (where, respectfully, chips account for 34.6%, logs for 3.7%, and pellets for 0.2%) and the share of natural gas is 61.5%.

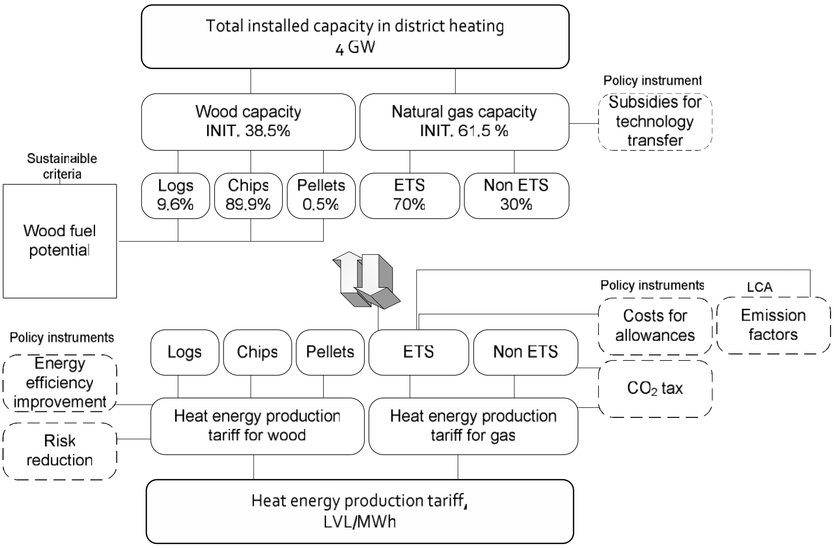


Fig. 4.4. Structure of the model

Both wood fuel and natural gas flows are divided into subflows. Wood fuel flows are divided into three subflows characterizing wood logs, wood chips and wood pellets and the natural gas flow is divided into two subflows splitting all natural gas operators into those participating in the EU ETS and those not participating in the EU ETS (referred to as non-ETS) with an initial share of 70% and 30%. Each part of the model is described in more detail later in this chapter.

The initial value of each stock represents the existing situation in fuel distribution and depends on the total heat energy produced (8000GWh), while taking into account 2000 hours of heating per year according to the following formula:

$$Cap_i^{init} = \frac{Q_T \cdot Share_i^{init}}{h} \tag{4.1}$$

where:

Q_t = annual consumption of heat energy = 8000 GWh,
Cap_i^{init} = initial value for the installed capacity for each resource;
$Share_i^{init}$ = initial share for each resource in respect to the total installed capacity.

The values Cap_i^{init} vary over time depending on the flows that affect the initial stock: investment and depreciation flows. The first are incoming flows that have a positive effect on the values of the wood based installed capacities. The second flows reduce the value within the stock of the installed capacities due almost entirely to the depreciation of the technology.

The model analyses the fuel distribution and district heat energy production tariffs over time under the influence of three different policy instruments and the ETS mechanism. The time step for the simulation was taken to equal one year, and the total simulation period was equal to 40 years starting from 2010 and ending in 2050.

The investment fraction, that in the model is directly linked with the heat production tariff for each of the installed capacities, is an element that represents the distribution of investments and depends on the factor α also called the logical function (between the value zero and one) characterizing the decision makers choice between natural gas and wood fuel [139].

The investment fraction has been represented by the formula 4.2.

$$I_i^S = \frac{e^{-\alpha \cdot T_i}}{e^{-\alpha \cdot T_1} + e^{-\alpha \cdot T_2} + ... + e^{-\alpha \cdot T_{i-1}} + e^{-\alpha \cdot T_i}} \tag{4.2}$$

where:

I_i^S = share of the investment for a single installed capacity (wood pellets, wood logs, wood chips, natural gas within ETS and natural gas non-ETS);
α = logical function = 0.2;
T_i = fuel tariffs (for wood- and natural gas-based energy production), *LVL/MWh*;

A higher alpha leads to a situation where the decision-makers have been more similar in their decisions. In the model, it has been assumed that the alpha value is equal to 0.2 – meaning that there is no affinity of decision makers when they choose [138].

The model guarantees that the total amount of the shares of investment among the different types of energy sources (both wood-based and natural gas-based) have to be equal to 100%, in other words:

$$\sum\nolimits_1^i I_i^S = 1 \tag{4.3}$$

The model calculates the fraction of produced energy from each resource, multiplying the installed capacity at a certain time for the hours in reference to the total demand of the constant heat. This can be summarized in the formula:

$$E_{share,i} = \frac{Cap_i \cdot h}{E_{tot}} \tag{4.4}$$

where:
$E_{share,i}$ = share of each fuel;
Cap_i = Installed capacity of each resource (wood-based, natural gas- based):
h = working hours = 2000
E_{tot} = total thermal energy produced = 8000 GWh/year

The total heat energy demand DM_T can be defined as:

$$DM_T = \sum_{1}^{i} E_i = const. = 8000 GWh/year \tag{4.5}$$

where:
DM_T = total annual heat energy demand, GWh/year;
E_i = amount of heat energy from each of the energy sources, GWh/year;

The formula 4.6 reflects the equilibrium model proposed.

At the same time, the total demand of heat energy DM_i for each type of fuel can be determined with the following formula:

$$DM_i = DM_T \cdot E_{share,i} \tag{4.6}$$

According to the whole system model presented in Appendix, the cumulated wood-based fuel consumptions represent the consumption of the energy produced from these sources. Consequently, this is also the indicator for the public experiences. This means that the greater the consumption of wood fuels the more positive experiences the society will receive.

It has been mentioned that in order to increase the share of biomass in district heating, the system policy instruments related to subsidies for technology transfer from fossil to wood fuel based boiler houses, energy efficiency improvement of wood fuel use, and risk reduction regarding the use of biomass have been implemented.

This can be seen in Figure 4.4 and 4.5, only subsidies as a policy tool directly affect the outflows from the central stocks of the installed capacities (decreasing the typical technical life of the technologies). The other two types indirectly lead to a decrease of the total tariff for wood-based energy production.

For the last two mentioned policy tools, this effect is modelled with a parameter that respectively increases the efficiency of the wood-based system and decreases the total risk for the use of wood fuel-based technologies. In fact, this simulates a “leaning-effect” on cumulating experiences while using wood-based technologies in the society that is evaluated with the following formula implemented when it is activated in the model:

$$EXP_n = e^{-\frac{B_i}{E_i^{init}} \cdot \quad n} \tag{4.7}$$

where:
EXP_n = learning effect on risk reduction (for the implemented tool), *GWh/year*;
B_i = fuel consumption;
E_i^{init} = initial energy produced for each wood fuel resource, *GWh/year*;

β_η = year of decrease of 63% of risk reduction (β_η = 100 years for efficiency improvement test and 10 for risk reduction test).

The energy production tariffs for each type of wood fuels' installed capacity are calculated with the following formula that consists of: fuel costs (based on wood-fuel price, boiler house efficiency and net calorific value), fix costs (based on operational and maintenance costs), investment costs (based on the initial capital costs and internal interest rate), the risk factor (decreasing when experiences are cumulated due to the implementation of the policy measure), the cost decrease due the ETS quotas, whether a natural gas operator switches to wood fuel .

$$T_i = \frac{C_i^{wood}}{Q_i \cdot \eta_i} + C_K^O + \frac{C_i^{cap} \cdot 10^3}{T_{H,i}} \cdot \left(i + \frac{1}{\tau_i^{ref}}\right) + R - \left(C_{quotas} - C_i^{invest}\right) \tag{4.8}$$

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} = economical 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} = incomes from selling emission quotas from switching to wood-based technology, *LVL/MWh.*
C_i^{invest} = extra cost for investment of natural gas operators switching to wood-based technology, *LVL/MWh.*

The energy production tariffs for the natural gas based boiler houses have been calculated according to the following formula where fuel costs, fix costs, and investment costs define the final value of the tariff:

$$T_j = \frac{C_{NG}^j}{Q_j \cdot \eta_{NG}} + C_{NG}^O + \frac{C_{NG}^{cap} \cdot 10^3}{T_{H,j}} \cdot \left(i + \frac{1}{\tau_{NG}^{ref}}\right) + C_{CO2,j} \tag{4.9}$$

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;
τ_{NG}^{ref} = economical 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 allowance purchases, LVL/MWh (for ETS operators).*

4.3.2 Policy instruments for increasing the use of wood fuel under the sustainable criteria

The impacts of three different policy instruments and one policy mechanism have been analysed within the proposed system dynamics model as well as their combination:

- Subsidies – a policy instrument that provides subsidies for district heat producers for the replacement of natural gas installations with wood fuel technology (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 the policy instrument is to encourage the public to choose wood-based technologies. This is related to marketing actions 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 like “Research and Design” (R&D) strategies (defined as P_η tool).
- ETS and CO_2 taxation – a policy mechanism that works based on the “polluter pays” principle. Natural gas operators, who participate in the emission trading system, can buy emission allowances. While natural gas operators, who do not participate in the emission trading system, must pay the CO_2 tax (defined as P_{ETS} tool).

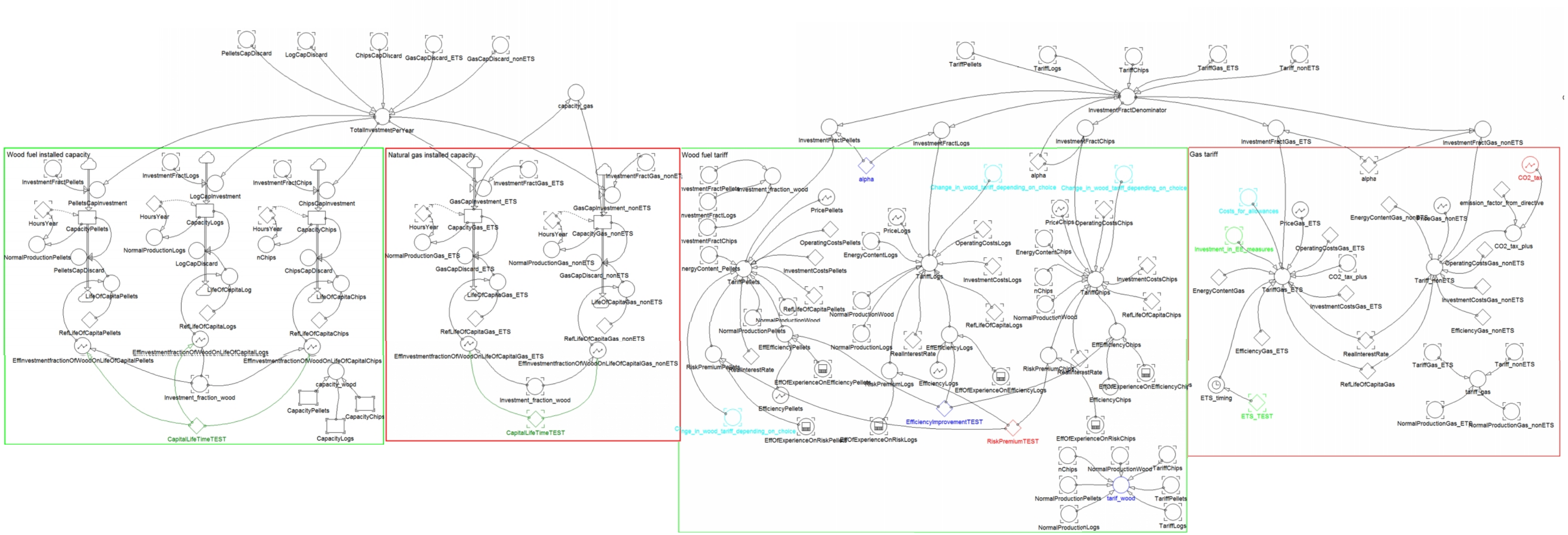


Fig. 4.5. The central part of the model represents the four policy tools available. In the square defined as “Capital life TEST” when active (value equal to 1) the policy measure of subsidies is implemented; when the square defined as “Risk premium TEST” is active (value equal to 1) the risk reduction mechanism is implemented; when the square defined as “Energy improvement TEST” is active (value equal to 1) the measures to improve the efficiency of wood fuel use are implemented; when the green square representing the “ETS TEST” is active (value equal to 1) the ETS mechanism is implemented. Hence, when each tool is activated in the model the corresponding “policy scenario TEST” element assumes a value equal to 1. Conversely, when the same scenario is deselected the value is zero.

Effects of the first three policy instruments on systems behaviour were extensively analysed in the base model developed in 2010 [138]. The updated version of the model offers an opportunity to analyse the effect of the ETS combined with the CO_2 taxation both individually, and together.

The influence of the policy instrument is integrated with the sustainability of forest resources, evaluating the potential effects of the increasing use of wood fuel consumption over time. This is described in more detail in Chapter 5.

Consequently, within the model, it is possible to select a given policy instrument or a combination of them in order to evaluate the mutual effect in a period of 40 years (2010-2050).

4.3.3 Implementation of the European Union Emission Trading System

As described in Chapter 1, the EU has determined the ETS to be one of the main instruments to reduce industrial GHG emissions in a cost-effective way. The EU plans that ETS will significantly promote the implementation of energy efficiency measures in the energy sector including the transfer from fossil to renewable energy sources. The importance of this policy instrument is demonstrated in that it was implemented in the system dynamics model in respect to the Latvian district heat production sector.

In the Latvian case, around 70% of natural gas boiler houses are mandatory participants of EU ETS. This is because their installed capacity exceeds 20 MW. This means that operators are obliged to cover their GHG emissions with CO_2 emission allowances at the end of each year. Natural gas operators that are not mandatory participants of EU ETS, and have not decided to participate in the system, voluntarily pay CO_2 tax for their CO_2 emissions.

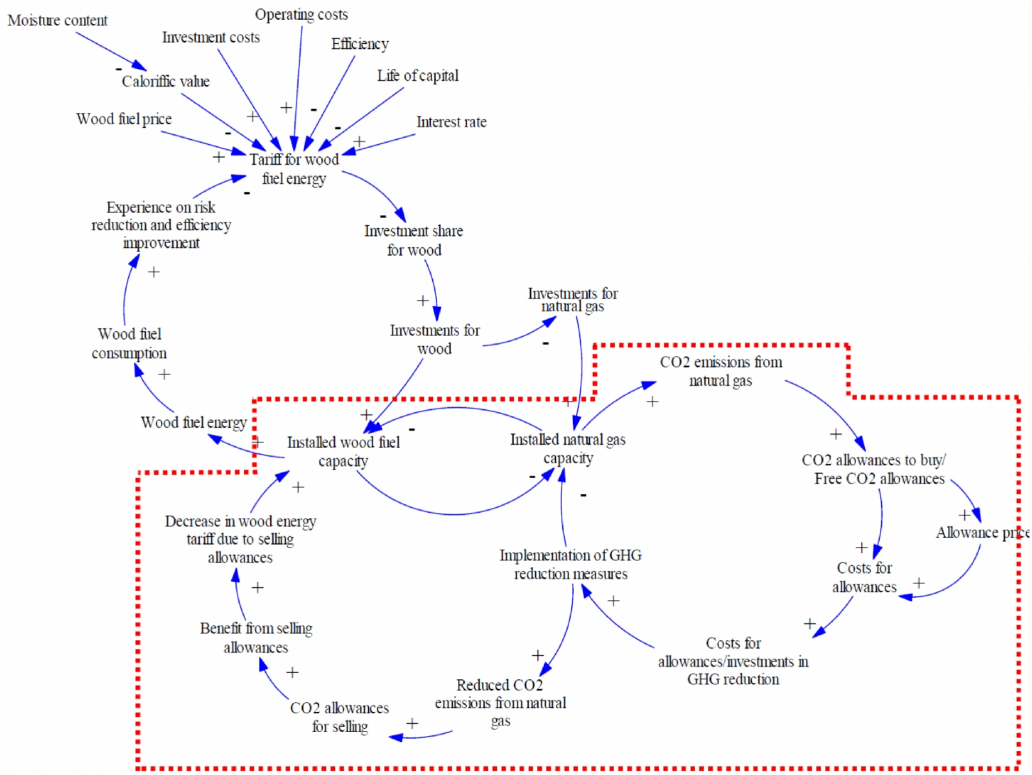


Fig. 4.6. Casual loop diagram of the model. The Emission Trading System is represented within the dotted red line

During the first and second period of EU emission trading, the largest part of the CO_2 allowances was allocated to operators for free, and costs for allowances were relatively low. Starting from the third trading period, the EU plans to reduce the amount of “free” allowances from 80% in 2013 to 30% in 2020 and to 0% in 2027 [63, 214]. At the same time, due to the reduction of the total amount of “free” allowances, the allowance price will increase. This means that natural gas operators will be obliged to spend more money on buying CO_2 allowances. In this light, an increase of the heat energy production tariff for natural gas and other fossil fuel operators can be expected.

The structure of the emission trading module integrated within the whole system dynamics model is represented in Figure 4.6 in a casual loop diagram. In this diagram, the three types of wood-fuels are summarized under the category “wood fuel”.

The ETS effect is incorporated in the model based on the assumption that district heating operators will transfer from natural gas to wood-fired installations the moment when costs for emission allowances will be higher than investment costs in GHG emission reduction measures. GHG reduction measures in this case are considered a transition to wood-fuel technologies in terms of “green investments”. In line with EU ETS policy, it is assumed that in the first steps of modelling the operators do not need to buy any CO_2 allowances to cover their annual emissions (until the year 2013). In other words, the amount of “free” allowances is equal to the amount of CO_2 emissions produced by natural gas installations operating in ETS. Starting from 2013 the amount of “free” allowances decreases linearly so that 80% of allowances are allocated for operators for free in 2013 and only 30% in 2020 (see Table 4.1). This occurs up to 2027 when the allocation of “free” allowances decreases to 0% and in the end of the year ETS ends its operation as a policy instrument according to the ETS Directive and implemented in the Latvian National Allocation Plan (NAP).

Table 4.1.

Free allowances allocation according to Latvian NAP 2008-2012 [89]

2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
0.8	0.7286	0.6571	0.5857	0.5143	0.4429	0.3714	0.3

The auctioning of emission allowances will guarantees the increase of the allowance price when “free” allowances will decrease. The increasing in the allowance price will occur until a moment when it will be more economically feasible for the operator to invest in GHG emission reduction measures (transfer to wood fuel) than to continue buying allowances.

In the case that weather costs for allowances are lower than investments in GHG emission reduction measures for the heat energy production tariff for operators that are participating in ETS a component representing costs for emission allowance buying (see formula 4.9) has been added. Naturally, these operators are not paying the CO_2 tax. In case the costs for allowances are larger than investments in GHG reduction measures, operators take the decision to convert to wood-fired technology. In this case, from one side there are investment costs related to technology transfer, but from the other side the operator gets a benefit from selling its CO_2 allowances. This benefit is taken into account in the wood fuel heat energy production tariff.

The quotas emitted by each natural gas operator have been calculated through an emission factor directly calculated from the specific LCA study reported in Chapter 3. This was made for the production of thermal energy for a natural gas based boiler house. In reference to that, the heat benchmarking methodology has been applied.

From the same figure, Figure 4.6, it is possible as well to distinguish the main effective loops: the first describes that for a larger installed capacity of wood-based technology the thermal energy produced from the wood fuel increase as well as the consumption of wood fuel (B_i in formula 4.7). This behaviour consequently increases the level of experience for the use of wood-based technology and consequently decreases the risks correlated with this use of the technology and increases the level of the technological experience (referring to formula 4.7). As it can be seen, these two last parameters are directly connected with the heat tariff that is due to a greater consciousness in society about the use of the wood technology.

Based on what was previously mentioned, the following algorithm has been implemented within the SD model in order to define when it is convenient for the natural gas operators within the ETS to invest in switching to wood-based technology.

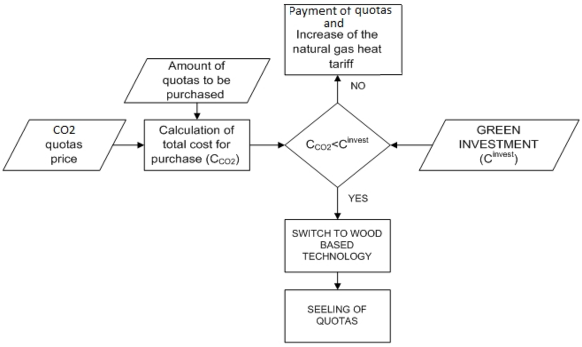


Fig. 4.7. ETS algorithm

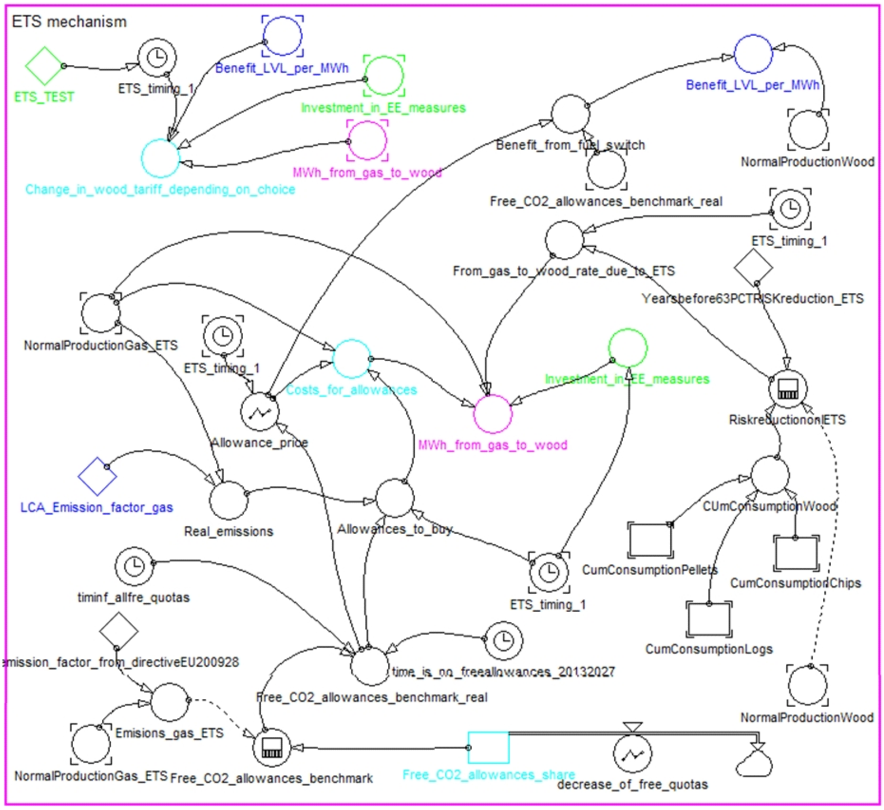


Fig. 4.8. Casual loops for the ETS scheme

The mechanism has been implemented in the model with the specific model scheme.

In regard to the previous picture, it is possible to distinguish the main stocks and variables that affect the model. First of all in the stock in reference to the yearly decrease of the free allowances starting from 2013 according to Latvian NAP ("Free CO2 allowances share") is represented in cyan. This variable has been evaluated taking into account heat benchmarking according to a value of 0.228 tCO_2/MWh_{th}. The total emissions in reference to the installed capacity of operators involved in the ETS mechanism ("emission gas ETS") has been evaluated taking into account the heat benchmarking using the carbon footprint (in terms of kg of $CO_{2\ eq}$ emitted from the whole thermal production system) directly from the specific LCA made for the evaluation of the whole impact of the district heating system and described in the Chapter 3 with a value equal to 0.26 tCO_2/MWh_{th}.

Then, according to the allowances price distribution ("allowances price"), is the base scenario that has been taken into consideration with an S-shape varying between 10 and 40 LVL/tCO_2. The total "Cost for allowance" that an operator needs to occur in case the total emissions to overcome the benchmark level is then calculated. This value is also added in the final heat tariff calculation for the ETS operator according to the formula 4.9 (see also Figure 4.5).

The model also implements the theoretical cost of the green investment for the ETS operators ("investments in EE measures") that should be compared with the previous cost to purchase allowances. If in this step, it is more convenient for an operator to invest instead of purchasing allowances (defined by a value 1 in the "MWh from gas to wood") there will be a beneficial effect ("benefits LVL per MWh") translated in terms of a decrease within the wood tariff to the operator that switches to wood fuel technology.

Moreover, the model foresees that not all the ETS operators will decide to invest in green technology, when green investments will be favourable, but only a portion of the total depending on the risk of the investment of the wood fuel-based technology ("risk reduction ETS"). This decreases once the share of the production of the wood based thermal energy increases according to the following formula 4.10.

$$EXP_{gi} = e^{-\frac{B_i}{E_{gi}^{init}} \cdot \ {}_{gi}} \qquad (4.10)$$

where:

EXP_{gi} = learning effect related to risk reduction for green investment, *GWh/year*;

B_w = cumulated wood-fuel consumption;

E_{gi}^{init} = initial energy produced for each wood fuel resources, *GWh/year*;

B_{gi} = year of decrease of 63% of risk reduction = 10 for risk reduction test.

The benefits given by the possibility to sell the amount of CO_2 saved within the transfer to a wood-based technology are calculated in the next steps. This amount is evaluated in terms of LVL/MWh in the variable defined as "Benefit LVL per MWh", as can be seen in Figure 4.8.

The last step, implemented is within the dynamics of this ETS modelpart,is demanded for the calculation of the decrease of the wood energy tariff: in fact the economical incomes related to the quotas selling are translated into a decrease of the heat tariff depurated by the incurred investments ("Change_in wood_tariff_depending_on_choice", see figure 4.8) always in terms of LVL/MWh.

When the ETS test has a value zero, the model is not implemented into the mechanism. This means that the heat tariff for all natural gas operators includes only the variable of the CO_2 taxation.

4.3.4 Forest sustainability

The question about the possible negative impacts on sustainability of local forest resources in relation to the increase use of wood fuel is one of the arguments of natural gas adherents. Taking into account the pressing concern of this topic, the proposed system dynamics model includes a module for the evaluation of forest sustainability. The model calculates the amount of wood fuel available to meet the demands of thermal energy over time. This takes into account the annual forest planting, growing, cutting, and ageing. The model assumptions are illustrated in Figure 4.9, and implemented in the part of the model as shown in Appendix.

In order to calculate the potential use of the forest resources available for energy purposes, it is assumed that there will be a yearly maximal allocation of the harvestable volume from the total stock of the adult forest equal to 2%. This value respect the criteria of a sustainable forest management [194].

The total forest stock in Latvia is roughly 631 mil.solid-m^3. In the model, it is stated that the initial total forest stock (year 2010) consists of: young forest stock (356 mil. solid-m^3) – see Figure 4.10 the “young_forest_stock”, harvestable forest stock (215 mil. solid-m^3) – see Figure 4.10 the “adult_harvestable_forest”, and old forest stock calculated taking into account a value of 12.9 mil. solid-m^3 of harvested forest – see Figure 4.10 the “overgrowth_forest” with an initial value of 60 mill. solid-m^3.

The young forest stock represents forest that grows until it has reached the proper age for cutting. Young forest stock is increased by annual new forest planting (1.6% of total forest stock) – see Figure 4.10 “forest_planting_fraction” – and by the overgrowth of agricultural lands (approx. 3.7 mil.solid-m^3) - see Figure 4.10 “Agricultural_land_overgrowth”.

The forest planting factor is sensitive, and has strict parameters in order to guarantee the sustainability of the wood-based energy resource sector. A more detailed sensitivity analysis will be provided in the Chapter 5.

It is assumed that in 40 years’ time, the young forest becomes harvestable forest (“average_growth_duration”). Annual forest processing in Latvia is around 12.9 million solid-m^3. A share of 90% of forest processing materials is related to the wood processing industry (pulp wood and timber) while the remaining part is directly used for energy purposes, such as wood fuel – see fig. 10 “wood_fuel_fraction_from_harvesting”. Half of the wood materials sent to the industry later become wood fuel as production residues (saw, chips, and offcuts) – see Figure 10 “fraction_of_wood_residues”. It has been assumed that wood fuel is partly consumed in Latvia (70%), and partly exported (30%) – see Figure 10 “wood_fuel_export_share”.

Not all forests that hava reached the proper age is harvested. Nevertheless, it is still possible to use this type of forest in wood processing. After a time of 60 years, the forest becomes old and has been assumed usable for energy production purposes.

Therefore the total stock of wood fuel consists of three incoming wood material flows from:

- forest processing;
- wood processing;
- harvesting and management of the overgrown forest.

The part of the model in reference to forest dynamics is reported in Figure 4.10

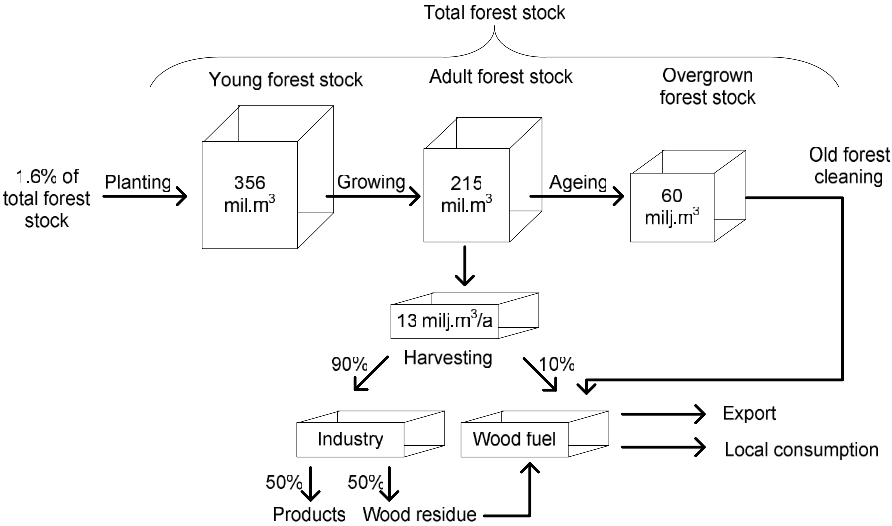


Fig. 4.9. The structure of the wood fuel potential calculation module

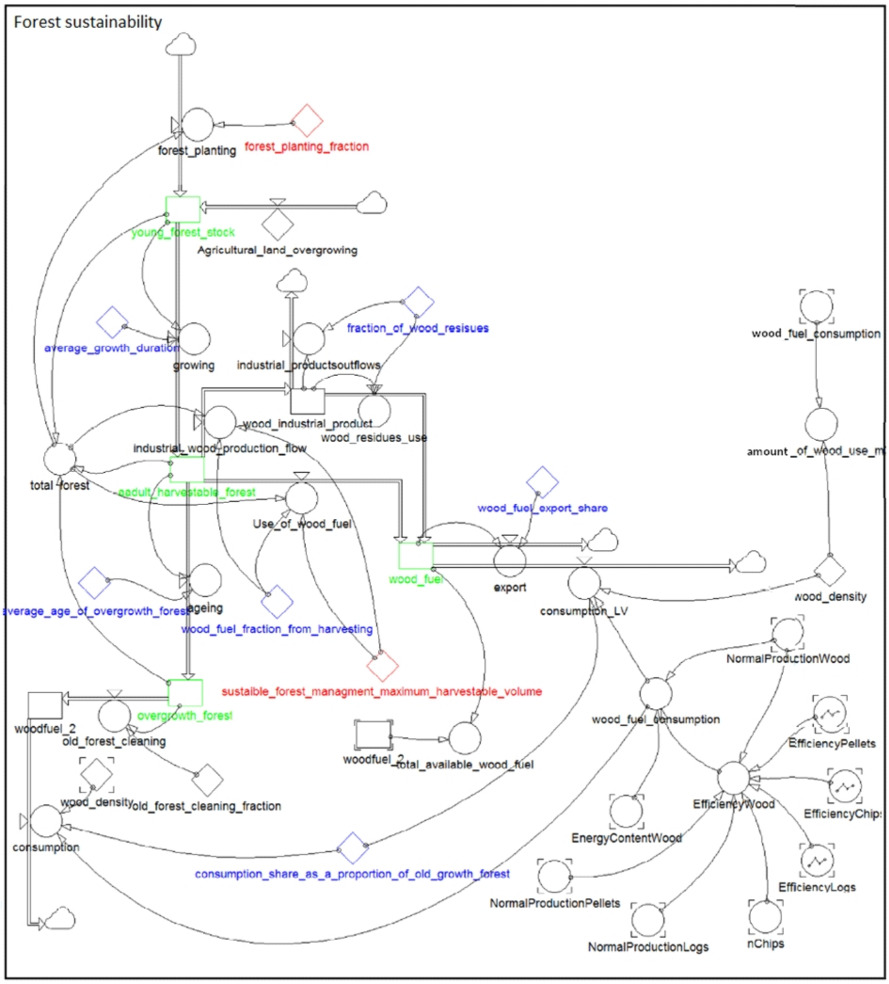


Fig. 4.10. Forest sustainability part

.In reference to the previous picture, it is possible to see the main stocks, flows and variables of this part of the model. More specifically:

- the young forest stock (“young_forest_stock”),
- the adult forest stock (“adult_harvestable_forest”),
- overgrowth forest stock (“overgrowth_forest”),
- the wood-based products from the industrial sector (“wood_industrial_product”),
- the total stock of wood fuel (from forest cleaning and from the direct use after the harvesting and the use of industrial wood residues (“total_available_wood_fuel”),
- the forest replanting factor (“forest_planting_fraction”),
- the average age for the harvested forest and the average age to become an old forest (“average_growth_duration”, “average_age_of_overgrowth_forest”),
- the flow of wood fuel for the use of direct harvested wood as wood fuel (“use_of_wood_fuel”)
- the wood fuel consumption flow in Latvia and exports (“consumption_LV”, “export”),
- sustainable forest management can be defined as the maximum volume rate of the harvestable forest from the total stock available, equal to approximately 2% of the total stock “sustainable_forest_management_maximum_harvestable_volume”),
- the variable of the wood fuel consumption demanded (“wood_fuel_consumption”),
- constant parameters (wood density, wood fuel export share, fraction of use of wood residues as wood fuel approximately equal to 50%), - “wood_density”, “wood_fuel_export_share”, “fraction_of_wood_reissues”.

4.3.5 Summary of the main data sources and assumptions

The following assumptions have been taken into account in the model:

- The initial share of wood fuel (RES) in district heating systems equal to 38.8%, of which 0.5% is the share of wood pellets, 89.9% the share of wood chips, and 9.6% the share of wood logs [215];
- The initial share of natural gas (fossil fuel) in district heating systems equal to 61.5%, of which 70% of installations are mandatory participants of EU ETS, while the remaining 30% pay the CO_2 tax;
- The total installed capacity in district heating systems constant over time (4 GW);
- Total district heat energy demand constant over time (8 TWh/year);
- Factors affecting energy production tariffs:
  - *Fuel price,*

    the initial price of natural gas has been based according to the Latvian State Company "Latvija Gase” [216] and the projections provided the United States Energy Information [217]. Within the model, prices vary between 236 LVL/1000 Nm3 (2010) and 312 LVL/1000 Nm3 (2050);

    the initial price for the wood fuel has been assumed equal to 20 LVL/t for wood-chips, 15 LVL/t for wood-log and 85 LVL/t for wood pellets according to the Latvian market situation. A linear increase over time with final prices equal to 40 LVL/t for woodchips, 35 LVL/t for wood-log and 105 LVL/t for wood-pellets has been assumed.
  - *Moisture content,*

    according to the EU requirements in regard to the energy wood moisture content for all the types of wood fuel, the decreasing S-shape trend with the asymptotic value for the year 2025 has been assumed. Within the time period considered, the wood fuel types assumed the following value: 40%-20% for wood-chips, 55%-25% for wood-logs, and 15%-8% for wood-pellets.

- *Operational and maintenance costs,*

  constant over time with values among 2.0 – 5.0 LVL/MWh$_{th}$ for wood fuel-based district heating systems and 10.0 LVL/MWh$_{th}$ for natural gas-based district heating systems have been assumed;
- *Investment costs,*

  the initial invest costs have been assumed between 1.0 – 3.8 LVL/MWh$_{th}$/year for wood fuel-based district heating systems and 1.8 LVL/MWht$_{h}$/year for natural gas-based district heating systems;
- *Fuel energy content*, as net calorific value

  A value of 9.3 MWh/Sdm^3 has been assumed for natural gas, while the formula 4.11 [218] has been used for the wood fuel:

$$Q_{LHV,woodfuel} = (18{,}317 - (0{,}2018 \cdot MC)) \cdot 0{,}28 \tag{4.11}$$

where:

$Q_{LHV,woodfuel}$ = low heating value of the wood fuel, MWh/t;

MC= moisture content, %.

- *Efficiency of technologies,*

  they vary over time linearly for the wood fuel-based district heating, specifically, for wood chips among 73% (2010) and 88% (2050), for wood logs among 35% (2010) and 73% (2050) and for wood pellets among 86% (2010) and 96% (2050); for natural gas-based technology the efficiency has been considered constant over time.
- *CO_2 taxation,*

  it varies over time between 0.70 and 14.00 LVL/tCO_2 [89, 219];
- *Costs for purchase of emission CO2 quotas*,

  they vary over time between 10.0 and 40.0 LVL/tCO_2 [89, 219];

- The amount of free allowances decreases by the following trend:
  - In 2010 the amount of “free” allowances is 100% [63];
  - In 2013 the amount of “free” allowances is 80% [63];
  - In 2020 the amount of “free” allowances is 30% [63];
  - In 2027 the amount of “free” allowances is 0% [220];
- Investment costs in GHG reduction measures: 3 LVL/MWh;
- Annual forest harvesting is 2% of the total forest stock;
- The emission factor for natural gas-based district heating has been deducted by the LCA modelling with Simapro software [162]. The results are reported in chapter 2, 0.26 t$CO2_{eq}$/MWh$_{th}$.

In regard to investment costs for the GHG reduction measure, prices of wood-fuels and natural gas, allowances price and CO_2 taxation a sensitivity analysis is proposed in the next chapter in order to validate the model. This will also provide important indications about the robustness of the model.

5 Results

5.1 LCA results

The three LCA studies highlighted the complexity of the evaluation of the environmental performances through the cradle-to-grave methodology.

These aspects are reflected in a not unique quantification of the impact related to a specific bioenergy route. Basically, this is related to a high number of variables that are involved. For example, the choice of initial assumptions and data are site oriented. The boundaries (and expanded boundaries) can be different each time within the modelling.

Again, in relation to the principal outcomes of the LCA provided, the determination of the environmental performances is difficult in the light of different combinations related to: the choice of the feedstock, the type of conversion routes, the choice of fuels, the scale of the technology used, the transportation distances due to different productivity yields, the end-use technological solutions and the choice of the impact method selected. The use of different approaches for the quantification of indirect effects which may have a strong influence on the final outcomes (e.g. indirect land use impact) is still a matter of concern.

A conclusion can be stated concerning the environmental sustainability of the bioenergy chains: 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. Since, the overall sustainability cannot be related to a specific stage in the life cycle, but to a combination of them.

It was pointed-out that bioenergy does not directly mean sustainable energy, since through a cradle-to-grave study the final environmental performances cannot be beneficial within the sustainability criteria.

On the other hand, within the forthcoming EU strategies and policy objectives in the light of the Kyoto protocol and EU Directive 2009/28/EC governments will promote bioenergy and biofuels as one solution to achieve the set targets of GHG emission savings. In this context, the LCA methodology can play a primary role as an accounting methodology. Nevertheless, sensitive questions concerning indirect emissions in the life cycle of bioenergy must be overcome and provide a standardized calculation methodology that at the moment is still a primary step within the scientific arena. For example, in order to offset different types of methods such as Indirect Land Use, a change of the evaluation of the carbon pool associated to biomass based product guidelines should be defined and standardized.

From the results presented in Chapter 3, it can be identified that the main aspects that justify the use of the outcomes from the LCA within system dynamics modelling.

- The LCA results and outcomes will be of primary importance as support for public and private stakeholders and decision-makers, for the evaluation of the real beneficial effects of a certain bioenergy and biotechnology choice within a decisional policy context. In fact, LCA methodology can play an important role within the improvement of the eco-efficiency for faster diffusion of the bioenergy in the whole energy market. Therefore, since there are remarkable holes in a holistic approach using the current decisional system, the use of the life cycle approach in the bioenergy policy system, including energy certification and economic mechanisms (incentive and subsidies schemes), is a statement connected with the outcomes of this work.
- The choice of promoting a certain bioenergy route is not separated from social and economic consequences. In fact, the evaluation of beneficial environmental effects,

well-implemented in the outcomes from the use of LCA methodology, have to be accomplished with social and economic effects in a combined analysis that will give a wider and clearer picture for decision-makers to find the most sustainable solution for the environmental questions. Hence, it is advisable to use the LCA modelling interconnected with the use of the classical energy planning tools described in the first chapter. This conclusion is in fact the main starting point for the use of an energy plan modelling (like system dynamics methodology) supported by environmental aspects from the LCA methodology.

- It is reasonable to implement the results of the analysis of a bioenergy system through the LCA methodology within a system dynamics modelling tool acting on evaluating the policy effect for a certain bioenergy system when it is evident that a higher environmental performance was evaluated with the LCA.
- Moreover, the integrated methodology is more implementable when the LCA bioenergy model is stable within the sensitivity analysis provided.

5.2 System Dynamics results

5.2.1 Policy strategies implementation: analysis of results

The analysed 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 summarized in Table 5.1. In total 16 scenarios have been compared starting from the base scenario (or “business-as-usual”) – where none of the policy tools were implemented – until the implementation of all possible policy measures within scenario 16 (or “fast green” scenario).

Table 5.1.

Policy instruments

Scenarios	**Policy instrument**			
	P_S	P_R	P_η	P_{ETS}
1. Base scenario (“business-as-usual”) - no implementation policy instruments – ***(BS1)***	0	0	0	0
2. Only subsidy measures	1	0	0	0
3. Only risk reduction measures through information campaigns – ***(C1_best)***	0	1	0	0
4. Only improvements of energy efficiency measures of wood-based technology	0	0	1	0
5. Only emission trading mechanisms ***(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 are implemented (fast-green scenario) – ***(C4_all)***	1	1	1	1

In order to harmonize the explanation of the results, the attention was mainly focused on the comparison between 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 achievement of the best results (C2_best) and the scenario where all the policy measures have been implemented (C4_all).

Moreover, important aspects related to the validation of the model and sensitivity analyses are reported within this chapter. Specifically, these have involved: changes in the price distribution of allowances in the market, changes in the CO_2 taxation system, changes to “green investment” within the ETS, an unpredicted strong decrease of the natural gas price, and changes to the parameters within the sustainable management of the forest resource.

5.2.2 Base scenario “business as usual” – BS1

This scenario defines the situation implemented when none of the policy measures proposed to increase the proportion of wood fuel use is implemented. This means no grants are used to replace natural gas heating equipment with energy wood heating equipment; no information campaign is implemented with a higher possibility of investment in the exploitation of wood technology. At the same time, any action for strategic improvements of energy efficiency within the use of a wood-based plant is proposed.

However, as it can be seen from Figure 5.1a over a period of 40 years, a natural increase in wood fuel use is observed. This can be explained firstly by a natural increase in the efficiency of wood fuel installations over time and, secondly, by a beneficial decrease of the moisture content according to the assumptions of section 4.3. In fact, the combination of these assumptions reduces the tariff for the production of wood-based heat. This causes an increase in investments in this sector.

The heat tariff within the BS1 scenario for natural-gas installed operators and wood-fuel operators is shown in Figure 5.1b. The heat tariff for the wood-fuel operators are summarized in a single curve (tariff_wood) taking into account the different share of pellets, logs and chips within the whole system. It is possible to see an initial decreasing trend of the wood-fuel, because the model includes the assumptions of a decreasing value for the wood moisture content and a natural increase in plant efficiency. After this point, since all the wood-fuel is foreseen, a linear natural increase of the fuel price (according to Section 4.3) will prevail.

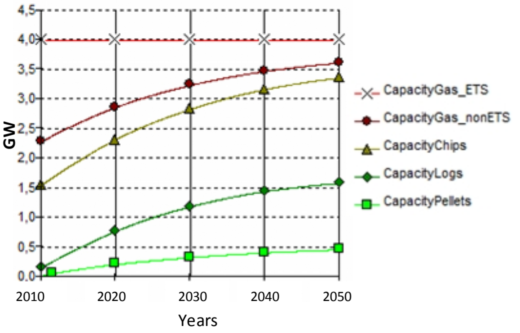


Fig. 5.1a. Base scenario BS1 – structure of the installed capacities for the primary energy mix for the district heating system

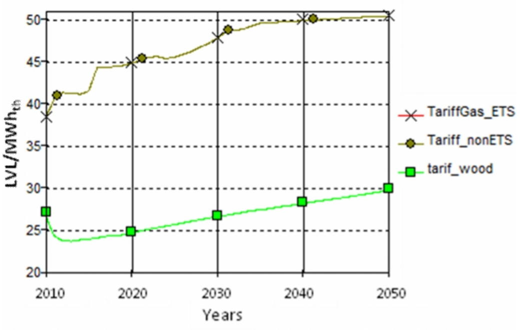


Fig. 5.1b. Base scenario BS1 – energy tariffs

For the natural-gas based scenario, it is possible to distinguish only one trend. It is the same for ETS and non-ETS operators since the “P_{ETS}” is not active. This means that there is not any theoretical effect from the implementation of the ETS scheme, as it is only possible to always see the heat tariff increase. In reference to the year 2014, it is possible to see the effect given by the assumption to consider an increase of the CO_2 emitting taxation according to the assumption proposed in section 4.3.

5.2.3 Scenario C1_best

This scenario represents the strongest effect given by a single policy tool implemented. This is related to the implementation of an information campaign with the risk of decreasing the investment and exploitation of wood technologies.

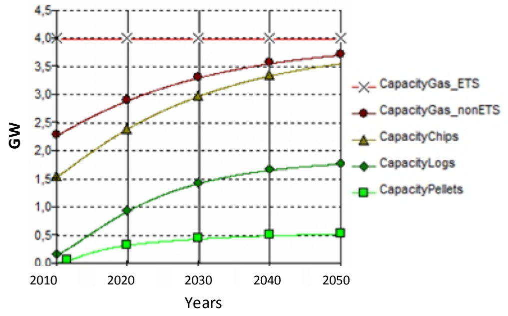


Fig. 5.2a. Scenario C1_best – structure of the installed capacities for the primary energy mix for the district heating system

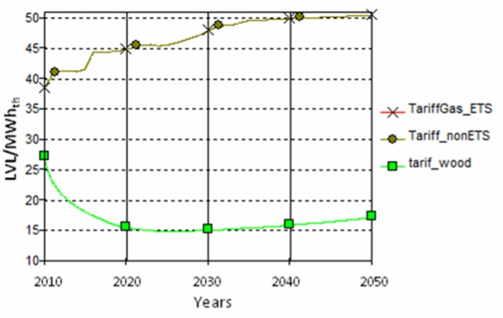


Fig. 5.2b. Scenario C1_best – energy tariffs

Figure 5.2a shows the share of the total installed capacity of wood-fuel based heat producers: compared with the BS1 scenario it can be seen as a value of 3.6 GW installed capacity in the year 2050. This is higher than the one predicted in the BS1 (around 3.4 GW). This effect is connected with the implementation of the risk reduction measure favouring the investment and exploitation of wood-fuel technologies. In the light of this behaviour, the heat tariff presents a decreasing trend within the first 15 years.

5.2.4 Scenario C2_best

This scenario implements two of the four suggested policy instruments in models, P_S and P_R. This means that subsidies are implemented in order to encourage the transfer to a wood-based heating system (P_S) and at the same time an information campaign aimed to reduce the risk (P_R).

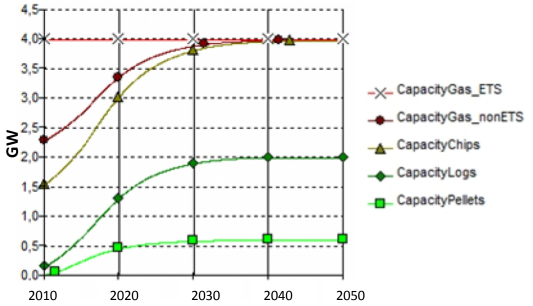


Fig. 5.3a. Scenario C2_best – structure of the installed capacities for the primary energy mix for the district heating system

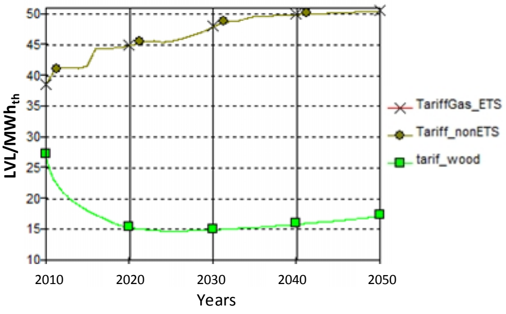


Fig. 5.3b. Scenario C2_best – energy tariffs

As it can be seen from Figure 5.3a, the combination of these two tools provides important effects within the share of wood fuel for the primary energy structure. In fact, after 10 years the use of wood fuels (taking into account wood-chips, wood-logs, and wood-pellets) in the share of the installed capacity increases from 38.5% until 77%. In regards to the wood pellets fraction, it is possible to see a light decrease in the last 15 years of the model (2035-2050) since the component of a higher price, while the two other types of wood-fuels prevail in the long-term perspective.

The effect of the combination of the two policy instruments proposed is reflected in the heat tariff (see Figure 5.3b) where an important decrease within the first 10 years is detectable. This wood-tariff trend is similar to one of the C1_best scenario, except for the duration of the tariff decreasing that has been extended until 2028. The natural gas heat tariffs present an increasing tariff rising with the price of natural gas.

If compared with the scenario where 2 or 3 policy instruments were implemented (see Appendix) the C2_best represents the minimum combination of policy instruments that allow for achieving the best results regarding the installed capacity of wood fuel in the district heating systems.

5.2.5 Scenario C1_ETS

The effects that regulated the implementation of the ETS scheme are evaluated in this scenario. Looking at Figures 5.4 and 5.5a, it can be seen that there are no evident effects, in terms of the higher share of wood-based capacity. Below the comparison with the BS1 scenario is shown.

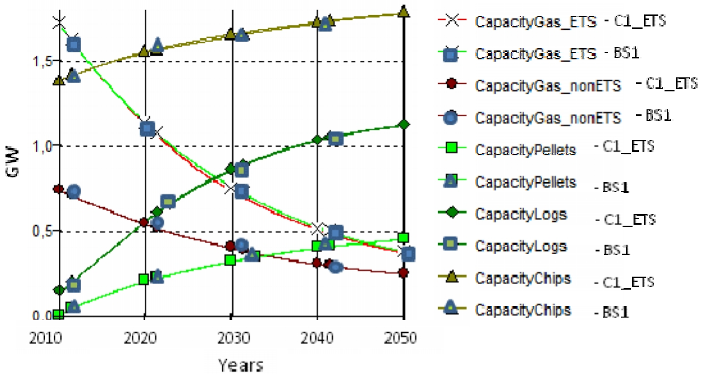


Fig. 5.4. Scenario C1_ETS and BS1 comparison – structure of the installed capacities for the primary energy mix for the district heating system

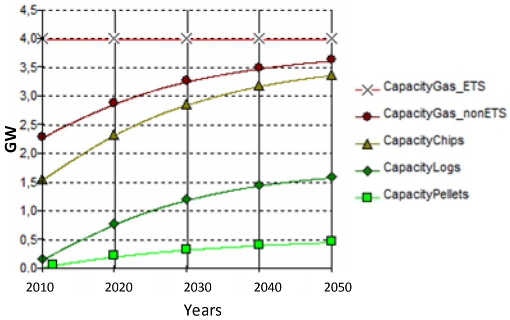


Fig. 5.5a. Scenario C1_ETS – structure of the installed capacities for the primary energy mix for the district heating system

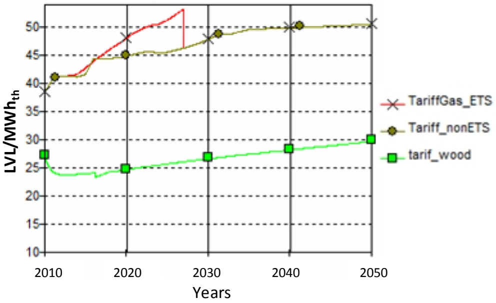


Fig. 5.5b. Scenario C1_ETS – energy tariffs

In the other graph, 5.5b, the effect within the heat tariff for this scenario is reported. As it possible to see that two effects are happening: the first one shows an increase of the wood tariff for ETS operators with respect to those not participating in the ETS scheme, the second is in reference to a small decrease (starting from 2016). These two effects are consequences of the model part that regulate the ETS mechanism.

In fact, according to formula 4.9 the heat tariff for ETS operators during the period of implementation of the third phase of ETS mechanism (2013-2020 with extension until 2027) the increase is more than one for non-ETS operators. This trend is regulated by the cost to purchase the CO_2 quotas (increasing over time with an S-shape depending on scarcity of free quotas in the market) for the ETS operators and by the CO_2 taxation for the non-ETS operators that, in the assumptions, presents values always lower than the price of allowances.

The decrease for the wood-tariff evident in the year 2017 is justifiable according to the scheme presented in Figure 4.7 where a beneficial effect in the whole wood-tariff was allocated due to those operators that decided to invest in wood-based technology. This mechanism occurs only when the costs for “green investment” are lower than the costs for quota purchases (see Figure 5.6).

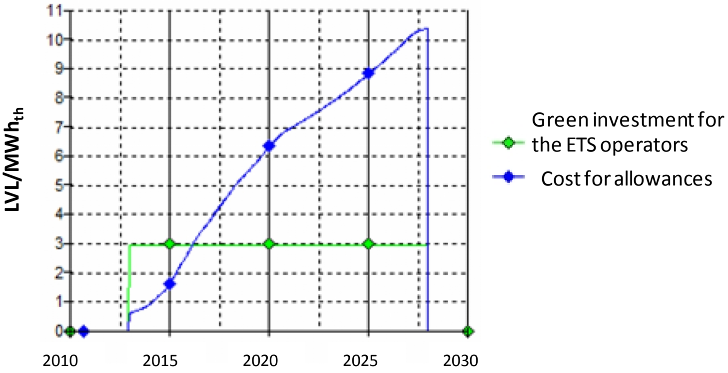


Fig. 5.6. Investment costs for GHG reduction measures compared to costs for allowances

In Figure 5.7 the graphic 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 Chapter 4 is reported. The difference between the two trends brings the calculation of the total cost for the amount of CO_2 quotas that the natural gas operator should purchase and consequently evaluate if there is a reliable green investment.

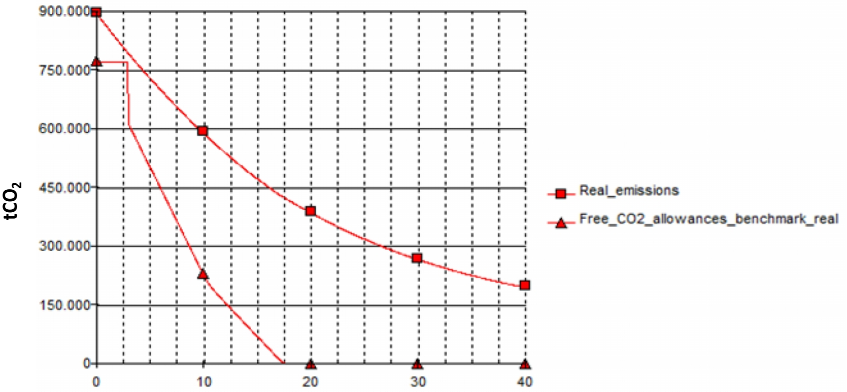


Fig. 5.7. CO_2 allowances benchmark compared to real emissions for C1_ETS scenario

5.2.6 Scenario C4_all

Figure 5.8a shows the results concerning the implementation of all policy measures (P_S, P_R, P_η, P_{ETS}). The scenario resembles the results presented for the C2_best scenario; nevertheless, from 2023, an increase of the share of the installed wood-fuel capacity when compared with the C2_best scenario is detectable. In comparison with the B2_best scenario the share of wood-pellets does not show any decrease, but a constant increase until an asymptotic value. Within this scenario the portion of the use of wood fuel allocated to wood-chips is the most prominent over time, but the increase of the wood-logs use shows the strongest increase over years. In approximately 15 years, it registered a 90% use of wood-fuelled primary energy within the district heating system in regard to the heat generation from boiler houses.

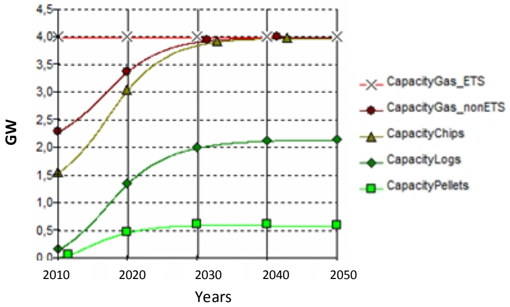


Figure 5.8a. Base scenario C4_all – structure of the installed capacities for the primary energy mix for the district heating system

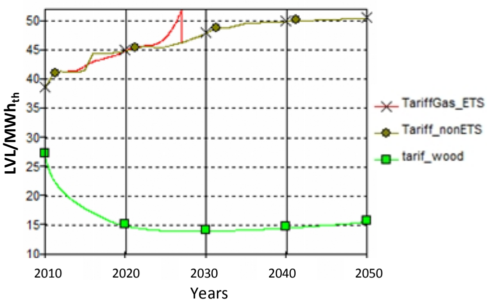


Figure 5.8b. Base scenario C4_all – energy tariffs

The heat tariffs presented in Figure 5.8b show for the wood-fuel tariff a trend similar to the B2_best scenario. For the natural-gas heat tariff results presented in Figure 5.8b shows that during the implementation of the ETS scheme, the tariff for the non-ETS operators are lower until approximately the year 2021 when the increase of price due to the scarcity of free allowances prevails in the total amount of the calculated heat tariff for ETS operators.

5.2.7 ETS scenario aspects

Figure 5.9 shows the costs for investments in GHG emission reduction measures as compared with the costs for buying emission allowances in two cases: the first when the market develops on the base of C1_ETS scenario, the second case when the combination of four policy instruments is implemented to speed up the transfer to RES.

From the results, it can be seen that in scenario C1_ETS (respect the C4_all scenario) the deficit of free allowances stimulates natural gas operators to switch to wood-fired boilers earlier, because the costs of the purchasing emission allowances exceeds the investment costs in GHG reduction measures already in four years after the beginning of the third emission trading period (2013). This is also due to the fact that in the B4_all scenario there is the effect of the other policy instruments that decrease the emissions of the operators decreasing as well the cost of the CO2 quotas to be purchased (i.e. less scarcity of free allowances). The previous figure represents a good tool to evaluate when a green investment for the conversion to wood-fuel based technology is beneficial for ETS operators.

In the case when additional policy instruments are implemented to increase the share of wood fuel, the total amount of CO_2 emissions from natural gas operators is smaller because they have already switched from natural gas to wood fuel under the influence of these policy instruments.

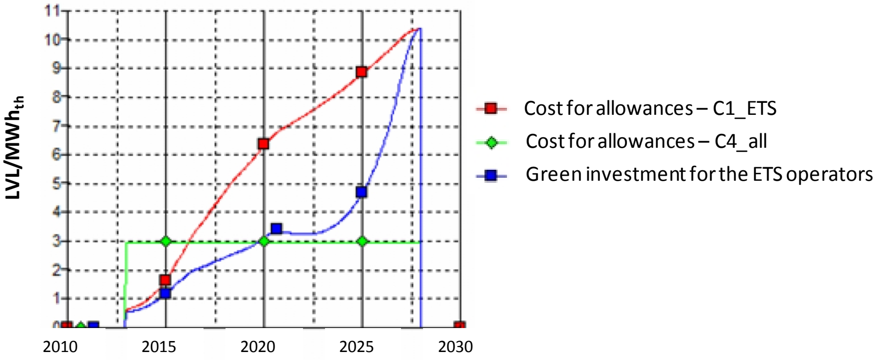


Fig. 5.9. Investment costs for GHG reduction measures compared to costs for allowances for scenario B1_ETS and scenario B4_all

Figure 5.10 compares the free CO_2 emission benchmark level (calculated according to the Annex 1 of the EU Directive 2003/87/EC [63], with the real emissions from natural gas installations in the case of C1_ETS scenario and C4_all scenario. From this figure, it can be seen that, in the case that the all national level policy instruments are applied in the system, total emissions from natural gas emissions significantly decrease.

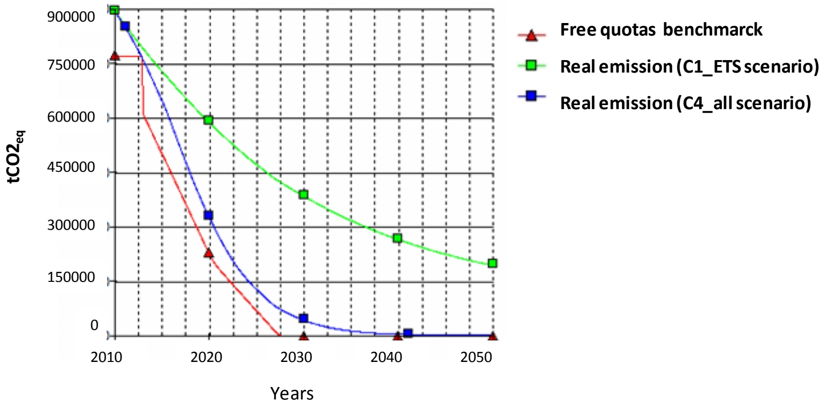


Fig. 5.10. CO_2 allowances benchmark compared to real emissions for C1_ETS scenario and C4_all scenario

As a result, less emission allowances are bought by natural gas operators and the effect of emission trading as a policy instrument decreases. In fact, there is a smaller necessity to buy emission allowances and the costs for buying emission allowances are lower due to a bigger amount of free quotas in the market. Consequently, the time when it is more economical for natural gas operators to switch to wood fuel moves further into the future.

However, it should be taken into account that despite the fact that due to the implementation of other policy measures, the amount of “free” allowances increased in the local market, it is clear that at the EU level there will always be a demand for emission allowances.

5.2.8 Sustainability of the forest resource

Figure 5.11 represents the changes in the total forest stock and wood fuel potential use over time for the scenario B4_all when the maximum use of the wood fuel is foreseeable.

The results of the modelling shows that with the existing rates of forest harvesting and new forest planting according to the sustainable management of the forest (see Chapter 4), the total amount of forest stock in Latvia will have a slow decreasing tendency with an asymptotic final value over time.

This is a necessary trend to compensate a higher demand of wood fuel. The decreasing trend can be explained by changes in connection with the forest age structure.

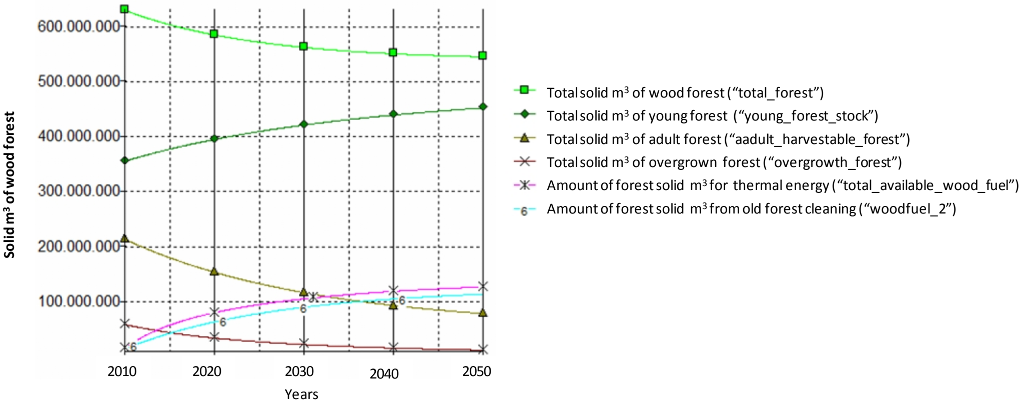


Fig. 5.11. The structure of forest stock and wood fuel potential

Due to higher in-flows that are effecting the stock of the young forest (“forest_planting” together with “Agricultural_land_overgrowth”, see Figure 4.8) the flows that regulate the growing of the adult forest “growing”, the volume of the young forest stock increases over time. At the same time, the rate of the forest harvesting that regulated the out-flow of the adult forest stock (“industrial_wood_production_flow” and “use_of_wood_fuel”, see Figure 4.8) exceeds the rate of annual forest increase (flows “growing”, see Figure 4.8). This results in the decreasing behaviour of the stock of harvestable adult forest. However, despite the decline in stock of the forest for felling, existing forest resources still can fully cover wood fuel consumption in district heating systems. Increasing wood fuel stock from old-forest cleaning (“woodfuel_2, see Figure 4.8) indicates that there is a high potential to use these forest resources for wood fuel preparation.

5.2.9 Comparison of all scenarios

Appendix reports the whole comparison of the installed capacities in reference to the analysed scenarios.

Figure 5.12 summarizes the primary energy use structure for the wood-based operators (i.e. taking into account the sum of the three types of wood-fuels analysed: chips, logs, and pellets).

Three different types of trends can be defined. The first one where a non-linear relationship among the implementation of the policy and the resulting share of fuel in the energy mix defining a gradual increase close to the *BS1* behaviour (scenario *C1_SUB*, *C1_BEST*, *C1_ETS* involving P_{ETS}, *C2_5* involving P_{η} and P_{ETS}). The second one with a non-linear tendency defining a moderate increase (scenario *C1_SUB* involving P_S, *C1_BEST* involving P_R, *C2_2* involving P_E and P_h, *C2_3* involving P_S and P_{ETS}, *C2_4* involving P_R and P_{η}, *C2_6* involving P_S and P_{ETS}, *C3_3* not involving P_R, *C3_4* not involving P_S). The third one where there is a strong non-linear increase in the use of wood fuel in the structure of the energy mix close to the *C4_all* behaviour (scenario *C2_BEST* involving P_S and P_R, *C3_1* not involving P_{ETS}, *C3_2* not involving P_{η}).

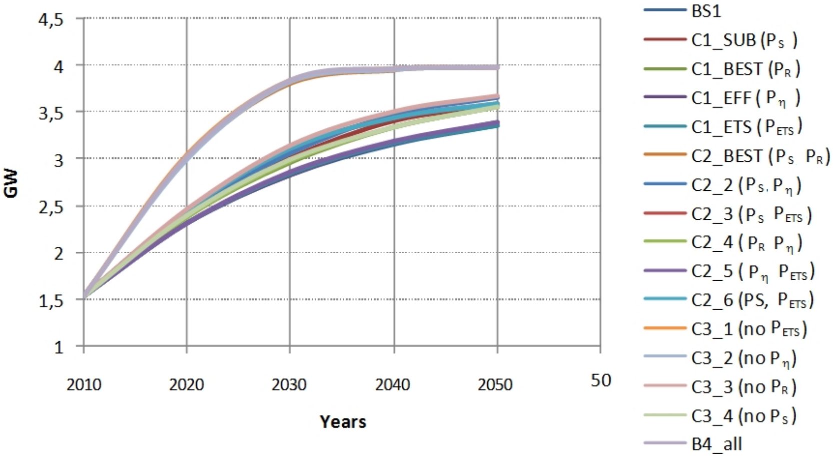


Fig. 5.12. Share of wood-based fuel in the primary energy mix for district heating systems under different policy scenarios

It can be seen in the scenario *B2_best* (where the P_S and P_R instruments are used), that it is the minimum combination closest to maximal effects obtained with the *C4_all* where all of the instruments are activated within the model. This is reflected when three policy instruments are implemented, meaning that to have a similar behaviour the implementation of P_S and P_R is necessary.

From Appendix A it can be seen that mainly wood chips dominate the whole wood fuel share, varying from 47% until 53%.

All the scenarios present non-linear behaviours, and the share of wood based fuels by the end of 2050 are in the range of 82%-100% (see Appendix).

Comparing the energy wood heat tariff changes in run scenarios, (see Appendix) two main similar trends are detectable: the first presents a moderate tariff reduction, the second scenario group a comparatively faster energy wood tariff reduction.

In regard to the wood tariff from the run simulations, the results demonstrate that to make the most wood tariff reduction possible, the most important role is a policy instrument for the implementation of at least P_R, because it is common to all scenarios of the second group.

5.2.10 Model testing and validation

Model testing and validation focuses on verifying the reliability of the model and providing confidence for the model application. The aim of the structural validation is to evaluate the effects on the model of different assumptions in order to increase the confidence of the proposed model structure.

According to books edited by A. Blumberga [139, 144] a structural validation test methodology based on the extreme condition test and a behaviour sensitivity test has been applied.

The structural and numerical assumptions, made within the model, reflect aspects of the real system based on consultations with experts of the energy sector and system dynamics modelling. Therefore, the use of the parameters implemented in the model acts in accordance with the real life values within a confidence boundary.

According to the objectives related to the definition of the model, the model boundary adequacy is provided. The model is designed as a supporting tool in order to understand the reasons of not fully exploiting the wood fuel source in the district heating sector. In light of that, the effects of different types of policy tools and mechanisms are investigated. This takes into account a sustainable management of the wood-fuel resource.

The models have been tested under different extreme conditions, like a null value to the investment flows. The model reacts positively showing an expected decrease of the total installed capacity due to a lack of investments.

An historical behaviour matching test has been conducted based on the 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 terms of wood chips, logs and pellets) from the year 2000 until 2010. This has also taken into account the price for each fuel source used, always according to the historical trends [215]. In the following figure, Figure 5.13, the simulated data are compared with the historical ones.

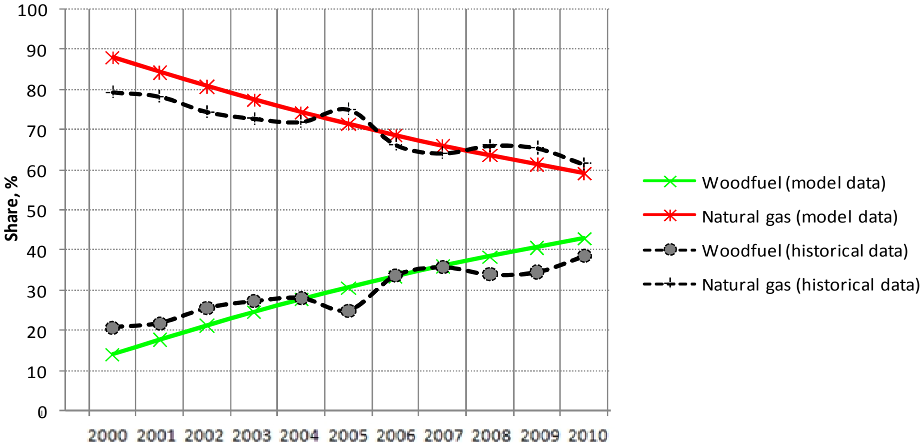


Fig. 5.13. Historical and simulated data for the historical behaviour matching test

It is important to remark that the simulated data define only the trends instead of precise numbers. Therefore, it is important to define the relations among the dynamic structures that compose the model rather than the real precision of the simulated data. In the trend line of the natural gas share, it is evident that fluctuations can be related to unpredicted variables that modify the natural trends (e.g. an unpredicted decrease of fuel price, or a particularly cold winter).

As it can be seen in Figure 5.13, given the fluctuations in prices of the fuel resource (natural gas and wood fuels in terms of chips, logs and pellets), and the initial share of fuel use in the year 2000, the results of the model-simulated primary energy share seems to match the historical data with reasonable confidence.

Other extensive behaviour sensitivity elements have been applied in regard to the changes of fuel prices, CO_2 taxation, green investments within the ETS scheme, free CO_2 quotas price, changes in the investments costs and operating costs for wood fuel technologies, changes in moisture contents and a different value of the rate of the forest planting with respect to the total forest stock.

1. The following table refers to the sensitivity analysis provided for different types of natural gas prices over time. The sensitivity analysis is compared with the base scenario BS1. Three different types of natural gas changes have been considered, taking into account a constant low price over years (BS1-ngas_low scenario), a constant high price over years (BS1-ngas_high scenario), and an unpredicted decrease of the natural gas during the ETS time assumed for the year 2014 (30% reduction - BS1-ngas_30% - and 50% reduction - BS1-ngas_30% - scenarios).

Table 5.2.

Sensitivity analysis for the price of natural gas

	Price of natural gas over year [LVL/1000 Nm^3]					
Scenario	2010	2014	2020	2030	2040	2050
BS1 (base scenario)	236.0	257.0	265.0	290.0	307.0	312.0
BS1-ngas_low	50.0	50.0	50.0	50.0	50.0	50.0
BS1-ngas_high	500.0	500.0	500.0	500.0	500.0	500.0
BS1-ngas_30%	165.0	178.0	185.0	203.0	215.0	219.0
BS1-ngas_50%	118.0	128.0	132.0	145.0	153.0	156.0

Within the scenario *BS1-ngas_low* the share of natural gas-based installations increases due to a favourable investment in this type of fuel. The final share in 2050 is around 68% compared to 85% within the BS1 scenario. A strong increase of the price of natural gas affects the total heat tariff. This increases the share of wood fuel-based installations over time with a value of around 95% for the year 2050. If unpredicted natural gas price reductions are implemented (BS1-ngas_30% and BS1-ngas_50% scenarios) results show a decrease of the installed capacity for wood-fuel based installations. This is shown in the values of 67% and 58%.

2. Changes in the CO_2 taxation has been applied with the following conditions:

Table 5.3.

Sensitivity analysis for CO_2 tax

	CO_2 tax [LVL/tCO_2]					
Scenario	2010	2013	2014	2027	2040	2050
BS1 (base scenario)	0.7	2	14	14	14	14
BS1-CO2_1	0.7	2	7.0	14	14	14
BS1- CO2_2	0.7	2	3.5	14	14	14
BS1- CO2_3	0.7	30	30	30	30	30
BS1- CO2_4	0.7	30	30	30	30	30

A change on the CO_2 taxation affects the calculation for the heat tariff for natural gas operators. The increase of such a value should positively affect the transfer to a wood-based technology and vice versa. The model is sensitive only to the *BS1-CO_4* when a higher value of the CO_2 taxation is implemented resulting in a share of wood-based technology up to a level of 92% for the year 2050.

3. According to Europe's Energy Climate Package, the power sector allowances will foresee an auctioning system starting from 2013. Nevertheless, the trend of CO_2 taxation cannot be predicted properly within reasonable confidence levels. In fact, prices will depend on several factors related to economic growth and emission growth. In light of that, it is evident how the price of CO_2 allowances, within the implementation of the ETS scheme, plays a significant role influencing the whole system behaviour. The increasing price of emission allowances results in the increasing costs for purchase allowances and vice versa. Thus, the transition from natural gas to renewable technology is either promoted or hindered. Within the base scenario an S-shape trend of the allowance prices has been assumed, varying from 10 LVL/tCO_2 until 40 LVL/tCO_2. Different schemes for the distribution of the free allowance prices have been implemented assuming: an exponential trend (from 10 LVL/tCO_2 till 40 LVL/tCO_2) and a low price for the free allowances over years (always 10 LVL/tCO_2).

For the first exponential scenario results show that the time when the cost for green investment are lower than the costs to purchase the allowances is moved 4 years later (2021), lowering the effect on the transfer to wood based technologies. The second assumed hypothesis shows how the ETS fails with a low value of the allowances within the market, in fact natural gas operators are more incentivised to purchase quotas instead of investing.

From what was mentioned before, it can be stated that the CO_2 allowance price will be a key aspect in order to improve the wood-based plants and that a higher CO_2 quotas price will enable long-term green investments.

4. Concerning forest sustainability, the annual forest planting and forest growing are very sensitive factors. Making small reductions of these parameters and the total forest stock is affected by important decreases without reaching an asymptotic value.
5. A high increase of the investment costs and operating costs for wood fuel technologies and a high increase in moisture contents within the wood fuels are reflected in the calculations of the wood heat tariff. This decreases the share of the wood-based technology calculated in the base scenario BS1.

Since all cases analysed are considered to be plausible, the confidence in the model increases as the model is able to describe the behaviour of the real system.

DISCUSSION

Bioenergy is a complex system where the implementation of policy tool requires long-term management together with capable institutions and policymakers. In fact, within the scientific and policy arena, the risk occurs in having an incorrect evaluation of the biodiversity, GHG emissions and climate change. Moreover, the whole bioenergy sector needs to be investigated in relation to the possible alternatives, both as substitution of the fossil-based energy routes and in bioenergy route alternatives, and in reference to sensitive problems as the competition between energy crops and food crops grows, and is enhanced by competing demand for land and water for agriculture.

This complexity in the bioenergy system also determines an increment of risks and uncertainties in this field. Leading to a situation where the possibility of investors to be more active in the bioenergy sector is hindered. The consequence of this is that the maximum potential of the sector is not fully exploited. In this context, the comparison between GHG emissions of the bioenergy chains against natural gas shows standard results. This stresses the fact that bioenergy is not always preferable to fossil-based energy.

The quantifications of the GHG emissions of the bioenergy chains have been a primary issue in relation to policy developments. This is the reason why the development of LCA methodologies – capable of accounting for each type of the bioenergy production, and also an evaluation of the effects of co-products and/or biowastes that contribute to the economic and environmental reliability and viability– has recently increased.

It is evident that the activities associated with the growing of feedstock, as well as within transportation, provide indirect effects in terms of the contribution to GHG emissions. The advantages of undergoing an LCA approach to a bioenergy supply chain LCA are in the fact that specific particular processes (feedstock collection or biomass conversion) can be optimized as new data become available.

The use of the system dynamics modelling was developed in the second part of this work. The model proposed allows the possibility to investigate the effects of the EU Emission Trading System on the primary energy mix in district heating systems and was built based on a previously developed system dynamics model applied to the case study of Latvia [137, 138, 220]. The initial structure of the original model was retained, and despite the changes made to the new model, it has demonstrated development trends shown by the original model.

Different from the base model, the improved system dynamics model allows the splitting of installed capacities for the district heating systems into subflows. The capacity of wood fuel-based installations was split into three subflows, representing the installed capacities of three different wood fuel types: wood logs, chips, and pellets. The capacity of natural gas installations was divided into two subflows, representing operators that do or do not participate in the EU ETS. The results of the modelling indicate that wood logs and wood chips will play the most important role in the future fuel mix proportion, and no significant increase in the use of pellets can be expected, even despite the higher fuel efficiency (in terms of heating values and technologies). This can be explained by the high price of wood pellets compared to other wood fuel types.

The evaluation of the policy instruments has shown that the implementation of separate wood fuel promoting measures does not give significant results. This indicates that a combination of policy instruments is necessary. The best results (in terms of installed capacity) with a minimum combination of policy instruments can be achieved by applying risk reducing measures in combination with subsidies to encourage the transfer of technology. This means that potential wood fuel users have to be enticed in two ways: first, by encouraging the choice of wood-fired technologies and, second, by providing funds for initial investments

The EU Emission Trading System, as a policy instrument, seems to have more influence on the heat energy production tariffs than the installed capacity. With current fuel prices, and EU plans for the third emission trading period, it can be forecasted that in approximately three years' time, after the start of the third ETS period, it will be more economically feasible to invest in GHG reduction measures than to keep buying CO_2 emission allowances. If compared to the CO_2 tax, the ETS has a greater influence on heat energy production tariffs in Latvia.

The proposed system dynamics model has paid attention to the sustainability of wood fuel resources, respecting the increase in wood fuel consumption due to the implementation of policy measures.

In fact, investments in the bioenergy sector are strictly related to the supply of raw material from the forest sector. In order to fully exploit the wood fuel resource, a sustainable forest management is mandatory. It must focus on the reduction of deforestation and an increase of the area of planted forest. Forest sustainable management covers different economic, social/cultural and environmental dimensions in reference to a different base knowledge of the forest systems.

With the implementation of this criteria in the model results indicate that in order to guarantee forest sustainability in a long-term perspective an annual forest harvesting must be balanced with constant wood replacement. Based on the model assumptions with the existing rates of forest exploitation and new forest planting, it is possible to fully offset the wood fuel consumption in district heating systems in Latvia, even if it is significantly increased due to policy instruments which are applied to support the transfer from fossil fuel (natural gas) to wood fuel.

This particular case study was applied to Latvia's conditions. By adjusting the necessary input data, the proposed system dynamics model can be used as well for other countries and energy systems that deal with problems on how to find the best strategies for converting from fossil fuels to renewable energy source based economies.

In the light of what was previously mentioned, this is the reason why this dissertation has proposed an interconnected analysis taking into account the holistic approach of the LCA (but static over time) and the forecasting and provisional effect of system dynamics modelling (dynamic over time).

CONCLUSIONS

The challenges posed to the European community and proposed at the national level within the European Union's climate and energy package, in terms of energy efficiency improvements, climate change, lowering of health impacts, sustainability and improvement in the use of renewable resources make the bioenergy sector a priority and imperative to be accomplished.

Connected with that, several bioenergy technologies have developed rapidly within the last decade. This favours a competition with the matured fossil fuels alternative. Consequently, the investments related to the set renewable energy national targets increased within the same time period.

Nevertheless, the incentive framework from the last EU directive still lacks the correct support in the development and diffusion of bioenergy technologies in order to have a gradual substitution of the fossil-based sources.

This aspect is mainly related to two critical aspects: the complexity of the bioenergy production system, and the improper use of the bioenergy modelling tool to support policy makers and stakeholders.

Moreover, the bioenergy sector seems to be one of the most promising renewable energy possibilities. However, aspects related to their sustainability are still a matter of concern.

This doctoral dissertation deals with the problem of proposing a correct approach based on a proposed methodology in order to evaluate the potential impact assessment of different bioenergy routes through LCA methodology and evaluate the implementation of policy measures and a mechanism act to improve the use of bioenergy technologies despite a phasing-out of the fossil based production chain within the use of system dynamics.

Within this integrated approach, the LCA is used as an analytical tool able to catch the system complexity and mutual system dependencies. Within the LCA method, it is possible to provide a holistic eco-balance aimed to also study the sustainability of the bioenergy chains and the net benefit from fossil fuel substitution. Meanwhile, the implementation of white box modelling as system dynamic modelling, where the calculation from the LCA are involved, provides a good tool for the forecasting energy developments and trends depending on the choice of certain policy measures.

In the first part of the thesis, 3 classical LCAs were performed for 3 types of bioenergy routes:

- LCA for the use of biodiesel in an off-road vehicle in Latvian conditions;
- LCAs for the production of biogas from algae substrate in Italian and Latvian conditions;
- LCAs for the production of thermal energy with a boiler house supplied by wood fuels (chips, logs, pellets).

All the LCAs in this work have 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 the analysis of the results according to the ISO standard 14040-44.

The LCAs carried out show that many alternative technologies offer the potential to reduce most emissions, compared to the fossil based alternative. At the same time, it also shows some weak points within the use of alternative bioenergy technologies (i.e. questions related to the use of the bio-wastes and co-products within the bioenergy system, aspects related to the system boundary considered, calculation of the impact related to the direct and indirect impact of land use change, carbon neutrality).

The results from the LCAs provided show how the determination of the environmental performances within a bioenergy system is difficult in the light of different combinations. These pertain to: the choice of the feedstock, the type of conversion routes, the choice of fuels, the scale of the technology used, the transportation distances due to different productivity yields, the end-use technological solutions, and the impact method chosen.

Concerning the environmental sustainability of the bioenergy chains, it can be stated that all life cycle phases within the choice of the fore-ground and back-ground LCA systems (i.e. practically the definition of the primary and secondary sub-systems) must be carefully considered and defined, since there is no single dominating point or aspect in the life cycle impacts, but rather several of them affecting the overall sustainability.

It can be pointed-out that bioenergy does not directly mean sustainable energy, since through a cradle-to-grave study the final environmental performances are not always beneficial within the sustainability criteria.

In this context, the choice with which to replace the fossil-based energy is of great importance. Within the implementation of the three LCAs, it was found that the impact of particulates matter (PM) within the combustion processes largely affect the comparison to fossil based power plants in terms of the potential impact to human health.

The LCA analyses provided present the reduction potentials of alternative bioenergy technologies concerning GHG and other types of pollution emission in comparison to the fossil-based alternative. All the proposed LCAs show higher environmental performances in respect to the fossil based reference scenario. Specifically, the LCA scenario concerning the use of macroalgae as a substrate for the production of biogas provides the total beneficial environmental burden (i.e. negative value of the whole impact) but as well the LCAs from the production of biodiesel present an important decrease of the total environmental burdens in comparison to a fossil-based scenario. This is quantifiable at a maximum of 10 times reduction (biodiesel LCA) and 4.5 times reduction (production of thermal energy by using wood-logs).

In the sensitivity analyses that have evaluated the influence of data uncertainty, the state-of-the-art technologies proposed, and the assumptions of the different LCA impact assessment methods. The choice of the impact assessment method depends on the types of problem n question. It is necessary that the problem fits the LCA impact assessment tool.

From the LCAs provided, the results give evidence how this tool can be implemented in order to assist decision-makers within the evaluation of new bioenergy choices, with the aim to improve the overall environmental performance.

The analyses carried out within the LCA are related to static conditions, in order to evaluate dynamic behaviour and non-linear relationships within elements of a certain system in order to forecast the effects of certain policy choices. To do this the implementation of an energy planning modelling tool is necessary. Nevertheless, it can be pointed out that the LCA is a very useful tool for the static evaluation of the environmental performances of the bioenergy routes. This is the reason why system dynamics has been implemented in combination with the LCA methodology.

Since it is evident how the bioenergy sector is strictly connected with social and economic benefits. These ideas also play a primary role in overall sustainability. They merge a life cycle approach with a bioenergy planning tool where bioenergy policies and economic incentive schemes are implemented. This will provide a comprehensive approach that would increase the total effectiveness of a certain policy strategy, and avoid problem shifting. This is the reason why it is important to embrace a combined method where the LCA method is implemented in an energy model. In this dissertation, the systems dynamics modelling and a specific model have been proposed in the second part of the work in regard to the Latvian district heating sector. Specifically, this model targets the evaluation of the effects of different policy tools and the EU Emission Trading System on a regional fuel mix in the district heating systems for a period of 40 year (2010-2050), and is focused on the heat produced from boiler houses.

The analysis aimed to evaluate the primary energy mix within a sector and decide which policy instrument can play a preeminent role to foster wood-based fuels. The model included the main outcomes from the LCA of the use of wood fuel for thermal energy in a Latvian boiler house.

The policy instruments were 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 campaign for the use of wood based fuels decreasing risk perception, iii) supporting measures for the improvement of existing energy efficiency in the wood fuel installations. Moreover, the implementation of the ETS scheme and a CO_2 taxation frame has been implemented as a policy instrument that works based on the “polluter pays” principle.

The results of the simulation within the proposed system dynamic model showed the greatest impact in the fuel structure of the Latvian District Heating. This is done in order to increase the share of fuel wood-based operators who rely on the combination of at least two of the proposed policy tools. Specifically, these are represented by state subsidies to promote the development of wood-based technologies in the market, and solutions acting to guarantee a risk reduction perception for investors.

The best effect represented by the implementation of a single scenario is the scenario related to the measures on favouring the decrease of risk reduction perception from an investor. This is directly acting on the calculation of the heat tariff that decreases due to an accumulation of positive experience and good practice dissemination.

From the heat tariff perspective, the model predicts a constant increase of the price of natural gas in the scenarios analysed.

The model shows that implementing all the chosen policy tools, approximately after 15 years (2025) will lead to a share of 85% of wood-fuel use. In a long-term perspective (2050) a full use (100%) of wood-fuel within the district heating system is achievable.

The EU Emission Trading System as a policy instrument seems to have more influence on the heat energy production tariffs than the installed capacity.

With the current fuel prices and EU plans implemented in the Latvian CO_2 allocation plans for the third emission trading period, the model forecast - in the case only this mechanism is implemented in the model - in approximately three years’ time after the start of the third ETS period. For natural gas operators, it will be more economically feasible to invest in GHG reduction measures than to keep buying CO_2 emission allowances.

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. Results of the model indicate that in order to guarantee forest sustainability in a long-term annual forest, harvesting must be balanced with wood increments to adhere to sustainable forest management principles. It can be concluded that based on the model assumptions, the existing rates of forest exploitation and new forest planting, it is possible to fully offset the wood fuel consumption in district heating systems in Latvia. This can be done despite significant increases due to policy instruments which are applied to support the transfer from fossil fuel (natural gas) to wood fuel.

As a general conclusion, it can be stated that the analysis of different bioenergy technologies is a very complex task involving technological, economic, ecological, and societal parameters.

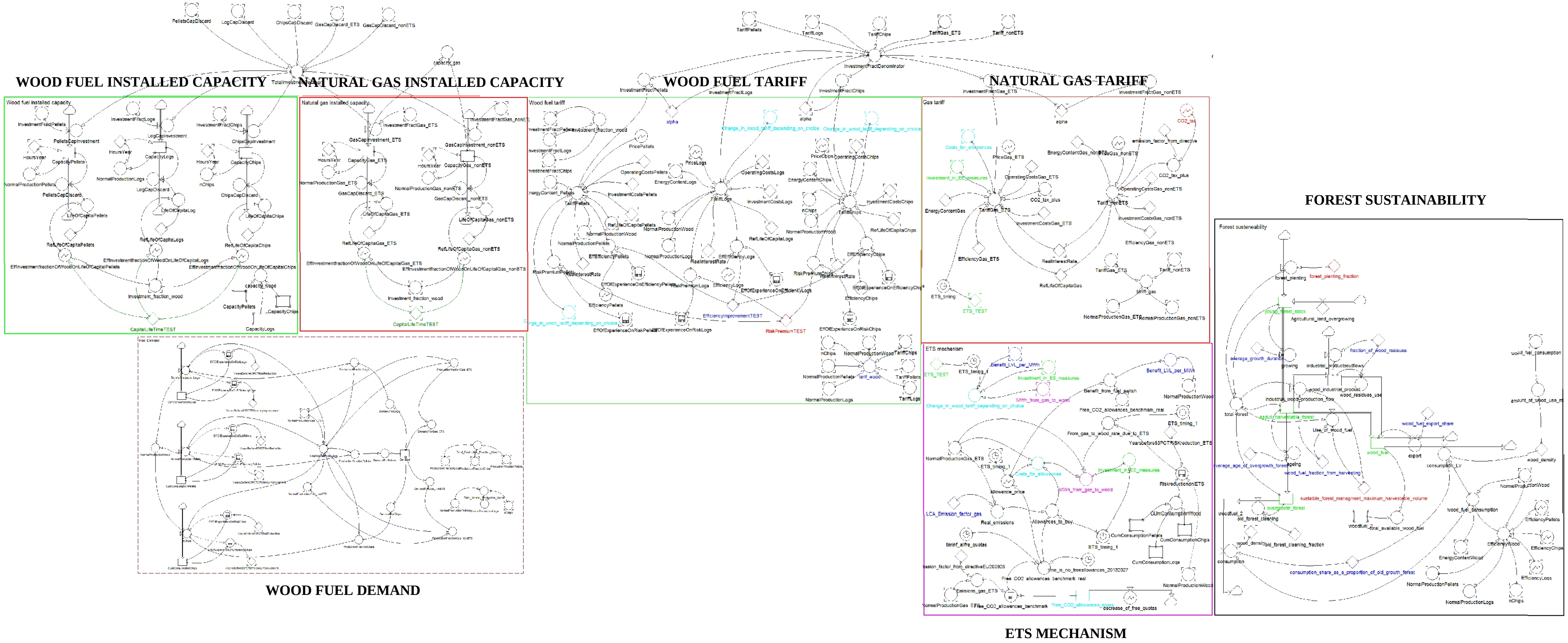
The method developed in this thesis, the integration of the Life-Cycle Assessment and system dynamic methods, can significantly increase the understanding of bioenergy technologies within a certain policy frame. This method offers the possibility to include different aspects (e.g. life-cycle emissions, costs and tariffs, competing energy uses, learning effects in the society and industry).

The use of an integrated approach aimed to merge LCA methodology and white box modelling with the Systems Dynamics method has proven to be a reliable and valuable tool for the comparison of different technology implemented in a wider frame where the effects of different policy strategies are implemented.

It can also be concluded that by adjusting the necessary input data, the proposed system dynamics model (in combination with the LCA results) can be used for other countries and energy systems that deal with the problem on how to find the best strategies to convert from fossil fuels to renewable energy sources based on the economies in different energy sectors.

APPENDIX

Appendix A: SD model scheme – key plan and single parts



WOOD FUEL INSTALLED CAPACITY

NATURAL GAS INSTALLED CAPACITY

WOOD FUEL TARIFF

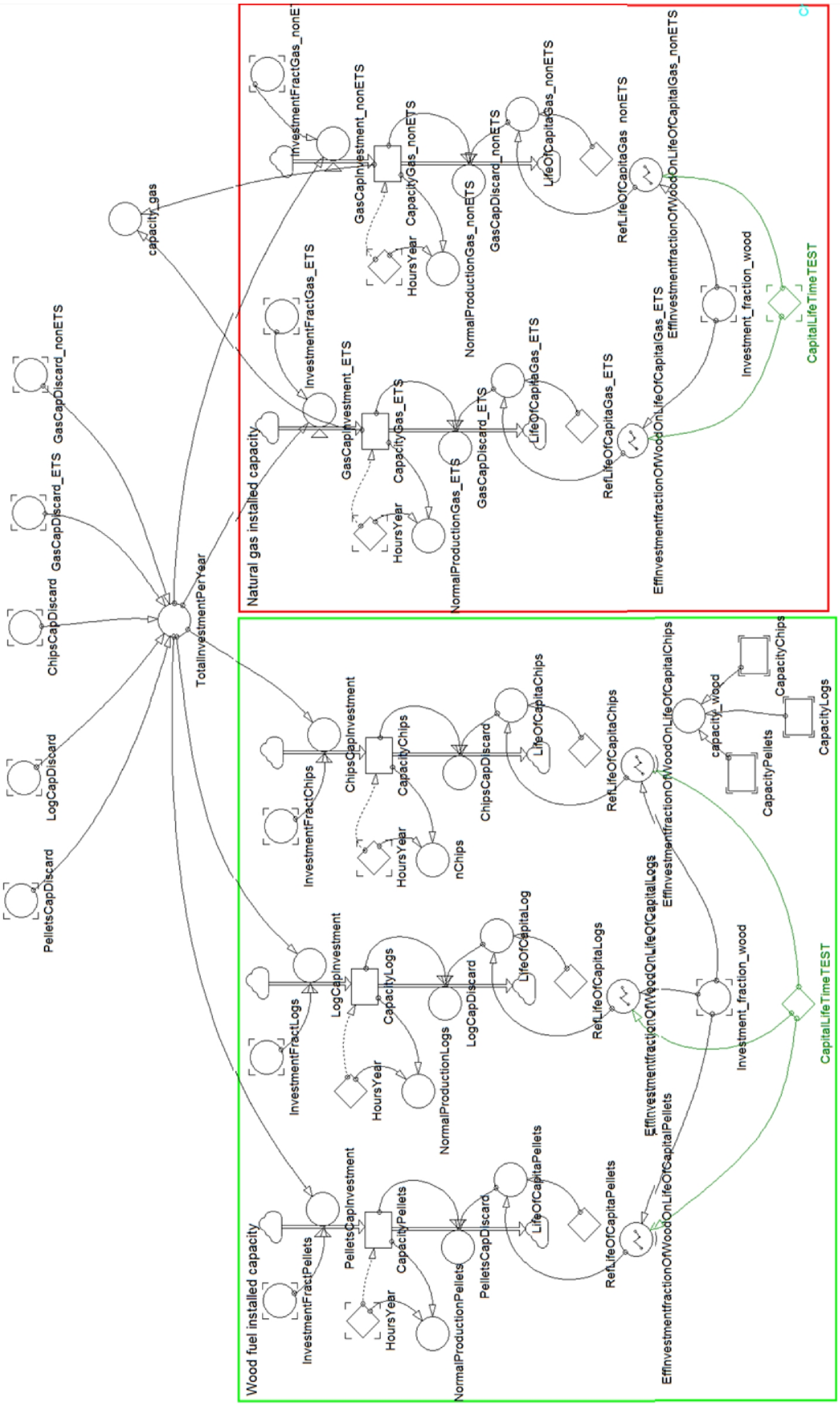
NATURAL GAS TARIFF

FOREST SUSTAINABILITY

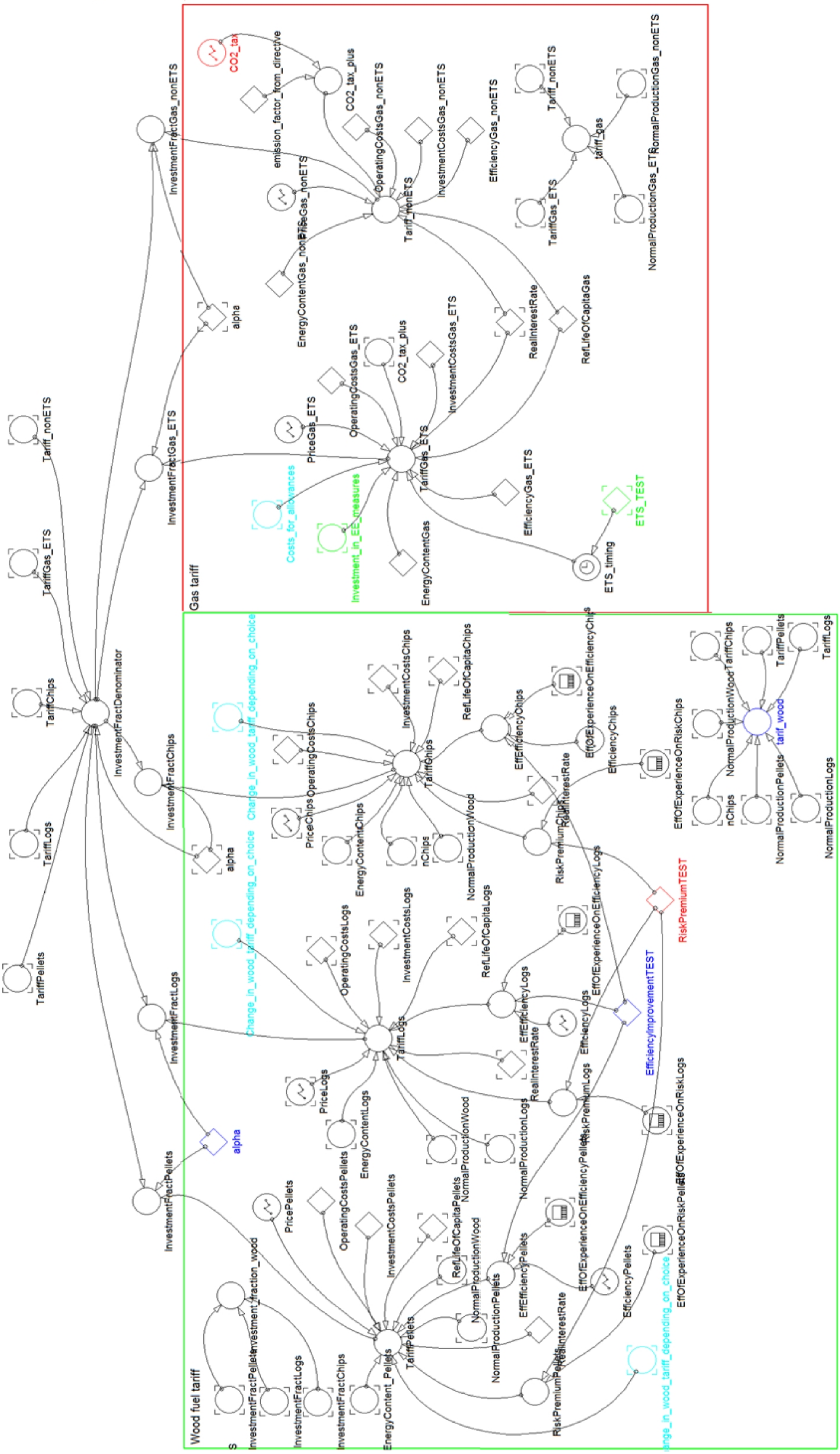
WOOD FUEL DEMAND

ETS MECHANISM

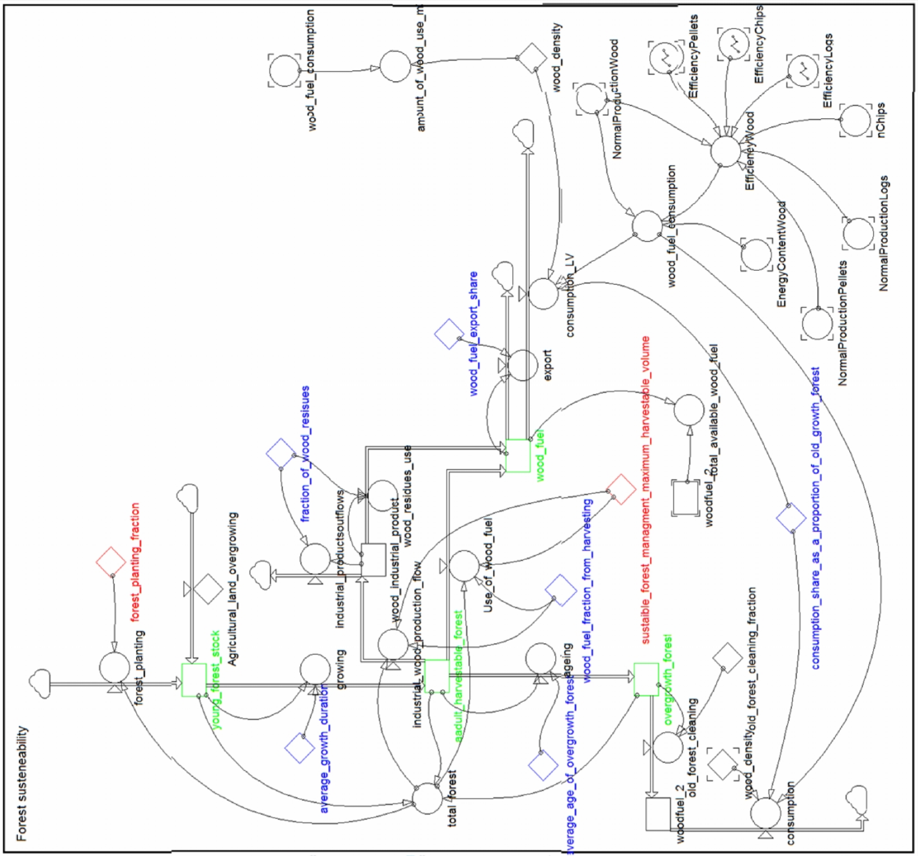
Appendix B: SD model scheme – wood fuel and natural and gas installed capacity parts

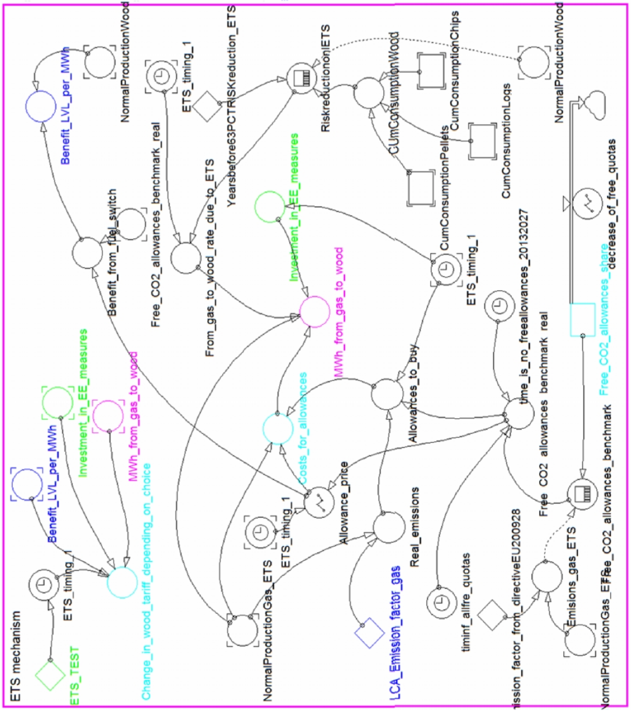


Appendix C: SD model scheme – wood fuel and natural gas tariff parts

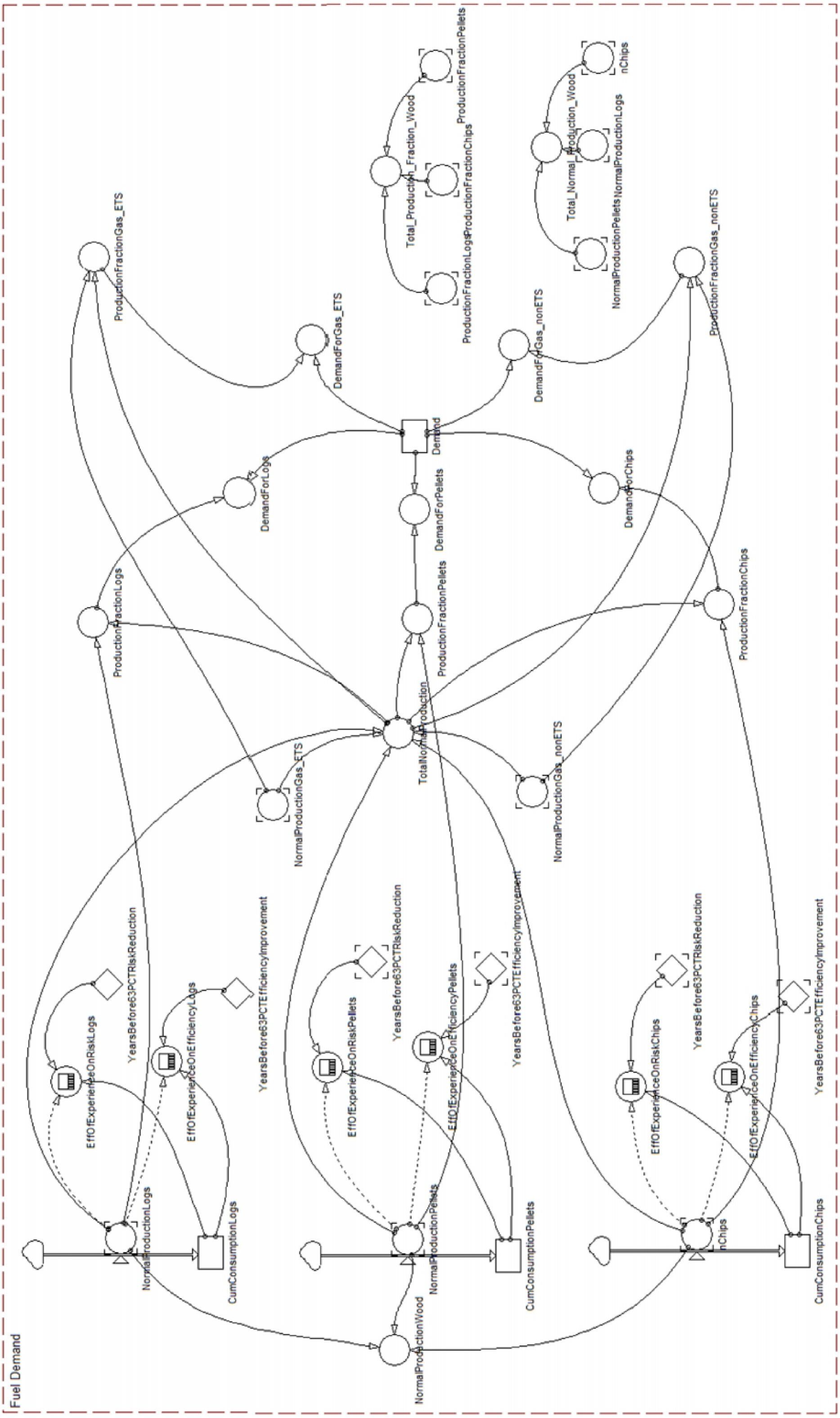


Appendix D: SD model scheme – ETS mechanism and Forest sustainability parts



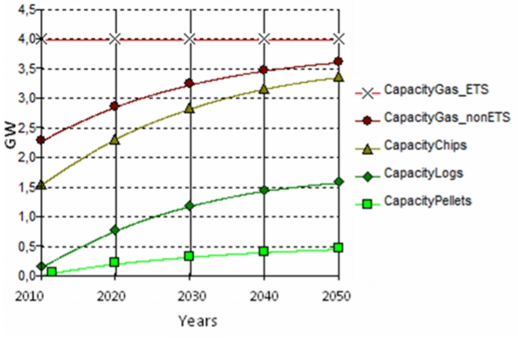


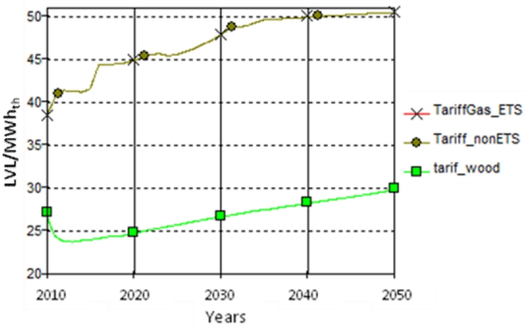
Appendix E: SD model scheme – wood fuel demands



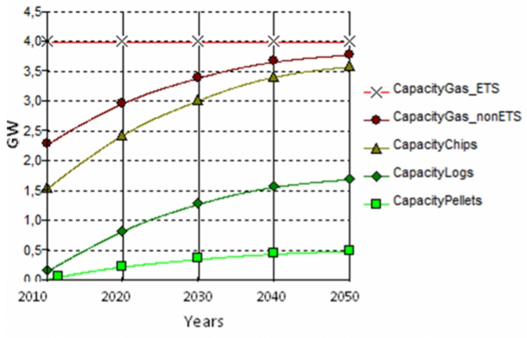
Appendix F: results of all scenarios of the SD Model

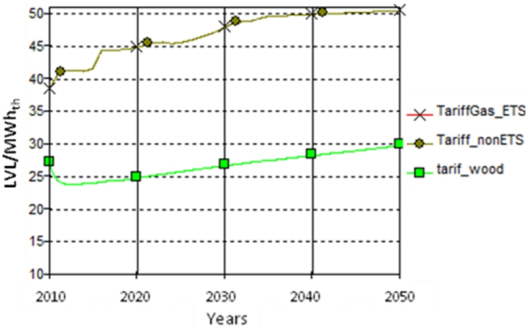
1. *Scenario BS1*



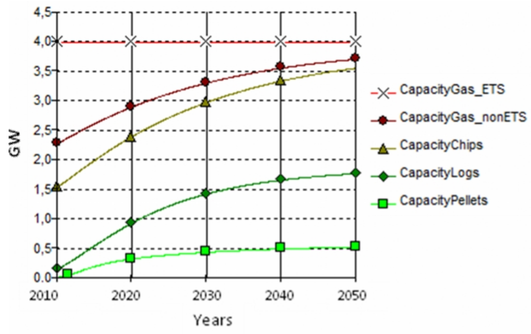


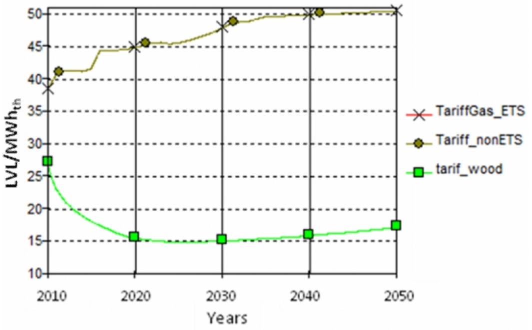
2. *Scenario C1_SUB (P_S)*



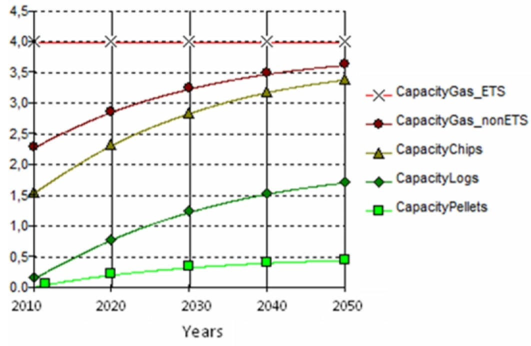


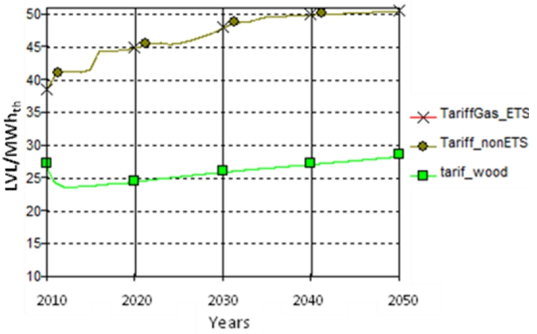
3. *Scenario C1_BEST (P_R)*



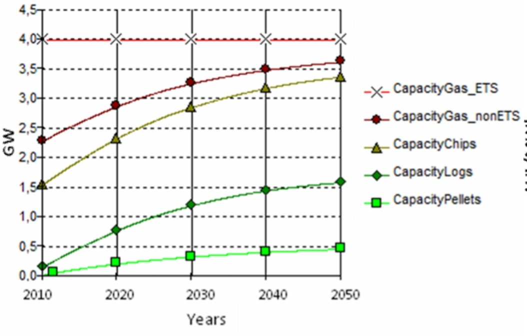


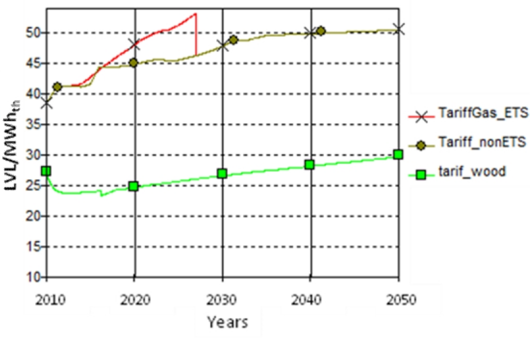
4. *Scenario C1_EFF (P¦)*



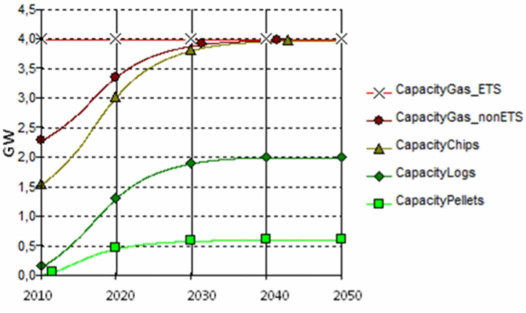


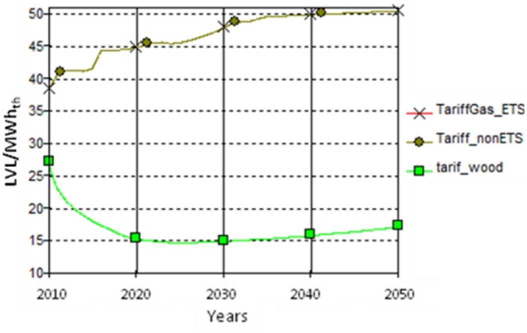
5. *Scenario C1_ETS (P_{ETS})*



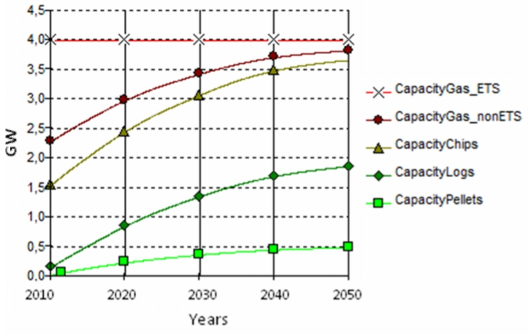


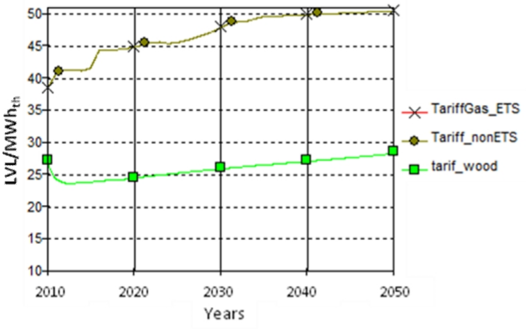
6. *Scenario C2_BEST (P_S, P_R)*



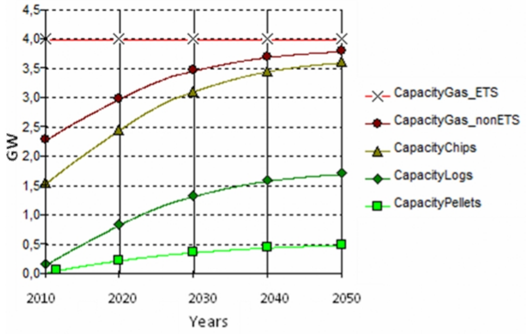


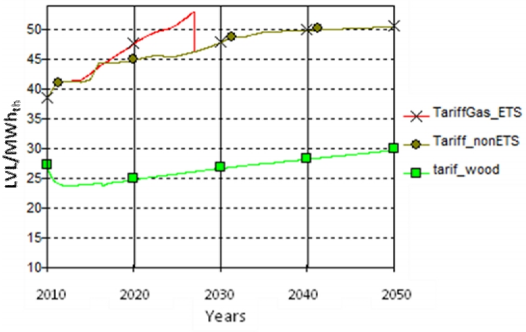
7. *Scenario C2_2 (P_S, $P_{¦}$)*



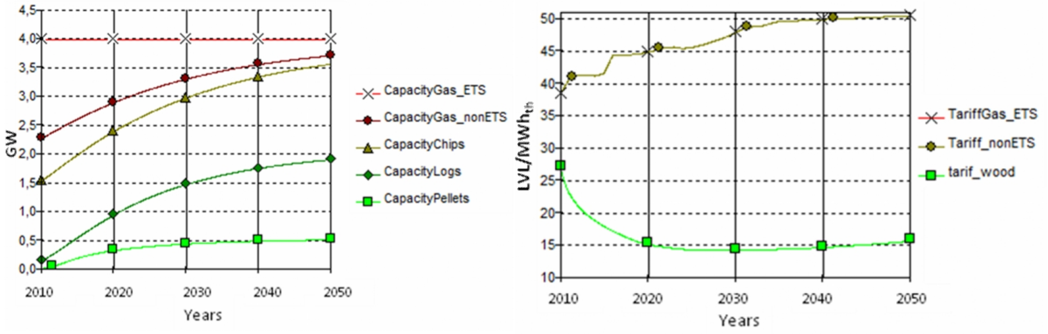


8. *Scenario C2_3 (P_S, P_{ETS})*

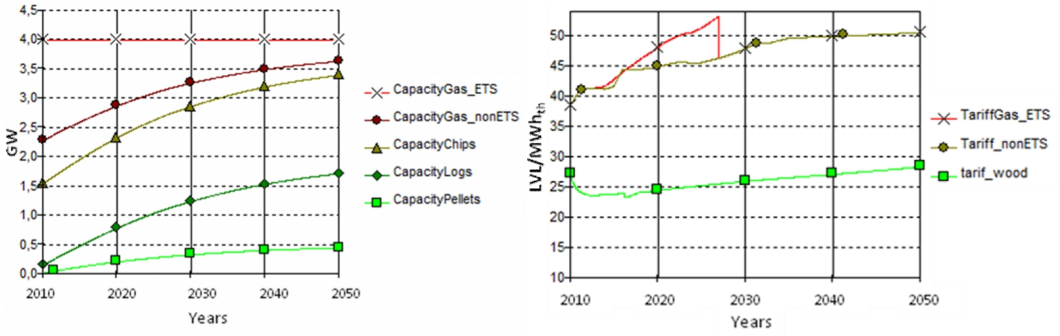




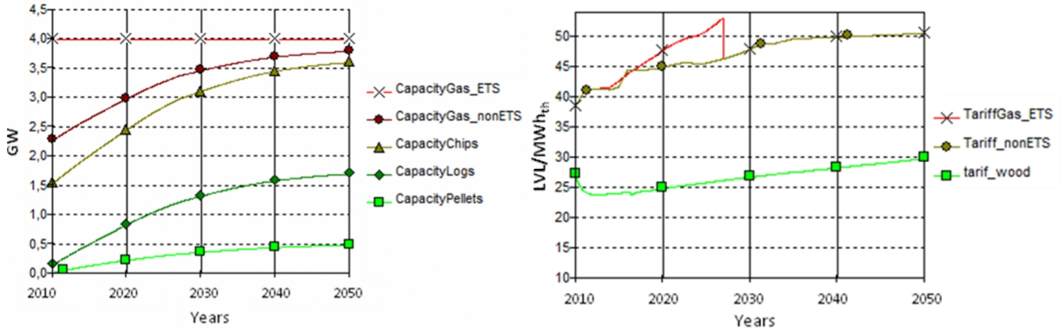
9. Scenario C2_4 (P_R, $P_{¦}$)



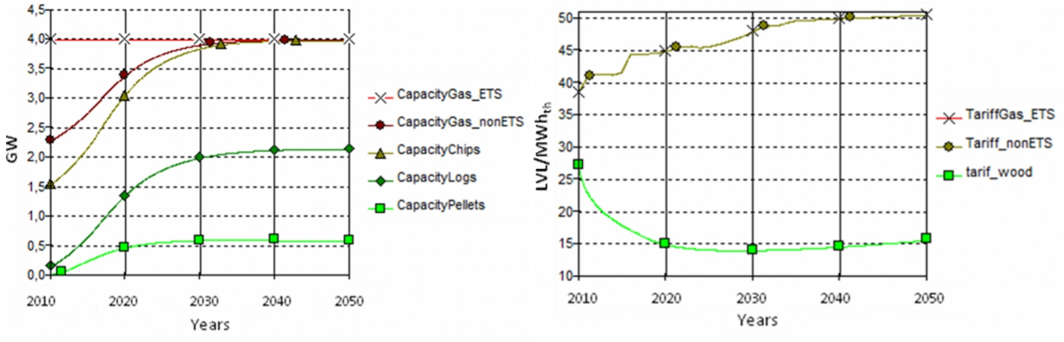
10. Scenario C2_5 ($P_{¦}$, P_{ETS})



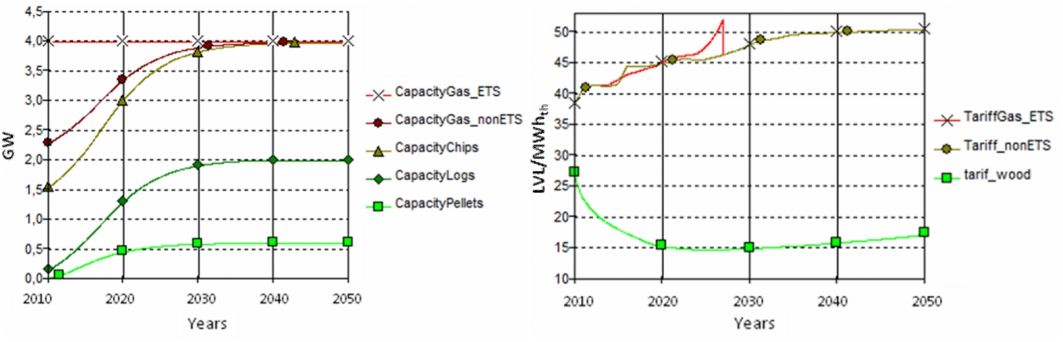
11. Scenario C2_6 (P_S, P_{ETS})



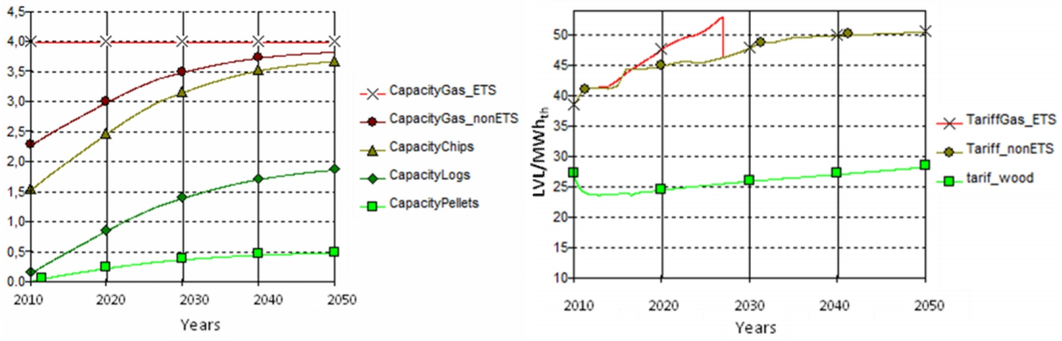
12. Scenario C3_1 (no P_{ETS})



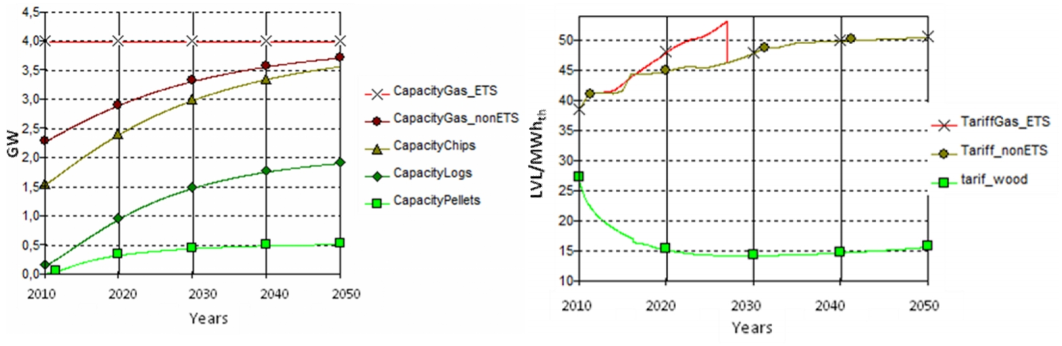
13. Scenario C3_2 (no $P_{\text{¦}}$)



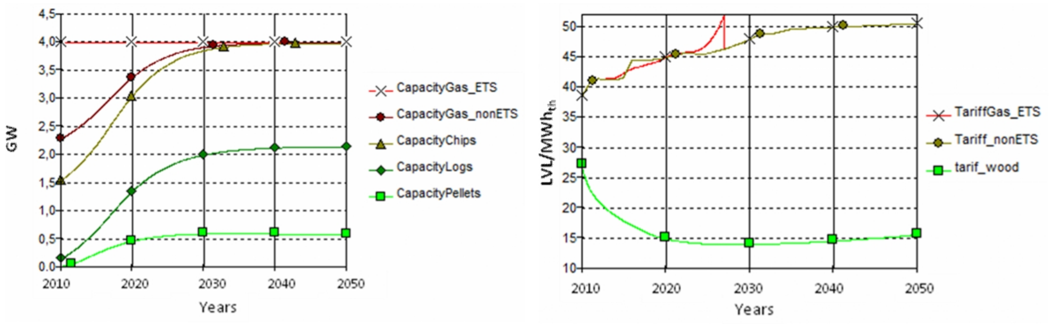
14. Scenario C3_3 (no P_R)



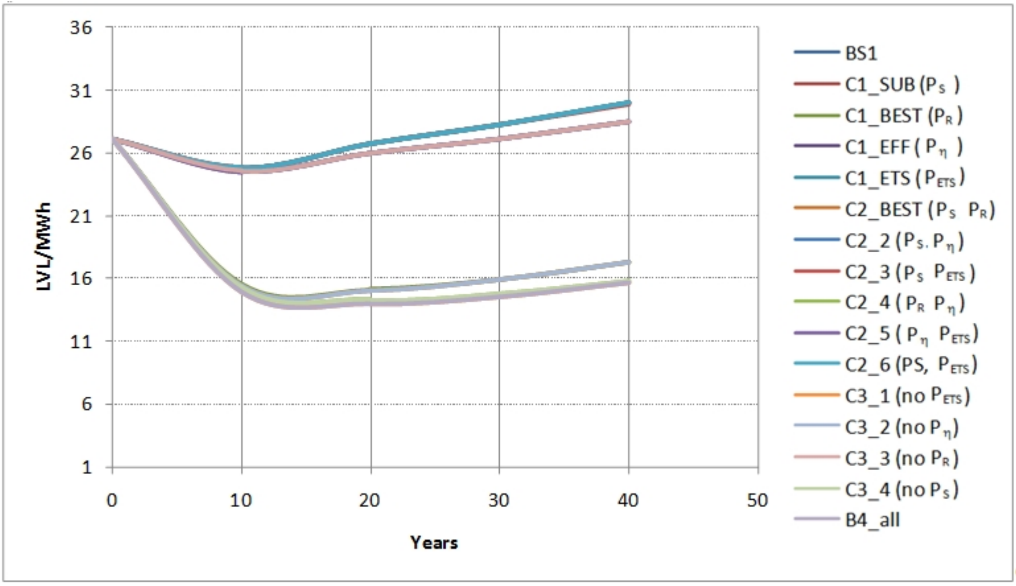
15. Scenario C3_4 (no P_S)



16. Scenario B4_all



Heat tariff for all scenarios: comparison



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