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Master of Science – Energy Engineering

Improved formulation of a MILP methodology and GHG evaluation for a bio-methanol supply chain

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Sommario

Questo documento affronta l'analisi per lo sviluppo di un modello di supply chain che mira a produrre il sistema di fondo per la produzione di biometanolo, a partire dall'utilizzo di biomasse residue e della tecnologia CONVERGE. Lo studio si concentra sul miglioramento di un modello già esistente con l'obiettivo di renderlo più consono ad una sua applicazione nel mondo reale. Inoltre, si occupa anche di presentare e discutere risultati che si otterrebbero applicandolo a dei contesti specifici che sono stati studiati.

In primo luogo, è stata condotta una revisione della letteratura per assimilare le informazioni utili riguardanti i sistemi di descrizione e di implementazione del problema. Ciò si è rivelato importante per trovare sia le possibili modifiche ed integrazioni da apportare al modello che gli aspetti su cui condurre alcuni studi. La principale modifica consiste nel sistema di trasporto stradale, a cui verrebbe conferita una caratterizzazione ed una modellizzazione più realistica. Successivamente, è stato delineato il caso di studio assegnato, riguardante i residui legnosi in Svezia, ed è stata eseguita la sua implementazione nel modello. Attraverso l'ottimizzazione economica si è trovata la configurazione più conveniente per la filiera e si sono successivamente analizzati i risultati finali riferiti a più livelli di decisione. Il modello è stato implementato anche per il caso italiano (già definito), in modo da evidenziare le differenze prodotte nei risultati con un caso diverso, ma anche per verificare la versatilità del modello alla base.

Lo studio finale è stato condotto sulla valutazione delle emissioni antropiche calcolate a partire dai risultati ottenuti tramite l'ottimizzazione economica del modello applicata sia al caso svedese che italiano. I relativi risultati confermeranno che il metanolo rinnovabile rappresenta un'alternativa valida e sostenibile al metanolo fossile commerciale.

Parole chiave

Supply chain, biomassa residuale, biometanolo, emissioni di gas serra, trasporti, MILP, ottimizzazione, biodiesel, potenziale tecnico-economico, realistico

Abstract

This document addresses the analysis on the development of a supply chain model, which aims to produce the background system that allows the production of bio-methanol from residual biomass, by employing the CONVERGE technology. The study focuses on the improvement of an already existent model to make it more feasible for a real world application. Moreover, it deals with presenting and discussing the results that would be obtained in more specific realities, which have been studied.

Firstly, it has been conducted a literature review to assimilate useful information for the whole systems of description and implementation of the problem. This has been revealed important to find the main possible changes and additions to apport into the model, but also to discover aspects on which to conduct some studies. The majorly investigated feature consists into the road transport system, which has been characterized and modelled more realistically. Afterwards, the assigned case study, regarding woody residues in Sweden, has been defined and, therefore, it has been implemented in the model. Through the economic optimization, the most convenient configuration of supply chain has been found and the final outcomes, which are referred to different levels of decisions, are analysed. The model has been implemented also for the Italian case (already defined in the precedent work) to evidence the differences produced in results by another situation and also to verify the versatility of the model.

The final study has been done on the estimation of the anthropogenic emissions calculated from the outcomes of the economic optimization of the model applied to both Swedish and Italian cases. The relative results will confirm that the green methanol produced with this system consists into a valid and sustainable alternative of the commercial fossil methanol.

Key words

Supply chain, residual biomass, bio-methanol, GHG emissions, transports, MILP, optimization, biodiesel, technoeconomic potential, realistic

Extended Abstract

1 Introduction

From quite some time, the EU countries have pledged to reduce the emissions of the transport sector following the European directives, which request the achievement of 10% of renewable energy use in transports by 2020 [1] and the 14% by 2030 [2].

The biofuels, which are gradually becoming involved in the fuel market, can give a contribution to reach this new target, because their main advantage consists into representing a valid possibility for an immediate transition to a lower carbon emissions scenario.

The EU commission has imposed several restrictions upon the biofuels produced from food, feed crops and with high indirect land-use [3]. Nevertheless, it supports the '*Advanced Biofuels*', namely the ones produced by residual biomasses listed in Part A of Annex IX in [4] (in Appendix B), and their adoption is encouraged by [4], in which their share inside the energy consumption of transport sector should be as high as 3,5 % by 2030.

The main barriers connected to the *second generation* fuels are both technical and economic, as they involve complex conversion processes and supply chain management [5]. Moreover, the continuous operation of the biorefineries requires a constant, reliable and cost efficient supply system of biomass and distribution system of biofuel, which contribute considerably upon the production cost.

1.1 Supply chain and literature review

More in detail, the problem of the supply chains is addressed in this paragraph.

The supply chain consists into the complex system of entities involved in different processes and activities, which allow a certain product to arrive to the final consumer [6]. In this case, regarding biomass, which represents the exploited resource, it is composed by phases of harvesting, collection, storage, pre-treatment and transport [7], while for the biofuels, which represent the final products, it accounts their transformation and their distribution to potential purchasers or intermediators. Therefore, it allows a managerial and logistical control, responsible of the final cost of production for the biofuel and for the correct working of the whole background system respecting the legislation.

The biomass supply system involves a high level of variability produced by many factors and the main challenge of this vast issue is to achieve its optimal configuration [5]. There are many studies present in literature, which analyse different possibilities. Some of them are discussed in [5]:

- Decision level, which defines the temporal detail given by the analysis and it can include the following decisions of types [8]: strategic (long-term) [9], tactical (medium-term) [10] and operational (short-term) [11].
- Structure: represents how the biomass supply chain is arranged, in other words the connection between points that could result into flow of information and material.
- Modelling approach, which consists into the mathematical equations that describe the situation and there are different types of it: stochastic [12], deterministic (single objective [13] and multiple objective [14]; linear [15]and mixed-integer linear programming [16]; non-linear programming [17]), hybrid [18].
- Problem approaches could be different: heuristic [19], multi-criteria decision analysis [20], GIS-based [21], time discretization.

About the model approach, a widespread and effective methodology, for the biomass supply chains, is the deterministic mixed-integer linear programming (MILP). This category has the great advantage to find always an optimal solution (if exists) [22] and it is commonly used with commercial solvers [23].

The optimization function could be based on different criteria, but the most common ones are focused on the economic field, for example the cost of production for the *second generation fuels* must be the lowest possible to have an acceptable profitability [24]. Moreover, there are many others listed in the document [25], which not necessarily regard the economic aspect, such as the minimization of the GHG emissions and thus the overall environmental impact.

An interesting study for the supply chain could be based on the minimization of costs and of GHG emissions, defining a multi-objective problem. In this case there is not a single optimal solution, but a set of them (Pareto set), each one being a compromise as no one of the objective functions can be optimized without penalizing the others [26].

A commonly discussed aspect in supply chains is about the centralization or the decentralization of the system. A centralized system is characterized by a low number of entities selected between the proposed ones and it could be convenient from an economic point of view when the investment costs of the facilities are characterized by strong economies of scale, but also by low operating costs and easy management [27]. On the other hand, a distributed system could bring to lower transport costs favoring an intermediate pre-treatment of biomass and/or to tendency of choosing smaller and numerous plants. Accordingly, another study [28] has observed higher GHG emissions with the centralized option, due to the higher transport employment.

Another aspect to be analyzed is the difference generated through the adoption of tactical/operational decisions to the basic strategic ones into the model. They consist into have more detailed information (about the quantities harvested, collected, produced, pretreated and transported and on time planning of the operations) in a short time frame and the consequent possibility to optimize them. This approach has relevant advantages for multi-period planned problems when for instance: there are seasonal biomasses, operation of the plant that could be defined by the optimization, pre-treatments, which require certain time to wait, etc.
However, a model with this temporal detail requires a time period discretization, therefore the number of variables will increase, and may result in consistent CPU time concern. [25]

1.2 Context background

The study, conducted in this thesis, is part of the CONVERGE project, which participates to the research and innovation programme Horizon 2020. It involves the development of a technology, which must comply with principles of low-carbon production, efficient use of resources and exploitation of residual biomasses [29], chosen from the listed ones inside Annex IX of [4].

The CONVERGE technology performs a thermochemical transformation of biomass, where the final product consists into bio-methanol. Moreover, it consumes electricity, because the self-produced one is not enough to satisfy its demand.

1.3 Thesis objectives

This thesis will deal with the definition of the chain entities, phases and also with the draft of a supply chain model, in which to integrate the CONVERGE technology. The model will be implemented with the MILP methodology, in order to find the optimal configuration from the given data in input (entities location, biomass potentials, capacities, etc.). It strongly refers to a previous work (Milani's one) [30] and it can be seen as a its improvement.

Then, the arising model will be tested on two real cases, in order to analyse the results produced regarding the decision level and also to make some considerations upon other aspects, mentioned in paragraph 1.1.

The innovative contribution given by this thesis work consists of:

- including some characteristics of supply chains designed for real cases (constrained demand, distribution system, fields of interest for the end-product, specific case adaptations);
- implementing a more detailed modelling of some aspects, as for road transports and CONVERGE technology;
- conducting a more accurate analysis of the data for the specific case of study;
- estimating the anthropogenic emissions produced in each step of the supply chain, in order to find some eventual greener improvements to apply on the supply chain system.

2 Bio-methanol supply chain

The supply chain problem, in general, can be described and defined by the following features [5]:

- Geographical area, which can offer an important potential of residual biomass.
- Residual biomass, selected between the available ones, that can be exploited for the bio-methanol production and it is characterized on different aspects;
- End-product decision, which for this study consists into bio-methanol and no other co-products.
- Entities definition, which represent the production points, storages, terminals, biorefinery and finally purchasers. For each one, it should be defined the possible processes occurring with the necessary information about them, their possible sites location and the specific limitations;
- Transports, which permit the fluxes (of raw matter, products, co-products) between the different entities of the entire system. Different typologies of them could be exploited in the same supply chain.
- Distances and the whole costs that may arise inside the supply chain analysis.
- Assumptions: useful to simplify the problem and to make statements in it.
- Restrictions: such as supply and demand side, maximum capacities of entities and of infrastructure.

The conceptual architecture of biomass supply chain can be simplified into three different parts [25]:

- *Upstream*: gathering all the stages from the production of biomass until its arrival to the conversion facility. Therefore, it also comprehends the transport and the possible phases of collection of biomass, storage and pre-treatment in between.
- *Midstream*: regards the conversion process itself occurring at the biorefinery.
- *Downstream*: covers the storage of the biofuel and its own distribution.

The upstream part can have a vast variety of options according to the biomass type and it is determinant for the resultant supply chain that could arise.

2.1 Supply chain characterization

The features of the bio-methanol supply chain, considered for the definition of the model, are briefly detailed here referring also to the precedent work [30]:

- Biomass ($\mathscr{B}$) is defined by its characteristics in terms of: moisture content (MC), bulk density, chemical composition, physical state, lower heating value and period of availability. Some of them may vary along the supply chain path if pre-treatments are forecasted.
- Bio-methanol produced has defined characteristics, which are the same of the commercial fossil one.

- Harvesting/production phase ($\mathcal{I}$) is the starting process of the supply chain where the biomass is collected from its natural state or is produced if it derives from industry. It can be very variable according to the biomass in question: mostly agricultural and forest residues need a more complex planning of this stage, because they are characterized by the harvesting phase. Usually, the period of harvesting is followed by an on-site (or roadside) storage of the biomass to do a first drying.
  Anyway, for this primary general discussion this phase is not analysed specifically and it can be considered as a unique block, in which it is known about the available specific biomass: the yearly producibility (in ton/y) and its purchasing price at this point.
- Storage phase ($\mathcal{J}$) represents the place where the residues can be stacked for the time required, allowing the right operation of the biorefinery. It is an indispensable entity for the seasonal biomasses and it could become for the non-seasonal ones (as wood) an economical possibility for their further drying during their permanence. Otherwise, the other alternative is the industrial dryer with lower drying time, but with high operational costs.
- The pre-treatment is a procedure, in which the biomass can improve some properties in terms of preservation (reducing dry matter losses) meeting the requirements for storage [31] (MC < 20-25%) and for the thermochemical process (MC in input of the CONVERGE gasifier equal to 10%). In this analysis, it is performed at the storages.
  As asserted by Milani [30], the pre-treatments can be summed into: comminution/chipping, drying and densification. Moreover, the humid biomasses can be dried into two steps, instead of a total long one and, when the biomasses achieve a certain MC, they can face a process of densification, which could give important advantages regarding the volume occupancy and a further little drying. The high operative costs due the energy consumption that regard the forced drying are not trivial and they may constitute into an obstacle for the choice of this process.
- Biorefinery ($\mathcal{K}$), where the technology used for the transformation of biomass into purified methanol is the CONVERGE one. Its size has been limited between 10 and 300 MWth of biomass in input for computational limits and reliability about costs.
  The only aspects of interest are its total conversion efficiency of biomass into methanol, the ratio between the net electrical power absorbed from the grid and the input thermal power of biomass and, finally, the separate sizing of the industrial dryer. They can vary with different MC states of the biomass entering the biorefinery, namely the conversion efficiency remains constant until biomass has MC lower than 35%, after which it starts to be penalized. Then, with the increasing of MC, the electricity purchased increases until it stabilizes with MC higher 35% (when the auxiliaries start to be fed only with the purchased one), while the size of dryer proportionally increases.
- Methanol users ($\mathcal{M}$): the main possibility available nowadays, which consists into a sure and already developed field, where the bio-methanol is certainly requested to meet lower levels of carbon dioxide, are the biodiesel plants.
- Terminals ($\mathcal{R}$), which represent the points used to change type of transport, limited to trucks and trains. They are used to load or unload the biomass/biofuel and, for this model, are always matched with the truck transport that can reach every place on the land.

2.2 Transports

Between the transports considered, truck and railway, the trucks are indispensable for the supply chain and an alternative and detailed analysis has been conducted on them. Therefore, like an independent transport company, it has been assumed to purchase trucks and to recruit drivers, which both are assigned to a certain entity and they are required to transport the biomass/biofuel from that point to the others. This assignation results very useful when the distances to cover are high, so when it is difficult to manage the transport system from one central point of reference.

Three different types of trucks have been considered according to the nodes that they serve and they are assigned with the relative arcs number: 1) 60 ton chip truck [32], for smaller transported quantities of biomass; 2) 75 ton chip truck [32], for larger quantities of biomass; 3) 60 ton tanker truck, to transport bio-methanol.

The estimation of the number of drivers and trucks is decided according to the time required (h) to do the operations (loading, unloading, driving, waiting) that is limited by the number of weekly working hours of each single truck and driver.

About the railway transport (with arc n. 11), it is considered that the service is provided by a third-party company with the cost function based on the filled wagon of train, which has a maximum capacity of 60 m^3.

The table of distances will be structured as reported in Table 1, in which the road ones are represented in red [33] and the rail ones in yellow [34], while with empty cell the connection is not effectuated. Then, the added arcs numbers correspond to the type of connection decided between the different entities ($\mathcal{I}$ harvesting point, $\mathcal{J}$ storage, $\mathcal{R}$ terminal, $\mathcal{K}$ biorefinery, $\mathcal{M}$ demand):

Table 1. Distance type (rail and road) distinction and connection types between supply chain entities

	$\mathcal{I}$	$\mathcal{J}$	$\mathcal{R}$	$\mathcal{K}$	$\mathcal{M}$
$\mathcal{I}$		1	1	1	
$\mathcal{J}$			2	2	
$\mathcal{R}$			11	2	
$\mathcal{K}$			3		3
$\mathcal{M}$					

2.3 Improvements on Milani's Model

The actual model presented in this thesis work refers to [30], which has been improved in order to get more realistic results.

The main changes apported are:

1) Equal subdivision along the year of the collection phase in sites with large biomass potential.
2) The percentage of technical and economical available biomass is considered to each production site instead to the total ones.
3) Different modelling of the truck transport costs: it has been assumed to own directly the transport company, in order to analyze directly the costs connected. Moreover, this choice has been encouraged by the difficulty into finding reliable economic information about third-party companies of transport, for which it is difficult to have access.
4) Different rail transport costs, which have lower fixed costs and higher variable ones.
5) Improved component modelling of the industrial dryer, according to the size that is left free to variate, and consequent its separate cost estimation.
6) CGE updating for each possible biomass characterization/moisture content that could enter the conversion facility and deletion of burning a part of residues to dry wet biomass.
7) Introduction of electric ratio, which is the ratio between electricity input and the LHV biomass input defined for each type of biomass state at input of biorefinery.
8) Selection of existing biodiesel plants, instead of petrochemical refineries.
9) Limitation of the quantity sold to the biodiesel plants according to their yearly production capacity of biodiesel.

10) Establishment of ship ports or collecting points for methanol of very large capacities, when the local demand is too low for the producible quantity of biomethanol.

3 Methodological Framework and MILP formalization

3.1 MILP structure and criteria selected

First of all, by referring to the previous paragraph 1.1 the selected modelling approaches are here reported:

- Single objective function based on overall NPV, in order to obtain the most economical configuration, as in general the production costs of *second generation* fuels are really high. A subsequent analysis will be performed on the GHG estimations for its production and on the emissions saving due to its usage inside the biodiesel production.
- Multiperiod approach, because the study deals with both strategic and tactical decisions, as it is forecasted a diversified trend along the year of operation.

The model has been subdivided into definition of:

- Sets, which comprise the categories of subjects analysed:
    - Biomasses at initial state, after a first and second drying, densification and final biomethanol, traduced in $\mathcal{B}$ = {*Basrec, Bdried1, Bdried2, Bdens, Bfuel*}.
    - Chain points ($\mathcal{N}$), which are harvesting/collecting points($\mathcal{I}$), storages ($\mathcal{J}$), terminals ($\mathcal{R}$), conversion facilities ($\mathcal{K}$) and biodiesel plants ($\mathcal{M}$);
    - Representative year discretized in periods ($\mathcal{T}$)
- Objective function: representing the function to be minimized. It is defined as inverted yearly NPV, by considering the costs positive and the revenues negative.
- Parameters, variables and constraints.

In this model, the economic analysis has been performed on a representative year in which the supply chain is fully working.

The MILP problem, which has to be solved, is represented with the following formulation [35]:

$$\min \quad Z = c\,y + bx$$

$$s.t. \;\; Ay + Bx \leq b$$

Where $y \,\epsilon\, \{0,1\}, x \,\epsilon\, R_0^+, c, b$ are vectors of coefficients and A, B are matrixes of coefficients.

3.2 MILP formulation

The MILP model is defined by numerous constraints and here it is mainly explained how the costs voices of objective function are found.

The objective function (in €/y) to be minimized, accounting for total costs and revenues, is:

$$obj = PurchBiom + Purchel + CT + O\&Mbio \; + \; OPEXstTOT + \frac{ir\,(1+ir)^{LFP}}{(1+ir)^{LFP}-1}\,INV - earn$$

where the LFP are the years of project lifetime and ir the internal rate of return.

The cost $PurchBiom$ is connected to the purchased biomass b ($transp_{t,b,i,jrk}$), which is limited by the yearly availability at the harvesting/production point i and, if it is planned, by the harvesting schedule. It is obtained as:

$$PurchBiom = \sum_{jrk \epsilon J \cup R \cup K} \sum_{i \epsilon I} \sum_{b \epsilon Basrec} \sum_{t \epsilon T} transp_{t,b,i,jrk} \cdot MF_b \cdot priceBiom_b$$

Where $priceBiom_b$ represents the price of the biomass considered and $MF_b$the relative mass factor, as the quantities of biomass are expressed on dry basis.

The contribution due to the purchasing of electricity is given by:

$$Purchel = \sum_{k \in K} elec_k \cdot Price_{el}$$

Where $elec_k$ represents the arising electricity purchased by each biorefinery, according to the electic ratio defined for each biomass state as explained in Chapter 2.

The majorly studied costs are the ones connected to transports:

$$\begin{aligned} CT = \sum_{nn \in N} \sum_{n \in N} \sum_{t \in T} \sum_{b \in B} & transp_{t,b,n,nn} \cdot MF_b \cdot dist_{n,nn} \cdot cton_{km} + Njroad_{t,n,nn} \cdot C_{fixed} \\ & + Njroad_{t,n,nn} \cdot dist_{n,nn} \cdot C_{km} + \\ + \sum_{n \in N \setminus M} N_n^{drivers} \cdot Cdriver_n + \sum_{n \in N \setminus M} & N_n^{truck} \cdot Ctruck_n + \sum_{rr \in R} \sum_{r \in R} \sum_{t \in T} Njrail_{t,r,rr} \cdot Ctrain_{r,rr} \end{aligned}$$

Inside the formula, some important variables can be outlined:

- transported quantity of $\mathcal{B}$ between nodes $\mathcal{N}$ ($transp_{t,b,n,nn}$) at each investigated time period $\mathcal{T}$ decided by the overall optimization;
- number of journeys by truck and train between $\mathcal{N}$ for each $\mathcal{T}$ ($Njroad_{t,n,nn}$ and $Njrail_{t,r,rr}$), decided according to the payload of trucks and to maximum volume of train wagon;
- necessary number of drivers $N_n^{drivers}$ and trucks N_n^{truck} required in points $\mathcal{N}$ excepting the biodiesel plants, because they constitute into the end of the path. They have been selected according to the time required to do the operations and the effective operating hours of drivers and trucks.

The part of investments INV is actualized along the whole project lifetime and they are calculated for the different facilities according to their size. Regarding the:

- storages building and land, the size has been chosen by referring to the maximum stored quantity of biomass in one period t along the year.
- pretreatment machines, they are dimensioned according to the maximum quantity of biomass processed in one period t along the year.
- biorefinery block, it is selected the maximum thermal power of biomass input verified along the year.
- biorefinery dryer, which is properly sized according to the maximum value verified along the year of evaporated water from the biomass in one second instant

Then, it is accounted the $O\&Mbio$, which considers the cost due to operation and maintenance, excluding the electricity use, and it is represented by the 4.6% of the total biorefinery investment costs.

The operating costs due to the storage logistics (connected to the inventory carrying cost) and pre-treatments of the biomass are summed into $OPEXstTOT$. The pretreatment contribution of process g at storage j is dependent on the converted quantity from one state to another $conv_{t,bb,b,j}$ and it is limited between 0 and the maximum stored biomass in j $MAXstorage_j$. This quantity is equal to 0 when process g is not chosen ($z_j^g = 0$):

$$0 \le conv_{t,bb,b,j} \le z_j^g \cdot MAXstorage_j \qquad t \in T, j \in J, bb \in B, b \in B$$

Here, it is reported a representative balance of the biomass b stored in j ($bs_{t,b,j}$) in a period t of the year, where are present respectively the biomass stored at the precedent period decreased by the dry matter loss dml_b, the new incoming biomass, the subtracted/added one from the pre-treatment process and the exiting one :

$$bs_{t,b,j} = bs_{t-1,b,j} \cdot (1 - dml_b) + transp_{t,b,i,j} + conv_{t,b,bb,j} - transp_{t,b,j,rk}$$

$$t \in T, i \in I, j \in J, rk \in R \cup K, bb \in B, b \in B$$

The revenues part comes exclusively from the selling of biomethanol to the purchasers m:

$$earn = \sum_{t \epsilon T} \sum_{kr \, \epsilon \, K \cup R} \sum_{m \epsilon M} transp_{t,b,kr,m} \cdot price_{biofuel} \qquad b \epsilon Bfuel$$

3.3 GHG evaluation a posteriori

The greenhouse gas emissions have been estimated, in order to define if this possibility of producing methanol from residues could constitute into plausible alternative from the fossil one.

This is an analysis made a posteriori on the results of the supply chain model.

The formula used for the estimation of the $CO_{2_{eq}}$ of a common biofuel is calculated according to the directive [1], which does not account of emissions connected to manufacture of machinery and equipment.

It is important also to count the contribution of the other greenhouse gases (different from CO_2) in the $CO_{2_{eq}}$, through the use of the Global Warming Potential (GWP).

The general formula for the estimation of emissions at each production phase i can be summed with:

$$e_i \left[\frac{gr_{CO_{2,eq}}}{MJ} \right] = \frac{CO_{2_{eq,i}}}{tot_{\substack{biometh \\ produced}} \cdot LHV_{methanol}}$$

It represents the ratio between the yearly produced emissions at phase i and the equivalent LHV energy of yearly bio-methanol produced.

From the outcomes, it is calculated the harvested volumes of biomass, the electricity exploited by the biorefinery and by trains and, finally, the fuel consumed by trucks for their operations to make estimations upon the anthropogenic emissions. For this purpose, it was used the following literature to calculate this quantities, by using also the proposed emission factors: [36], [37], [38], [39], [32], [34], [40].

4 Cases of study

The model was mainly applied to optimize the supply chain of the forest residues in Sweden, indeed, for each entity type, it has been made an accurate research of the specific characteristics approaching more to reality. Then, it has been investigated also the 'Italian case' (with data selected from the precedent work) to compare between the two different cases and models.

The following table 2 represents the main characteristics and assumptions for the two respective cases:

Table 2. Main differences between Swedish and Italian cases

	Swedish case	Italian case
Geographical area	Latitude ϵ [55.8,65.24] Longitude ϵ [9.67, 21.63]	Latitude ϵ [40.5, 44.04] Longitude ϵ [10.12, 17.17]
Biomasses	Non seasonal: Chips from wood residues	Non seasonal: Chips from wood residues Seasonal: Grape marc and Olive pomace
Availability Period	All year	Wood residues Autumn-Winter-Spring Grape Marc January-February Olive Pomace January-March
Biomass as received state	MC Wood residues 35%	MC Wood residues 35% MC Grape Marc 55% MC Olive Pomace 12%
Biomass price	Wood residues 55 €/ton	Wood residues 55 €/ton Grape Marc 22 €/ton Olive Pomace 75 €/ton
Economic biomass potential	Wood residues 2123 kton/y	Wood residues 280 kton/y Grape Marc 19 kton/y Olive Pomace 125 kton/y
Connections by rail	From storages to conversion facility and from conversion facility to the biodiesel plant	From collection point to conversion facility and from storage to conversion facility
Demand	Biodiesel plants and ship port	Petrochemical refineries
N. total points	64	53

The sites location selected for Sweden are represented in figure 1, where the size of collecting points is proportional to their annual availability, while for the biodiesel plants it is proportional to their maximum annual capacity:

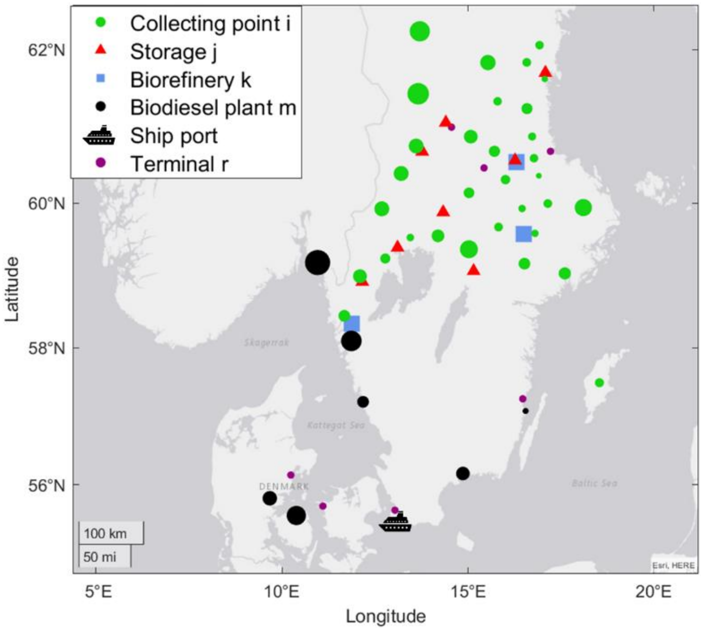

Figure 1. Location sites of supply chain entities proposed for the Swedish case

The same has been done for the Italian case, in which some points can be found in southern (figure 2) and others in central Italy (figure 3):

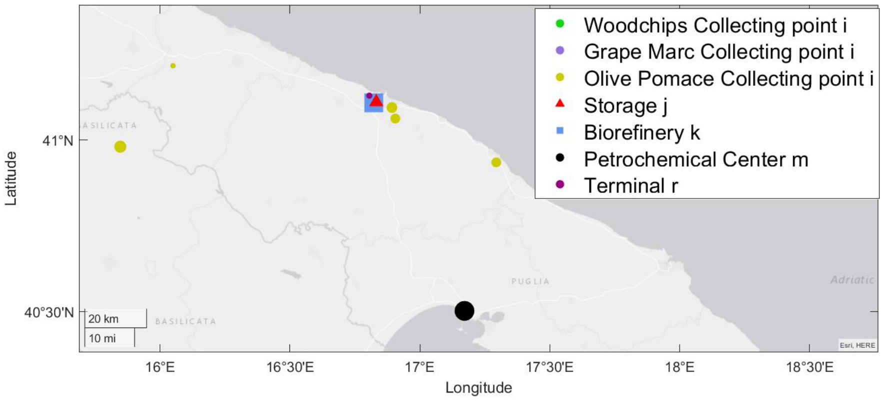

Figure 2. Location sites of supply chain entities proposed for the Italian case in southern Italy

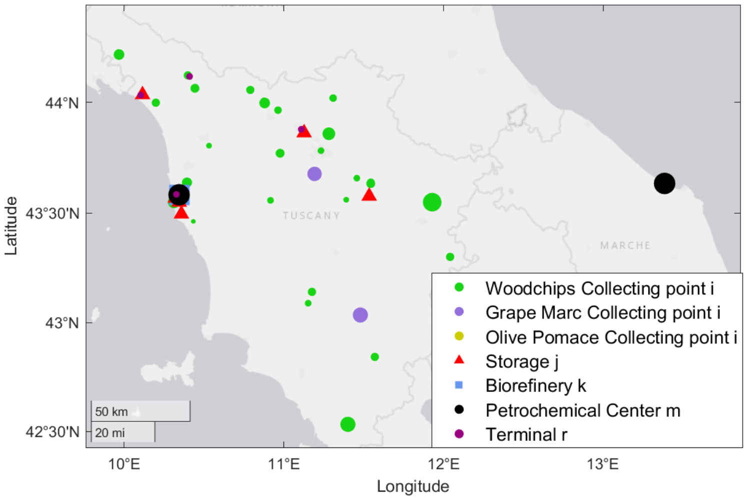

Figure 3. Location sites of supply chain entities proposed for the Italian case in central Italy

For the Italian case, the results were obtained with the actual model, but omitting the points (paragraph 2.3): 1) for low biomass potentials of the single harvesting points; 8), 9) and 10) because, between the available data for the Italian case, there are no information about the biodiesel plants and therefore about potential demand of bio-methanol. As there is no limitation of the demand points, it results not necessary the selection of ship ports, where to let merge the produced bio-methanol in excess to demand of biodiesel plants.

For each case, it was used a time discretization of two weeks, which has revealed to be compatible with their specific problem description.

Moreover, it has been defined the *Base case,* the situation of reference, and alternative studies obtained by varying some aspects of it. They are shown in the following table 3:

Table 3. Presentation of scenarios proposed for both Swedish and Italian case

Scenarios of Sweden		**Scenarios of Italy**	
S.0	*Base case*	**I.0**	*Base case*
S.1	No limitation to biodiesel capacities	**I.1**	Milani's modelling of transport costs
S.2	No limitation to biodiesel plants and increase of power size range until 350 MWth	**I.2**	Increased price of bio-methanol
S.3	Increased price of bio-methanol	**I.3**	Decreased price of bio-methanol
S.4	Decreased price of bio-methanol		

5 Results

The following results were obtained implementing the model on Matlab 2020b with language POLIMIP, which refers to YALMIP, and optimizing with CPLEX IBM version 12,10.

For the Swedish case, the *Base case* produces the following layout of supply chain in figure 4, in which it is expressed, in yearly kton, the sold biomethanol to the specific demand points:

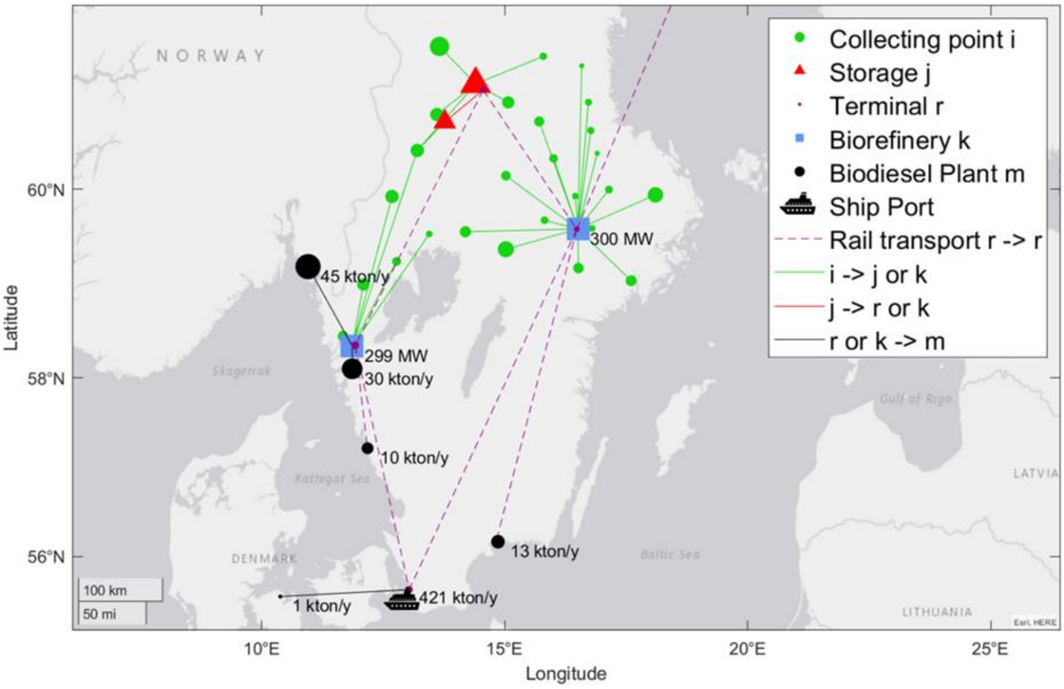

Figure 4. Resultant supply chain layout of Base case S.0

The limited demand represents a disadvantage for the supply system, which prefers to exclude the selling of a higher quantity of bio-methanol towards the further remaining biodiesel plants, because it results not economically convenient. Therefore, by seeing table 4 the biomass is used partially (77%) and the methanol production cost is pretty high (achieving 524 €/ton), due to the long distances covered by the supply and distribution system. On the other side, without these strict constraints on demand (S.1), the biomass is more exploited, profits are higher, but the marginal ones are lower because one more plant is chosen.

A salient point of Swedish case is the usage of storage as collecting points, where biomass merges in order to reach the rail terminals. Differently from the results of the Italian case obtained with the precedent model, the intermediate depots are not anymore used to face the seasonality of the biomass and their trend is almost constant. The same can be said for biomass input and methanol output in the biorefinery, which presents a very constant trend along the year.

Moreover, by comparing S.1 with S.2, it has been found that another limiting factor for the high biomass potential contexts is the maximum size of the biorefinery plant. In S.2 (table 4), it is visible that it is more advantageous to exploit the economies of scale by building large plants at maximum size and to avoid the construction of an additional small one to produce methanol from the remanent 10% of available biomass. Despite that, the profits are furtherly higher and the LCOF lower. The problem tends to assume a centralized scheme (paragraph 1.1), but even if the cost share of transports becomes higher in this case, the road transport decreases, while the rail is surprisingly boosted without incrementing emissions.

By watching the scenarios S.3 and S.4, it is evident an important influence of the bio-methanol price on the overall and marginal profits, while the structure of the supply chain is not remarkably affected.

For the Italian case, the results of the reference scenario show the following layout in figures 5 and 6:

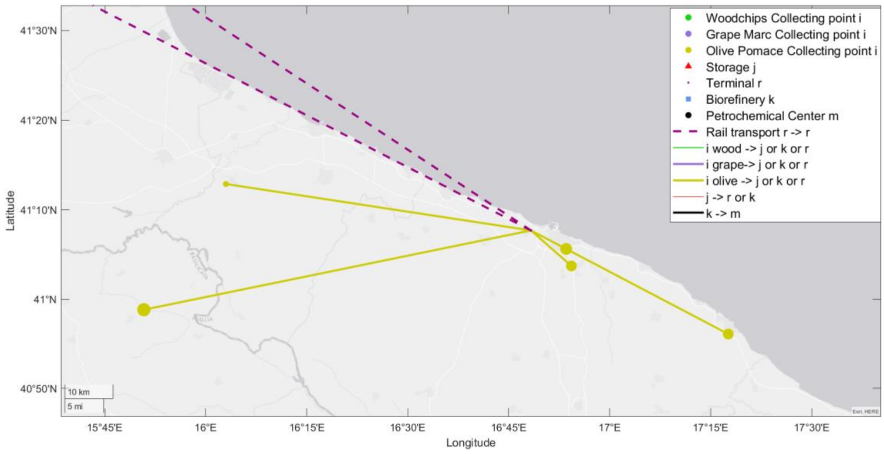

Figure 5. Resultant supply chain layout for Base case I.0 in southern Italy

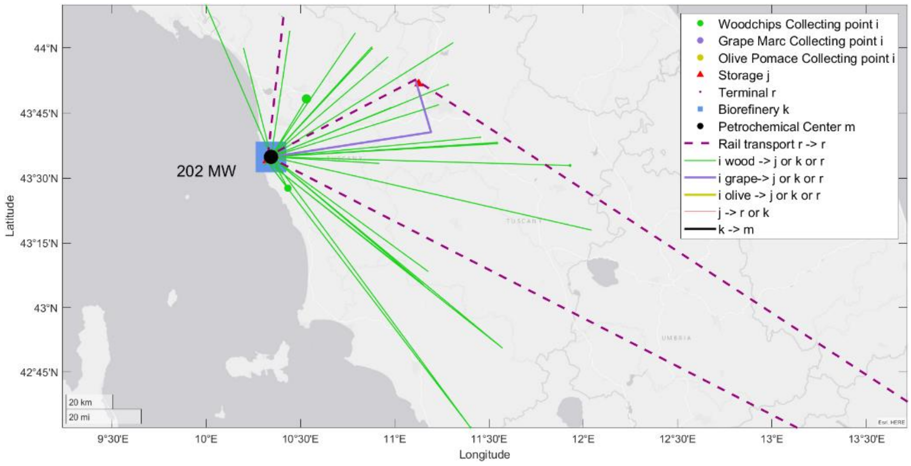

Figure 6. Resultant supply chain layout for Base case I.0 in central Italy

It has been confronted with the one of Milani [30] and some differences have been evidenced in: higher LCOF ($487\ €/ton$), mainly due to the higher price of olive pomace; train transport chosen also for medium distances, encouraged by the different costs (paragraph 2.3); finally higher profit and lower biomass utilization. They will be furtherly discussed during the comparison with the other scenarios.

However, the centralization of the problem towards the biorefinery based in 'Livorno' is still present and, comparing the size of it with the ones of S.0, it is important the difference given by the diverse biomass potentials.

In addition, the biomass planning at the storage and biorefinery is different and it is shown in the following graphs:

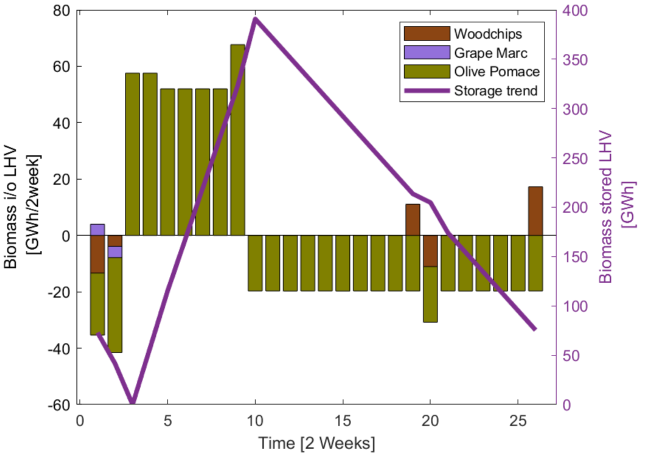

Figure 7. Periodic net fluxes of biomass inside the storage and total biomass stored every two weeks (expressed in GWh) of scenario I.0

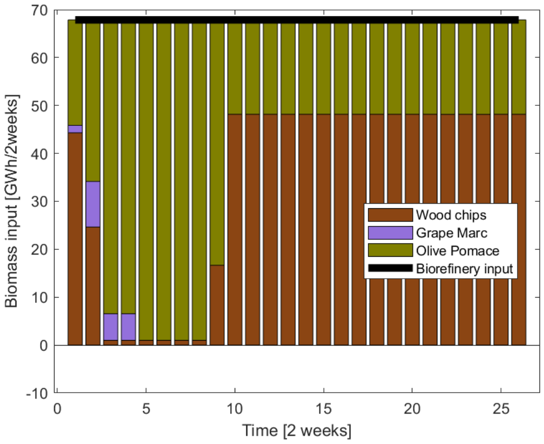

Figure 8. Periodic biomass input into biorefinery every two weeks (expressed in GWh) in scenario I.0

In the left side image, it is shown, with bars, the net bi-weekly flux of each biomass type into intermediate depots (referred to the left axis) and with line plot the total stored biomass (right axis). On the other side, it is shown, with bars, the bi-weekly biomass input at the biorefinery and with line plot the total one.

It is noticeable that the biomass stacked at the storage has not a constant trend and the residue that majorly necessitates to be accumulated is the olive pomace, because it is seasonal and available in high quantity. At the biorefinery, it is more exploited during months in which the wood residues are not available to maintain a constant biomass LHV input, while the grape marc as soon as is available it is immediately converted into methanol

Then, the case I.1, compared with I.0, presents lower costs due to transport and consequently a decrease of LCOF. The profits have increased with approximately the total biomass usage. Indeed, for this context characterized by seasonal biomasses and low potential production points, it has been found not optimal the assignation of drivers and trucks to the upstream part made by the actual model, because it is more suggested when there is a uniform use of transport along the year with larger harvesting points. Moreover, this scenario is more similar to the one obtained with precedent model just in terms of biomass utilization, rail connections and storage sites, but still different on LCOF.

Again for Italy, it has been tested the model subjected to the bio-methanol price fluctuation (I.2 and I.3) and, like for Sweden, the outcomes do not show particular differences in the supply chain layout respect to the *Base case*. For I.2, there is a slightly higher usage of biomass and an increment of profit of about 45%, while for I.3 there is a subtle change in biomass usage too, but in fault, and an important decrease of profit.

From the results with low price of bio-methanol, the model starts to fail bringing to a drastic increment of the computational time (S.4) or requiring high memory availability (I.3), which induce the arrest of the simulation still at high gaps. Then, the profits would particularly suffer of this decrement, but it is the normality for the *second generation fuels*, which are characterized by high production costs [24].

Other interesting outcomes are here reported in table 4 (where N.F. stands for Not Foreseen):

Table 4. Final results of all scenarios analysed

		Sweden					Italy			
		S.0	S.1	S.2	S.3	S.4	I.0	I.1	I.2	I.3
Annual profit [M€/y]		41.367	49.033	53.82	68.181	14.169	20.366	22.57	29.48	11.35
Bio-methanol [kton/y]		546.3	699.6	638.1	543.6	545	180.85	184.1	183.8	179.8
Plants size [MWth]		300 299.5	280 300 188	350 350	296.6 300	300 298.4	202	205.6	205.3	200.8
LCOF [€/ton]		524.3	529.9	515.7	524.6	524	487.4	477.7	489.6	486.9
Biomass use										
Wood		76.9%	98.4%	89.8%	76.5%	76.7%	98%	98%	98%	97%
Grape							47%	100%	96%	47%
Olive							100%	100%	100%	100%
n. sites chosen										
hv. points		26/32	32/32	31/32	25/32	26/32	33/35	35/35	35/35	31/35
storages		2/8	4/8	3/8	3/8	3/8	2/8	2/8	2/8	2/8
terminals		9/12	7/12	7/12	9/12	9/12	5/5	2/5	5/5	5/5
biorefineries		2/3	3/3	2/3	2/3	2/3	1/2	1/2	1/2	1/2
demand		7/9	1/9	1/9	7/9	6/9	1/3	1/3	1/3	1/3
N. drivers		189	261	211	192	187	55	N.F.	68	53
N. trucks		63	86	72	65	64	35	N.F.	40	33
n. journeys by train in one year		1104	1107	1566	1086	1093	148	106	137	149
N. constraints		50833	49498	49498	50833	50833	42048	40246	42048	42048
N. variables	**Integer**	116	116	116	116	116	64	64	64	64
	Continuous	71449	70123	70123	71449	71449	70192	70092	70192	70192
Gap		3%	3%	3%	3%	5%	3%	3%	3%	13%
Computational time [s]		31292	8596	26368	14288	86526	33744	788	3105	5400
System		Polimi's computer 16 GB RAM Intel Core i7-2600 CPU 3.4 GHz					Personal computer 4 GB RAM Intel Core i5-5200 CPU 2.2 GHz			

Then, from the available results of the base cases S.0 and I.0, the emissions connected to the final product can be calculated for the two situations:

Table 5. Greenhouse gases emissions of bio-methanol obtained for both cases, share between phases and relative reduction respect to the fossil one

	GHG $\left[\frac{gr_{CO_{2,eq}}}{MJ}\right]$	Shares (%)			Reduction
		Harvesting	Processing	Transports	
Swedish bio-methanol	10.4	56 %	4%	40%	-90%
Italian bio-methanol	13.8	36%	56%	8%	-86%

The two cases are featured by different electric carbon intensities, for which electricity of Sweden results to be much greener than Italy [41]. As the processing part absorbs high quantities of electricity, the Swedish one resulted to be less affected by this contribution. Indeed, if for Sweden it was considered the same carbon intensity of Italy, the Swedish bio-methanol would have presented a higher impact than the Italian one, due to longer distances covered and also to larger harvested volumes of biomass. Moreover, a consistent reduction of emissions respect to the fossil methanol is verified in both cases.

Hence, the final estimation has been conducted on the avoided emissions for the biodiesel production with the usage of green methanol and they amount approximately to 7 $gr_{CO_{2eq}}/MJ_{FAME}$. Despite of that, there are still other facets, linked to the biodiesel production, on which one could intervene. For example, about the heat production necessary for the transesterification process, the same supply chain of bio-methanol could provide residues to be burnt for this purpose. When there are available high biomass potentials, like Sweden, this could be an evaluable alternative, instead of using natural gas.

6 Conclusions

In this thesis, it was wanted to define a supply chain for the CONVERGE technology, respecting principles of low-carbon production, efficient use of resources and exploitation of residual biomasses, by creating a MILP formulated model. Afterwards, the optimal configuration for the studied cases and the relative emissions have been found. This study can be seen as an improvement of a precedent work [30] and, in few words, it was reformulated the relative part to the modelling of CONVERGE technology, proposed a more sophisticate approach to model the truck transport and then added constraints related to the real world demand side and harvesting part.

The limitation of demand has made a particular difference, as investigated for the Swedish case, mostly on the side of profits and consequently on biomass utilization. While, from the comparison between the Swedish and the Italian cases, it was found that the truck/driver assignation method, even if it was interesting to cover long distances (as Swedish case), it has revealed to be more effective when there is a constant use of the transport during the year, which does not regard the upstream part in presence of seasonal biomasses.

The final topic examined in this study regards the evaluation of emissions produced by putting in practice this system. The outputs are interesting and effectively an important reduction of $CO_{2_{eq}}$ is verified, which benefits the production of bio-methanol, instead of the fossil one.

On the implementation side, the main barriers encountered to perform this study were:

- low CPU and memory available to do the optimization with a more complex model, traduced in long simulation time and lower optimality of the accepted solution (gap 3-5%).
- lack of usage of a GIS-software that would have made the difference, mostly, in the visualization of the data and of the results.
- the lacking knowledge of some costs, in general, and of interested local purchasers (demand) to produce a more realistic supply chain.

For the future works, there is still a good margin of improvement for this model. The most interesting points, which could be furtherly developed and improved are mainly four:

- Find an improved solution for the assignation of trucks and drivers for the upstream part;
- Inclusion of a residues supplying system for the biodiesel plants to further decrease the emissions, only if the single case permits it.
- Arrangement of a distribution system for the biodiesel produced towards the blending entities. Its implementation could be made a posteriori on the final results.
- Inclusion of the open-air storages option and improved economic data on the pre-treatment machines, but anyway the CONVERGE technology has revealed to be efficient for the phase of drying with biomasses of MC between (10-35%). If the biomasses were really humid, this analysis should be delved into.

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1 Introduction

The sensibility to the climate change, energy security and resources depletion is already established between the majority of earth's inhabitants. The next step is to act solving these problems that are already visible nowadays and that could have a major impact in the future decades, increasing the quality of humans' life at the same time.

The solution has been found into the renewable energy sources, such as wind, water, sun, geothermics, biomass, etc., which are exploitable in wider geographical areas than the concentrated ones, which host the fossil resources [42]. An energy source could be considered renewable, when its regeneration rate is equal to its utilization rate, avoiding a its depletion. More in detail, the discussion upon the renewability of biomass could be extended to the concept of carbon neutrality (or almost). On the contrary, if the utilization and the regeneration are not balanced, it results into a positive CO_{2eq} impact and into a negative one of biomass source.

The biomass seems to be the oldest source of energy used by the humans, as it has been exploited since the oldest civilizations. On the other side, in recent times interesting new developments are regarding it on different energetic branches, mostly for the transport sector that is still dominated by the fossil fuels.

The idea of EU commission consisted into promoting the use of renewable resources inside the transport sector by requiring to each EU Member States the achievement of the prefixed target of 10% share of renewable energy in transports by 2020 [1].

In general, European average did not reach the goal, even if the trend was positive during the last decade. Anyway, some countries overtook surprisingly it like Sweden, as it is visible from the following graph in Figure 1, where the renewable energy in the transport sector has achieved the share of 30.3%:

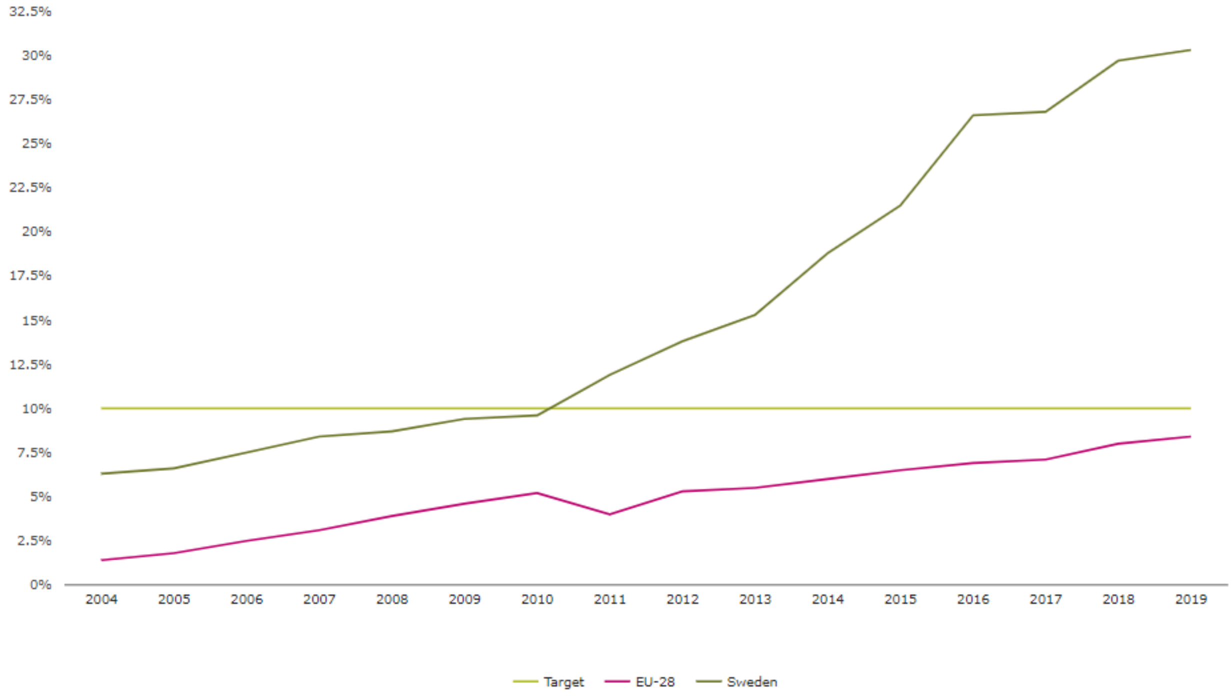


Figure 1. Shares of energy from renewables sources used in transport in Europe and Sweden. Source: [43]

The biofuels have given their contribution and are gradually becoming involved in the fuel market, because their main advantage consists into representing a valid possibility for an immediate transition to a lower carbon emissions scenario. In some cases, they can be used to feed directly the actual, already in use, technologies or with some appropriate changes. For these reasons, they result to be convenient for a smooth energetic transition taking advantage also of their storage possibilities, which is one of the most discussed issues for the transport sector.

Therefore, they can be good candidates to encourage a rapid leaving of the fossil fuels from the transport sector, in which they are the major players.

The bioenergy is an already affirmed field in Europe and the facilities that permit its production are the biorefineries. A rapid overview of the existent biorefineries in Europe is given by the following map in Figure 2 updated to the year 2017:

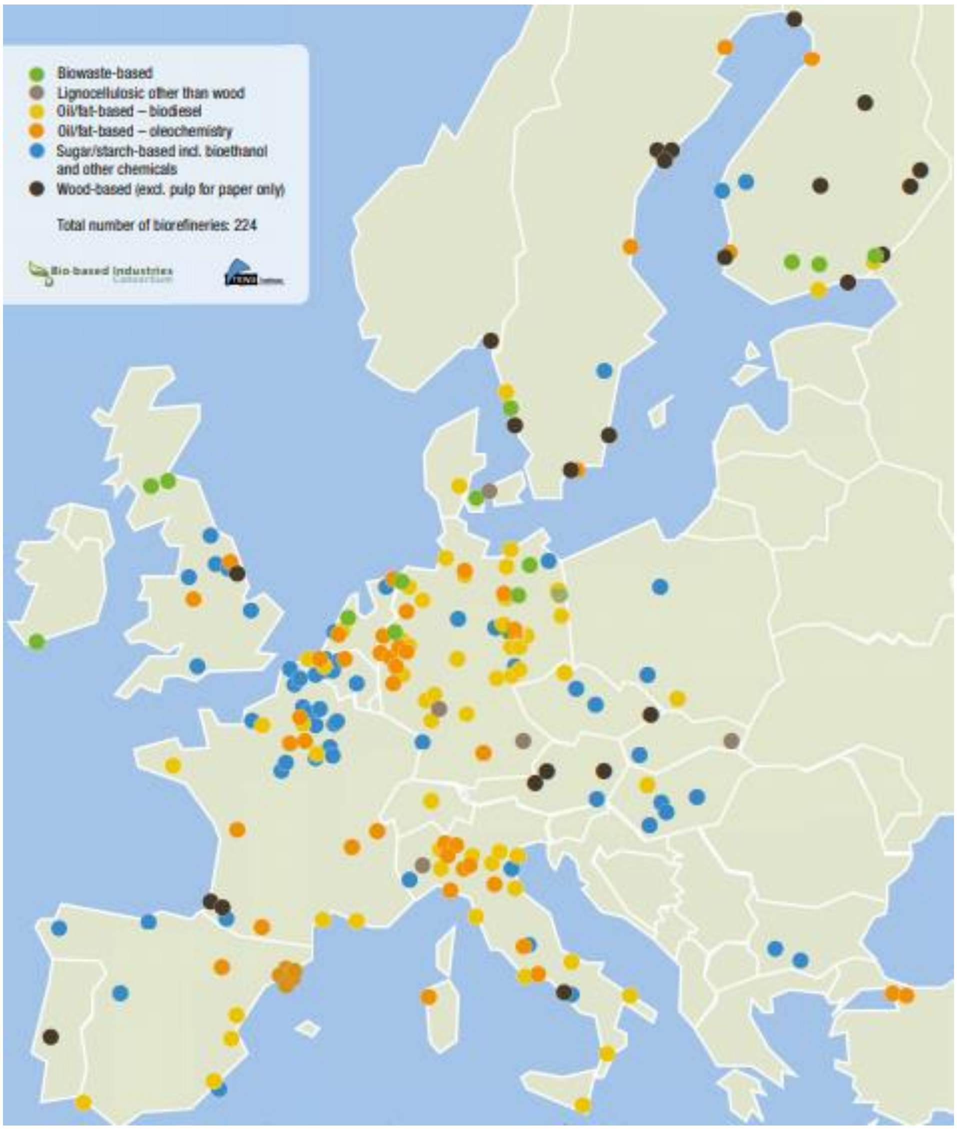


Figure 2. Biorefineries in Europe 2017. Source: [44]

They are differentiated for categories of feedstock processed. It is visible that each geographical area has a its own predominant feedstock used: central and southern Europe has a large number of plants exploiting the oily/fatty biomasses; in the Scandinavian area the woody ones; mostly in the central Europe, there is large use of sugar/starches. It is evident that some countries/zones are focused on specific biofuels, as Italy on biodiesels or the northern France on bioethanol. This could be due to many factors:

- Availability of certain biomass types;
- Development on specific technologies;
- Subsidies for determinate technologies and regulations from the State.

As already mentioned, there is an almost carbon neutrality connected to the biomass exploitation, if it occurs on the right way. Therefore, the GHG emissions for the biofuels cannot be estimated with the same method of the common fossil fuels, even though at the moment of the combustion of the biofuels, there is a visible production of air gases pollutants. The estimation is much more complicated:

- Primarily, if the renewability of the biomasses exploited is verified, the equivalent emissions due to their usage is zero or almost zero. Otherwise, its contribution should be accounted;
- Then, as the biomass is not available in nature at the required state, the procedures for the production and management of biofuels are still not carbon free nowadays and the relative emissions should be accounted.

The EU is already on the direction to further decarbonize the transport sector, where according to the [2] each Member State should require the fuel suppliers to ensure a minimum share of the total fuel consumption equal to 14% coming from renewable sources by 2030.

While in some states, there are biofuels that are already affirmed in the market, like ethanol from sugarcane in Brazil.

1.1 Biofuels introduction and directives

The biofuels could be categorized according to two different criterions: one based on their production process and the other upon their competition with food.

According to the first one, the conversion processes that convert the biomass into a biofuel, or to a product exploited for the biofuel production, can be summed into the thermochemical, bio-chemical and physical/chemical ones. The available processes that belong to them are briefly reported in Table 1 with their main products:

Table 1. Biomass conversion processes for biofuel production

Type of conversion process	**Type of process**	**Products**
Thermochemical	Combustion, gasification, pyrolsis	Heat, syngas, pyrolysis gases
Bio-chemical	Fermentation, anaerobic and aerobic digestion	Bio-ethanol, biogas, heat
Physical-chemical	Oil extraction, transesterification, compactation	Oil, biodiesel, pellets

Then, in Figure 3 it is shown, in general, how these processes can be applied to the biofuel production, according to the biomass types involved, the necessary intermediate steps, the final products and co-products. Moreover, a single product could be produced by different processes and the same single biomass could be exploited by multiple processes:

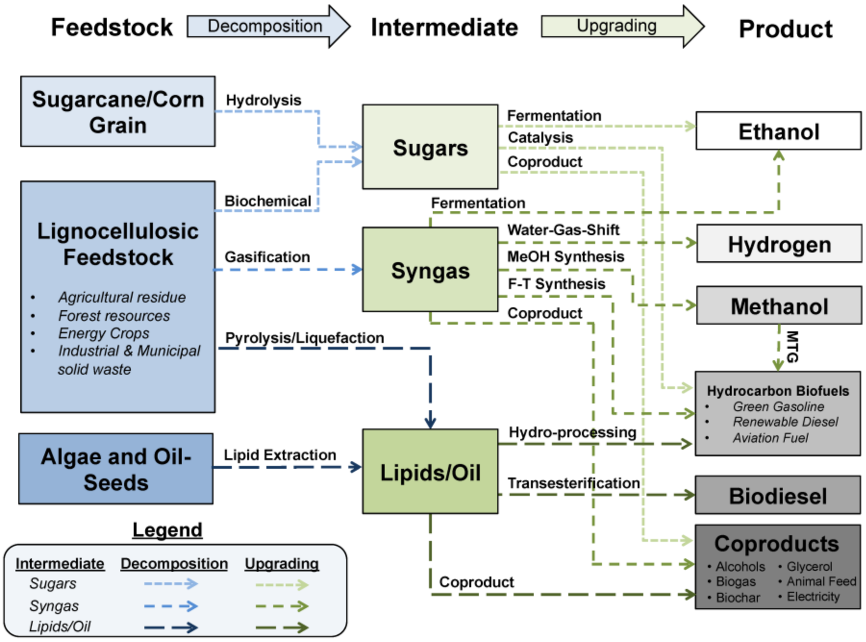


Figure 3. General overview of the biofuel production processes. Source: [45]

The possibilities are numerous with remarkable advantages and weak points. Therefore, the availability of a certain biomass in the desired location and a costs/benefits analysis will be determinant in the decision of the most appropriate process to choose.

It is noticeable, from Figure 3, that for the production of the biofuel the operations of decomposition and of upgrading are always required and, usually, many passages and sometimes sophisticated technologies are involved.

From the transformation/upgrading processes, some co-products are produced, which can be useful not only into the energetic field, but also into the industrial one, livestock, etc. and their selling can contribute to lower the biofuel price, making it more competitive.

Otherwise, according the second criterion the biofuels can be subdivided into three types [24]:

- *First generation,* which come from biomass that is also a food source. They could be discarded when the food would start to run out (i.e. sugarcane, barley, potato, sugarbeets, whey, maize, oily plants and seeds). The main types of transformations involved with these biomasses are the oil extraction with the subsequent transesterification (to transform the oil into biodiesel) and the fermentation (ethanol production);
- *Second generation,* which come from biomass that does not compete with food, as non-edible lignocellulosic biomass. (i.e. wood, agricultural/ forest residues and municipal solid wastes). The price of the biomasses involved is lower than the ones of first generation, but the transformation process is still expensive due to new technologies. The main processes involved are the thermochemical one, where the main fuel produced is methanol, and for the biochemical, the ethanol;
- *Third generation,* which regards mainly the algal biomass with high lipid content. Differently from the biomasses involved for the second generation fuels, the growth yield and also the oil yield are higher. Then, the extracted oil is used to produce biodiesel through transesterification/hydrogenolysis.

Regarding the biofuels and bioliquids produced from food and feed crops, included in *first generation* category, the EU commission has imposed some restrictions, in which their share in the energy supply ‘shall be no more than one percentage point higher than the share of such fuels in the final consumption of energy in the road and rail transport sectors in 2020 in that Member State, with a maximum of 7 % of final consumption of energy in the road and rail transport sectors in that Member State.’ [3]

Moreover, the fuels produced from feedstocks with high indirect land-use that implicate high carbon-stocks will be definitely no more accepted in the future by EU commission, which has set that ‘From 31 December 2023 until 31 December 2030 at the latest, that limit shall gradually decrease to 0 %’. [3]

An emergent category of biofuels that consists into the ‘*Advanced Biofuels*’ is produced by the residual biomasses listed in Part A of Annex IX in [4](listed in Appendix B), which belong to the *second generation* category. The EU encourages their production by imposing that their share inside the energy consumption of the transport sector should be at least 0,2 % in 2022, at least 1 % in 2025 and at least 3,5 % in 2030. [2]

Therefore, inside the idea of future for Europe, the bioenergy will still have an important role, but with more precautions to sustainability for the environment and reduction of GHG emissions.

The main barrier connected to the *second generation* fuels consists into their commercialization, because, on technical and economic point of view, they involve complex conversion processes and supply chain management [5]. Moreover, the continuous and constant operation of the biorefineries requires a constant, reliable and cost efficient supply system of biomass and distribution system of biofuel, which contribute considerably upon the production cost.

1.2 Supply chain of biomass

The supply chain consists into the complex system of entities involved in different processes and activities that allows a certain product to arrive to the final consumer [6], starting from the harvesting phase of the raw matter. In this case, the biofuels represent the final products of the supply chain, while the biomass the source that permits their production.

About biomass, it manages the different phases of harvesting, collection, storage, pre-treatment and transport [7]. While, for biofuels it accounts also their transformation and their distribution to purchasers or intermediators. Therefore, it allows a managerial and logistical control, responsible of the final cost of production for the biofuel and for the correct working of the whole system behind, respecting the legislation.

The final scope of the biomass supply chains is to succeed into the sale of the end-product, in this case the biofuel, on which is based all the system.

Their production sometimes is not as simple as their applications because their origin comes from biomass, available in nature (in many cases), where its accessibility is pleased by the technological means currently available. In this field, there is a lower interest of improvement in terms of efficiency and emissions than for the process of transformation, as the technologies of the latter are always object of research.

The link between the gain of biomass, its own transformation into a fuel and then its sale is the transport, which consists into the main focus for the supply chains. It plays an important role for the determination of the structure and operation of the whole supply system. Moreover, there are different types of transports available, each with interesting strong points:

- By road, it makes accessible many places on the land, but it could result not convenient when the distance becomes long and when the quantity to be transported is large;
- By rail, it is a promising conveyance, also for the future, because it uses electricity. Then, it results to be more convenient than truck for long distances;

- By ship, it is suitable for places surrounded by water and particularly when the transported quantity is important, but the time of travelling is consistent;
- By air, it is appropriate for very long distances, but for very low quantities transported. It constitutes into the most expensive type of transportation and also into the most polluting one.

By analysing the different processes behind a product, it is possible to do also a LCA (Life Cycle Analysis) of it, which also accounts for the emissions. In a realistic scenario, which is represented by the current technology, the CO_{2eq} should be accounted for the production of the biofuels, due to biomass extraction, handling, transportation and transformation.

1.3 Context Background

After this very general digression upon the supply chains and biofuels, it is important to depict the background, where this thesis is collocated.

The study led in this thesis is part to the CONVERGE project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 818135.

This project involves the development of a context near to reality, in which to integrate the commercial application of CONVERGE technology, always respecting the principles of low-carbon production, efficient use of resources and exploitation of residual biomasses coming primarily from agriculture and forest residues, followed by forest and agro-forestry industry products. [29]

More clearly, from [2] Art.2:" 'residue' means a substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it;"

The feedstocks of interest for this purpose have been chosen from the listed ones inside Annex IX of [4], which have been proposed for the production of *Advanced Biofuels*.

The main macro categories in which they can be classified are:

- Agricultural residues
- Forestry residues
- Agro-forestry industrial residues and wastes

For the quantification of the CO_{2eq}, it is important to make the distinction between waste/residue and by-product. The main definitions arising from document [46] are:

Waste: 'means any substance or object which the holder discards or intends or is required to discard'.

By-product: 'when substances or objects resulting from a production process not primarily aimed at producing such substances or objects are by-products and not waste, as being a by-product only if the following conditions are met:

(a) further use of the substance or object is certain;
(b) the substance or object can be used directly without any further processing other than normal industrial practice;
(c) the substance or object is produced as an integral part of a production process;
(d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.'

The definition of biomass type should be done also basing on its chemical-physical characteristics. Then, the decision on the appropriate type of pre-treatment process to meet the requirements for transformation is mainly based by the analysis on parameters of humidity, LHV and C/N ratio.

The CONVERGE technology performs a thermochemical transformation of the biomass, where at chemical level is requested a C/N ratio higher than 30 and on as received weight basis the moisture content should be lower than 50% [29], but the lower it is the higher is the performance of the process.

The CONVERGE technology performs precise processes, which together have the finality of producing bio-methanol, and they are [47]:

- biomass drying, necessary when the biomass is humid (MC > 10%);
- gasification, responsible for the production of syngas;
- syngas cleaning and conditioning and methanol synthesis, which allow the production of bio-methanol from the syngas through the contribution of the electric energy from the grid;
- off-gases internal recovery and heat integration, which is an important characteristic that allows the exploitation all the wasted heat to other processes (as for a low pressure steam cycle).

The final product, resulting from this sequence, consists in bio-methanol, while the electricity produced by the steam cycle is completely absorbed by the plant and it is not enough to satisfy the demand of it. Hence, a consistent quantity is purchased from the grid.
In addition, no co-products are considered.

1.4 Study on biomass potentials in EU

This paragraph highlights the European areas that could result interesting for the integration of the CONVERGE technology.

From the stakeholders' available data of biomass relative to each macro-area, it has been analysed the relative economic potential to make manageable the decision of which geographical area could be convenient to frame a supply chain for the CONVERGE technology. [48]

The bioeconomic potential represents the effective available quantity of biomass for the supply system in question. In other words, it consists into the total harvested/available biomass, from which it is subtracted the quantity for primary uses, and then, in turn, from this part is detracted the quantity destinated to other competing applications.
The results obtained for each European country are the following in Figure 4:

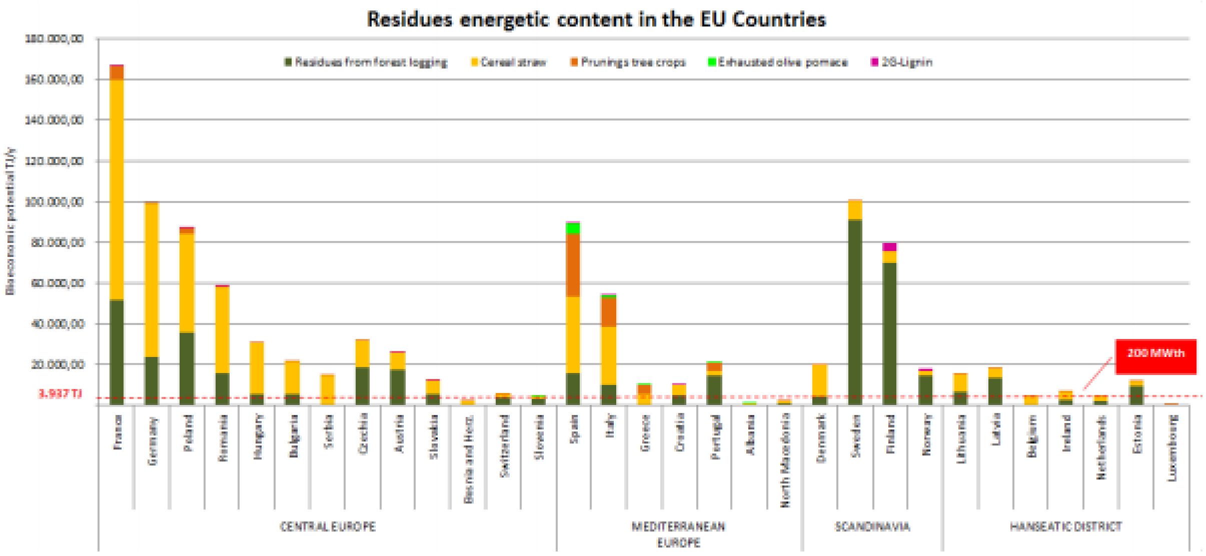


Figure 4. Yearly bioeconomic potential of each EU State member. Source: [48]

It is noticeable that the major biomass holder is the Central Europe district, then Scandinavian and Mediterranean ones follow. Although, the Hanseatic has the lowest potential.

From the resultant potentials, it is possible to make some forecasts for possible plants with the relative feeding system.

Firstly, it is possible to individualize in which area it is not convenient to instore a plant of commercial size of 200 MWth. Then, it is investigated if some countries need to use a multi-feedstock supply to fulfil the capacity of the plant or if it is enough just one single feedstock.

The 81% of the EU countries can feed the plant just with cereal straw residues, while the 77% with forest logging residues. About the other feedstocks, they are characterized by lower percentages.

After this first analysis, a certain quantity of regions was grouped into 29 Biomass Supply Regional Clusters (BSRC), where are met the biomass, logistic and plant size requirements. They are shown in the following map in Figure 5:

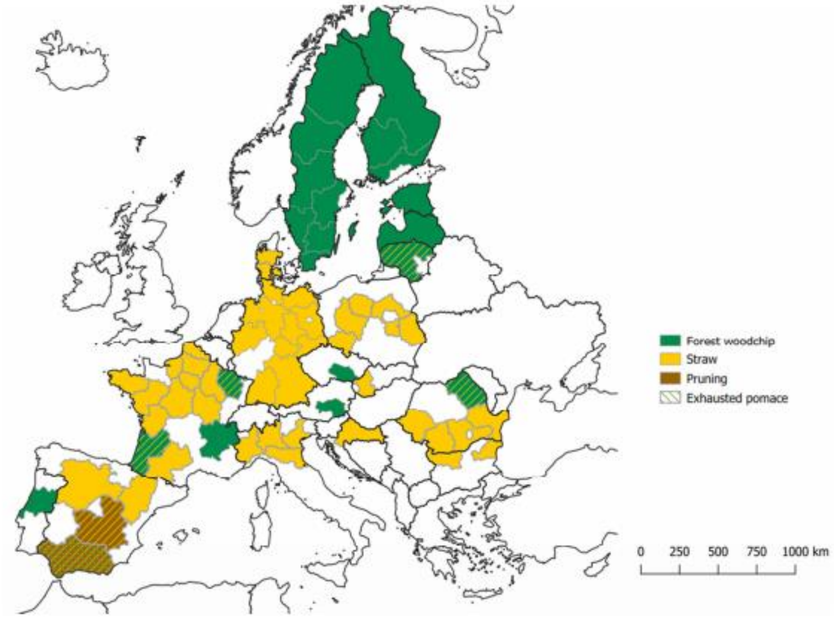


Figure 5. Resultant Biomass Regional Clusters between European countries. Source: [48]

Each cluster represents a zone, where the promising configuration is to have a mono-feedstock plant with size higher than 200 MWth.

After the analysis on the bioeconomic potential in each BSRC, the Multi-Criteria Analysis will define the most convenient biomass supply chain for each EU district by giving weighted scores for each biomass type in each district.

The outcome is reported in the following Table 2:

Table 2. Resulting best achievable supply chain for each EU district from multi-criteria analysis

District	Best supply chains
Scandinavian	Residues from forest logging
Central EU	Cereal straw
Hanseatic	Cereal straw
Mediterranean EU	Exhausted Olive Pomace Cereal straw

To summarize, the Scandinavian and Central Europe hold the highest biomass potentials of forest residues and cereal straw, respectively. This can permit a mono-feedstock supply for large plant sizes.

Although, the Mediterranean and Hanseatic ones have a lower biomass potential and they have to rely on a multi-feedstock system to exploit the economies of scale for the biorefinery, even though this modality is discouraged by the complex systems of transport, pre-treatment and storage. This is the reason why the multi-feedstock chain for this last two districts have received a lower score, than the mono-feedstock system.

However, it will be the specific economical optimization that will define the convenience of a mono or multi-feedstock system. In this regard, the optimization made for the Italian case [30] has demonstrated that various biomasses are preferred than single one, even if the distances are large and the biomasses have different seasonality.

1.5 CONVERGE project and thesis objectives

The scheme suggested to follow for the definition of an 'adequate, fairy and suitable' supply chain for the CONVERGE technology [29] is:

1. 'the biomass identification, based on the analysis of partners' and stakeholders' questionnaires and literature sources;
2. the geographical area characterization, shaping in order the different specificities of the North Sea, Scandinavian, Mediterranean or Central European area.
3. the chain phases definition, describing the collection, handling, transport and storage conditions as well as the associated costs (i.e. investment and operating costs). Particularly, the usual agricultural machines and transport means will be assumed, indicating also their operating capacity, annual operation time, power, fuel consumptions.
4. sustainable criteria assessment compliance with the directive EU 2018/2001, traceability assessment.
5. site addressing, potentially suitable locations for thermochemical conversion plant.'

The first point has been developed in the document [48] and explained in previous paragraph 1.4, where different areas between the EU districts have been identified with some types of feedstock available from accorded stakeholders.
Subsequently, with the view of the available biomasses in each studied geographical area, it has been calculated the bioeconomic potential of each one.

This is an important step to shrink the analysis towards the most interesting geographical areas with the associated main biomasses.

Then, this thesis will deal with the definition of the chain phases and entities and with the draft of a supply chain model able to decide the best achievable configuration from the given data in input (entities location, biomass potentials, capacities, etc.).

The model should be flexible and easily adaptable to different geographical contexts and biomasses types, in order to be applied to the multiple situations, but also able to incorporate changes related to the specific case when needed.

Then, the arising model will be tested on two real cases, in order to analyse the results produced regarding the decision level and also to make some considerations upon other aspects, mentioned in paragraph.

Furtherly, the innovative contribution given by this thesis work consists into:

- highlight and include the real world limitations, which regard the supply and distribution system;
- implementing more realistic approaches possible to the modelling of some aspects, such as transports, and incrementing their level of detail, as the operation of the biorefinery for the multiple cases.
- conducting a more accurate analysis on the research of the data for the specific case of study, to approach towards the reality.
- Moreover, the interest will be addressed, also, to the detailed estimation of the anthropogenic emissions produced in each step of the supply chain to prove the importance of proposing the alternative method to produce methanol from residual biomass and to find some eventual greener improvements to apply to the supply chain system.

The actual supply chain model strongly refers to a previous work [30] and it can be seen as a its continuation. Indeed, during this thesis the two models will be always compared to highlight their differences and similarities on their definition and also on their produced results.

2 Bio-methanol supply chain description

In general, a biomass supply chain can be described in [5]:

- Entities: which represent the biomass source, storages that are used to store biomass and also to do some pre-treatments, terminals to allow the switch between different transport types, biorefinery that has the task of transforming the biomass into biofuel, blending or biodiesel plants that purchase the biofuel produced.
- Biomass type: which could come from different areas of interest (in this case from forestry and agricultural residues and agro-forestry industrial residues and wastes).
- End-products: which includes the biofuel and also other useful products as electricity and/or heat produced by the specific transformation of the biomass [49].
- Assumptions: useful to simplify the problem and to make statements.
- Restrictions: such as supply and demand side, maximum capacities of entities and of infrastructure.
- Transports, which permit the fluxes (of raw matter, products and co-products) between the different entities of the entire system.

The conceptual architecture of a biomass supply chain, shown in Figure 6, can be simplified into three different parts [25]:

- *Upstream*: gathering all the stages from the production of biomass until to its arrival at the conversion facility. Therefore, it also comprehends the transport and the possible phases of storage and pre-treatment in between.
- *Midstream*: regards the conversion process itself occurring at the biorefinery.
- *Downstream*: covers the storage of the biofuel and its own distribution.

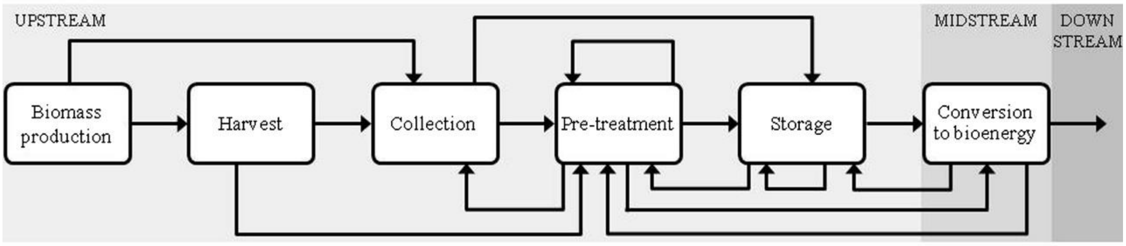


Figure 6. Architecture of the biomass supply chain

2.1 Literature review

Upon biomass supply chains, many studies have been conducted to find the optimal configuration and features studied for this research are [5]:

- the decision level, which defines the temporal detail given by the analysis and it can include the following decisions of types listed in [8]:
    - strategic (long-term): regarding the selection in the number of sites, location and their capacity. Then, biomass allocation between facilities and transportation mode. It regards also the technologies selected for all steps of the chain and the economical, social and environmental impact. [9]
    - tactical (medium-term): regarding logistic aspects, as inventory planning, fleet management, pre-treatment of biomass and transportation modes. [10]
    - operational decisions (short-term): regarding details of operations, daily inventory management and vehicle tracking, in order to permit an efficient working of biorefineries and, generally, a complete biomass supply chain management. [11]

- Structure: represents how the biomass supply chain is arranged. It represents the connection between points that could result into flow of information and material. There are different shapes of layouts, but, in this thesis, it will not be considered a precise structure, just the optimal one arising for the specific case.
- Modelling approach, which consists into the mathematical equations that describe the situation. The available ones are:
    - Stochastic: they are of probabilistic type, where parameters are uncertain and random. [12]
    - Deterministic: where parameters are known and fixed with certainty. It can be furtherly classified into: single objective [13] and multiple objective [14]; linear [15]and mixed-integer linear programming [16]; non-linear programming [17].
    - Hybrid: both deterministic and stochastic [18]
- Performance measure for the system: quantitative one is expressed numerically such as cost.
- Problem approaches:
    - Heuristic, which looks for a good solution solving in short time complex problems. It is a fast approach, but it does not guarantee the optimality. [19]
    - Multi-Criteria decision analysis, which allows the comparison between different alternatives or situations according to many criteria guiding to a careful solution. [20]
    - GIS-based, which applications are used to analyze the spatial information, as determining accessible roads and the distances with the different type of transports. Furtherly, it can also edit the map according to the requirements. [21]

About the model approach, a widespread and effective methodology, for the biomass supply chains, is the deterministic mixed-integer linear programming (MILP). By formulating the optimization problem as a MILP, two main advantages can be exploited: i) contrary to other optimization approaches, MILP models are able always to find an optimal solution (if exists) and, therefore, they state how far the current solution is from the optimality (i.e. compute the optimality gap); ii) once the problem is formulated, MILP solutions can be obtained by exploiting extremely fast and well-proven commercial solvers. [23] Not coincidentally, it is commonly used for real world problems, usually of large scale. [35]

It is characterized by using binary, integer and real variables and by linear objective functions and constraints [28].

For the biomass supply chains implementation, these options could be useful as [28]:

- the binary variable can be used to model logical proposition, as the selection storages, conversion facilities and/or to decide to do some pre-treatments in the location sites available, which otherwise will be hardly incorporated in the modelling environment.
- Integer one, to indicate the number of units required to do certain operations.
- Real one, for the quantities of biomass harvested and pre-treated, of biofuel produced, of biomass/biofuel/by-product flowing, from one point to another, or sold.

Then, the optimization function could be based on different criteria and it could be minimized or maximized according to the type of quantity calculated. The most widespread methods of optimization are focused on the economic field, for example the cost of production for the *second generation* fuels must be the lowest possible to have a minimum profitability [26], but there are many others listed in the document [25], which not necessarily regard this aspect. A relevant one consists into the minimization of the GHG emissions, which in present times have become an important issue due to the even more strict regulations on them imposed with the purpose of facing the climate change.

Therefore, an interesting study could be the definition of a biomass supply chain for biofuel production based on the minimization of costs and of GHG emissions. This type of supply chains, with more than one objective function, is defined multi-objective. In this case, there is not a single optimal solution, but a set of them (Pareto set), representing a compromise since no one of them cannot be optimized without penalizing the others [26]. Indeed, the study [28] highlights the fact that in any analysed case when profit is maximized, it never corresponds also into a minimization of the emissions. Whereas, by considering the maximization of the energy output, it never reaches the same results through the minimization of emissions, but it achieves results nearer to it respect in the other case.

The discussion about energy, biomass use and GHG emissions is object of the Life Cycle Analysis (LCA), which nowadays has acquired importance and even more for the future to promote a sustainable use of the resources and low emitting scenarios.

Another commonly discussed aspect in supply chains is about the centralization or the decentralization of the system. A centralized system consists into low number of entities selected between the proposed ones, mainly storages and transformation facilities, that participate to the supply chain. This type of approach could result advantageous from an economic point of view for the low operating costs and easy management, as asserted by [27], and also when the investment costs of the facilities are characterized by strong economies of scale with the achievement of large capacities. On the other hand, a distributed system could bring to lower transport costs favoring the intermediate pre-treatment of biomass or anticipating some steps connected to its conversion in smaller and numerous plants.

It would be the specific-problem optimization that would decide the most convenient configuration from an economical view, but there are some studies about the demand behavior that would prefer one respect to the other. It is when the demand decreases, the distributed system verifies a smaller decrease of profit per ton of biomass processed respect to a centralized configuration. [27]

Furthermore, another study [28] remarks the fact that higher GHG emissions are verified with the centralized option, due to the higher transport employment.

The last aspect analyzed is the difference generated through the insertion of tactical/operational decisions to the basic strategic ones. This one consists into have more detailed information about the quantities harvested, collected, produced, pretreated and transported in a short time frame and the consequent possibility to optimize them. It has relevant advantages for multi-period planned problems when for example: there are seasonal biomasses, operation of the plant that could be defined by the optimization, pre-treatments which require certain time to wait, etc.

However, as the models with this temporal detail require a low time resolution discretization, the number of variables will increase, resulting in consistent CPU time concern. [25]

2.2 Supply chain characterization

The supply chain is characterized by some aspects and subdivided in different phases, which are both detailed here for a general application of the CONVERGE technology (the scheme strongly refers to Milani's one [30]).

2.2.1 Biomass and bio-methanol ($\mathscr{B}$)

The biomass investigated is defined by the characteristics of:

- Moisture content (%)
- Density and bulk density $\left(\frac{ton}{m^3}\right)$, which respectively represent the physical density and the real occupied volume from one ton of biomass.
- Chemical characterization (%), namely the composition in elements of C, N, O, H, S, Cl, etc. on dry basis.
- Physical state, which can be multiple, as chipped, comminuted, sawdust, densified.
- Lower Heating Value on dry basis $\left(\frac{MJ}{kg_{dry}}\right)$.

- Period of availability, which could be equally distributed along the year or limited to a time period.

Some of them may vary along the supply chain path if pre-treatments are forecasted.

On the other side, the bio-methanol produced has defined characteristics, which are the same of the commercial fossil one, excepting the selling price that is higher:

Table 3. Assumed biomethanol characteristics

LHV	19.9	$\left[\frac{MJ}{kg}\right]$
Density	0.8	$\left[\frac{ton}{m^3}\right]$
Price	600	$\left[\frac{€}{ton}\right]$

2.2.2 Harvesting/production phase ($\mathcal{I}$)

It is the starting phase of the supply chain where the biomass is extracted from its natural state or is produced if it derives from industry.

It can be very variable according to the biomass in question, mostly for agricultural and forest residues, which need a more complex planning of this stage, because they require the harvesting phase. Usually after the period of harvesting, it is followed an on-site (or roadside) storage of the biomass to do a first drying, where, inevitably, the dry matter losses are present due to the uncontrolled environment in temperature and humidity.

The features at this level, which regard the time required for the eventual first drying and dry matter losses, are dependent on the biomass type, on its state (bundled, chips, sawdust) and on the climate of the area. Moreover, there are different available techniques to manage this phase, which can be defined in the case specific analysis.

Anyway, for this primary general discussion this phase is not analysed specifically and it can be considered as a unique block, in which it is known for each specific biomass the:

- yearly producibility in ton/y;
- purchasing price at the harvesting/production point;

Regarding the biomasses that do not result manageable at the raw state, as wood residues, it is usually done a chipping or comminution before or at the moment of the collection. Other possibilities could be to do that at the storage or at the biorefinery, but the handling and transportation phases would not take advantage from it. Indeed, for example in Sweden the predominant one (covering the 75-80%) is the roadside chipping [50].

2.2.3 Storage phase ($\mathcal{J}$)

The storage, or intermediate depot, represents the place where the residues can be stacked for the time required allowing the right working of the biorefinery. It is an indispensable entity for the seasonal biomasses and it could become for the non-seasonal ones (as wood) an economical possibility for their further drying during their permanence. Otherwise, the other alternative consists into the industrial dryer, which takes lower time, but implies higher operational costs.

There are two categories of storages analyzed and the consequent Table 4 highlights the advantages/disadvantages connected to them:

Table 4. Storage categories available for biomass

Type	Advantages/Disadvantages
Open-air uncovered/covered	Economically convenient (+) Important dry matter losses (-) Long drying time with consequent large areas required (-) Impossibility to control the moisture (-)
Indoor	Lower dry matter losses (+) Lower drying time (+) Higher investment costs (-)

The open-air type results economically advantageous, but it has real problems of re-moisten to already dry biomasses and of providing important dry matter losses for the biomasses left there to dry.

As they consist into important issues for biomasses destinated to a thermochemical process, the possible storage types taken into account are the indoor ones (like in the precedent model [30]). Anyway, the drying matter losses are not totally eliminated, but surely reduced, and for this reason they have to be accounted also at this level according to the moisture content of the biomasses.

The assumed maximum height for this type of storage is of 5 m [30] and the relative room factor is calculated according to each biomass type, through it and the bulk density.

For the right operation of an ordinary storage, there are operative costs, connected to the biomass management (called inventory carrying cost) and risks, to take into account beyond the investments.

This entity is not an obligatory passage, actually it is possible to bring the biomass also directly at the biorefinery.

2.2.4 Pre-treatment option

The pre-treatment is a procedure, in which the biomass can improve its properties in terms of preservation (reducing dry matter losses) meeting the requirements for storage [31] (MC < 20-25%) and for the thermochemical process (MC in input of the gasifier equal to 10%). Therefore, it is assumed to perform the pre-treatment at the storage facility, in order to surely meet the previous requirements.

As asserted by Milani, the possibilities are many according to the biomass in question:

- Comminution/chipping
- Drying
- Densification

By considering the Milani's model [30], for humid biomasses there are two further states that the biomass can achieve: 'Bdried1', which means after a first drying, and 'Bdried2', after a second drying. Then, the biomasses that satisfy the maximum value of MC requested of 17-18% can face a process of densification (or pelletization), which could give important advantages regarding the volume occupancy and a further little drying. This process is usually related to a comminution process that occurs before the densification.

For the humid biomasses, it is given the possibility to subdivide the drying phase in two parts to let define the optimal drying configuration from the optimization, without imposing a single one which requires a lot of time, energy and area of storage.

The pre-drying processes explored are: natural drying, the most economical, and forced drying. Their main characteristics may be represented in Table 5:

Table 5. Drying possibilities at the storage

Type	Advantages/Disadvantages
Indoor with natural drying	Lower dry matter losses (+) Lower drying time (+) Higher investment costs (-)
Indoor with forced drying	Lowest drying time (+) Lowest dry matter losses (+) Higher investment costs (-) High OPEX (-)

The high operative costs and the energy consumption that regard the forced drying are not trivial and they may constitute into an obstacle for the choice of this process.

2.2.5 Biorefinery ($\mathcal{K}$)

The technology used for the transformation of biomass into purified methanol is the CONVERGE one. However, it is not object of study in this analysis.

The aspects of interest are its total conversion efficiency of the entering biomass into methanol and the ratio between the net electrical power absorbed from the grid and the input thermal power of biomass.

The only component belonging to the technology that is studied is the industrial dryer, placed at the beginning of the conversion. It appears interesting for this study, as its investment cost depends on the quantity of water that has to be removed from the biomass (based on kg_{H_2Oevap}/s). The dryer is modular [51], where each module has a maximum capacity of 5.55 kg_{H_2Oevap}/s and, therefore, a related cost function of the dryer investment can be evaluated in the way that follows with an approximated linear function (Figure 7):

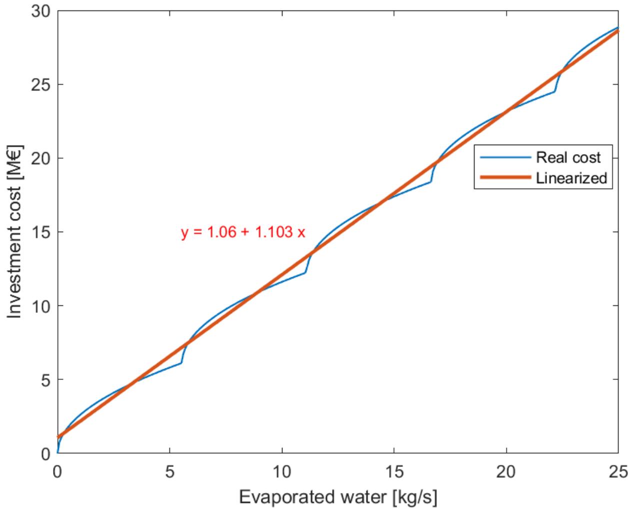


Figure 7. Industrial dryer cost functions: Real and Linearized one

The optimization tool should decide at which MC state the biomass should arrive at the plant, then it is called into question if to use a larger dryer or choosing the pre-treatments overcoming inside storages.

The variability of the MC states of the biomass entering the plant implicates also different quantity of electricity purchased from the grid at the same biomass input (MWth), as it is subtracted steam from the power cycle to feed the dryer. Higher is the MC, lower is the electricity produced and higher is the one purchased.

More in detail, by the ASPEN simulation of the CONVERGE technology it has been demonstrated that, when the biomass in input has a humidity of 35%, the power cycle does not exist anymore, as the steam produced from the heat recovery hardly can feed both the industrial dryer and other internal processes of the plant (i.e. steam reformer). Consequently, a part of useful syngas is subtracted by its conversion into methanol, in order to be burnt to produce the lacking steam. In terms of CGE, this is surely a less efficient option for the biorefinery, but it has to be evaluated together with the whole supply chain.

The behaviour of the CGE for the different examined states of biomass at dryer input can be more clearly explained by the following graph in Figure 8, regarding the woody biomass, where the CGE is relative to the biomass input of the gasifier (so at fixed MC equal to 10%):

$$CGE[\%] = \frac{(\dot{m} \cdot LHV)_{methanol}}{(\dot{m} \cdot LHV)_{\substack{biom \\ gasifier}}}$$

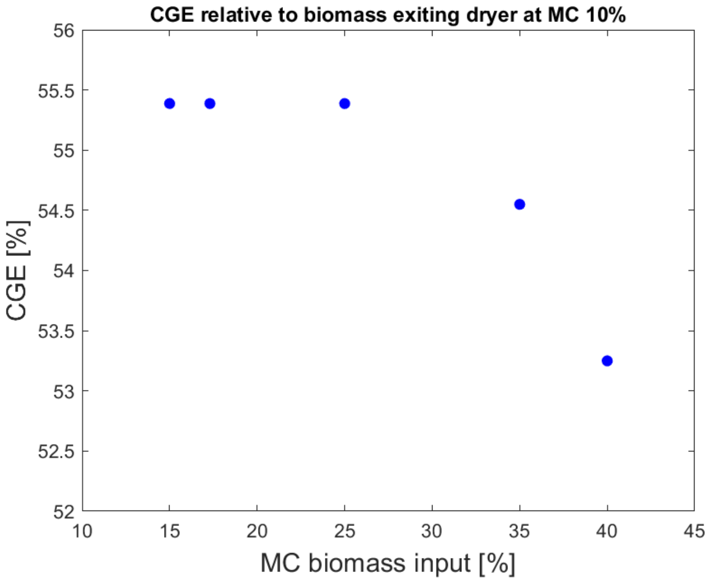


Figure 8. Cold Gas Efficiency relative to the biomass entering the gasifier at MC 10% defined for the different MC states at input of the dryer

When the biomass at dryer input starts to have a MC higher than 35%, it is noticeable a drop, because a lower quantity of methanol is produced for the same biomass gasifier input.

The electric ratio is defined as: $\gamma_{el}[\%] = \frac{P_{el,tot}}{(\dot{m} \cdot LHV)_{\substack{biom \\ gasifier}}}$, where $P_{el,tot}$ represents the electric power purchased from the grid and it is equal to the balance between the demanded power by the auxiliaries (negative sign) and the one produced by the steam cycle (positive sign).

Its trend is represented by the image that follows (Figure 9):

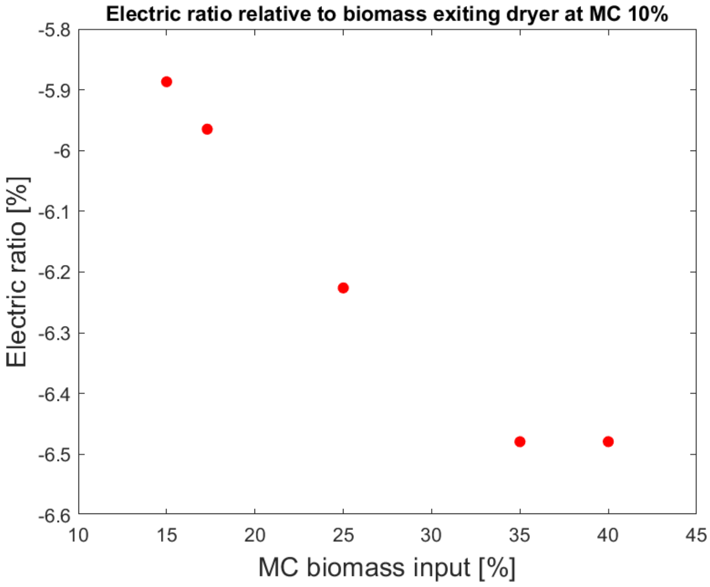


Figure 9. Electric ratio relative to the biomass in input of the gasifier defined for the different MC states at input of the dryer

With the increase of biomass humidity at input, the purchased electricity increases as well, because of the higher quantity of steam subtracted from the steam cycle. When biomass achieves the moisture of 35%, the steam cycle is not anymore considered and, therefore, the whole electricity needed in this case is supplied from the grid.

All the units of biorefinery, keeping the dryer aside, are considered aggregated and their overall investment cost is known for three different sizes (10, 100, 300 MWth), so through their linear interpolation the cost for other sizes can be roughly estimated (as shown in Figure 10):

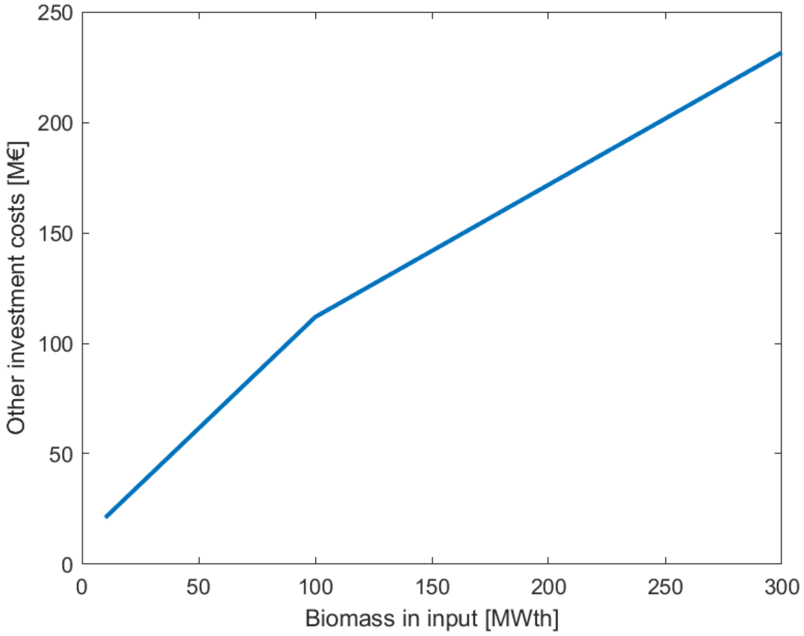


Figure 10. Total investment cost of CONVERGE technology, excluding the dryer investment. Source: [47]

The biorefinery size has been limited between 10 and 300 MWth of biomass in input for computational limits and for the reliability about the costs. Moreover, it is allowed for the plant to operate between the 60% and the 100% of the future established plant size [30].

Other costs are here specified in the following Table 6:

Table 6. Biorefinery O&M and cost information to calculate the Total Overnight costs of biorefinery. Source: [47]

Biorefinery's annual O&M costs	4.6%
Investments	
Costs of installation	30%
Indirect costs	22%
Contingency costs	20%
Interest rate	5%

Biorefinery's annual O&M costs are calculated as 4.6% of total investment costs.
The costs of installation, indirect costs and contingency costs (respectively 30%, 22% and 20% of the investment costs) are added to the investment costs, generating the Total Overnight Cost (TOC). In addition, the interest rate (5%) should be added to the TOC [47].
Finally, the biorefinery can stop, but minimum two consecutive weeks (Minimum Down-Time) are requested to wait before to re-start it, and it should operate for minimum 4 consecutive weeks (Minimum Up-Time) [30].

2.2.6 Methanol users ($\mathcal{M}$)

The methanol produced by the CONVERGE technology could be employed for several uses, but the common interest for this project is its integration inside the field of the fuels destinated to transports.
The main possibilities available nowadays that surely could be applied are:

- The production of biodiesel, through the transesterification (FAME) of an oil. This would avoid the use of the fossil natural gas to produce methanol.
- Its own blending with gasoline. Different types of percentage of methanol inside the gasoline could be present, but for the EU members only fuels with less than 3 vol% and more than 30 vol% of methanol are allowed. The ethanol for some EU states is already blended with gasoline and a further blending with 3-4% of methanol to it could be applied. Then, a blend composed by 15% of methanol and 85% of gasoline does not require any change of the vehicle engine, but it is not permitted in the EU.
  In Sweden, the Flex-vehicles are really spread, which are designed to run with 85% of ethanol (E85) and it was proved by a study of the university of Luleå that this type of vehicles run correctly with the equivalent methanol blend M56 (56% of methanol), which gives the same air-to-fuel ratio [52].
  The blending of methanol with gasoline has to be done in the controlled environment of a refinery or in an appropriate storage tank, in order to check the vapor pressure and the quality of the fuels [53].
- Another way which is not employed nowadays is the transformation into DME (Dimethyl Ether). There is only an industrial plant in EU, which produces DME in a renewable way, and it is situated in Domsjö, Sweden. Anyway, this is still a small reality and it will not be considered in this thesis.

The purchasers of bio-methanol selected appositely for this supply chain are the biodiesel plants for the moment. They consist into a sure and already developed field, where the bio-methanol is surely requested to meet lower levels of carbon dioxide. Whereas, the field of blending directly with gasoline is still little stated and it would be difficult to predict its annual demand.
The annual demand of methanol from the biodiesel plants, on the other side, can be easily found from their real annual production of biodiesel and from the knowledge that about 0.2 litres of methanol and 1 litre of oil are required to produce 1 litre of biodiesel [54].
In some cases, it could result that the ideal producible quantity of methanol from the available quantity of residues is much larger than the exploitable one by the local biodiesel plants.

Unfortunately, on the market there are not yet vehicles powered only with methanol and the methanol to gasoline plants are not present in the EU. Therefore, the only alternative, to exploit higher quantities of the available residues, is to bring the remanent part of methanol to some commercial terminals to sell it to farer and foreign interested purchasers. Usually, they consist into international ship ports used for the transport of chemicals and fuels.

2.2.7 Terminals ($\mathcal{R}$)

Inside the model, some terminals should be considered. They represent the points used to change type of transport, in this case only from truck to train or vice versa, and they are used to load or unload the biomass/biofuel into or from the train wagon.

Inside the biomass supply chains, the limit of the railway is that it cannot connect many geographical areas. For this reason, it is always matched with the truck transport, which can reach every place on the land.

Furthermore, the available commercial rail terminals are not many and a certain distance should be travelled by truck to reach the terminal. The great advantage that makes this type of transportation competitive is the low variable cost per km, indeed it becomes preferable to truck for long distances and when the territory is well served by the rail infrastructure.

2.3 Transports

The transport system is mainly subdivided into truck and railway for this analysis.

As the transport with trucks is indispensable for the supply chain, a more detailed analysis has been conducted on it. Therefore, like an independent transport company, it has been assumed to purchase trucks and to recruit drivers, which both are assigned to a certain entity and they are required to transport the biomass/biofuel from that point to the others.

The transports characteristics assumed for the supply chain can be schematized by the following Figure 11, where each transported product is specified with the following nomenclature: '*Basrec*', for the humid biomass; '*Bbiom*', for all biomasses humid, dried and densified; '*Bfuel*', for the methanol.

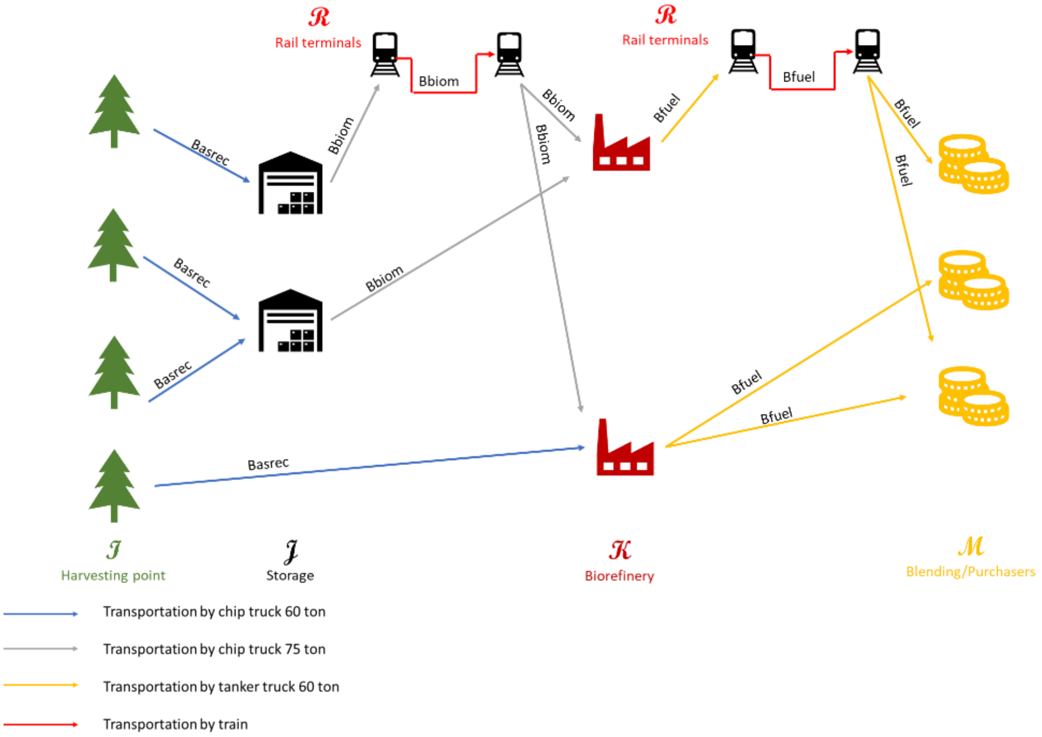


Figure 11. Supply chain connections between entities

Three different types of trucks have been selected according to the nodes that they serve:

- 60 ton chip truck [32], used to transport the biomass from the harvesting point to the storage or directly to the biorefinery. This choice has been done on the basis that the collecting points have lower biomass available to be collected than storages and it is not advantageous to use larger and more expensive trucks that, probably, would not be totally filled. Moreover, the accessibility to the collecting points is harder with a larger truck.
- 75 ton chip truck [32], used to transport biomass from the storages to the biorefinery or to the rail terminals, otherwise from the rail terminal to the biorefinery.
- 60 ton tanker truck, used to transport bio-methanol from the biorefinery to the biodiesel plants or terminals, otherwise from the rail terminal to the biodiesel/ship terminal.

In addition, the drivers of tanker trucks have a higher salary than the drivers of the chip trucks [55].

The overall costs involved in a real company of transports are reported in the Appendix A and they can be subdivided into costs dependent on:

- either weight of payload and travelled distance $C_{ton\_km}\left[\frac{€}{ton \cdot km}\right]$, mainly due to fuel consumption;
- travelled distance $C_{km}\left[\frac{€}{km}\right]$, due to fuel consumption of empty truck, maintenance, oil substitution and others;
- number of journeys $C_{fixed}\left[\frac{€}{n.journeys}\right]$, due to the loading and unloading phase;
- number of drivers $C_{driver}\left[\frac{€}{n.drivers}\right]$, which represent the yearly cost of a single driver;
- number of trucks $C_{truck}\left[\frac{€}{n.trucks}\right]$, which represents the yearly depreciation cost of a single truck.

More in detail, the estimation of the fuel consumption has been performed by referring to the following graph in Figure 12:

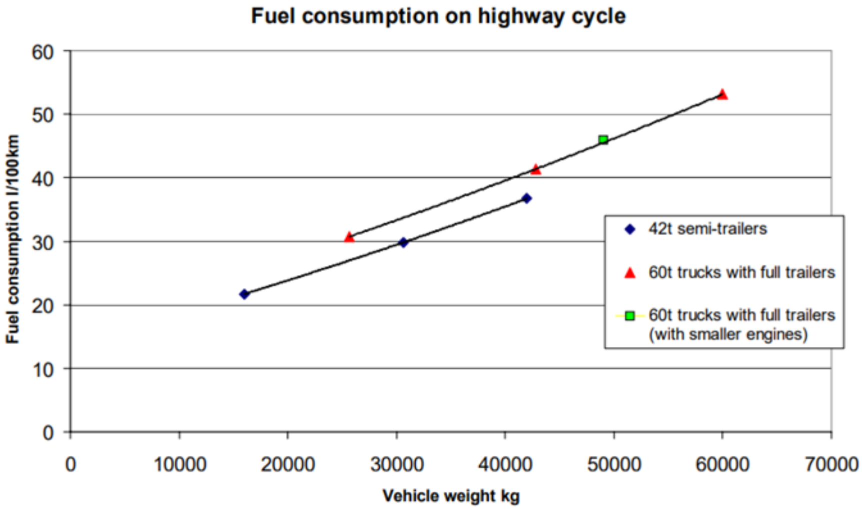


Figure 12. Kilometric fuel consumption of each category of truck related to the gross vehicle mass. Source: [56]

By considering the trend of the 60 t trucks with full trailer, it has been found the fuel consumption as a function of the gross vehicle weight for all the categories of trucks (for the 75t too). Then, it has been extrapolated the fuel consumption for the void vehicles, which becomes function only of the travelled distance. Whereas the fuel consumption due to the payload is an adding cost item that is applied when the truck is loaded and it is dependent on payload weight and distance.

The lifetime of the trucks has been assumed equal to 7 years and a selvage value is assigned for each category of truck [32].

The estimation of the number of drivers and trucks is decided according to the time required (h) to do the operations (loading, unloading, driving, waiting) that is limited by the number of weekly working hours of each single truck and driver. The truck can work every day of the year 16 h/day, while a driver works 207 $days/year$ for $8h/day$. By calculating the number of working hours in one year and dividing for the number of weeks, it can be easily found that each truck works 112 $h/week$, while the drivers 32 $h/week$. Therefore, it means higher is the time spent for the operations more drivers and trucks are needed.

Therefore, the annual truck transport costs will be modelled, as follows:

$$C_{truck} \cdot N_{trucks} + C_{driver} \cdot N_{drivers} + C_{fixed} \cdot N_{journeys} + (C_{km} \cdot dist) + (C_{ton\_km} \cdot transpBiom \cdot dist),$$

where the first and second term represent the costs due to the employment of a certain number of trucks (N_{trucks}) and of drivers ($N_{drivers}$). Then, the third consists into the loading and unloading costs, which are related to the number of journeys performed ($N_{journeys}$) and finally the last two terms are given by the travelled distance ($dist$) and by the transported biomass in weight ($transpBiom$).

About the railway transport, it is considered that the service is provided by a third-party company, where the cost function is based on the filled wagon of train, which has a maximum capacity of 60 m^3. For each journey of one wagon, the cost (in €) is calculated as [57]:

$$C_{fixed} + C_{var} \cdot distance(km).$$

2.3.1 Distances calculation and arcs

The distances between the different possible points are calculated a priori by two different systems, according to the means of transport: rail distances [34] only between rail terminals, while road distance [33] between the other points. They are both expressed in km.

The following Table 7 represents in red colour the connections made by road and in yellow by rail, while with empty cell the connection is not effectuated. In addition, the arcs numbers are added, which assign the type of transport for each possible connection between the different entities ($\mathcal{I}$ harvesting point, $\mathcal{J}$ storage, $\mathcal{R}$ terminal, $\mathcal{K}$ biorefinery, $\mathcal{M}$ demand):

Table 7. Transport distance typologies and arcs number, which specify the type of transport used between the different entities

	$\mathcal{I}$	$\mathcal{J}$	$\mathcal{R}$	$\mathcal{K}$	$\mathcal{M}$
$\mathcal{I}$		1	1	1	
$\mathcal{J}$			2	2	
$\mathcal{R}$			11	2	
$\mathcal{K}$			3		3
$\mathcal{M}$					

Each number inside the table corresponds to the type of transport adopted to connect certain nodes, which has been clearly explained previously:

1. 60 ton chip truck
2. 75 ton chip truck
3. 60 ton tanker truck
11. Train wagon 60 m^3

When road distance between some points is very low, the costs of transports could be avoided. This is almost verified when a rail terminal is owned by the biorefinery or biodiesel plant.

2.4 Improvements on Milani's Model

The current model presented in this thesis work refers to [30], which has been improved in order to get more realistic results.

Some differences in results will be evidenced, due to the following main changes:

1) Equal subdivision along the year of the collection phase in sites with large biomass potential;
2) The percentage of technical and economical available biomass is applied to the available one of each site instead to the total one of the all production sites;
3) Different modelling of the truck transport costs: it has been assumed to own directly the transport company, in order to analyze directly the costs connected. Moreover, this choice has been encouraged by the difficulty into finding reliable economical information about third-party companies of transport, for which it is difficult to have access.
4) Different costs of rail transport, which have lower fixed costs and higher variable ones.
5) Cost modelling of the industrial dryer according to the size that is left free to variate.
6) CGE updating for each possible biomass state that could enter the conversion facility and deletion of burning a part of residues to dry wet biomass.
7) Introduction of a parameter, defined for each type of biomass state at input of the conversion facility, regarding the ratio between electricity input and the LHV biomass input. Then, it can be used to calculate the yearly electricity purchased and the relative cost.
8) Selection of existing biodiesel plants, instead of petrochemical refineries that are responsible of blending biodiesel produced with gasoline.
9) Limitation of the quantity sold to the biodiesel plants according to their yearly production capacity of biodiesel.
10) Establishment of ship ports or collecting points for methanol of very large capacities, when local biodiesel plant demand is lower than the producible quantity of methanol.

3 Methodological Framework and MILP formalization

3.1 Main model definitions

The model should provide an interesting possibility of development for a bio-methanol supply chain from:

- A selected geographical area (paragraph 1.4), which can offer an important potential of residual biomass;
- The selected residual biomasses that can be exploited for the bio-methanol production and its consequent characterization on different sides;

Then, starting from this primary information, the supply chain can be defined on:

Table 8. Summary of the information required for the model definition

Production point ($\mathcal{I}$) • Individuation of the locally available production points • Yearly available economic potential • Period of the biomass availability	Storage ($\mathcal{J}$) • Choice of location sites • Characteristics of building (i.e. hight) • Constraints (i.e. max land area) • Costs information
Biorefinery ($\mathcal{K}$) • Choice of location sites • Operation characteristics • Efficiencies • Constraints • Costs information	Methanol users ($\mathcal{M}$) • Individuation of the locally available biodiesel plants or potential purchasers • Yearly demand
Terminals ($\mathcal{R}$) • Individuation of the locally available terminals	Transports • Definition of connections types (paragraph 2.1) • Constraints (weight and volume, driver and truck operational hours,etc.) • Costs
Biomass ($\mathcal{B}$) • Chemical composition • LHV • MC • Density • Purchasing price	Bio-methanol ($\mathcal{B}$fuel) • Density • LHV • Selling price

From the material available, the model can be built, according to the different typologies (paragraph 2.1), and implemented with an appropriate programming language. Afterwards, it is ready to be solved to find the best solution that most satisfies the imposed criteria.

3.2 MILP structure and criteria selected

First of all, by referring to the previous paragraph the selected modelling approaches are here reported:

- Deterministic approach, where parameters are known and fixed with certainty.
- Single objective function based on overall NPV, in order to find the best configuration from an economic point of view as the selling price of bio-methanol is not competitive with the one of fossil methanol. A subsequent analysis will be performed on the GHG

estimations for the bio-methanol production and on the emission saving due to its usage for biodiesel production.
- Multiperiod approach because the study deals with both strategic and tactical decisions, as it is forecasted a diversified trend along the year of operation.
- The distributed/centralized approach was not taken into account, as different storage, conversion and demand sites will be proposed with their real limiting capacities. Therefore, the layout of the resultant supply chain will be the consequence of the real limits and of the available ranges in which the variables can change.

The model definition has been subdivided into:

- Sets, which comprise the categories of subjects analysed:
    - Biomasses at initial state, after a first and second drying, after densification and final biomethanol, traduced in $\mathcal{B}$ = {*Basrec, Bdried1, Bdried2, Bdens, Bfuel*};
    - Chain points ($\mathcal{N}$), which are harvesting/collecting points ($\mathcal{I}$), storages ($\mathcal{J}$), terminals ($\mathcal{R}$), conversion facilities ($\mathcal{K}$) and biodiesel plants ($\mathcal{M}$);
    - Representative year discretized in periods ($\mathcal{T}$);
- Parameters, which represent known and fixed numerical values to be inserted in the model;
- Variables, defined for certain sets and they can be of integer, real and binary nature;
- Constraints, which consist into equations that include variables and parameters that lead towards the solution of the problem respecting the requirements;
- Objective function: representing the function to be minimized. It is defined as inverted yearly NPV, by considering the costs positive and the revenues negative.

In this model, the economical analysis has been performed on a representative year in which the supply chain is fully working and the MILP problem is represented with the following formulation [35]:

min $\quad Z = c\,y + bx$

$s.t.\ Ay + Bx \leq b$, where $y \in \{0,1\}, x \in R_0^+, c, b$ are vectors of coefficients and A, B are matrixes of coefficients.

After its formulation, it is generally solved with LP – Branch & Bound solvers that provide upper and lower bounds of the solution and giving , at the same time, information about its optimality [35].

3.3 Tools and simplifications

The whole model has been implemented on Matlab 2020b with the language POLIMIP, which refers to YALMIP, while the optimization was performed with CPLEX IBM 12,10 version.

The actual model refers to [30], which has been reproposed in a more detailed way on some aspects and with other changes, such as: transport costs and their modelling, conversion facility characteristics, limitations of the demand points. This detailed analysis has induced a simplification of the model upon the temporal discretization, namely the year has been discretized in periods of 2 weeks, instead of one [30]. It was decided to avoid a coarser discretization because otherwise, it could have compromised the precision of the solution.

The best discretization that could reduce remarkably the simulation time and giving together the same results of a finer temporal discretization has been found simulating three different trials of the same model on a reduced case for 1,2 and 4 weeks, as time discretization periods of the year. The results obtained are found in chapter 0.

3.4 MILP formulation

The formulation of the model is explained in this section, but it is not completely reported.

The objective function (in €/y) to be minimized, accounting for the total costs and revenues, is:

$obj = purchBiom + Purchel + CT + \ OPEXbioTOT \ + \ OPEXstTOT + \frac{ir\ (1+ir)^{LFP}}{(1+ir)^{LFP}-1}\ INV - earn$,
where the LFP are the years of project lifetime and ir the internal rate of return.

The different terms are obtained in the following passages of this paragraph.
The biomass b, in any case, is considered to be purchased from the harvesting/production point i ($transp_{t,b,i,jrk}$) at a certain price $priceBiom\ _b(€/ton)$:

$$purchBiom = \sum_{jrk\epsilon J\cup R\cup K} \sum_{i\epsilon I} \sum_{b\epsilon Basrec} \sum_{t\epsilon T} transp_{t,b,i,jrk} \cdot MF_b \cdot priceBiom_b$$

3.4.1 Harvesting phase and collection (harvested biomasses)

The biomasses that are characterized by the harvesting phase can be subjected to a planning of the cutting phase for each single harvesting point.
At the single harvesting point i, the yearly quantity cut and harvested of residues must not exceed its economic potential one:

$$\sum_{t\epsilon T} cut_{t,i} \ \cdot MF_b \leq tep \ \cdot \ Prody_i \ , \qquad i \ \epsilon \ I, \qquad b \ \epsilon \ Basrec$$

The variable $cut_{t,i}$ represents the quantity cut of residues in each harvesting point i in time t on dry basis and, for this reason, it is multiplied for the mass factor MF_b, to be compared with the given yearly available quantity at the harvesting point i on as received basis ($Prody_i$). Moreover, to this term is multiplied the parameter tep, which represents the correspondent percentage of technical and economic available quantity of the total extractable biomass.
The harvesting points with high potentials have a regulated cutting phase and, for them, it is decided to subdivide it in a uniform way along the year or along the time period of availability T_b:

$$cut_{t,i} \ \cdot \ MF_b \leq \frac{Prody_i}{T_b} \ \ t \ \epsilon \ T, \qquad i \ \epsilon \ I, \qquad b \ \epsilon \ Basrec$$

The cut residues are left roadside covered by tarp or not, which is breathable and prevents the rainwater from penetrating into it, for minimum $NdryR$ periods:

$$Prodw_{t+NdryR,i} = cut_{t,i} \ \ t \ \epsilon \ T, \qquad i \ \epsilon \ I$$

Then, after this period the residues could be left roadside for longer until when it is more convenient for them to be collected. However, the residues left roadside are subjected to a loss in dry matter of $dmlR1$ or $dmlR2$ every instant t, according to the season:

$$bsRoadside_{t,i} = bsRoadside_{t-1,i} \cdot (1 - \ dml_{R2}^{R1}) + Prodw_{t,i} - transp_{t,b,i,jrk}$$

$t \ \epsilon \ {}_{TW,TAU}^{TSU,TSP}$ $, b \ \epsilon \ Basrec, i \ \epsilon \ I, jrk \ \epsilon \ J \cup R \cup K$, where the $transp_{t,b,i,jk}$ represents the quantity of biomass b transported at that instant t from the collecting points towards storages, terminals or directly the biorefinery.

3.4.2 Collection (non-harvested biomasses)

On the other side, the residues of industries or more in general biomasses, which do not need the harvesting phase, present the following constraint due to its direct collection:

$$transp_{t,b,i,jrk} \ \cdot MF_b \leq \frac{tep \cdot Prody_i}{T_b} \ , \qquad i \ \epsilon \ I, \ \ b \ \epsilon \ Basrec,$$

where T_b represents the number of periods t, in which is available the biomass b.

3.4.3 Transportation

About transport, the number of journeys ($Njroad_{t,n,n}$ by truck and $Njrail_{t,r,r}$ by rail), performed during t from point n to another point n, are here regulated according to the values of $arcs_{n,n}$. For trucks:

$arcs_{n,n} = 1,2,3$

$$transp_{t,b,n,n} \cdot MF_b \leq Njroad_{t,n,n} \cdot Wtruck_{1,2,3} \quad t \in T, b \in B, n \in N \backslash R$$

where $Wtruck_{1,2,3}$ is the weight capability of each truck type.

$arcs_{r,r} = 11$

$$transp_{t,b,r,r} \cdot MF_b / \rho_b \leq Njrail_{t,r,r} \cdot Vtrain \quad t \in T, b \in B, r \in R,$$

where $Vtrain$ is the volume capability of one wagon of train.

Then, it is calculated the time spent (in h) during the operations of loading, unloading, waiting and travelling (counted twice) performed with truck's service (of type 1,2,3):

$$Troad_{t,n,n} = Njroad_{t,n,n} \cdot \left(tload_{1,2,3} + tunload_{1,2,3} + twait + \left(distance_{n,n} \cdot 2\right)/velocity_{1,2,3}\right)$$

$$t \in T, n \in N \backslash R$$

With the knowledge of time required for the operations at each period t between nodes n $Troad_{t,n,n}$ and the working hours of each driver and truck ($hdriver$ and $htruck$), it is possible to determine the number of drivers $Ndrivers_n$ and of trucks $Ntruck_n$ required to transport biomass/fuel from point n to the others:

$$\textstyle\sum_{n \in N} Troad_{t,n,n} \leq Ndrivers_n \cdot hdriver, \quad \sum_{n \in N} Troad_{t,n,n} \leq Ntruck_n \cdot htruck \quad t \in T, n \in N$$

There are some cases in which the terminal and the entity (storage j, biorefinery k, blending m) are in the same location or better than that when the terminal is owned by the entity. In this case, the transport is considered between them, but the costs due to the involvement of truck and driver is not accounted.

The biomass/biofuel can be transported $transp_{t,b,n,n}$ just between few points according to the table below:

Table 9. Biomass type or biofuel decided to be transported between the entities I collecting point, J storage, K biorefinery and M demand, where $Bbiom = \{Basrec, Bdried1, Bdried2, Bdens\}$.

	$\mathcal{I}$	$\mathcal{J}$	$\mathfrak{R}$	$\mathcal{K}$	$\mathcal{M}$
$\mathcal{I}$	0	Basrec	Basrec	Basrec	0
$\mathcal{J}$	0	0	Bbiom	Bbiom	0
$\mathfrak{R}$	0	0	B	Bbiom	Bfuel
$\mathcal{K}$	0	0	Bfuel	0	Bfuel
$\mathcal{M}$	0	0	0	0	0

where $t \epsilon T, b \epsilon B (or\ Basrec, Bbiom, Bfuel), n \in N, Bbiom = Basrec, Bdried1, Bdried2, Bdens\}$

The balances at terminals, in order to allow the transport of biomass between nodes is here reported:

$$\sum_{ijk \in I \cup J \cup K} transp_{t,b,ijk,r} = \sum_{rr \epsilon R} transp_{t,b,r,rr} \quad t \in T, \quad b \in B, r \in R, rr \in R$$

$$\sum_{rr \epsilon R} transp_{t,b,rr,r} = \sum_{jkm \epsilon J \cup K \cup M} transp_{t,b,r,jkm}$$

$$\sum_{ijk \in I \cup J \cup K} transp_{t,b,ijk,r} + \sum_{rr \epsilon R} transp_{t,b,rr,r} = \sum_{rr \epsilon R} transp_{t,b,r,rr} + \sum_{jkm \epsilon J \cup K \cup M} transp_{t,b,r,jkm}$$

The total transport cost of the whole supply chain are summed in the variable CT:

$$CT = \sum_{nn\epsilon N\setminus R}\ \sum_{n\epsilon N\setminus R}\ \sum_{t\epsilon T}\ \sum_{b\epsilon B} transp_{t,b,n,nn}\cdot MF_b\cdot c_{ton\_km}\cdot dist_{n,nn} + Njroad_{t,n,nn}\cdot C_{fixed} + Njroad_{t,n,nn}\cdot C_{km}\cdot dist_{n,nn} + + \sum_{n\epsilon N} N_n^{drivers}\cdot Cdriver_n + \sum_{n\epsilon N} N_n^{truck}\cdot Ctruck_n + \sum_{rr\epsilon R}\ \sum_{r\epsilon R}\ \sum_{t\epsilon T} Njrail_{t,r,rr}\cdot Ctrain_{r,rr}$$

Where c_{ton_km}, C_{fixed} and C_{km} are explained in the previous paragraph 2.3.

$Cdriver_n$ and $Ctruck_n$ are annual costs defined for each node n that is served by trucks, because, according to the previous chapter, there are three different trucks available with relative different investment costs and salary of their driver.

$Ctrain_{r,rr}$ is the cost for the journey of one wagon between terminals r and rr. It is defined as sum of the fixed cost for one journey of one wagon, costs of loading and unloading and the variable cost that is already multiplied for the rail distance between each node.

3.4.4 Storage

The storage facility selection could be made by the optimization, where it is possible to perform a first natural drying waiting $Ndry1$ periods or with forced ventilation, then a second drying of the biomass could be possible by waiting further $Ndry2$ periods . Once it is achieved the level of $MC_{b\epsilon Bdried2}$, the densification could be executed. These strict constraints, where one involves other ones, are here developed:

$$z_j^{dry1} \le z_j^{storage} \qquad z_j^{dryF} \le z_j^{storage} \qquad z_j^{dry1} + z_j^{dryF} \le 1 \qquad j\ \epsilon\ J$$

$$z_j^{dry2} \le z_j^{dry1} \qquad z_j^{dens} \le z_j^{dry2} \qquad j\ \epsilon\ J$$

Then, it is made the mass balance at the storage, in which is accounted the loss in dry matter dml_b, and the maximum quantity collectible has been limited:

$$bs_{t,b,j} = bs_{t-1,b,j}\cdot(1-dml_b) + transp_{t,b,i,j} + conv_{t,b,bb,j} - transp_{t,b,j,rk}$$

$$\textstyle\sum_{rk\ \epsilon\ R\cup K} transp_{t,b,j,rk} \le bs_{t,b,j}\cdot(1-dml_b) \quad t\epsilon\ T, b\ \epsilon\ Bbiom, bb\ \epsilon\ Bbiom, j\ \epsilon\ J, rk\ \epsilon\ R\cup K$$

The variable $conv_{t,b,bb,j}$ represents the quantity of biomass b that is transformed in biomass bb. It has a particular trend: negative from b to bb, because, in the balance above at the storage j, it represents a subtraction of biomass at state b in order to be converted in bb type. Whereas, its same absolute quantity is positive from bb to b because in the balance of $bs_{t,bb,j}$ the quantity subtracted in the previous balance comes into play here.

It is dependent on the binary variables shown previously. Therefore, primarily if the storage $j\ \epsilon\ J$ is not chosen, the conversion at j is not done of any type. Then, according to the other variables the conversion from a certain biomass b to another one bb of a certain quantity could or could not be done:

$$0 \le conv_{t,bb,b,j} \le \left(z_j^{dry1} + z_j^{dryF}\right)\cdot MAXstorage_j \quad t\ \epsilon\ T, j\ \epsilon\ J, bb\ \epsilon\ Bdried1\ , b\ \epsilon\ \ Basrec$$

$$0 \le conv_{t,bb,b,j} \le z_j^{dry2}\cdot MAXstorage_j \quad t\ \epsilon\ T, j\ \epsilon\ J, bb\ \epsilon\ \ Bdried2, b\ \epsilon\ Bdried1$$

$$0 \le conv_{t,bb,b,j} \le z_j^{dens}\cdot MAXstorage_j \quad t\ \epsilon\ T, j\ \epsilon\ J, bb\ \epsilon\ \ Bdens, b\ \epsilon\ Bdried2$$

As explained before, $conv_{t,b,bb,j} = -\,conv_{t,bb,b,j}$. While, for other transformations the variable assumes value 0.

About the quantification of this variable, the following inequality defines its quantity:

$$conv_{t+Ndry1,bb,b,j} \le\ bs_{t,bb,j}\cdot(1-dml_{bb})^{Ndry1} + \left(1-z_j^{dry1}\right)\cdot MAXstorage_j \quad t\ \epsilon\ T, j\ \epsilon\ J,$$

$bb \in Bdried1, b \in Basrec$, where $Ndry1$ represents the time waited to pass from b to bb and the $conv_{t,bb,b,j}$ assumes a zero value when z_j^{dry1} is zero.

The same identical constraint is used for conversions from $Bdried1$ to $Bdried2$, with shorter waiting time $Ndry2$, and from $Bdried2$ to $Bdens$, with no waiting time.

The capacity of the storage at site j ($MAXbs_j$) is here defined:

$$0 \leq bs_{t,b,j}/RF_b \leq MAXbs_j \quad t \in T, j \in J, b \in Bbiom$$

where the periodic biomass stored in site j is divided by the room factor, computed as $RF_b = \frac{h_{storage} \cdot \rho_b}{MF_b} \quad b \in Bbiom$. The latter allows the transformation of the quantity in weight on dry basis of biomass b in j storage into the equivalent quantity in terms of m^2 of area that would be covered by biomass b, taking into account a defined hight of the storage $h_{storage}$.

Moreover, the $MAXbs_j$ has to be limited by the maximum area of the land bought:

$$MAXbs_j \leq \ z_j^{storage} \cdot MAXstorage_j \ \ j \in J$$

While, the capacity of the densifier $MAXdens_j$ at site j is here described:

$$conv_{t,bb,b,j} \leq MAXdens_j \qquad t \in T, j \in J, bb \in \ Bdried2, b \in Bdens$$

where $MAXdens_j$ is the maximum capacity expressed in tons of densified biomass per time period.

The formulas about costs of the storage facilities j are here reported:

$$INVst_j = z_j^{storage} \cdot INVstF_j + INVstV_j \qquad j \in J$$

More in detail: $INVstV_j = INVstv \cdot MAXbs_j + INVdens \cdot MAXdens_j + \ INVdryF \cdot \ z_j^{dryF}$

where $INVstv$ regards the cost per m^2 of the specific land, according to the chosen location, and the cost for the struct, while $INVdryF$ the investment cost of the forced drying machine.

About OPEX connected to the storage j and to the conversions that take part:

$$OPEXst_j = \sum_{b \in Bbiom} \sum_{t \in T} bs_{t,b,j} \cdot icc_b$$

where icc_b represents the inventory carrying cost for each biomass b.

$$OPEXdry1_j = \sum_{bb \in Basrec} \sum_{b \in Bdried1} \sum_{t \in T} conv_{t,bb,b,j} \cdot c_{n\_dry} + \left(1 - z_j^{dry1}\right) \cdot MAXstorage_j$$

where each biomass b has a its own operating cost per ton of biomass processed c_{n_dry}.

The equivalent calculation is made also for the OPEX for the other alternative (forced drying) or further conversions (drying and densification), in order to be summed into:

$$OPEXstTOT = \sum_{j \in J} OPEXst_j + OPEXdry1_j + OPEXdry2_j + OPEXdens_j$$

3.4.5 Conversion facility

At the biorefinery, the operation of the plant is regulated by the optimization, in other words it could be decided if it is worth to shut down the plant for a certain period. Anyway, this decision is taken between strict constraints, according to which the minimum up-time Dt_{up} and minimum down-time Dt_{down} are set:

$$z_{t,k}^{op} \leq z_k^{bio} \qquad z_{t+Dt_{up},k}^{op} \geq z_{t,k}^{op} - z_{t-1,k}^{op} \qquad 1 - z_{t+Dt_{down},k}^{op} \geq z_{t,k}^{op} - z_{t-1,k}^{op} \quad t \in T, k \in K$$

where the variable $z_{t,k}^{op}$ defines if the plant k will operate at time t.

Then, the capacity of the industrial dryer installed at the biorefinery k is defined below:

$$\sum_{b\epsilon Bbiom}\sum_{ijr\epsilon I\cup J\cup R} transp_{t,b,ijr,k}\cdot Mwater_b\cdot\frac{1000}{deltaT\cdot 24\cdot 3600}\left[\frac{kg_{H2O}}{s}\right]\leq water_k$$

$t\epsilon T, k\epsilon K$, where $Mwater_b$ represents the factor that converts the quantity of biomass b on weight dry basis into the equivalent water that must be evaporated, in order achieve the required moisture of 10% at inlet of the gasifier.

The capacity is defined upon the maximum quantity of water that has to evaporate from the biomass, measured in $\left[\frac{kg_{H2O}}{s}\right]$.

Its investment cost is computed with the linear function:

$$Cdryer_k^{bio} = CdryerF\cdot z_k^{bio} + CdryerV\cdot water_k$$

The size of each possible plant k pow_k should be limited between two physical constraints $MINpow$ and $MAXpow$:

$$z_k^{bio}\cdot MINpow\leq pow_k\leq z_k^{bio}\cdot MAXpow$$

Consequently, it is defined here the limitation of the biomass input in k between 60% and 100% of the power size pow_k (if in that period t it is working):

$$0.6\cdot pow_k\ -\left(1-z_{t,k}^{op}\right)\cdot MAXpow\leq\textstyle\sum_{b\epsilon Bbiom} gasified_{t,b,k}\cdot MF_b\cdot LHV_b\cdot\frac{1000}{deltaT\cdot 24\cdot 3600}\leq\ pow_k$$

$$\sum_{b\epsilon Bbiom} gasified_{t,b,k}\cdot MF_b\cdot LHV_b\cdot\frac{1000}{deltaT\cdot 24\cdot 3600}\leq z_{t,k}^{op}\cdot pow_k\quad t\epsilon T, k\epsilon K$$

Where the variable $gasified_{t,b,k}$ is defined just as:

$$gasified_{t,b,k} = \textstyle\sum_{ijr\epsilon I\cup J\cup R} transp_{t,b,ijr,k}\quad t\epsilon T, b\epsilon Bbiom, k\epsilon K$$

Finally, the quantity of bio-methanol produced is computed in the following way and is destinated to a terminal r or directly to the blending facility m:

$$\sum_{b\epsilon Bbiom} gasified_{t,b,k}\cdot MF_b\cdot LHV_b\cdot CGE_b = \sum_{rm\epsilon R\cup M} transp_{t,bb,k,rm}\cdot LHV_{biofuel}$$

The CGE_b has been computed for each biomass state b and it represents the cold gas efficiency for the biomethanol production.

The yearly quantity of methanol that each biodiesel plant m is willing to accept is here imposed to the yearly quantity of biomethanol transported to m:

$$\sum_{t\epsilon T}\sum_{rm\epsilon R\cup M} transp_{t,b,rm,m}\leq MAXbl_m$$

The yearly electricity requested by each biorefinery k is here calculated in MWh:

$$elec_k = \sum_{b\epsilon Bbiom}\sum_{t\cup T}\sum_{ijr\epsilon I\cup J\cup R} transp_{t,b,ijr,k}\cdot MF_b\cdot LHV_b\cdot\gamma_{el_b}\cdot\frac{1000}{3600}\quad k\epsilon K$$

γ_{el_b} represents the ratio between the requested electricity by the plant and biomass b LHV input into the plant.

Then, the total yearly cost due to the electricity consumption $Purchel$ can be easily found.

The investment costs of the biorefinery have three different linear trends according to the capacity (see paragraph 2.2.5) and to them are added the dryer investment, installation, indirect costs, contingency and interest during construction ($financial$). They are here reported for each biorefinery k:

$$INV_k^{bio} = \left(INVbioF_g \cdot z_k^{bio} + INVbioV_g \cdot pow_k + \; Cdryer_k^{bio}\right) \cdot financial \quad g \in \{1,2,3\}, k \in K$$

3.4.6 General costs

Therefore, the total investments can be computed as:

$$INV = \sum_{j \in J} INVst_j + \sum_{k \in K} INV_k^{bio}$$

The operation and maintenance costs are here reported:

$$OPEXbioTOT = \sum_{k \in K} \frac{INV_k^{bio}}{financial} \cdot O\&M$$

The revenues of the studied system are based on selling bio-methanol to the blending facilities or to the commercial ports. Thus, the total earning is computed as:

$$earn = \sum_{t \in T} \sum_{k \in K} \sum_{rm \in R \cup M} transp_{t,b,k,rm} \cdot price_{biofuel} \quad b \in Bfuel$$

3.5 GHG evaluation

The greenhouse gas emissions are one of the main factors, which conducts the energy sector towards the field of renewables. For this reason, they have been estimated also in order to define if this possibility to produce methanol from residues could constitute into a plausible alternative from the fossil one and, furtherly, it could be used to individualize some greener improvements to apport to the supply chain.

This is an analysis made a posteriori on the results found through the Net Present Value maximization.

The greenhouse gases are calculated on the basis of life cycle analysis. According to ISO 14,040 "Life Cycle analysis is a method to estimate the material and energy flows of a product to calculate the environmental effects in the total lifetime of the product – from cradle to grave" (ISO 14040:2006).

The greenhouse gas emissions from the production are calculated as [1]:

$$E_{biofuel} = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \quad \left[CO_{2_{eq}}/MJ_{biofuel}\right]$$

Where:

$E_{biofuel}$	total emissions from the use of the biofuel
e_{ec}	emissions from the extraction or cultivation of raw materials
e_l	annualized emissions from carbon stock changes caused by land-use change
e_p	emissions from processing
e_{td}	emissions from transport and distribution
e_u	emissions from the fuel in use
e_{sca}	emission saving from soil carbon accumulation via improved agricultural management
e_{ccs}	emission saving from carbon capture and geological storage
e_{ccr}	emission saving from carbon capture and replacement

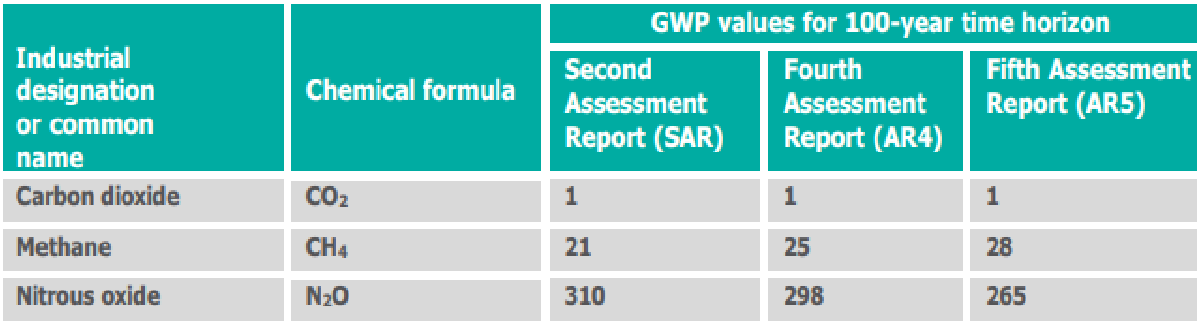
e_{ee} emission saving from excess electricity from cogeneration

This is the general formula for the estimation of the $CO_{2_{eq}}$ for a common biofuel and, according to the directive, the greenhouse gas emissions from the manufacture of machinery and equipment are not taken into account.

It is important to decide if treating the bio-methanol produced as a single biofuel or as a contributor for the biodiesel production with a consequent estimation of the overall $CO_{2_{eq}}$. Basing on the trend of the EU, the single methanol does not find a place as pure biofuel. Therefore, it could be useful also to understand how producing methanol in a renewable way can apport benefits to the total emissions of the FAME biodiesel, instead using fossil methanol.

It is important also to count the contribution of the other greenhouse gases (different from CO_2) in the $CO_{2_{eq}}$. The Global Warming Potential (GWP) is a parameter, defined for some categories of substances, that can express the impact of one unit in weight of the pollutant substance into the equivalent CO_2 amount in a certain time frame. In the following Table 10, the GWPs for the substances of interest with a 100-year time horizon are reported:

Table 10. Global Warming Potentials of CO_2, CH_4 and N_2O with a time horizon of 100 years. Source: [58]



Industrial designation or common name	**Chemical formula**	**GWP values for 100-year time horizon**		
		Second Assessment Report (SAR)	**Fourth Assessment Report (AR4)**	**Fifth Assessment Report (AR5)**
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	21	25	28
Nitrous oxide	N_2O	310	298	265

Then, the GWP should be multiplied with the correspondent quantity of emitted gas.

In this thesis, the emissions that can be estimated are the ones connected to the harvesting phase (if it is present), processing part connected to the transformation process and finally the part of transport and distribution. They can be calculated from the results of the simulation (volume of harvested biomass, quantity of purchased electricity, quantity transported in each node, number of journeys) and from some parameters (distance, truck mean velocity). Therefore, there are some other information requested for their calculation, which are not known directly from the outcomes of the model.

From the available results achieved through the optimization of model, the emissions related to each phase can be evaluated through formulas that follow.

Firstly, they are accounted just for bio-methanol and then for the potential arising biodiesel obtained with it.

3.5.1 Bio-methanol emissions

If the biomass requires a harvesting phase, the emissions connected to it have to be accounted. Otherwise, they can be considered null or should be estimated with other tools that are out of this thesis interest.

3.5.1.1 Emissions from the extraction or cultivation of raw materials and from land use

The $CO_{2_{eq}}$ at this level is quantified as:

$CO_{2_{eq,ec}}\left[\frac{ton}{y}\right] = \left(CO_2\left[\frac{ton}{Mm^3}\right]\cdot GWP_{CO_2} + NO_x\left[\frac{ton}{Mm^3}\right]\cdot GWP_{NO_x} + CO\left[\frac{ton}{Mm^3}\right]\cdot GWP_{CO}\right)\cdot Mm^3_{\substack{residues\\harvested}}$, where each emission factor is relative to the volumes of harvested biomass.

About the chipping procedure, the correspondent mean value of $CO_{2_{eq}}$ [59] is 4.27 $\frac{kg_{CO_2}}{m^3_{residues}}$.

Therefore, it can be calculated $e_{ec}\left[\frac{gr_{CO_{2,eq}}}{MJ}\right] = \frac{CO_{2_{eq,ec}}\left[\frac{ton}{y}\right]}{tot_{\substack{biomethanol\\ produced}}\left[\frac{ton}{y}\right]\cdot LHV_{methanol}\left[\frac{MJ}{kg}\right]\cdot 10^3} \cdot 10^6$

About emissions from carbon stock changes caused by land-use change (e_l), they are assumed equal to zero, as the biomass is residual [60].

3.5.1.2 Emission due to processing

The CONVERGE technology results to be efficient upon heat recovery from the processes overcoming in it, as the whole exploited heat comes from the biomass. On the other side, there is a consistent usage of electricity from the grid, which has not a zero impact. Figure 13 shows the European trend during the years of the greenhouse gas emission intensity per kWh of electricity generated ($GHG_{intensity}$), it is possible to assume the emission connected to the electricity usage equal to 275 $\frac{g_{CO_{2eq}}}{kWh}$. This value is variable according to the EU state and, in addition, in the future years this quantity could be considered even lower.

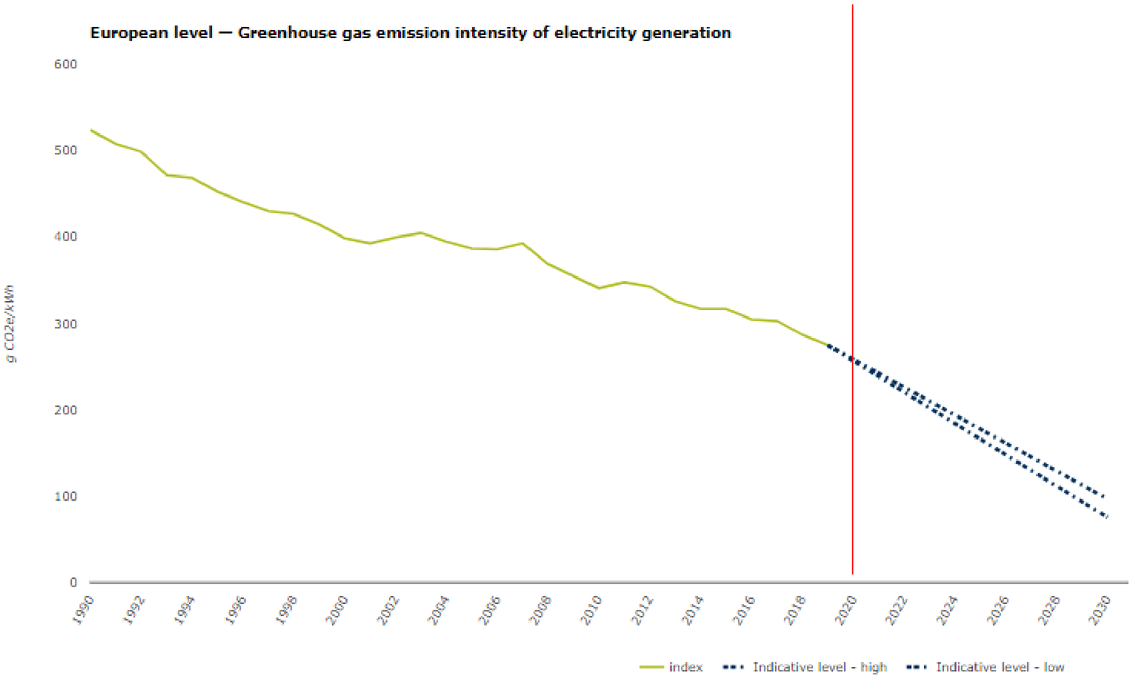


Figure 13. GHG emission intensity of electricity generation of EU average. Source: [41]

The $CO_{2,eq}$ is calculated by multiplying the $GHG_{intensity,el}$ with the sum of the yearly electric energy consumed by the CONVERGE technology, in each plant site chosen k:

$$CO_{2_{eq,p}}\left[\frac{ton}{y}\right] = (GHG_{intensity,el} \cdot \sum_{k\epsilon K} elec_k \cdot 10^3) \cdot 10^{-6}$$

The emissions due to processing are estimated as:

$$e_p\left[\frac{gr_{CO_{2,eq}}}{MJ}\right] = \frac{CO_{2_{eq,p}}\left[\frac{ton}{y}\right]}{tot_{\substack{biomethanol\\ produced}}\left[\frac{ton}{y}\right] \cdot LHV_{methanol}\left[\frac{MJ}{kg}\right] \cdot 10^3} \cdot 10^6$$

3.5.1.3 Emissions from transport and distribution

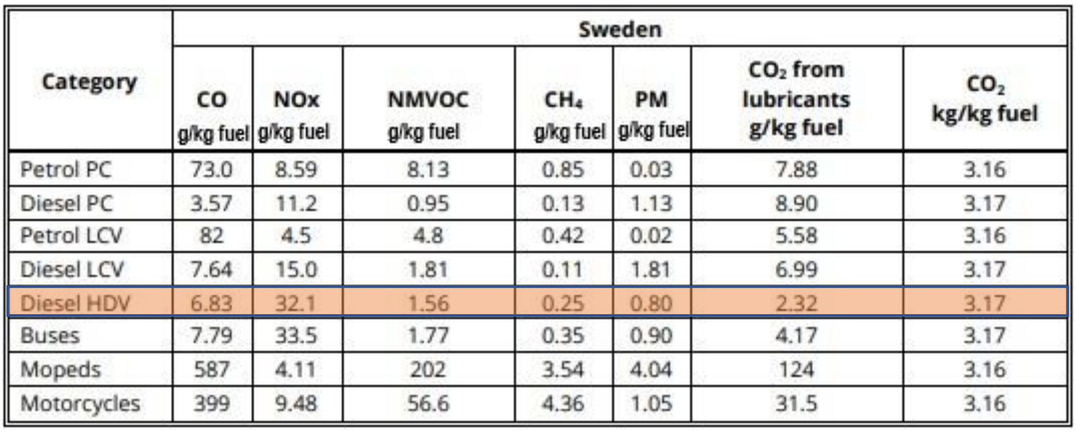
The emission category from road transport is the most complicated in terms of calculation, as it is considered the fuel consumption due to:

- Trips between points with loaded truck and with unloaded one, which comes back to the starting point.
- Loading and the unloading phases.

The fuel consumption is dependent also on the sizes of trucks selected for this analysis.

The $CO_{2_{eq}}$ is quantified by data from the available Table 11, which estimates the emission standards of a representative European country (Sweden) for each category:

Table 11. Emissions specific quantities related to the fuel consumption of each road transport category. Source: [38]



Category	Sweden						
	CO g/kg fuel	NOx g/kg fuel	NMVOC g/kg fuel	CH₄ g/kg fuel	PM g/kg fuel	CO₂ from lubricants g/kg fuel	CO₂ kg/kg fuel
Petrol PC	73.0	8.59	8.13	0.85	0.03	7.88	3.16
Diesel PC	3.57	11.2	0.95	0.13	1.13	8.90	3.17
Petrol LCV	82	4.5	4.8	0.42	0.02	5.58	3.16
Diesel LCV	7.64	15.0	1.81	0.11	1.81	6.99	3.17
Diesel HDV	6.83	32.1	1.56	0.25	0.80	2.32	3.17
Buses	7.79	33.5	1.77	0.35	0.90	4.17	3.17
Mopeds	587	4.11	202	3.54	4.04	124	3.16
Motorcycles	399	9.48	56.6	4.36	1.05	31.5	3.16

Inside the table, it is possible to know the emissions produced for each different transport category, as a function of the quantity of fuel consumed.

The selected category for this estimation is the Diesel HDV (Heavy Duty Vehicle) and the emissions are referred to the burnt quantity of common diesel. This last quantity can be easily found from the available results regarding the number of journeys ($Njroad_{t,n,n}$) made along the year between points n and from the given data about the distance between points ($distance_{n,n}$), which are taken from the model. Moreover, the fuel consumption during traveling is function of vehicle mass and km [56] and during loading and unloading phases $fuel\ cons_{\substack{load\\unload}}$ [32], function of time required to fill or to empty a truck/wagon.

The respective fuel consumptions per km travelled for a loaded $fuel\ cons_{travel\ loaded_g}$ and for an unloaded truck $fuel\ cons_{travel\ unloaded_g}$ have been calculated for each type of truck $g\ \epsilon\ [1,2,3]$ considered in this analysis for defined connections, as explained in the paragraph 2.3.1. In addition, it is calculated also the fuel consumption due the loading $fuel\ cons_{loading_g}$ and unloading phases $fuel\ cons_{unloading_g}$ of each truck type. These terms are used to compute the yearly total fuel consumption $fuel\ cons_{tot}$:

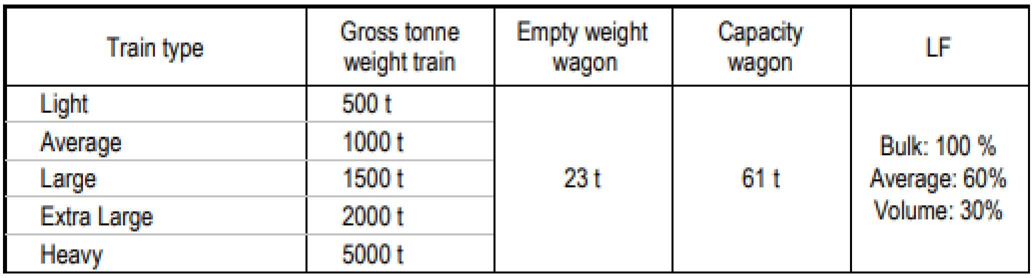
$$fuel\ cons_{tot}\left[\frac{kg}{y}\right] = Njroad_{t,n,n}\cdot\Big[fuel\ cons_{load_g} + fuel\ cons_{unload_g} + \Big(fuel\ cons_{travel\ loaded_g} + fuel\ cons_{travel\ unloaded_g}\Big)\cdot distance_{n,n}\Big] \qquad n\ \epsilon\ N, t\ \epsilon\ T$$

Then, from the found quantities of fuel consumption, the total $CO_{2,eq}$ can be found:

$$CO_{2_{\substack{eq,td\\road}}}\left[\frac{ton}{y}\right] = \left(CO_2\left[\frac{kg}{kg_{fuel}}\right]\cdot GWP_{CO_2} + NO_x\left[\frac{kg}{kg_{fuel}}\right]\cdot GWP_{NO_x} + CH_4\left[\frac{kg}{kg_{fuel}}\right]\cdot GWP_{CH_4}\right)\cdot fuel\ cons_{tot}\cdot 10^{-3}$$

Afterwards, the emissions connected to the rail transport can be roughly estimated, by assuming that all the trains travel just with electricity. The types available of trains are the following:

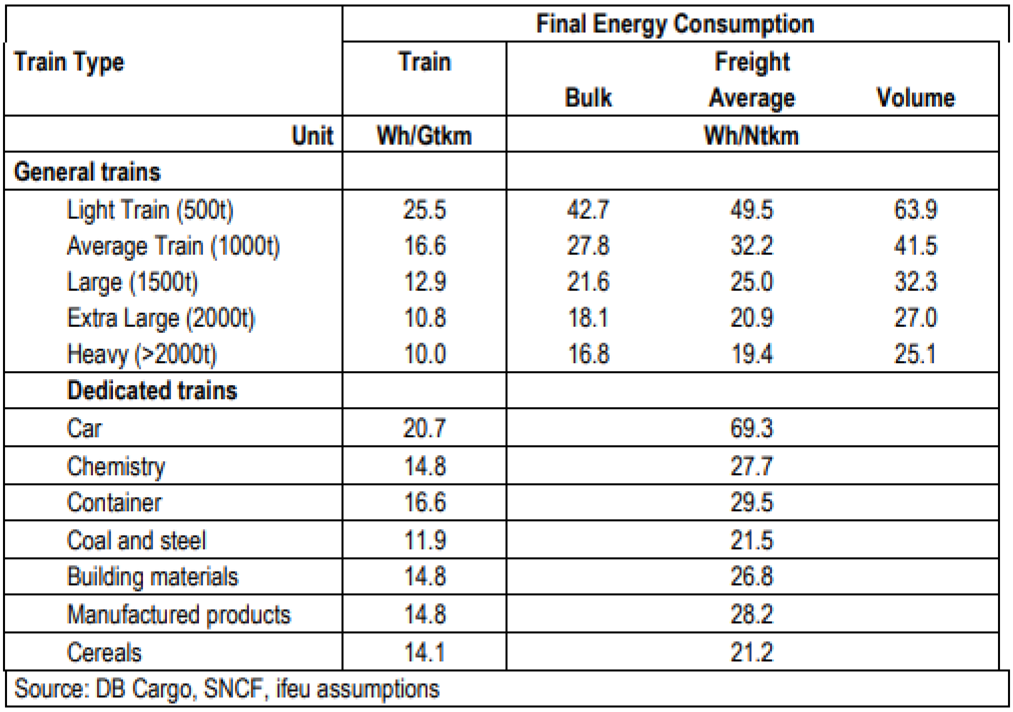
Table 12. Characteristics of the categories of train available. Source: [34]



Train type	Gross tonne weight train	Empty weight wagon	Capacity wagon	LF
Light	500 t	23 t	61 t	Bulk: 100 % Average: 60% Volume: 30%
Average	1000 t			
Large	1500 t			
Extra Large	2000 t			
Heavy	5000 t			

The load factor is the ratio between the payload in tonnes and the effective tonnes of biomass that fill fully a train wagon. It is different according to the transported product, as the residues have a bulk density of about $0.3 - 0.5 \frac{ton}{m^3}$ and bio-methanol of $0.8 \frac{ton}{m^3}$. Respectively, their load factors assumed are 30% and 80%, which can be approximated to the categories 'Volume' and 'Average'. By the available Table 13, it can be roughly estimated the quantity of energy used for the rail transport, which already accounts for the empty trips. It estimates the energy consumption only from a tank-to-wheel analysis (the energy consumed regards only the operation, without taking into account the upstream processes of maintenance and of construction):

Table 13. Energy consumption for the different train categories and transported item type (Bulk, Average, Volume). Source: [34]



	Final Energy Consumption			
Train Type	**Train**	**Freight**		
		Bulk	**Average**	**Volume**
Unit	**Wh/Gtkm**	**Wh/Ntkm**		
General trains				
Light Train (500t)	25.5	42.7	49.5	63.9
Average Train (1000t)	16.6	27.8	32.2	41.5
Large (1500t)	12.9	21.6	25.0	32.3
Extra Large (2000t)	10.8	18.1	20.9	27.0
Heavy (>2000t)	10.0	16.8	19.4	25.1
Dedicated trains				
Car	20.7	69.3		
Chemistry	14.8	27.7		
Container	16.6	29.5		
Coal and steel	11.9	21.5		
Building materials	14.8	26.8		
Manufactured products	14.8	28.2		
Cereals	14.1	21.2		
Source: DB Cargo, SNCF, ifeu assumptions				

The train types analyzed are:
1) Light (500 t)
2) Average (1000 t)
3) Large (1500 t)
4) Extra large (2000 t)
5) Heavy (>2000 t)

The most suitable type to connect the different terminals have been chosen according to these guidelines:

- Use of the larger type of train possible, in order to have lower electricity consumption per transported ton;
- Number of wagons per train should be lower than 45;
- In the calculation for the total weight of the train is accounted also the tare of each wagon;
- Calculation of the number of travelling trains should be done for each specific route.

It may result that different train types could be used in the whole supply chain, because the train type is assigned to each route from terminal r to other terminal r.

Therefore, from the train type chosen for each route and the correspondent specific energy consumption ($Wh/Ntkm$) relative to the net transported quantity and travelled distance (Table 13), it could be assigned between the rail terminals the specific energy consumption $E_{cons_{r,rr}}$. Consequently, the total energy consumption can be computed as:

$$E_{tot,rail}\left[\frac{kWh}{y}\right] = \sum_{rr\epsilon R}\sum_{r\epsilon R}\sum_{t\epsilon T}\sum_{b\epsilon B} transp_{t,b,r,rr} \cdot MF_b \cdot distance_{r,rr} \cdot E_{cons_{r,rr}} \cdot 10^{-3}$$

From the available electricity consumption, it is possible to find the emissions per kWh connected to the train transport with the same assumption made in the processing phase.

$$CO_{2_{\substack{eq,td\\ rail}}}\left[\frac{ton}{y}\right] = E_{tot,rail} \cdot GHG_{intensity,el} \cdot 10^{-6}$$

Finally, the emissions connected to transport and distribution are quantified:

$$e_{td}\left[\frac{gr_{CO_{2,eq}}}{MJ}\right] = \frac{CO_{2\substack{eq,td\\ truck}} + CO_{2_{\substack{eq,td\\ rail}}}}{tot_{\substack{biomethanol\\ produced}}\left[\frac{ton}{y}\right] \cdot LHV_{methanol}\left[\frac{MJ}{kg}\right] \cdot 10^3} \cdot 10^6$$

The remanent voices, as land use change e_l and others e_{sca} and e_{ccs} are not taken into account, because there are not available information about them. Furtherly, the negative contribution e_{ee} is null, because there is not electricity produced in this case.

Furthermore, the e_{ccr} (emission saving with carbon capture) can be estimated because the CONVERGE technology may have a carbon capture associated. In this thesis, this contribution is not accounted for the lacking data on it, but they can be accounted for a future work.

The total contributions calculated are summed obtaining $E_{biometh}\left[\frac{gr_{CO_{2,eq}}}{MJ}\right] = e_{ec} + e_p + e_{td}$.

3.5.2 FAME biodiesel total emissions

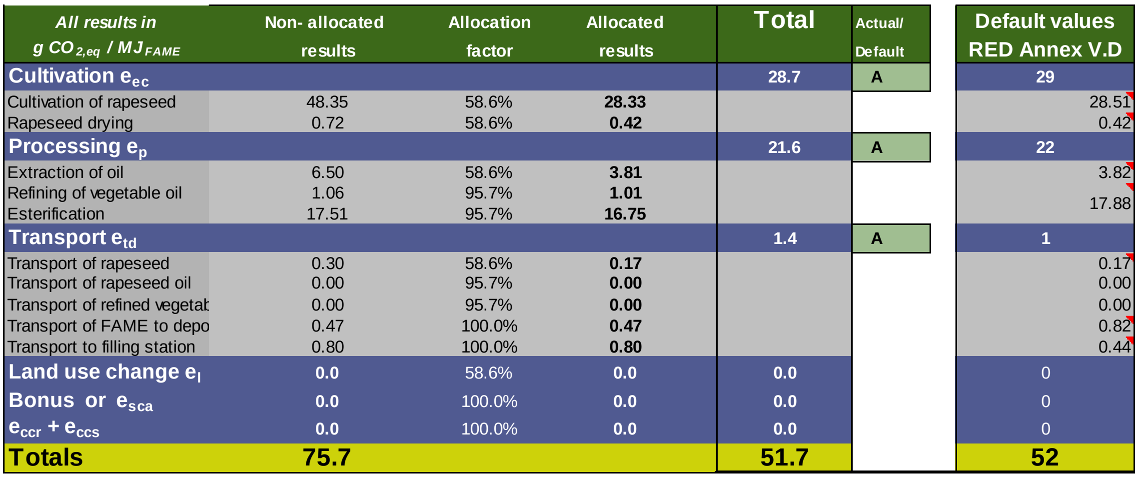
According to FAME biodiesel, it is important to consider also the greenhouse gases regarding the cultivation of oily feedstocks, their transportation and their oil extraction. Then, the oil refining and the consequent transesterification process are also required and usually performed at the biodiesel plant.

From Biograce-I tool [40], it is possible to estimate the emissions connected to FAME biodiesel without directly calculate some parts. This tool is available from 2008 and, in some parts, it makes use of some old technologies for nowadays, as it is discussed in the document [61].

As the most spread and representative FAME biodiesel comes from Rapeseeds, the attention would be focused on this type of biofuel.

The following Table 14 expresses each contribution that participates in the total final emission of the biofuel:

Table 14. CO_{2eq} emissions connected to each phase of biodiesel supply chain. Source: [40]

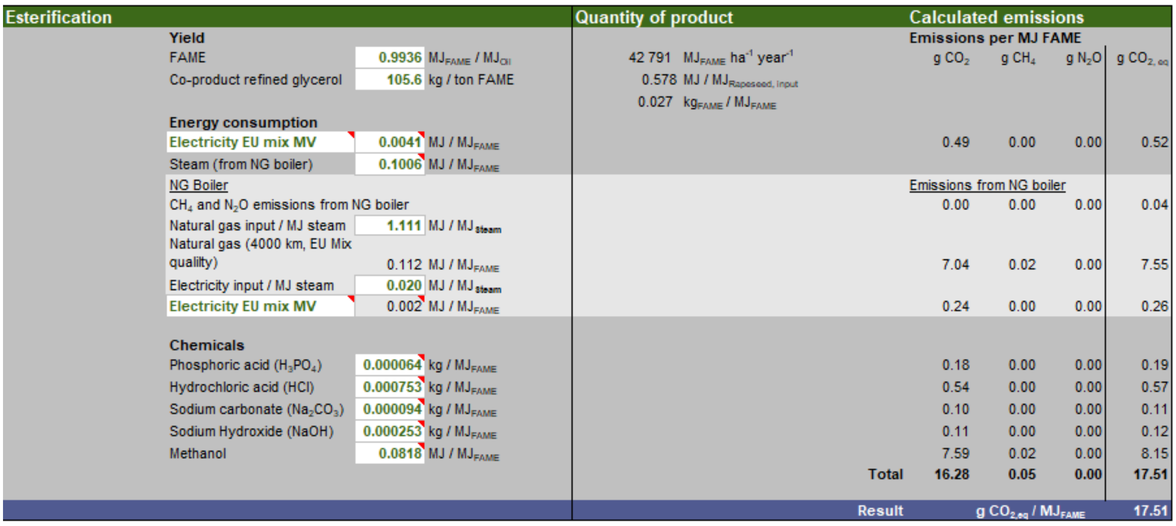


All results in g $CO_{2,eq}$ / MJ_{FAME}	Non- allocated results	Allocation factor	Allocated results	Total	Actual/ Default	Default values RED Annex V.D
Cultivation e_{ec}				28.7	A	29
Cultivation of rapeseed	48.35	58.6%	**28.33**			28.51
Rapeseed drying	0.72	58.6%	**0.42**			0.42
Processing e_p				21.6	A	22
Extraction of oil	6.50	58.6%	**3.81**			3.82
Refining of vegetable oil	1.06	95.7%	**1.01**			17.88
Esterification	17.51	95.7%	**16.75**			
Transport e_{td}				1.4	A	1
Transport of rapeseed	0.30	58.6%	**0.17**			0.17
Transport of rapeseed oil	0.00	95.7%	**0.00**			0.00
Transport of refined vegetat	0.00	95.7%	**0.00**			0.00
Transport of FAME to depo	0.47	100.0%	**0.47**			0.82
Transport to filling station	0.80	100.0%	**0.80**			0.44
Land use change e_l	0.0	58.6%	0.0	0.0		0
Bonus or e_{sca}	0.0	100.0%	0.0	0.0		0
$e_{ccr} + e_{ccs}$	0.0	100.0%	0.0	0.0		0
Totals	**75.7**			**51.7**		**52**

The emissions, due to cultivation and drying of this feedstock, are the highest between the other biodiesel types and they amount to 28.7 $g_{CO_{2eq}}/MJ_{FAME}$, due to the use of fertilizers. Even if this datum has been considered by [61] underestimated, it is a default value of the [1] Annex V.A.

About processing, Table 15 considers that the esterification process is performed through fossil methanol. More in detail this process involves also consumption of electricity, natural gas for the steam production and some chemicals as catalysts for the process. Their relative emissions are here reported:

Table 15. Detailed emissions due to the esterification process. Source: [40]



Esterification			Quantity of product	Calculated emissions: Emissions per MJ FAME g CO_2	g CH_4	g N_2O	g $CO_{2,eq}$
Yield							
FAME	0.9936	MJ_{FAME} / MJ_{Oil}	42 791 MJ_{FAME} ha^{-1} $year^{-1}$				
Co-product refined glycerol	105.6	kg / ton FAME	0.578 MJ / $MJ_{Rapeseed, Input}$				
			0.027 kg_{FAME} / MJ_{FAME}				
Energy consumption							
Electricity EU mix MV	0.0041	MJ / MJ_{FAME}		0.49	0.00	0.00	0.52
Steam (from NG boiler)	0.1006	MJ / MJ_{FAME}					
NG Boiler				Emissions from NG boiler			
CH_4 and N_2O emissions from NG boiler				0.00	0.00	0.00	0.04
Natural gas input / MJ steam	1.111	MJ / MJ_{steam}					
Natural gas (4000 km, EU Mix quality)	0.112	MJ / MJ_{FAME}		7.04	0.02	0.00	7.55
Electricity input / MJ steam	0.020	MJ / MJ_{steam}					
Electricity EU mix MV	0.002	MJ / MJ_{FAME}		0.24	0.00	0.00	0.26
Chemicals							
Phosphoric acid (H_3PO_4)	0.000064	kg / MJ_{FAME}		0.18	0.00	0.00	0.19
Hydrochloric acid (HCl)	0.000753	kg / MJ_{FAME}		0.54	0.00	0.00	0.57
Sodium carbonate (Na_2CO_3)	0.000094	kg / MJ_{FAME}		0.10	0.00	0.00	0.11
Sodium Hydroxide (NaOH)	0.000253	kg / MJ_{FAME}		0.11	0.00	0.00	0.12
Methanol	0.0818	MJ / MJ_{FAME}		7.59	0.02	0.00	8.15
			Total	**16.28**	**0.05**	**0.00**	**17.51**
			Result	g $CO_{2,eq}$ / MJ_{FAME}			17.51

The only voice that should be changed is about the emissions relative to methanol. From the knowledge that the necessary quantity of methanol to produce 1 MJ of FAME is equal to 0.0818 MJ, it is possible to estimate the CO_{2eq} produced with the usage of the green methanol. On the other hand, the GHG calculation for the other phases of esterification are left as in the document (e_{others}):

$$e_{esterification}\left[gr_{CO_{2,eq}}/MJ_{FAME}\right] = e_{others} + (0.0818 \cdot E_{biometh})$$

Then, the contribution due the esterification process is multiplied with its appropriate allocation factor and summed with the other ones connected to processing, left as in Table 15.

The final emissions due to usage of biodiesel obtained with the green methanol are calculated as:

$$E_{FAME}\left[gr_{CO_{2,eq}}/MJ_{FAME}\right] = e_{ec} + e_p + e_{td}\text{ , where } e_{ec} \text{ and } e_{td} \text{ are taken equal to the table.}$$

4 Cases of study and assumptions

The model was mainly applied to optimize the supply chain of the forest residues in Sweden, indeed for each entity type it has been made an accurate research of the specific characteristics approaching more to reality. Then, it has been investigated also the 'Italian case' (with data selected from the precedent work) to compare between the two different cases and models.

4.1 Swedish case

The assumptions and the main aspects that regard the Swedish case are here reported.

4.1.1 Geographic characterization

This case regards mainly the region of the Svealand in Sweden and the relevant aspects arising from this analysis can identify some characteristics connected to the supply chains of the Scandinavian area (point 2 paragraph 1.5).

This area, located in Northern Europe, is characterized by cold climate, more precisely mild during summers and very cold during winters.

The morphology of the territory is mainly flat and characterized by lot of lakes. Moreover, the forests are a constant presence in these lands, indeed the 69% of the Swedish territory is covered by them [62].

This area borders with:

- Norway to the west.
- Baltic sea to the east, easy to navigate.
- Götaland to the south, the most industrialized and commercial region of Sweden because of its vicinity to the other European countries.
- Norrland to the north, with high concentration of forests.

The forests represent a real economic source for many sectors of this country, an important one is represented by the paper industry.

The origin points from which this analysis will start are exactly the forests of this region. More precisely the forests that participate into the Mellanskog-Sogsagama consortium, which communicates the data provided for this study.

4.1.2 Biomass characterization

The forests represent the production points for the wood residues that will be exploited by the supply chain. In other words, they consist into branches, slush, bark, leaves and roots, but also damaged wood [50], so the parts or the whole trees that would be left on the ground once the primary parts have been collected for other uses, as for paper production, manufacturing industry and other energy uses.

There are two operations that are done into the forests, in which is possible to get some residues:

- Thinning, which consists into the removal of trees planted only just for the function of rising the permanent trees. This operation is performed in intervals of 10-30 years [63].
- Final felling, which is the removal of the permanent tree itself that is at the end of its life, which lasts about 80 years [63].

The trees removed with thinning operation consist about one third of the total harvested in Sweden each year.

The forests majorly spread are the coniferous (83%), then mixed forests (12%) and deciduous (5%).

Between the coniferous, the trees that stand out are the spruce, pine and birch, as Figure 14 shows:

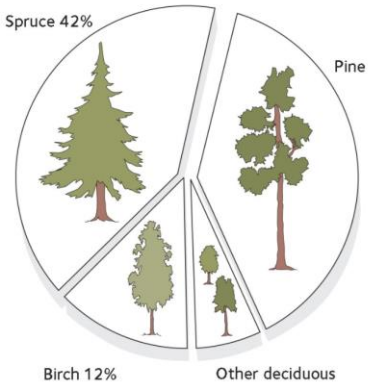


Figure 14. Share of forest tree types present in Sweden. Source: [63]

The common characteristics assumed for the wood coming from forests are reported in the following Table 16:

Table 16. Approximate and Ultimate analysis assumed for forest residues. Source: [64]

Proximate analysis (wt% on dry basis)	
Fixed carbons	17.75
Volatile matter	81.25
Ash	1
Ultimate analysis (wt% on dry basis)	
C	50.12
H	6.01
N	0.38
Cl	0.09
S	0.06
O	42.34

The C/N ratio results to be equal to 128.25, while the moisture content to about 50%. The moisture is not necessarily the same when it reaches the conversion plant. The same discussion can be done upon its physical state (chipped/sawdust/densified), as there are certain phases that wood passes before to be transformed into biofuel.

Furtherly, in Sweden there is not a specific period, in which this biomass is produced and harvested, therefore it can be assumed to have it available in every possible moment of the year.

4.1.3 Harvesting/Collection phase

The information about the origin points, communicated by partners [65], consist into geographic coordinates and yearly available potential quantity of residues in each point. These points are completely representative of a possible collecting point of each ideal polygon, in which the whole forest lands of Mellanskog are subdivided.

The subdivision can be shown by the following Figure 15:

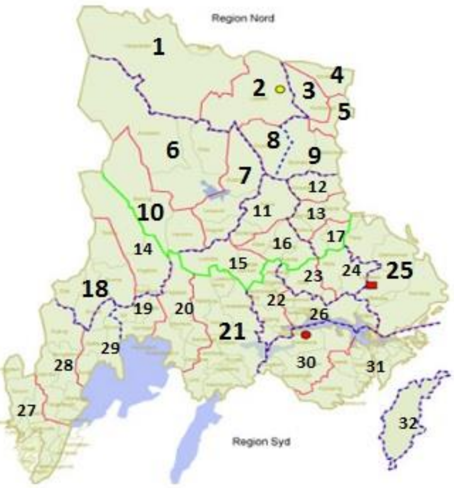


Figure 15. Subdivision of Mellanskog forest territory. Source: [65]

There are 32 polygons, each one represented by one collection point.

The different harvesting locations in the forests have not been considered because there are not estimations on them and their planning requires higher levels of knowledge.

The cutting of trees and the stumps extraction consist into the first procedure that composes the supply chain, which is performed during all the year.
Immediately after, the customary procedure is to leave the woody biomass on the ground and to pick up it in a second moment. Generally, during the harvesting phase the forest residues follow the same treatments of the wood logs, which represent the most expensive part of the tree. The main objective of leaving the wood on the ground for some months is to perform a first drying achieving approximately a moisture content of 35-40%. Indeed, the moisture of the fresh wood in the Swedish forests is between 50-55% that is really high to be immediately thermochemically processed.
The storage of humid biomass causes losses of dry matter, due to the microbial activity. Some studies [66] assert that the major factors that influence the microbial activity are: air temperature, relative humidity, exposure, precipitation, wind, tree species and particle size. Hence, they demonstrate that decomposition is lower when storing the entire residues than woodchips. For this reason, the chipping procedure will be executed just before their collection with trucks.

In the same studies [66], it is also analyzed, in a forest site of Germany, the benefit of covering residues with a fleet and the differences generated by storing them during winter (Nov.-Apr.) and summer (May-Oct.) (Table 17):

Table 17. Moisture and dry matter losses achieved by covering or not wood residues and storing them during winter and summer seasons in a forest site in Germany. Source: [66]

Season	Conditions	Moisture before (wt%)	Moisture after (wt%)	Dry matter losses (wt%)
Winter	Uncovered	51.1	52.7	7.8
	Covered	50.7	36.9	8
Summer	Uncovered	50.4	34.1	7
	Covered	56.8	34.2	11.1

From the data available, it is possible to notice that the use of a fleet covering reveals to be an important benefit upon the first drying of biomass at the harvesting/collecting point during winter. It makes the difference in this season avoiding the rewatering of biomass, which is an important aspect as it reduces considerably the drying time.

While during the summer season, it has an adverse effect, which is the increment of temperature inside the pile favouring the activities of the microorganisms responsible of the dry matter decomposition [67].

In summer, there are already the perfect conditions to dry the biomass in open air: the low relative humidity and the high ambient temperature [68].

The best configuration for this part of the supply chain would be:

1) during winter, to bring the just cut woody biomass to roadside and to cover it with fleet.
2) during summer, to leave it at the clear-felled area in the forest, so that it can defoliate and release some nutrients to the ground [68].
3) To leave the cut biomass for 6 months drying at the harvesting point, necessary to reach an acceptable MC to be collected. Only exception is done to the biomass cut in spring and summer, which could be collected just after 10 weeks.

The decision (3) is explained by the reworking of a study led on the woodchips drying [69], where from the available data of the monitored moisture of one year, it has been extracted a representative τ of each month. The τ has been found from the following relation [70]:

$MCdry(t) = MCe + (MCdry(t_0) - MCe) \cdot e^{-\frac{t}{\tau}}$, where $MCdry(t) = \frac{MC(t)}{1-MC(t)}$, MCe assumed equal to 0.13, while t and t_0 represent respectively the current instant and the initial one.

Then, it has been selected an intermediate day of each season, in which it is started the roadside drying, and it is modelled the trend of the MC that could be verified over time by using the previous formula. It was modelled in order to see the difference generated in terms of drying time by deciding to cut the trees in every moment of the year. The obtained results are shown in Figure 16:

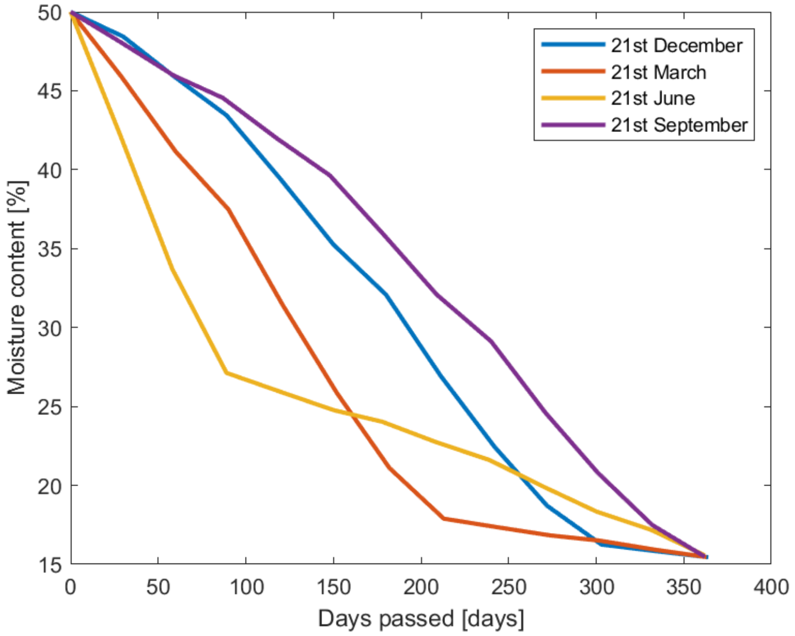


Figure 16. Moisture trend along the year for woody biomass covered by a tarp, which has been left drying roadside (or on site) starting from a representative day of winter, spring, summer and autumn

By seeing the graph in Figure 16, approximately after 6 months the biomass surely reaches the 35% of humidity. Moreover, the biomass dried during summer reaches an acceptable MC before, so it is given the possibility for the biomass harvested during spring to be collected after just 10 weeks.

The recommendations of the SFA (Swedish Forest Agency), it is required to leave at least 20% of the harvested forest residues on the ground of a clear-felled area for its own regeneration [68]. Then, the roadside chipping could be done through the combination of a truck-mounted chipper, which releases the woodchips on the ground, and of the chip truck, in which the chips are loaded through a crane.

Once the biomass has been chipped, it is ready to be purchased and transported to the other points.

The common price of woodchips considered in this analysis is around $50 - 55$ €$/ton$ [65]. The production cost of the woodchips has not been estimated, in this analysis, because the precise phases and means used at this level with the relative costs are out of this project control. Anyway, it is important to study the main passages happening at these points to have the knowledge of the characteristics of the biomass that is purchased.

Then, the biomass ready to be collected has the following characteristics listed in Table 18:

Table 18. Wood residues characteristics at the collecting point

LHV_{asrec}	11.54	$\left[\frac{MJ}{kg}\right]$
MC	35	%
Density	0.5	$\left[\frac{ton}{m^3}\right]$
Bulk density	0.3	$\left[\frac{ton}{m^3}\right]$
Price	55	$\left[\frac{€}{ton}\right]$
Availability	All year	
Average roadside storage time	6	months

4.1.4 Other entities

The storage sites have been chosen uniformly spread between the collecting points, as shown in Figure 17, and they represent realistic purchasable lands [71] chosen with their realistic price €$/m^2$.

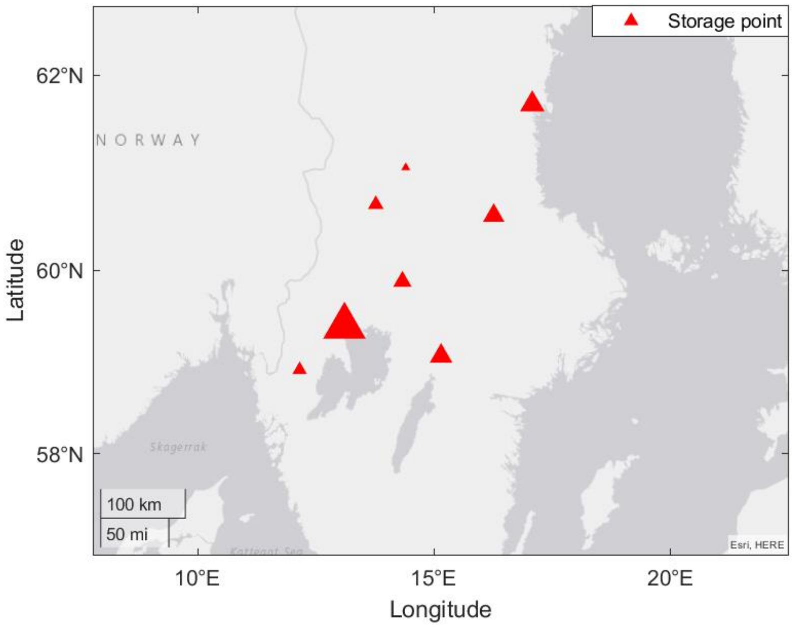


Figure 17. Storage sites selected uniformly in the Svealand territory (n.tot= 8 points)

In this case, it could be experienced the exploitation of the storage as a pre-treatment place.

Whenever it is chosen the natural drying, there are the possibilities to wait a certain number of weeks achieving a MC of 25% (Bdried1) or to wait other further weeks achieving the MC of approximately 17% (Bdried2). Like natural drying, also the forced drying is structured in the same manner, but with lower time to wait.

Moreover, once it is achieved the humidity of 17%, the biomass could be densified (Bdens). This could present great advantages upon the occupied volume, hence reducing the transport costs.

The choice of the conversion facilities is a crucial point. The criterions used are: a) in place of old shut down CHP plants, 2) vicinity to a rail terminal, 3) inside an industrial area, 4) towards the southern area of Sweden, to be closer to blenders/biodiesel plants/commercial ports.

The possible sites chosen are three as here represented in Figure 18:

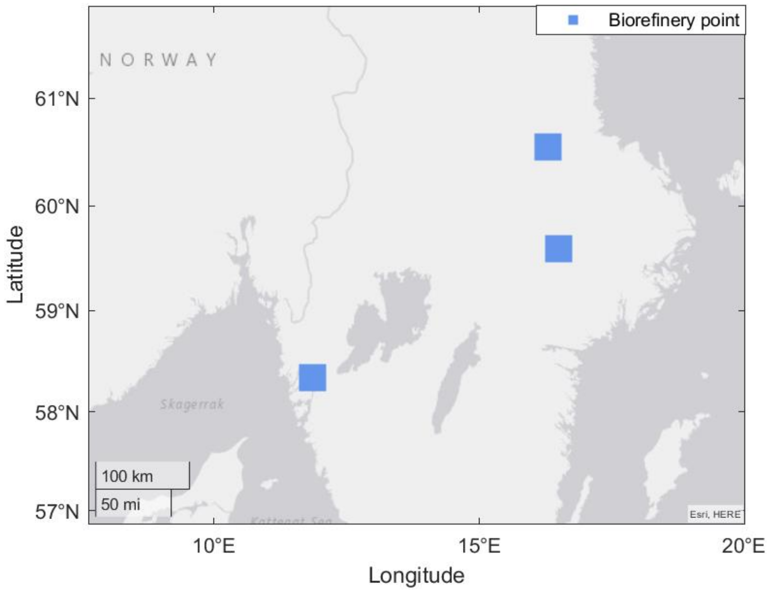


Figure 18. Chosen biorefinery sites (n.tot= 3 points)

For each possible wood residue state that could enter the biorefinery, the Cold Gas Efficiencies and electricity ratios are referred to the biomass in input of the dryer and are reported in Table 19:

Table 19. Cold Gas Efficiency and Electric Ratio estimated for each state that wood residues could assume in this analysis

State	CGE	Electric ratio
Basrec	57.71%	-6.85%
Bdried1	57.00%	-6.41%
Bdried2	56.10%	-6.04%
Bdens	55.85%	-5.94%

About demand side, the local biodiesel plants, which perform the esterification are reported in Table 20 with their annual production capacity of biodiesel:

Table 20. Local biodiesel plants reported with their yearly biodiesel production capacity

Plant	Capacity [tons biodiesel/y]	Type
Adesso Bioproducts As	150.000	RME (Rapeseed Methyl Esterification)
Perstorp Oxo AB	100.000	RME
Södra Cell Värö	low	Tall oil Methyl Esterification
Emmelev A/S	88.000	RME
Daka ecoMotion A/S	50.000	TME (Animal fats and cooking oil)
Ecobränsle i Karlshamn AB	44.000	RME
Södra Cell Mönsterås	low	Tall oil Methyl Esterification
SunPine	88.000	Tall oil Methyl Esterification

Moreover, it has been chosen a ship port sited in Malmo of very large capacity, about 421,000 tons/y of bio-methanol. This is accounted as a demand point, because the biofuel passes through it to reach the purchaser companies that are not considered in this thesis work.
Therefore, the demand sites can be summed in Figure 19:

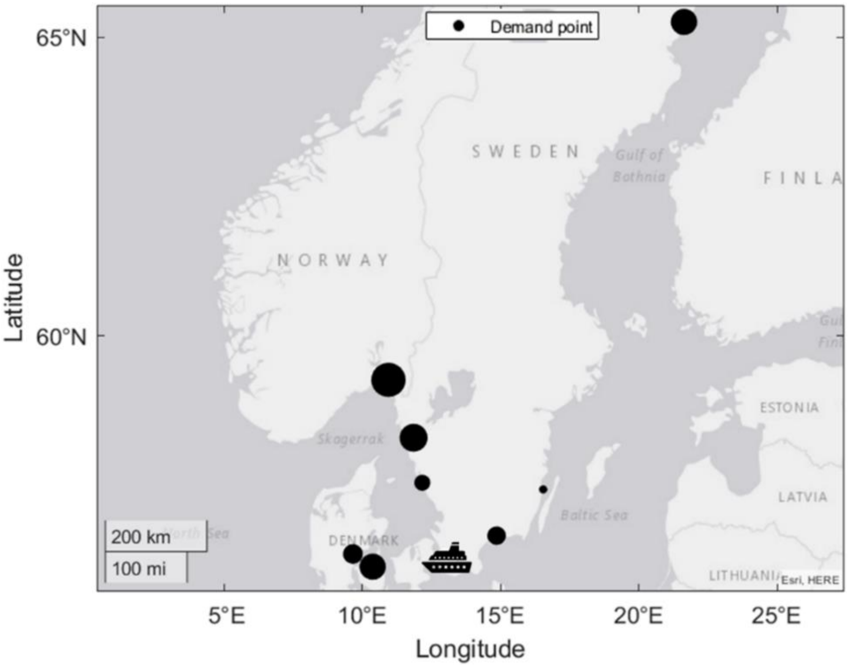


Figure 19. Demand points selected (n.tot=9 points)

About the transport sector, Sweden has a good rail infrastructure, mostly in the central and southern part. In some cases, there are comfortable rail terminals very close to the biodiesel plants, for which the distance to travel towards the plant with truck can be neglected.

The total rail terminals are here represented in Figure 20:

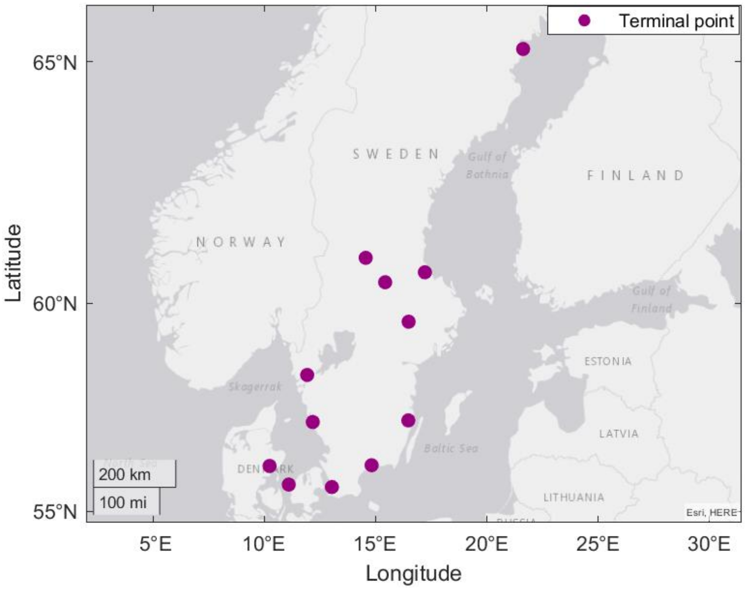


Figure 20. Rail terminal sites (n.tot=12 points)

The used transports are the ones explained into paragraph 2.3 and it has been decided to avoid the congestion of rail terminals with the arrival of numerous trucks coming from the different collecting points.

Therefore, the biomass should be brought to a storage point before to reach the rail terminal. In this way, the larger chip trucks are more exploited, reducing the traffic.

The different data used for the implementation of the model can be summed in the following Table 21:

Table 21. Summary of the data requested by the model for this case specific

Data		
Biomass (wt dry %) C 50.12, H 6.01, N 0.38, Cl 0.09, S 0.06, O 42.34 Non seasonal MC at cutting 50%, at the collection point 35%, MC at storage 35%, after first drying 25%, after secondary drying 17.3%, after densification 15%, at the gasifier 10% Relative densities at the different biomass states	**Storage** Location sites Maximum land area m^2 Land price $[€/m^2]$ Fixed [€] and variable investments$[€/m^2]$ OPEX Natural drying time required and dry matter losses for each season. Choice between Bdried1, Bdried2 and Bdens Investment and operating costs related	**Terminals** Location sites No storage possibility **Collection** Location sites Residues chipping Maximum yearly capacity of chipped residues of each collection point Purchasing price of biomass Economic potential Selection of the maximum quantity collected by truck each period
Harvesting Utilization of 80% of the yearly quantity of harvested residues Residues in bundles left roadside covered during winter (Nov.-Apr.) and in a clear-felled area not covered during summer (May-Oct.) for minimum 6 months Dry matter losses assigned for each season. **Methanol users** Location sites Yearly capacity **General** Project Lifetime 20 years Internal rate of return Selling price of bio-methanol	**Biorefinery** Location sites Investment costs Contingency, installation and indirect costs Size limits: between 10 and 300 MWth Price of electricity purchased Maximum Down-Time and Minimum Up-Time Operability limits: between 60% and 100% of plant size Cold gas efficiency Electric efficiency Dryer capacity based on maximum evaporated water per second	**Transports** Use of: Chip truck 60 ton, serving the collecting point. Chip truck 75 ton, serving the storages and rail terminals. Tanker truck 60 ton, serving the biorefineries and rail terminal Time required for the operations of loading, unloading, waiting and travelling (in h) Drivers and trucks: operative time (h/week) Train of 60 m^3: from a rail terminal to rail terminal Investment costs and annual costs related Service costs Road and rail distances

4.2 Comparison with Italian case

The Swedish case has been compared with the already defined 'Italian case' (in the precedent model [30]) to find the differences in results according to the different geographical areas, type and available quantity of residual biomasses.

The main differences between the cases are here reported in Table 22:

Table 22. Swedish and Italian case in comparison

	Swedish case	Italian case
Geographical area	Latitude ϵ [55.8,65.24] Longitude ϵ [9.67, 21.63]	Latitude ϵ [40.5, 44.04] Longitude ϵ [10.12, 17.17]
Biomasses	Non seasonal: Chips from wood residues	Non seasonal: Chips from wood residues Seasonal: Grape marc and Olive pomace
Availability Period	All year	Wood residues Autumn-Winter-Spring Grape Marc January-February Olive Pomace January-March
Biomass as received state	MC woodchips 35%	MC Wood residues 35% MC Grape Marc 55% MC Olive Pomace 12%
Biomass price	Wood residues 55 €/ton	Wood residues 55 €/ton Grape Marc 22 €/ton Olive Pomace 75 €/ton
Economic biomass potential	Wood residues 2123 kton/y	Wood residues 280 kton/y Grape Marc 19 kton/y Olive Pomace 125 kton/y
Connections by rail	From storages to conversion facility and from conversion facility to the biodiesel plant	From collection point to conversion facility and from storage to conversion facility
Demand	Biodiesel plants and ship port	Petrochemical refineries
Total nodes	64	53

The respective location points selected for the supply chain of the Italian case are summed in the following figures Figure 21 and Figure 22:

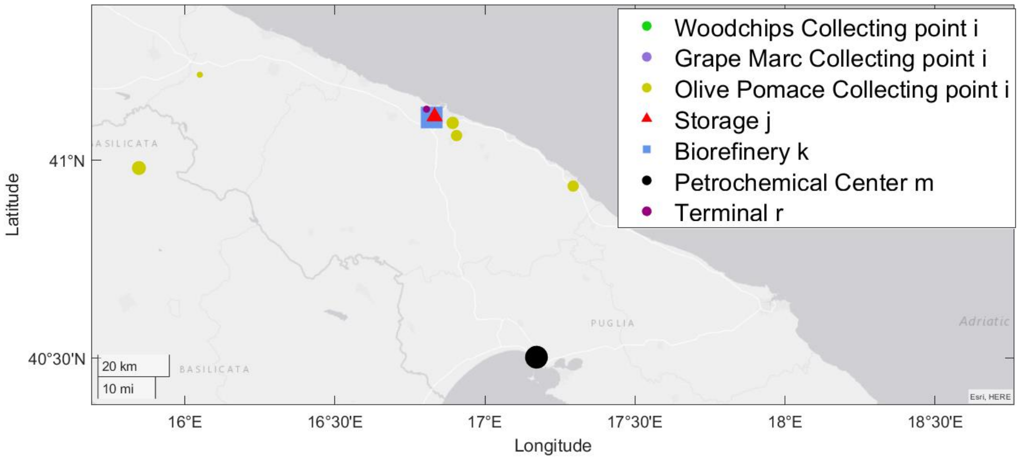


Figure 21. Supply chain points of Italian case in southern Italy

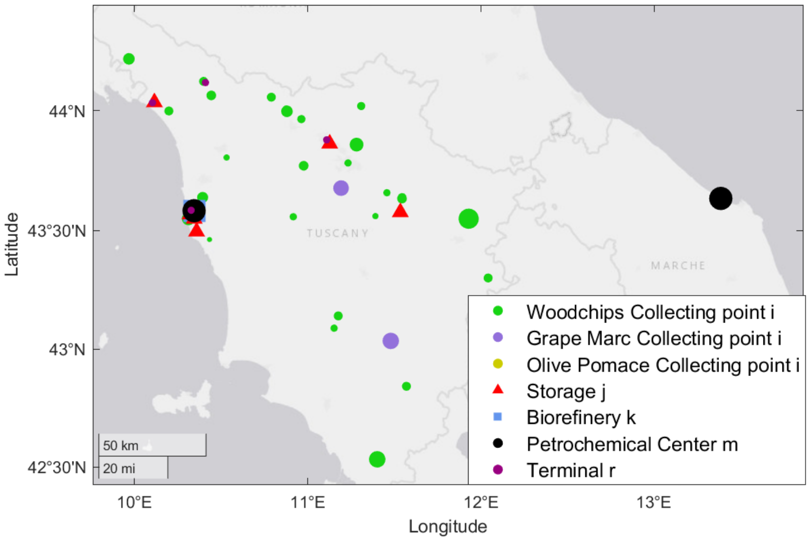


Figure 22. Supply chain points of Italian case in central Italy

For the Italian case, it has been corrected the purchasing price of the olive pomace, respect to the data used for the simulation of the Italian case with Milani's model [30]. Therefore, it is expected an increase of the costs in the current simulation of this case.

The difference in biomasses, respect to the Swedish case, requires an adaptation of the CGE and of the electric ratio according to the biomass type and state. From the available data of woody biomass, they have been recalculated for the different biomasses (by changing the LHV) and for the different MC states (through linear interpolation of the given data at certain MC states).

Moreover, for the Italian case it has been decided to use the same entities data of the precedent work, which did not consider biodiesel plants, but directly the blending facilities, from which it is not possible to predict the potential available demand of bio-methanol.

The last change in data has been made in reducing the 11 available sites of the biorefinery to 2, which consist into the ones always chosen by the optimization. This decision has been made to reduce the simulation time, which through the use of the piecewise cost function and of high number of biorefinery entities it increases drastically. However, to be sure of not compromising the final results with this choice, it will be always simulated, firstly, with all biorefinery sites to see if the two objective functions are similar.

For the Italian case, the extra information considered respect to Table 21 of Swedish case are:

Table 23. Additional information type respect to Swedish biomass

Data	
Biomass Wood: Autumn-Winter-Spring MC at cutting 50%, at the collection point 35%, MC at storage 35%, after first drying 25%, after secondary drying 17.3%, after densification 15% Grape Marc: January-February MC at production point 55%, MC at storage 55%, after first drying 25%, after secondary drying 18%, after densification 15% Olive Pomace: January-March MC 12% in all the supply chain path Relative prices and characteristics	**Harvesting** Utilization only of 80% of the yearly quantity of wood residues
	Storage Defined for each biomass: Dry matter losses Waiting time for drying
	Biorefinery Defined for each biomass: CGE Electric ratio

Referring to paragraph 3.3, the results obtained, at the same gap for three different time discretization, are reported in Table 24 and they have been mainly compared through the objective function, but also on LCOF and computational time:

Table 24. Outcomes of a simplified case simulated with the respective temporal discretization of 1,2 and 4 weeks

Time discretization	Gap	n. variables		n. constraints	Obj. function $[M€]$	LCOF $[€/ton]$	Time $[s]$
		binary	continuous				
1 week	5%	83	41726	35374	-9.0754	566.74	75,659
2 weeks	5%	57	20905	17725	-9.0045	566.89	1330
4 weeks	5%	44	10500	8815	-6.5430	574.42	260

The discretization with 2 weeks has revealed to be the most efficient one about the time spent for the simulation and for the results obtained, which are completely comparable with the ones achieved in the case with 1 week. For time simplification, in the following analysis the year has been discretized with periods of 2 weeks.

4.3 Scenarios presentation

The scenarios are different alternative studies proposed of the same case. They have been suggested for both the Swedish and Italian cases applied to the current model, presented in this thesis work.

For the Swedish case, the scenarios analyzed are:

S.0 *Base case*, with real limitation capacities added to the biodiesel plants and adoption of an international commercial port based in Malmo with very large capacity.

S.1 No limitation to biodiesel capacities (to see the effects of a limited demand)

S.2 No limitation to biodiesel capacities and increase of range power size until 350 MWth (to analyse the centralization/decentralization of the problem)

S.3 Supply chain affected by the increased selling price of bio-methanol (650 €/ton)

S.4 Supply chain affected by the decreased selling price of bio-methanol (550 €/ton)

For the Italian case, the studied scenarios are obtained by the actual model, but omitting the points 1), 8), 9) and 10) presented in paragraph 2.4, because:

- The biomass potentials of the single harvesting points of wood are low and therefore is not necessary a uniform planning along the year of the harvesting phase.
- Between the available data for the Italian case, there are not information about the biodiesel plants and therefore about potential demand of bio-methanol.
- As there are not limitation of the demand points, it results not necessary the institution of ship ports, where to let merge the unsold bio-methanol to the local customers.

By accounting these points, the scenarios studied are:

I.0 *Base case,* where all the assumptions highlighted for the Italian case are respected

I.1 Same of the previous one, but maintaining the modelling of transport costs of Milani [30], which considers the operation of a third-party company, instead of instituting a new owned transportation company.

I.2 Supply chain affected by the increased selling price of bio-methanol (650 €/ton)

I.3 Supply chain affected by the decreased selling price of bio-methanol (550 €/ton)

4.4 GHG data

As the forest residues require the harvesting procedure, the emissions at this level should be estimated. While, the other biomasses of the Italian case (Grape Marc and Olive Pomace) represent residues from industry, which do not require specific processes before the collection with trucks.

The part connected to the phases of harvesting/processing of the raw materials (considered under extraction voice e_{ec}) are taken from literature [72]. From this study, led on the forests in Finland and in Sweden, the emissions relative to the harvesting and transportation roadside of wood are considered. As the considered biomass is of residual type, the part of felling timber are counted only for the stem wood production, therefore, for this analysis, are considered roughly the emissions due to extraction and transport roadside of the residues [72], as evidenced in Table 25:

Table 25. Emissions due to extraction and roadside transportation for Mm^3 of harvested wood residues. Source: [72]

Process	$CO_2\left[\frac{ton}{Mm^3}\right]$	$CO\left[\frac{ton}{Mm^3}\right]$	$NO_x\left[\frac{ton}{Mm^3}\right]$
Extraction	2094.7	12.86	43.4
Transportation of logging machines	930.6	29.52	17.21
Total	3025.3	42.38	60.61

About the carbon intensity due to electricity production $\left(gr_{CO_{2eq}}/kWh_{el}\right)$, it assumes a different value between the two cases. In Sweden, the electricity production has made more progress than the European average and the emissions considered for the Swedish case amount to 13 $gr_{CO_{2eq}}/kWh_{el}$ [41]. On the other hand, the Italian trend is worse and the emissions assumed for its case are about 248 $gr_{CO_{2eq}}/kWh_{el}$.

5 Results

This section discusses the results of the optimization performed for two considered cases. The decision parameters (Table 26) addressed by the optimization tool are presented in the following results of the Swedish and Italian case, which have been also compared with the ones of the precedent work [30].

Table 26. Specified strategic and tactical decisions made by the supply chain model

Strategic decisions (Long term)	Tactical decisions (Medium term)
Location sites Storage maximum area Pre-treatments types Biorefinery size Dryer size Transportation modes Number of drivers and trucks	Harvesting and collection planning Inventory at the levels of: • Roadside storage • Storage Quantities of: • Pre-treated biomass • Different biomasses states approaching the biorefinery • Biomass transformed and bio-methanol production • Electricity purchased • Biomasses/biofuel transported between nodes • Bio-methanol purchased from the biodiesel plants Time required for the truck operations between points Biorefinery operation: power and on-off status Number of journeys by truck and train

Moreover, it was decided to accept the solution at a gap of 3%, due to the high complexity of the problem to be solved, which was not compatible with the system available to simulate and the time available to use this system.

5.1 Results of Swedish Case

They were obtained with Polimi's system 16 GB RAM Intel Core i7-2600 CPU 3.4 GHz and the simulation characteristics of the different scenarios are reported in Table 27:

	n. variables		n. constraints	gap	time [s]
	binary	continuous			
S.0	116	71449	50833	3%	31292
S.1	116	70123	49498	3%	8596
S.2	116	70123	49498	3%	26368
S.3	116	71449	50833	3%	14288
S.4	116	71449	50833	5%	86526

Table 27. Optimization features for each scenario analysed of Swedish case

It is visible from the table that for the last scenario it was accepted a solution with a lower precision, due to the high computational time required for the simulation.

The summarized results are here reported in Table 28:

Table 28. Scenarios results of Swedish case

	Sweden				
	S.0	S.1	S.2	S.3	S.4
Annual profit [M€/y]	41.367	49.033	53.82	68.181	14.169
Bio-methanol production [kton/y]	546.3	699.6	638.1	543.6	545
Plants size [MWth]	300 299	280 300 188	350 350	296.6 299.72	299.7 298.4
LCOF [€/ton]	524.3	529.9	515.7	524.6	524
Marginal profit [€/ton]	75.7	70.1	84.3	125	26
Biomass potential [kton/y]	2124				
Biomass use	76.9%	98.4%	89.8%	76.5%	76.7%
n. sites selected					
hv. points	26/32	32/32	31/32	25/32	26/32
storages	2/8	4/8	3/8	3/8	3/8
terminals	9/12	7/12	7/12	9/12	9/12
biorefineries	2/3	3/3	2/3	2/3	2/3
demand	7/9	1/9	1/9	7/9	6/9
Area storage [m^2]	7912	6882	11248	7841	7904
Cost transports [M€]	54.115	67.401	62.217	53.893	53.812
Pre-treated biomass (% of total)	1.9%	1.7%	1.7%	2%	2%
Saturated demand sites	6/9	N.F.	N.F.	6/9	6/9
N. drivers	189	261	211	192	187
N. trucks	63	86	72	65	64
n. journeys by train in one year	1104	1107	1566	1086	1093

5.1.1 Scenario S.0

For the Swedish case, as the limitation capacities of the local biodiesel plants imply a limitation for the production of bio-methanol, it has been decided to add a ship port with a very large capacity, in which to let merge the unsold bio-methanol from the local biodiesel plants.

The overall supply chain layout is here represented in Figure 23, where the yearly quantities of sold methanol to each demand point are expressed in terms of kton/y:

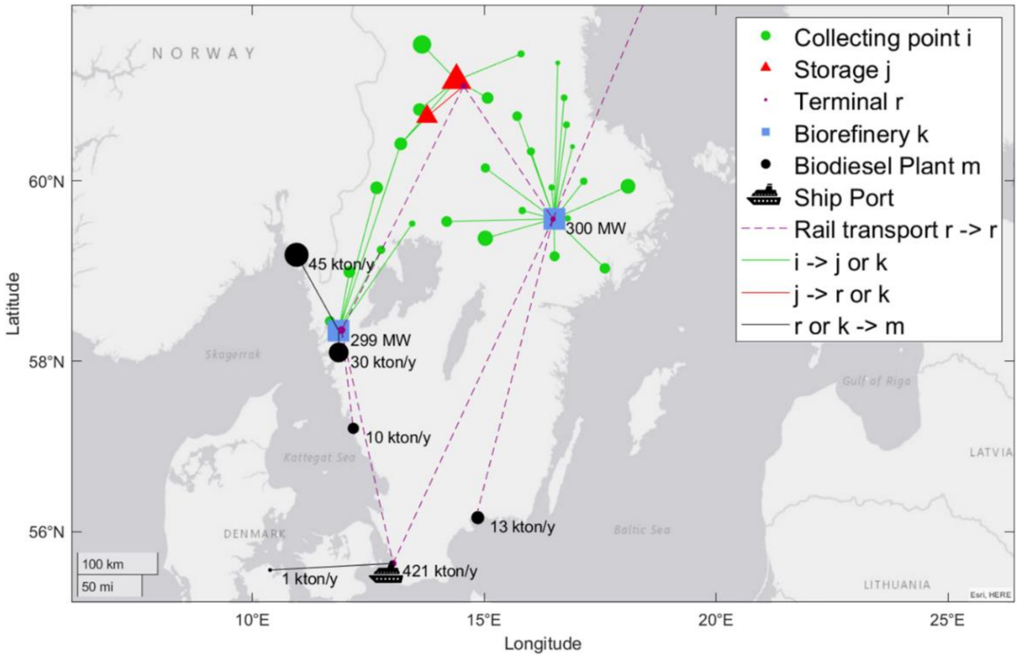


Figure 23. Supply chain layout of scenario S.0

From the map, it is possible to notice the usage of both transports available. The train reveals to be advantageous for the long distances and almost the whole bio-methanol produced is brought by train to the southern Sweden, where the purchasers and the commercial ports are concentrated. Moreover, the biodiesel plants or the ship ports usually own a rail terminal or they have an available one in the immediate proximity. This aspect further directs the choice of the optimization towards the exploitation of the railway.

Between the three conversion facilities available, just two are chosen, achieving almost the maximum size decided equal to 300 MWth of biomass input. It constitutes into a different reality from the Italian case, but it was expected by watching the available economic biomass potentials. The biomass exploitation of the economic available one is about 77%, against the almost totality for the base case of the Milani's model.

The two scenarios differ on many aspects: biomass type and potential, points distribution and demand.

It is noticeable that the upstream part of the supply chain is controlled by the demand of the biodiesel plants posed in the downstream part and it is not encouraged the total usage of biomass, which consists into a larger quantity respect the potential demanded one.

Moreover, the biomass usage is limited also by the maximum size of the biorefineries that has been assumed. Therefore, if the plant size would have been higher, it could have exploited the economies of scale and managed to fulfill the total demand of biodiesel plants.

The trend of the storage is here reported in Figure 24:

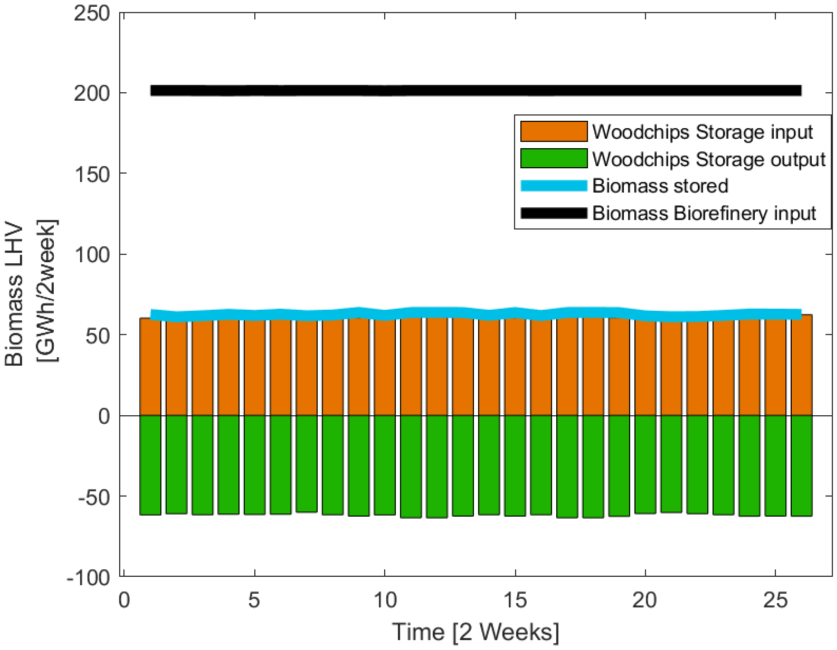


Figure 24. Total periodic (every 2 weeks) biomass input and output at the storages and biomass input of the biorefinery for scenario S.0 (expressed in GWh)

Another curious fact is the role covered by storages, because they are used as terminals where biomass merges in order to go to a rail terminal. Therefore, as they are not particularly used to dry woodchips, it could be considered the open-air type, which surely is much more economic providing a lowering of the production cost for the bio-methanol.

Differently from the base case of Milani's model, the intermediate depots are not anymore used to face the seasonality of the biomasses, as the biomass of this case study is of non-seasonal type, and their trend is almost constant.

The new aspect is the quantification of the drivers, trucks and trains involved in this supply chain: the Swedish case has revealed suitable for the road transport modelling applied, because the distances to cover are high and it results difficult to manage the transport system from one central point of reference. The solution was found assigning to some points the necessary number of resources that will exclusively serve them. An important characteristic is the continuous working of the transport system during the whole year.

The number of drivers is very large achieving 189 units, for trucks it is lower about 63 units, while the total yearly number of journeys, made by trains of 45 wagons each, are about 1104. These quantities give an idea of the dimensions of this supply chain.

The different costs that share the final LCOF of the bio-methanol are here reported Figure 25:

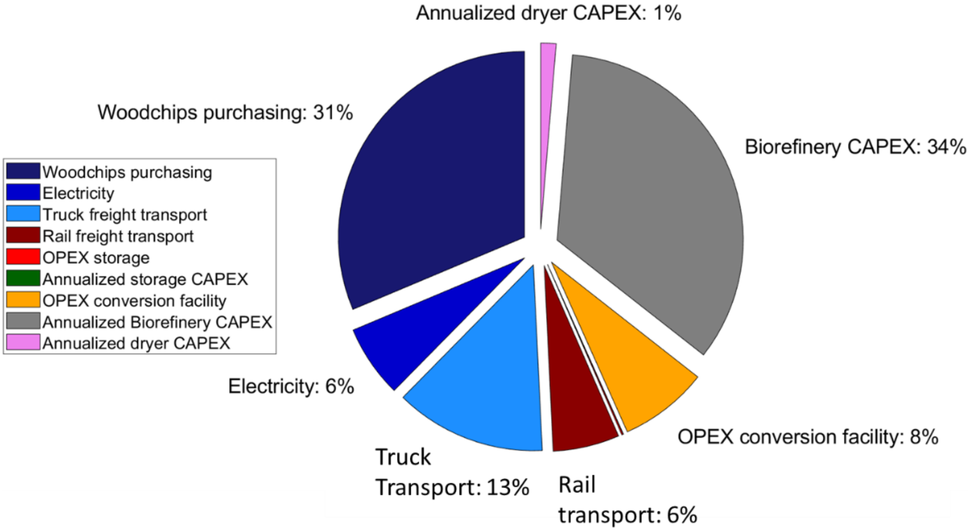


Figure 25. Costs share for production of bio-methanol in scenario S.0

The major contribution is covered by the capital costs of the conversion facility, as it can be intuitive, but also the woodchips purchasing has a great impact on it. Moreover, there is also an important contribution (19%) given by the transports, actually not surprising as this supply chain is interestingly complex, especially the downstream part is placed very far from the entities of the upstream one.

The LCOF is equal to 524.27 $€/ton$, which is particularly higher than previous study, and the gap between the selling price and the cost of production is very small.

5.1.2 Scenario S.1

This case is representative of how the limitation of the demand near to reality can apport considerable changes to the problem and also how much it can complicate it. Therefore, without the limitation on the annual capacities of the biodiesel plants, the resultant layout is:

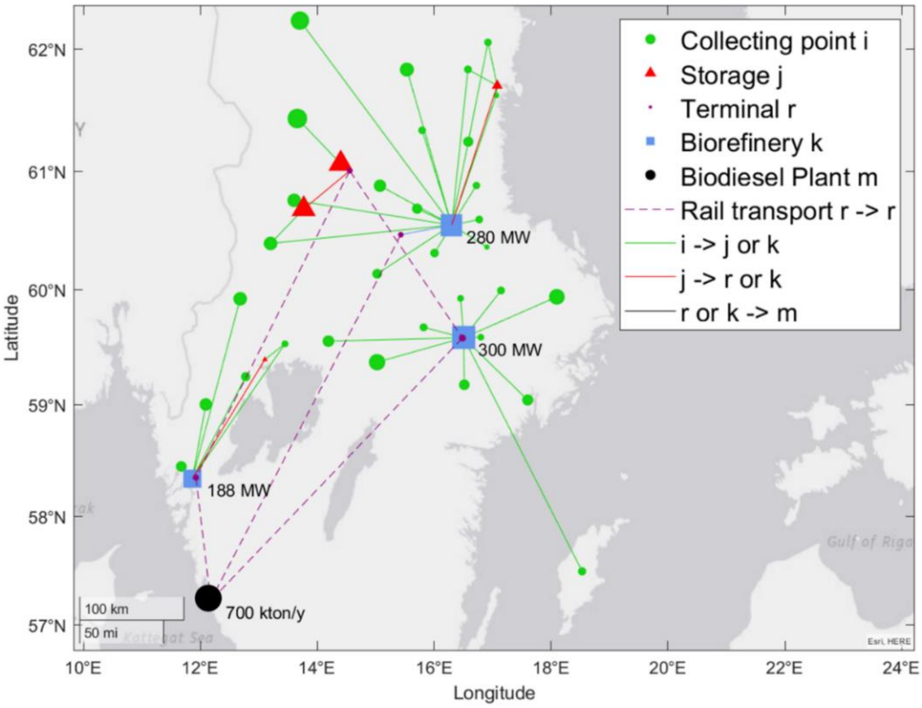


Figure 26. Overall supply chain layout of scenario S.1

It is visible, from Figure 26, that the bio-methanol merges towards the closest point available and the number of conversion facilities is increased achieving different sizes.

The biomass usage is increased broaching about the total economic available one.

About the pre-treatments at the storages, a very small percentage is decided to be dried in advance, which can be neglected as the previous case.

About the trends of the total biomass stored in the chosen sites and of the one in input to the biorefineries, it is verified in Figure 27 an increment of the bi-weekly biomass input to the biorefinery, while the stored one has remained almost the same:

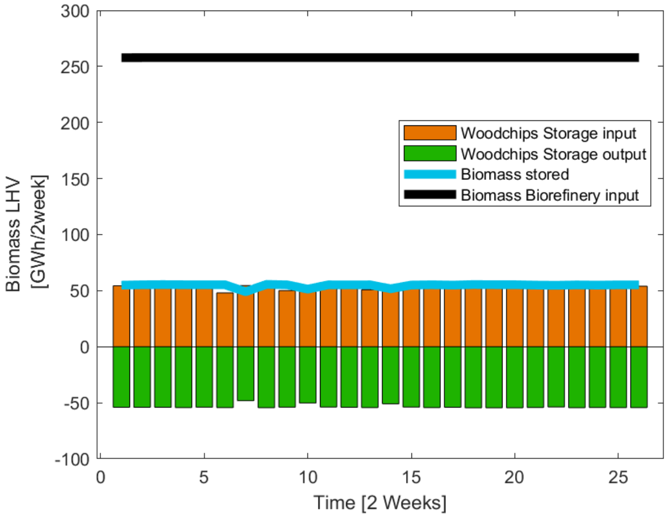


Figure 27. Periodic (every 2 weeks) biomass input and output at the storages and biomass input of the biorefinery in S.1

About the costs, the cost of production per ton of bio-methanol produced is increased of 5 $\frac{€}{ton}$, respect of before. The most significant increase regards the investments of the conversion facilities and consequently also the relative OPEX. Moreover, in Figure 28, the truck transport has undergone an increment, while the rail one the opposite, because the upper biorefinery is not very well connected with the railway.

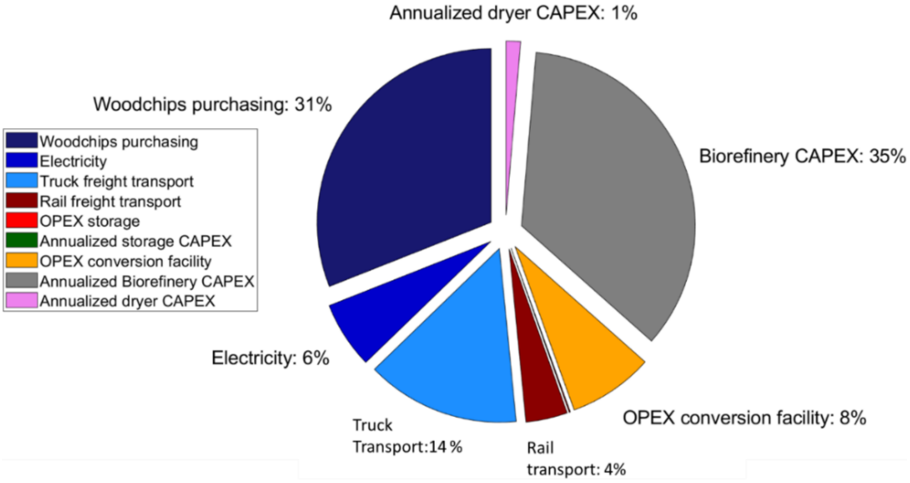


Figure 28. Costs share for production of bio-methanol in scenario S.1

5.1.3 Scenario S.2

In addition to the previous case, it has been investigated the 'centralized' and 'distributed' options for the models, mentioned in paragraph. It has been observed that the conversion facilities achieve the maximum power capacity possible, therefore, it has been found interesting to see which could be the optimal configuration if the biorefinery had had the chance of achieving higher sizes (up to 350 $MWth$).

It was decided to study the effect without considering the strong constraints onto the capacity of demand points, which affect consistently the final results.

In Figure 29, the supply chain changes considerably:

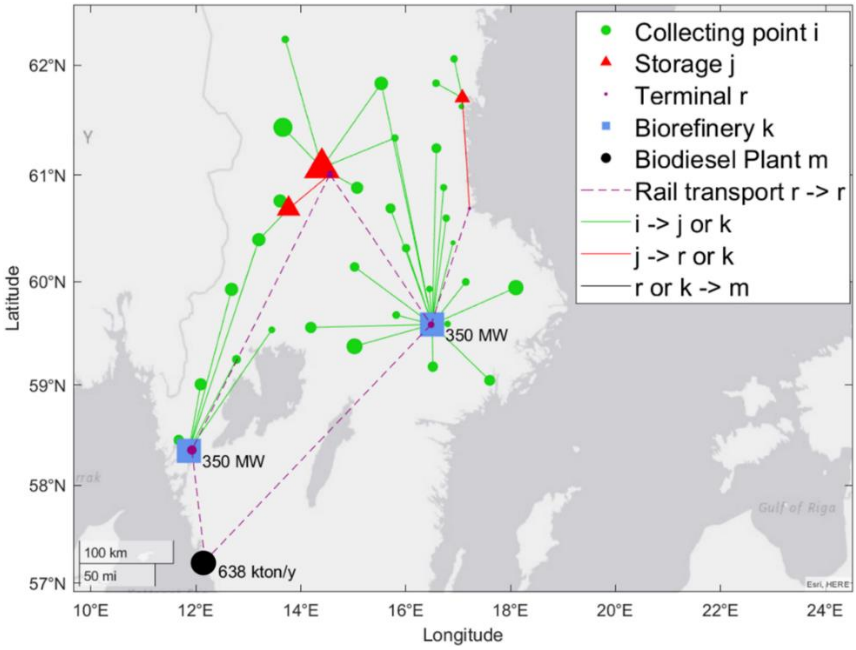


Figure 29. Overall supply chain layout of scenario S.2

In opposition to the previous case, the conversion facilities chosen are just two, as in the *Base case*, and it is evident that the economies of scale are exploited, by deciding that it was better to further increase the size of the conversion plants, than adding another one. Moreover, the quantity of sold bio-methanol is lower than previous case, because the model has retained that building a third conversion facility to produce and sell the remanent methanol is more costly than avoiding the investment and the selling of a lower quantity of biofuel.

After this reasoning, it is expected a lowering of the LCOF in the part of the biorefinery CAPEX and perhaps an increase to the transport costs, which actually is a really complex discussion.

The results achieved have confirmed the expectations and the most relevant changes to the LCOF are given by these specific contributions, respect to the previous case:

- Decrease of 13 $\frac{€}{ton}$, due to biorefinery CAPEX;
- Decrease of 9 $\frac{€}{ton}$, due to truck transport;
- Increase of 11 $\frac{€}{ton}$, due to rail transport;

The resultant reduced LCOF is equal to 515 $\frac{€}{ton}$.

In this case, the increment of transports is not matched with an increase of the GHG emissions, as [28] mentioned in paragraph, because it has been reduced the transport on the roads and incremented the one by railway, which is much greener.

It results more convenient to centralize the problem and to exploit the economies of scale, but this brings towards unachievable sizes. Indeed, practically in reality very large biomethanol plants are not existent, the largest programmed one is Vaermlands in Sweden with a maximum available capacity of 111 $MWth$.

5.1.4 Scenario S.3 compared with S.4

Their biomass utilizations and the LCOF contributions are almost equal to the *Base case*, due to the strong limitations of the downstream capacities. The only remarkable difference is in the revenues, because with higher price the marginal profit of biomethanol sold is 125 $\frac{€}{ton}$, whereas with the lower one it achieves about 26 $\frac{€}{ton}$. The discrepancy is evident and the selling price is crucial for the profit of the supply system.

Moreover, there are slight changes at the downstream part, but not relevant, therefore it has been demonstrated that price oscillations do not affect significantly the Swedish supply chain layout. On the other hand, they have significant consequences on the profits and more the price decreases more it will be encountered the risk of failure of the project.

5.2 Results of Italian Case

For the Italian case, many of the results have been obtained with a system of 4 GB RAM Intel Core i5-5200 CPU 2.2 GHz, instead of the Polimi's system due to its low time availability. This choice has surely increased the simulation time, as shown in Table 29:

Table 29. Optimization features for each scenario analysed of Italian case

	n. variables		n. constraints	gap	time [s]
	binary	continuous			
I.0	64	70192	42048	3%	33744
I.1	64	70092	40246	3%	788
I.2	64	70192	42048	3%	3105
I.3	64	70192	42048	13%	5400

From Table 29, it is visible that, as in S.4, the simulation had some problems and the consequent accepted gap is considerably high in this case. The encountered complication in this case, differently from S.4, is the immediate achievement of an important memory occupancy still at high gaps.

The results for this case are here summarized in Table 30:

Table 30. Results of scenarios of Italian case

	Italy			
	I.0	I.1	I.2	I.3
Annual profit [M€/y]	20.366	22.57	29.48	11.35
Bio-methanol production [kton/y]	180.85	184.1	183.8	179.8
Plants size [MWth]	202	205.6	205.3	200.8
LCOF [€/ton]	487.4	477.7	489.6	486.9
Marginal profit [€/ton]	112.6	122.3	160.4	63.13
Biomass potential [kton/y]	Wood: 280 Grape: 19 Olive: 125			
Biomass use				
Wood	98%	98%	98%	97%
Grape	47%	100%	96%	47%
Olive	100%	100%	100%	100%
n. sites selected				
hv. points	33/35	35/35	35/35	31/35
storages	2/8	2/8	2/8	2/8
terminals	5/5	2/5	5/5	5/5
biorefineries	1/2	1/2	1/2	1/2
demand	1/3	1/3	1/3	1/3
Area storage [m^2]	21322	20354	20302	21481
Cost transports [M€]	11.299	10.03	12.17	11.076
Pre-treated biomass (% of total)	0%	0%	0%	0%
Saturated demand sites	N.F.	N.F.	N.F.	N.F.
N. drivers	55	N.F.	68	53
N. trucks	35	N.F.	40	33
n. journeys by train in one year	148	106	137	149

5.2.1 Scenario I.0 compared with S.0 and Milani's Base Case

The supply chain layout presents just one biorefinery in Tuscany and therefore the major use of railway is destinated to the transport of the olive pomace.

In Apulia, the total olive pomace economically available is exploited and it is brought by truck to the rail terminal in 'Bari', from which it can be transported by train towards Tuscany.

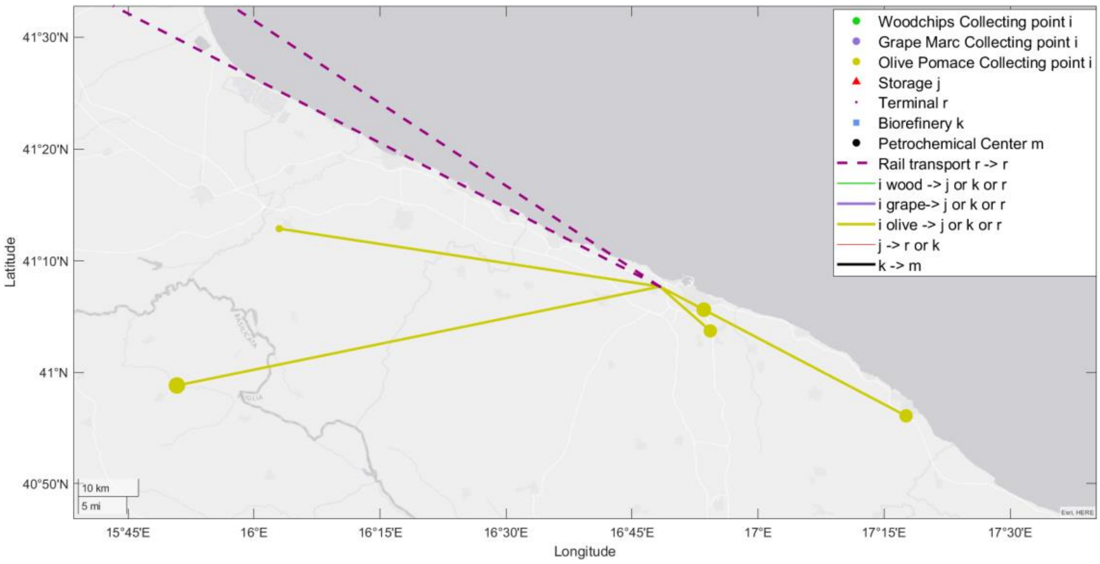


Figure 30. Overall supply chain layout of scenario I.0 in southern Italy

In Tuscany, the situation is much more complex because the number of harvesting points is larger than Apulia and each of them has low potential.

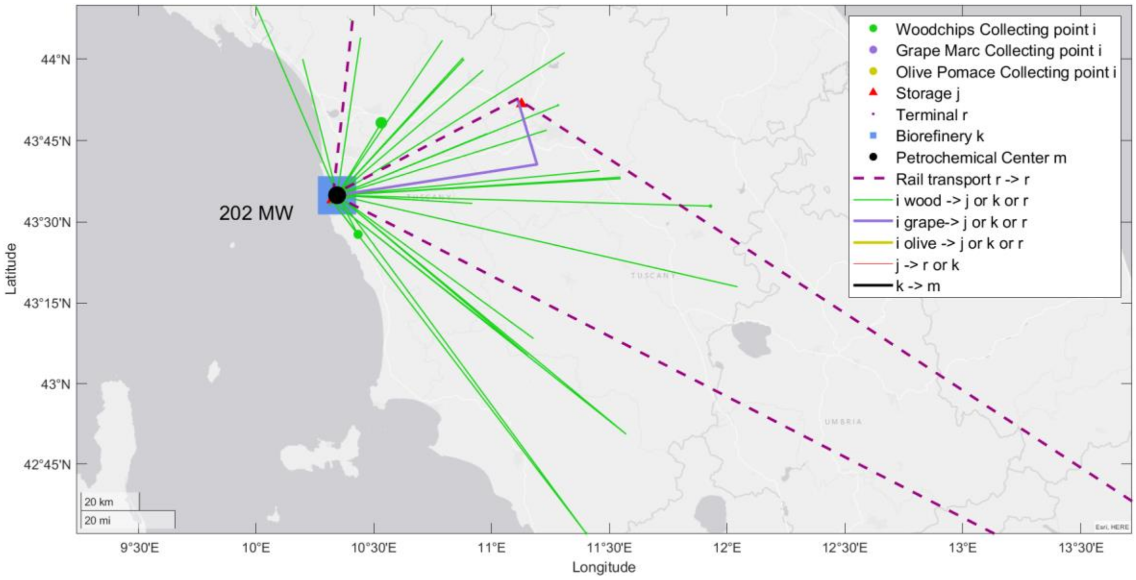


Figure 31. Overall supply chain layout of scenario I.0 in central Italy

The residual biomasses are all almost used, excepting the grape marc, for which just the 47% is exploited.

From the results, it is noticeable that the new model gives different outputs with the same case obtained by Milani's one.

By watching the chain layouts in figures Figure 30 and Figure 31, it is visible a major exploitation of the railway infrastructure, which performs connections of medium distance too and the consequent utilization of a higher number of terminals. This could be explained by the different used equation of costs for the railway transport, as it has a lower fixed cost and a higher variable cost per km respect to the one used in the precedent work [30].

Moreover, two storage sites, located in Tuscany, have been exploited and one (based in Arezzo) holds just olive pomace arrived by train from Apulia, while the other one (based in Livorno) houses all the biomass types. They are mainly used as buffers to allow a steady operation of the biorefinery, without waiting the necessary time for drying the humid biomasses (grape marc and wood residues).

The trends inside the storages selected are shown by the following Figure 32, where the overall bi-weekly biomass net fluxes at the storages are referred to left axis, while on right axis is referred the total biomass stored in that specific bi-weeks:

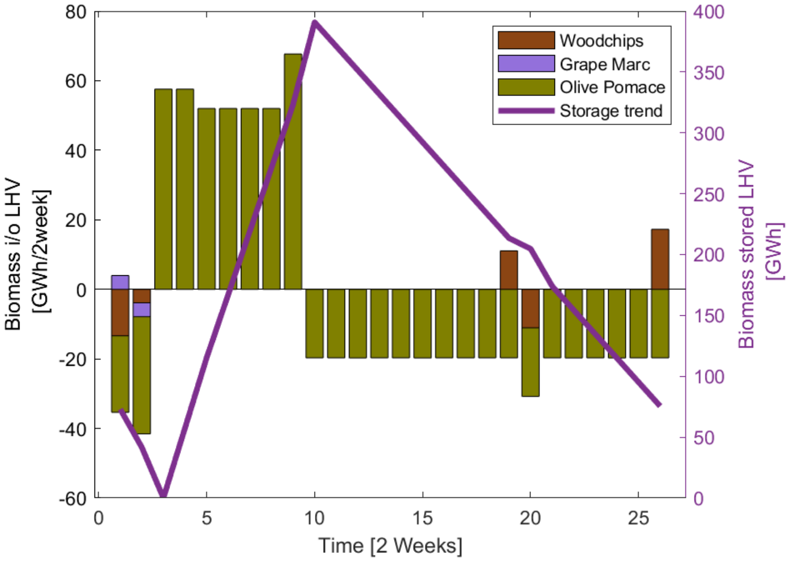


Figure 32. Periodic net fluxes of biomass through the storage facility (bars plot) and total stored biomass trend (line plot) in scenario I.0

It is evident that the olive pomace is the majorly stored biomass, because it is seasonal and it has also a quantitative and energetic potential higher than grape marc.

Like the trend of the storages, the location of the biorefinery based in 'Livorno' and the centralized solution of the model are characteristics that have been reproposed also with the new model.

About the exploited shares of biomasses, the plant sizes and costs, they present the following differences presented in Table 31:

Table 31. Differences in biomass utilization, plant size decision and costs between the actual and the previous model

	Actual Model (Scenario I.0)	Milani's Model (Scenario 0)
Biomass utilization		
Woodchips	98%	99%
Grape Marc	47%	100%
Olive Pomace	100%	99%
Plant size $[MW_{th}]$	202	234
LCOF $[€/ton]$	487	405
Annual profit $[M€/y]$	20.4	12.4

The remarkable difference into the plant size mainly consists into its different calculation. In the actual model, it is calculated with the biomass in input of the dryer, while in Milani's model with biomass in design conditions at input of the gasifier.

The LCOF of the bio-methanol amounts to 487 $€/ton$, which is considerably higher than the *Base case* with Milani's Model, but, beyond the expectations, the annual profit is higher too. This could

be explained by the fact that there is not anymore combustion of woodchips to dry the humid biomass, therefore with the same biomass input the methanol produced is higher.
On the other side, the LCOF is lower than the one of S.0 for the lower distances travelled, but the profit is about the half of the one of the Swedish case.

The trend of costs is here represented in Figure 33:

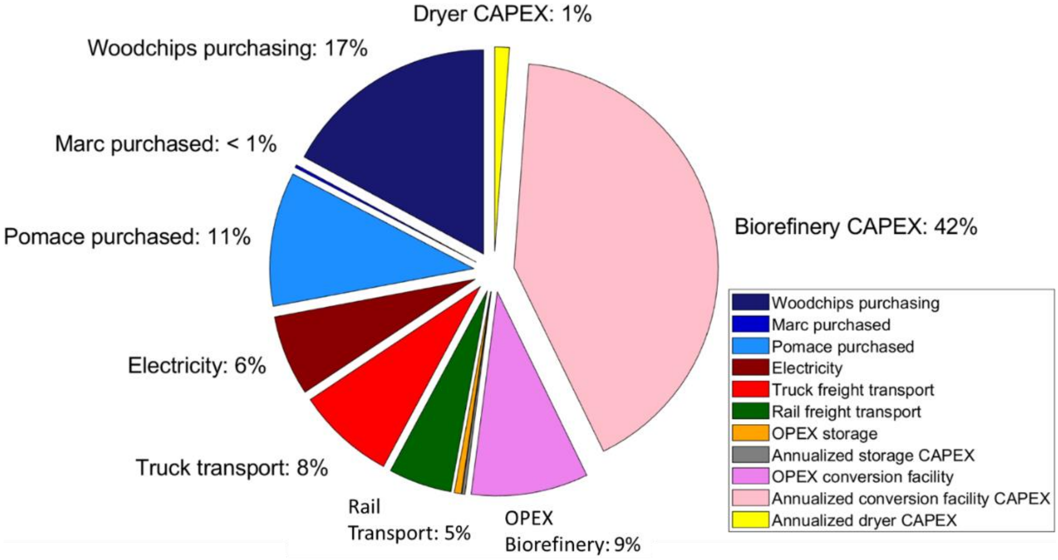


Figure 33. Costs share for production of bio-methanol in scenario I.0

In this case, the share of the biorefinery CAPEX is lower than in Milani's case, because the plant size considered is lower, whereas the share of pomace purchased is higher due to its higher price ($€/ton$) assumed.
The trend of the biomasses entering the biorefinery in each period (of 2 weeks) is here represented in Figure 34:

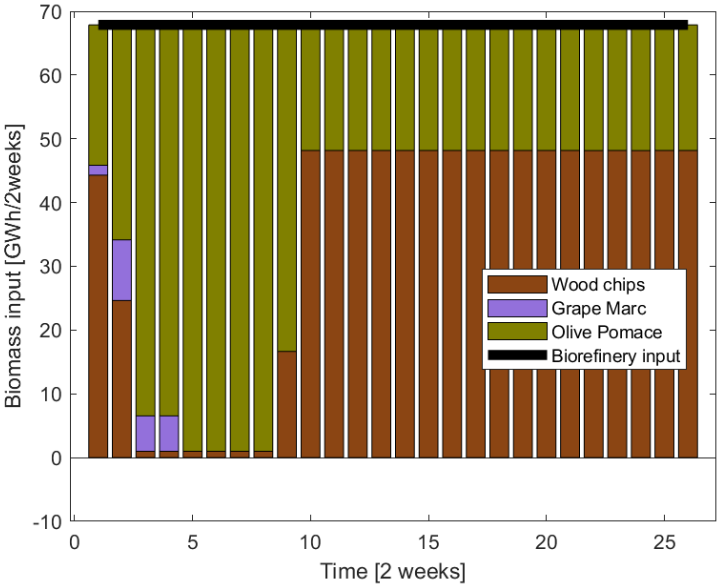


Figure 34. Periodic biomass input at biorefinery in GWh

It is visible that during the period in which the woodchips are not available, their lack is filled majorly with olive pomace.

5.2.2 Scenario I.1

It is interesting to make a comparison with the previous modelling of transport, which assumes the operation of a third-party company and different costs for rail transport.

The layout of the resultant supply chain is here reported, in figures Figure 35 and Figure 36, and it presents some differences.

In Apulia, instead of immediately sending the whole olive pomace available to Tuscany, it is used a local storage, where a part of the residues is stored for the required time and then sent, while the other one is sent immediately to the other region.

This storage site is exploited also in the Milani's *Base case*, but differently from it two more harvesting points have been considered. It seems that the difference has been made by the different application of the economic potential of olive pomace (50%), which in this model it was applied on the harvested pomace of each single point instead on the total.

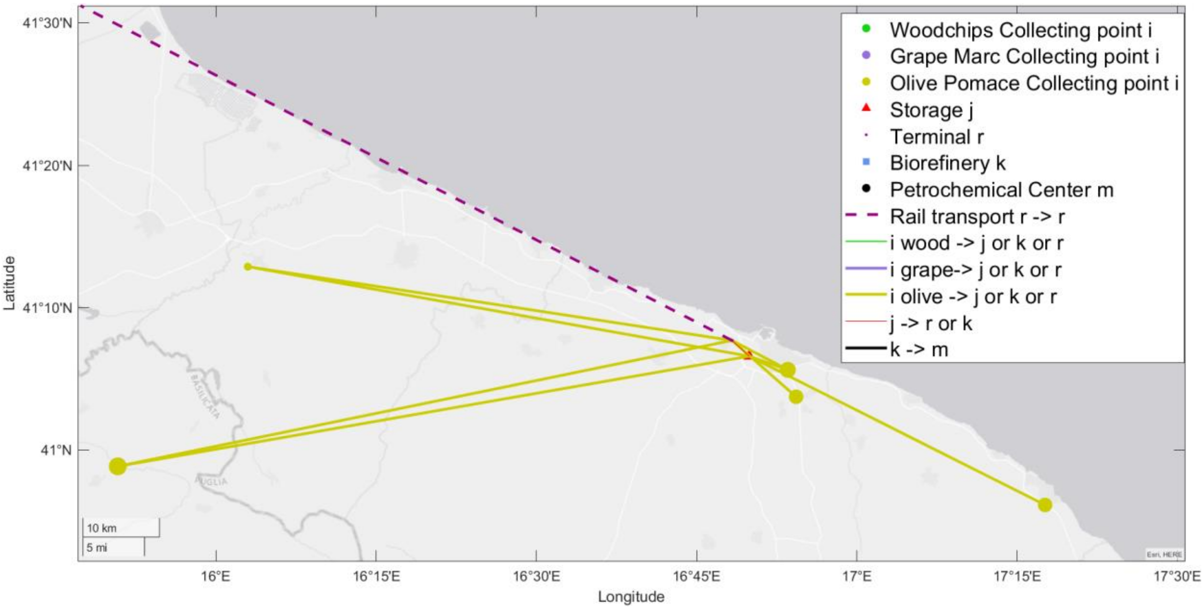


Figure 35. Overall supply chain layout of scenario I.1 in southern Italy

In Tuscany, it is possible to see from the following map that the olive pomace is directed to just one terminal based in 'Livorno'. Moreover, it uses only one connection by rail to connect the two distant regions, while in the other scenario I.0 the rail infrastructure has been exploited also for shorter distances.

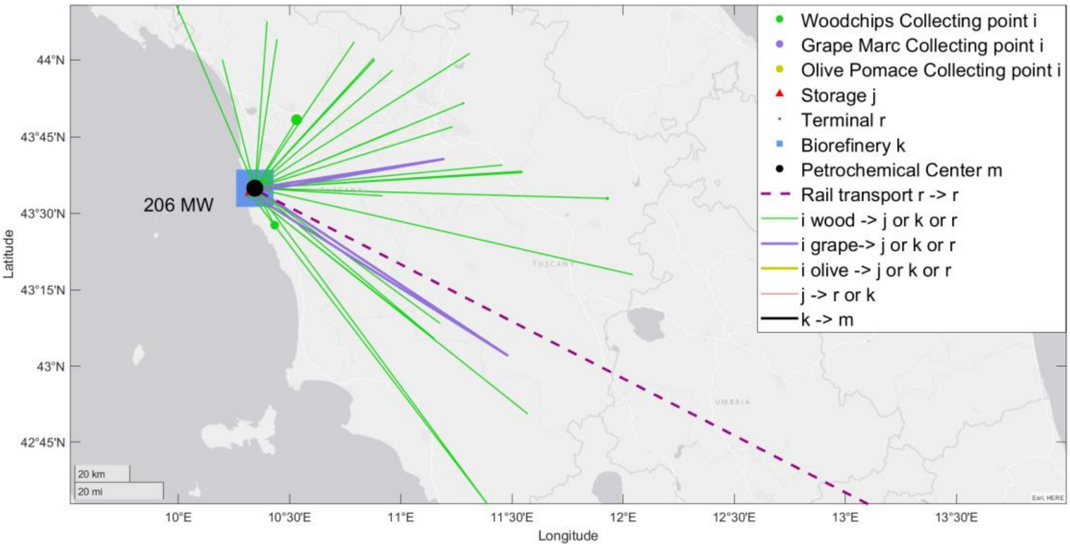


Figure 36. Overall supply chain layout of scenario I.1 in central Italy

There is a lower inclination to use the railway in this case, so it has been confirmed what it was supposed during the comparison of scenario I.0 with Milani's *Base case* about the different costs of rail transport.

Differently from I.0, both harvesting points of grape marc have been considered, which is reflected on a higher capacity of the biorefinery plant. The main reason of this variation consists into the fact that drivers and trucks are assigned to each point considered into the supply chain (excepting the blending facilities) and it may be too expensive to perform the transport service set in this way. At this point, it is important to analyse the most appropriate model of transports. In Sweden, the actual model has been revealed a good strategy, but on the Italian case it needs a different planning, as the biomasses are seasonal and the harvesting points have much lower potentials.

About the biomass stored, the situation does not considerably differ from the one of the *Base case* and, as shown in Figure 37, it has a smoother trend, probably due to the consideration of a more linear transport modelling*:*

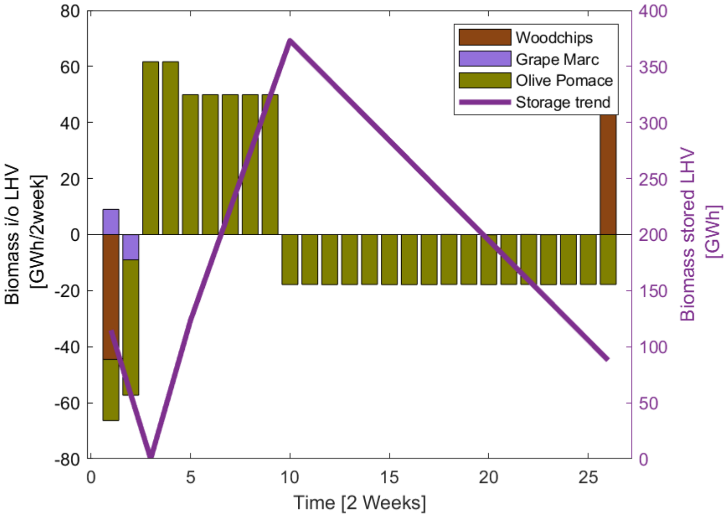


Figure 37. Periodic net fluxes of biomass through the storage facility (bars plot) and total stored biomass (line plot) in I.1

The share of the costs is here reported in Figure 38:

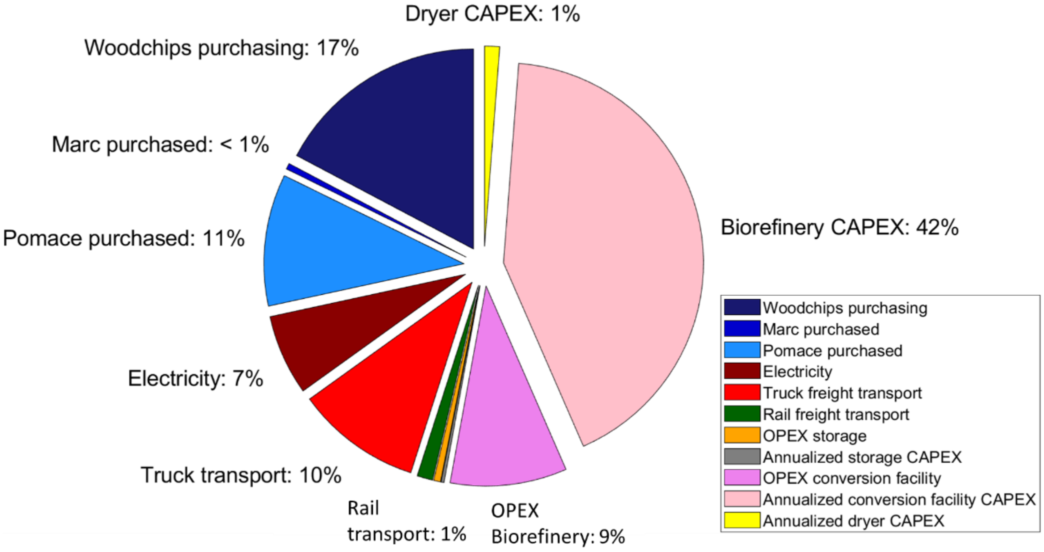


Figure 38. Costs share for production of bio-methanol in scenario I.1

In this case, the rail transport has a lower impact than before, while the truck transport a major one.

The LCOF is lower than case I.0 and it is equal to 477.68 $€/ton$, but still remarkably higher respect to the Milani's base case.

It is interesting to put in comparison the costs connected to transport for the two cases (I.0 and I.1) expressed in € per kilometre travelled and in terms of the total revenues and objective function.

Table 32. Costs comparison between different scenarios S.0, I.0 and I.1

	S.0	I.0	I.1
Rail transport [€/km]	1.24	1.14	0.253
Truck transport [€/km]	7.5	12.1	9.2112
Total Revenues [M€]	327.8	108.51	110.45
Objective function [M€]	-41.367	-20.366	-22.517

In Table 32, it is found that transports costs in scenario I.0 are higher than in scenario I.1, this is explained by the different models of transport used. Moreover, the specific road transport costs in Sweden with the actual model are lower than I.1.

Actually, this value could depend on many factors and therefore it could result also a bit hasty to make some assertions by watching this data. Anyway, this discussion is useful to say that the road transport model fits well to the Swedish case, while for the Italian one it is more suitable if proposed with another arrangement.

It resulted to be less appropriate to the Italian case because of the:

- large dimensions of trucks involved;
- method of assigning the number of trucks and of drivers is more suitable for collecting points of non-seasonal biomasses, which present a constant availability and very high potentials of biomass.

Noticing that in many harvesting points the number of drivers/truck assigned are equal to 1, it is evident that this model of transport is not convenient for seasonal biomass supply chains because the truck/driver would operate just few months every year. Whereas, this consideration does regard the transport of bio-methanol from the conversion facility, because it has a uniform production all the year and, for this reason, this transport model, as it is, could be still valid for the distribution level in Italian case.

5.2.3 Scenarios I.2 and I.3

For the Italian case, as well, it is investigated how the supply chain could be affected by the price fluctuation of bio-methanol. Anyway, the chain has been always optimized for the prices 550 and 650 $€/ton$.

When the price achieves 650 $€/ton$ (I.2), the chain layout characteristics remains nearly the same, but differently from I.0 the grape marc is fully exploited and directly destinated to the biorefinery. Moreover, the LCOF is slightly increased, while the annual profit is increased achieving 29.48 $\frac{M€}{y}$.

In case I.3, there are not many differences on the supply chain scheme, but there is a slight lower exploitation of the woodchips and, as a consequence, a lower biorefinery size is chosen. The annual profits are roughly the half of the ones of I.0 and one third of I.2.

From the results with low price of bio-methanol, the model starts to fail bringing to a drastic increment of the simulation computational time (S.4) or requiring high memory availability (I.3), which induces the quit of the simulation at higher gaps. Then, the profits would particularly suffer of this decrement, but it is the normality for the *second generation* fuels, which are characterized by high production costs [46].

5.3 GHG emissions to the base cases

The GHG emissions have been evaluated for the reference scenarios of each studied case (S.0 and I.0) and it has been investigated the contribution of each phase of the supply chain.

5.3.1 S.0 emissions

By considering the mean European carbon intensity of electricity, it is evidenced, in Table 33, a different share between the supply chain phases instead of using the greener electricity of Sweden.

Table 33. Shares of emissions for the supply chain phases

	Shares (%)			
	Harvesting	Processing	Truck transport	Rail transport
Bio-methanol (European electricity)	30%	47%	21%	2%
Bio-methanol (Swedish electricity)	56%	4%	40%	<1%

It is visible that the major emitting part is played by the electricity consumption from the biorefineries, but in Sweden it is the lowest. Surprisingly, the emissions due to rail transport are very low and, if the reliability of the data used is verified, it will both lower the cost of transport on long distance and help to reduce consistently the $CO_{2,eq}$ emissions.

By reducing the emission connected to the processing, the first impacting phase consists into the harvesting procedure, but its estimation is purely indicative and dependent on the technology available. However, it still involves fossil fuels due to the impossibility of bringing electricity in the forests and, therefore, its contribution can not be undervalued.

The difference, in terms of environmental impact, is evident between the fossil methanol and the green methanol in Table 34:

Table 34.GHG emission of bio-methanol compared with the fossil one for S.0

	GHG $\left[\frac{gr_{CO_{2,eq}}}{MJ}\right]$	Reduction
Fossil methanol	99.57	
Bio-methanol (European electricity)	19.4	-80%
Bio-methanol (Swedish electricity)	10.4	-90%

By contrast, standard levels of emissions for bio-methanol from forest residues [61] are much lower than the calculated ones, which amount to 5.03 $\frac{gr_{CO_{2,eq}}}{MJ}$.

From the emissions of green methanol, it can be calculated the new impact of biodiesel produced with it, by estimating the emissions due the usage of methanol at the transesterification level, which amount to 0.85 $\frac{gr_{CO_{2,gr}}}{MJ_{FAME}}$ instead of 8.15 $\frac{gr_{CO_{2,gr}}}{MJ_{FAME}}$.

The $\Delta CO_{2eq}/MJ_{FAME}$ produced is equal to 7 and the total final emissions with biodiesel produced with green methanol are here reported in Table 35:

Table 35. Comparison of RME biodiesel produced with fossil and green methanol for S.0

	GHG $\left[\frac{gr_{CO_{2,eq}}}{MJ_{FAME}}\right]$	Reduction
RME Biodiesel with fossil methanol	51.7	
RME Biodiesel with bio-methanol (EU)	45.38	-12%
RME Biodiesel with bio-methanol (SE)	44.7	-13.5%

The overall decrement in $gr_{CO_{2,eq}}$ due to the substitution of methanol provides a reduction, but the emissions involved into the other categories are still too high, mostly for RME (Rapeseed Methyl Esterification) biodiesel the emissions due to cultivation are important. While, investigating another biodiesel type, for example the one which comes from animal or oils waste (TME), the decrease is much evident:

Table 36. TME biodiesel emissions reduction with green methanol in S.0

	GHG $\left[\frac{gr_{CO_{2,eq}}}{MJ_{FAME}}\right]$	Reduction
TME Biodiesel with fossil methanol	21.3	
TME Biodiesel with bio-methanol	14.95	-30%

Another voice that can be revised for a future project is about the choice of producing steam from a boiler fed with Natural Gas, because it presents nearly the same quantity of emissions connected to the fossil methanol employed for the transesterification. A further improvement can be the usage of woodchips to produce useful heat for the steam production at this level and also exploiting the hot gases to produce some electricity.

This is an important option that is practically introducible for the Swedish case, as the producible green methanol for the available woodchips residues exceeds the demand of the biodiesel plants of the country. It could be an interesting option to further decarbonize the part of processing of biodiesel production.

5.3.2 I.0 emissions

About the Italian case, the harvesting emissions have been accounted only for the wood residues, while for the other biomasses they are not considered.

Italy presents a higher carbon intensity connected to electricity respect to Sweden following more the European trend and it has been chosen a GHG intensity equal to 248 $\frac{gr_{CO_{2,eq}}}{kWh}$ [41].

The resulting shares for the different phases are:

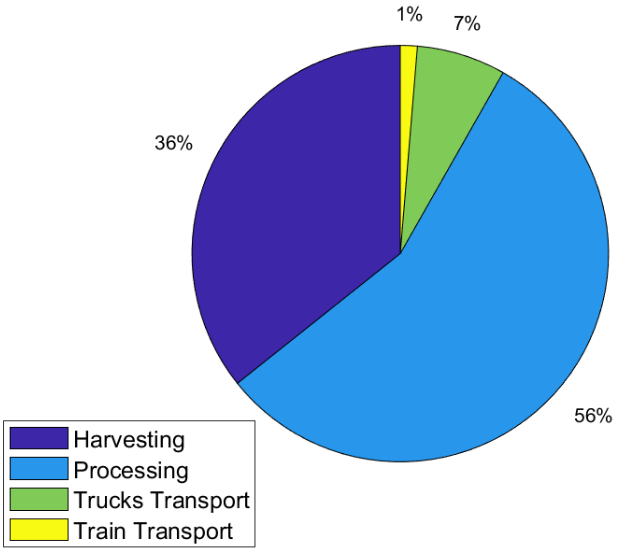


Figure 39. Pie chart of the GHG contribution emissions for bio-methanol production for scenario I.0 with Italian carbon intensity for electricity

In Figure 39, the processing phase gives an important contribution, but, as for the future is forecasted a further decarbonization upon the electricity production, there is still ample room of improvement. Anyway, in this case the emissions are higher than Swedish one, but lower if compared with the same carbon intensity for electricity production, because the distances covered by the supply chain are lower. The outcomes are highlighted in Table 37:

Table 37. GHG emission of the Italian bio-methanol compared with the fossil and Swedish one

	GHG $\left[\frac{gr_{CO_{2,eq}}}{MJ}\right]$	Reduction
Fossil methanol	99.57	
Swedish bio-methanol	10.4	-90%
Italian bio-methanol	13.8	-86%

About the RME biodiesel, the final emissions are found, where the difference given by the bio-methanol from the two cases is not really evident, but a certain reduction from the one produced with the fossil one is surely verified in both of them (as demonstrated in Table 38):

Table 38. Comparison of RME biodiesel produced with fossil and green methanol arising from S.0 and I.0

	GHG $\left[\frac{gr_{CO_{2,eq}}}{MJ_{FAME}}\right]$	Reduction
Biodiesel with fossil methanol	51.7	
Biodiesel with bio-methanol (SE)	44.7	13.5%
Biodiesel with bio-methanol (IT)	44.95	13%

6 Conclusions

In this thesis, it was wanted to define a supply chain for the CONVERGE technology, respecting principles of low-carbon production, efficient use of resources and exploitation of residual biomasses, by creating a MILP formulated model. Afterwards, the optimal configuration for the studied cases and the relative emissions have been found.

In this thesis, it was wanted to improve the work started by Milani that was addressed in defining an advanced biofuel supply chain. In few words, it was better determined the CONVERGE technology and its operation with the consequent adaptation on the biomass states investigated, which are important conditions to produce reliable results. Moreover, the modeling of the related costs (dryer, O&M, electricity, etc.) have been re-expressed in a different key.

Then, the road transports were the majorly investigated aspect of the supply chain, because they constitute into its main player and they can make the difference for the outputs. For this reason, it was tested a more complicated model, closer to reality, to see the effects on the system and to find its advantages and drawbacks.

From the comparison made between the Swedish and the Italian cases, it was found that the model has revealed to be more effective when there is a constant use of the transport in each point selected of the supply chain during the year. Indeed, this has been considered a disadvantage for the transport of the seasonal biomasses in the upstream part.

As transport, also the careful choice of the demand points has made the difference for the supply system, because the main constraints on the demand side consist into: finding the plant that may necessitate of the final product in question, accounting of long distances for the distribution system, the maximum available capacities of demand and finally the choice of selling towards other ways (for example on the international market).

These choices have made a particular difference, as investigated for the Swedish case, mostly on the side of profits, because unfortunately the local demand of methanol for the transport sector is limited and it may be extended towards the chemical industry.

The final topic examined in this study regards the evaluation of emissions produced by putting in practice this system. The outputs are interesting and effectively an important reduction of $CO_{2_{eq}}$ is verified, which benefits the production of bio-methanol, instead of the fossil one. The problem connected to the emissions is still rooted for the biodiesels production, because there are still phases that have an intensive carbon footprint.

The possibility proposed for the Swedish case was to use a part of available woodchips into the steam boiler to provide heat for the FAME production, as proposed in document [61], substituting the use of natural gas. Moreover, in some States like Italy, it has been verified also that high further reduction in emissions could be achieved by using a lower carbon intensive electricity.

On the implementation side, the model transfer on the computer requires surely programming skills and knowledge of the language used. Furtherly, numerous parameters and constraints are requested to implement this type of real world problems and, consequently, it is necessary a certain time frame to write them, but mostly to make working the whole system on the right way.

The main barriers encountered to perform this study were:

- low CPU and memory available to do the optimization with a more complex model. This has been traduced on long simulation time and lower optimality of the accepted solution (gap 3-5%).
- lack of usage of a GIS-software that would have made the difference, mostly, in the visualization of the data and of the results. Then, it could have been useful for making considerations at transportation level and to see the congestion provided on the infrastructure (roads and railway).

- The lacking knowledge of some costs in general and of the interested local methanol purchasers, in order to produce a more realistic supply chain.

For future works, there is still a good margin of improvement for this model. The most interesting points, which could be furtherly developed and improved are mainly four:

- Find an improved solution for the assignation of trucks and drivers for the upstream part, which is the only one that could have an important variation along the year;
- Inclusion of a residues supplying system for the biodiesel plants to further decrease the emissions at the heating boiler level, just if there is large availability of biomass for the final demand and if the biodiesel plants do not already feature of a green system to produce steam.
- Arrangement of a distribution system for the biodiesel produced towards the blending entities. Its implementation could be made a posteriori on the final results because the biodiesel plants with their limited capacities are the major players for the definition of the up-,mid- and down-stream parts. It could give also more advantage upon the simulation time and CPU occupancy;
- Inclusion of the open-air storages option and improved economic data on the pre-treatment machines, but anyway the CONVERGE technology has revealed to be efficient for the phase of drying with biomasses of MC between (10-35%). If the biomass were to be really humid (around 50%), maybe this analysis should be delved into.

The insertion of the first two points may require an increment of performances by the computer and therefore good skills for the simplification of the problem, where it is necessary.

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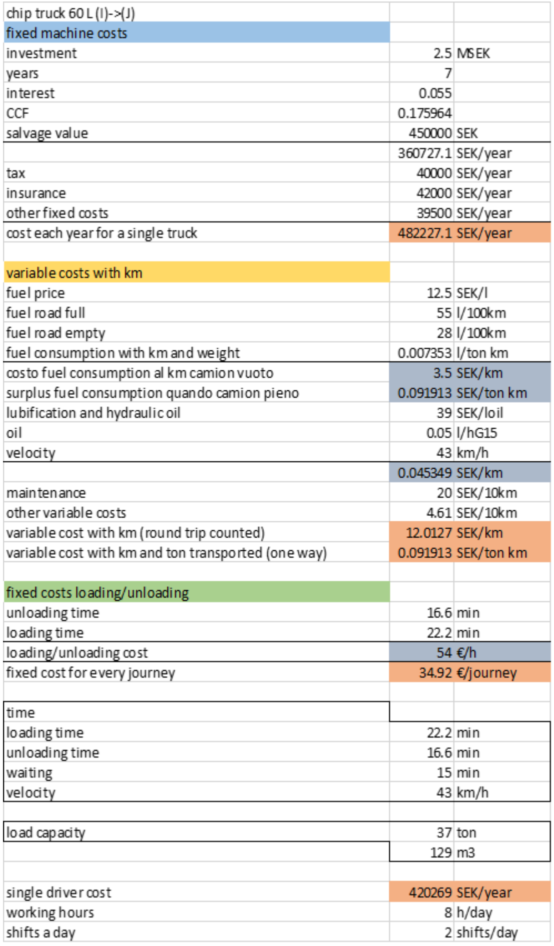
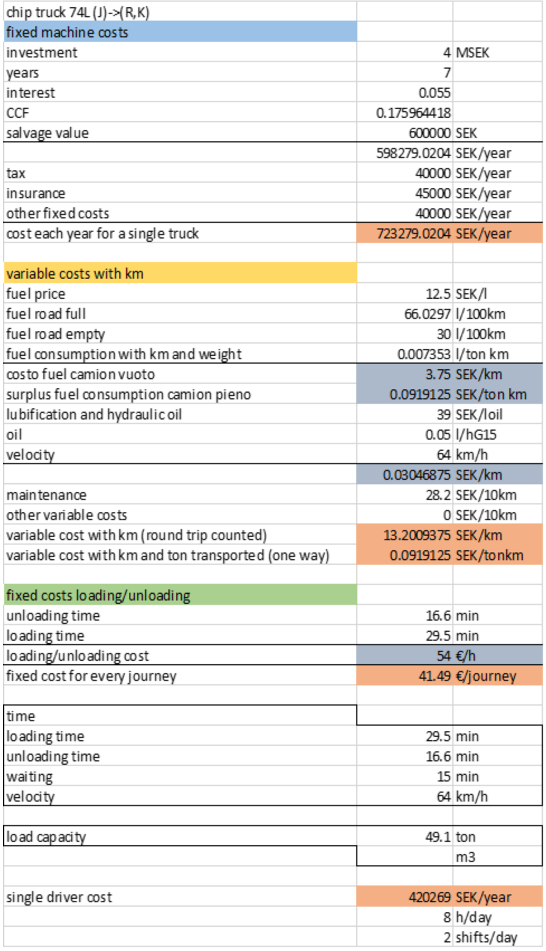
Appendix A



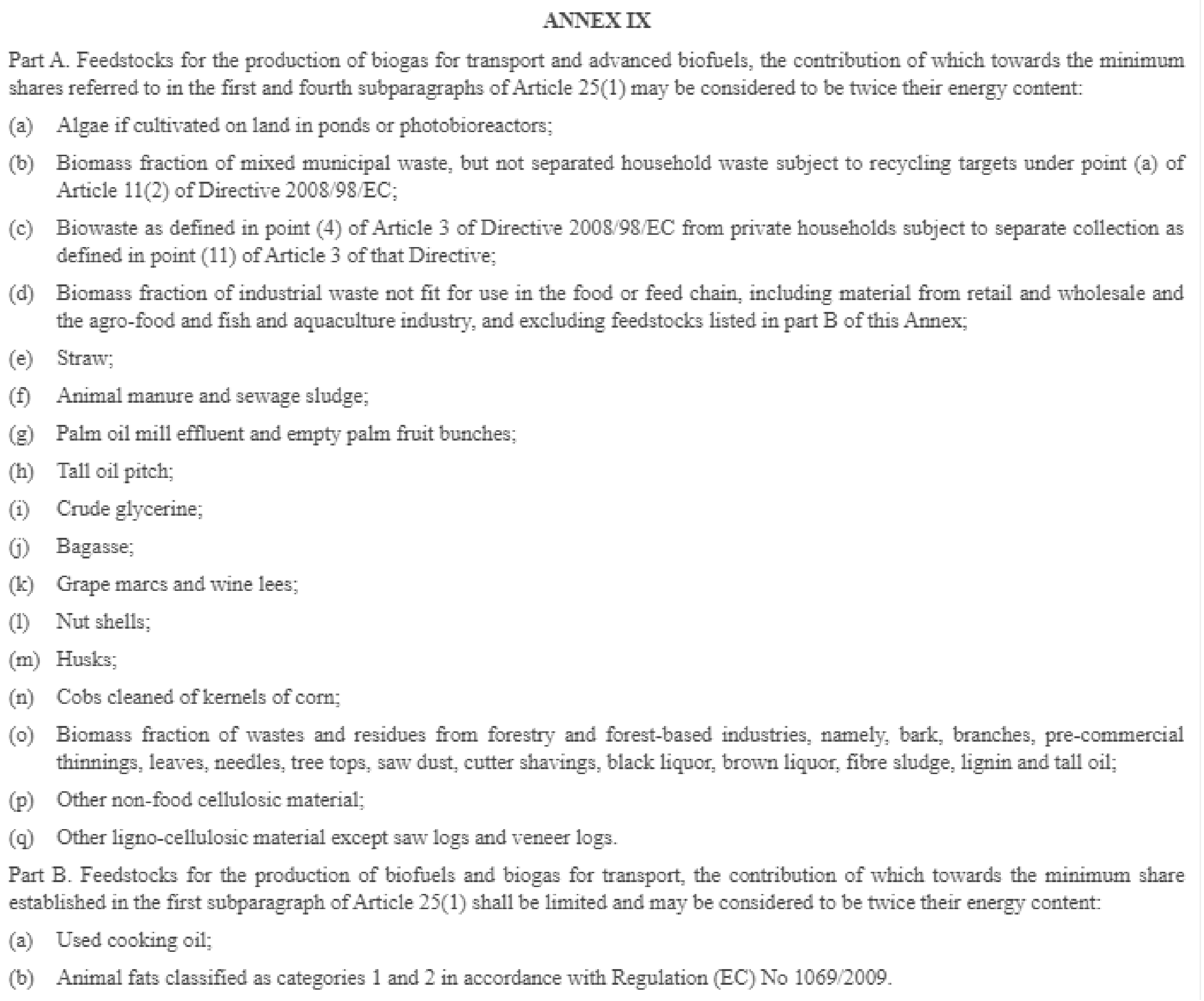
chip truck 60 L (I)->(J)		
fixed machine costs		
investment	2.5	MSEK
years	7	
interest	0.055	
CCF	0.175964	
salvage value	450000	SEK
	360727.1	SEK/year
tax	40000	SEK/year
insurance	42000	SEK/year
other fixed costs	39500	SEK/year
cost each year for a single truck	482227.1	SEK/year
variable costs with km		
fuel price	12.5	SEK/l
fuel road full	55	l/100km
fuel road empty	28	l/100km
fuel consumption with km and weight	0.007353	l/ton km
costo fuel consumption al km camion vuoto	3.5	SEK/km
surplus fuel consumption quando camion pieno	0.091913	SEK/ton km
lubification and hydraulic oil	39	SEK/loil
oil	0.05	l/hG15
velocity	43	km/h
	0.045349	SEK/km
maintenance	20	SEK/10km
other variable costs	4.61	SEK/10km
variable cost with km (round trip counted)	12.0127	SEK/km
variable cost with km and ton transported (one way)	0.091913	SEK/ton km
fixed costs loading/unloading		
unloading time	16.6	min
loading time	22.2	min
loading/unloading cost	54	€/h
fixed cost for every journey	34.92	€/journey
time		
loading time	22.2	min
unloading time	16.6	min
waiting	15	min
velocity	43	km/h
load capacity	37	ton
	129	m3
single driver cost	420269	SEK/year
working hours	8	h/day
shifts a day	2	shifts/day



chip truck 74L (J)->(R,K)		
fixed machine costs		
investment	4	MSEK
years	7	
interest	0.055	
CCF	0.175964418	
salvage value	600000	SEK
	598279.0204	SEK/year
tax	40000	SEK/year
insurance	45000	SEK/year
other fixed costs	40000	SEK/year
cost each year for a single truck	723279.0204	SEK/year
variable costs with km		
fuel price	12.5	SEK/l
fuel road full	66.0297	l/100km
fuel road empty	30	l/100km
fuel consumption with km and weight	0.007353	l/ton km
costo fuel camion vuoto	3.75	SEK/km
surplus fuel consumption camion pieno	0.0919125	SEK/ton km
lubification and hydraulic oil	39	SEK/loil
oil	0.05	l/hG15
velocity	64	km/h
	0.03046875	SEK/km
maintenance	28.2	SEK/10km
other variable costs	0	SEK/10km
variable cost with km (round trip counted)	13.2009375	SEK/km
variable cost with km and ton transported (one way)	0.0919125	SEK/tonkm
fixed costs loading/unloading		
unloading time	16.6	min
loading time	29.5	min
loading/unloading cost	54	€/h
fixed cost for every journey	41.49	€/journey
time		
loading time	29.5	min
unloading time	16.6	min
waiting	15	min
velocity	64	km/h
load capacity	49.1	ton
		m3
single driver cost	420269	SEK/year
	8	h/day
	2	shifts/day

tanker truck (R,K)->(M)		
fixed machine costs		
investment	3.344155844	MSEK
years	7	
interest	0.055	
CCF	0.175964418	
salvage value	501623.3766	SEK
	500184.5706	SEK/year
tax	40000	SEK/year
insurance	42000	SEK/year
other fixed costs	39500	SEK/year
cost each year for a single truck	621684.5706	SEK/year
variable costs with km		
fuel price	12.5	SEK/l
fuel road full	55	l/100km
fuel road empty	28	l/100km
fuel consumption with km and weight	0.007353	l/ton km
costo fuel consumption al km camion vuoto	3.5	SEK/km
surplus fuel consumption quando camion pieno	0.0919125	SEK/ton km
lubification and hydraulic oil	39	SEK/loil
oil	0.05	l/hG15
velocity	43	km/h
	0.045348837	SEK/km
maintenance	20	SEK/10km
other variable costs	4.61	SEK/10km
variable cost with km (round trip counted)	12.01269767	SEK/km
variable cost with km and ton transported (one way)	0.0919125	SEK/ton km
fixed costs loading/unloading		
unloading time	50	min
loading time	50	min
loading/unloading cost	54	€/h
fixed cost for every journey	90	€/n.journey
time		
loading time	50	min
unloading time	50	min
waiting	15	min
velocity	50	km/h
load capacity	35	ton
	40	m3
single driver cost	446132.6531	SEK/year
working hours	8	h/day
shifts a day	2	shifts/day

Appendix B



ANNEX IX

Part A. Feedstocks for the production of biogas for transport and advanced biofuels, the contribution of which towards the minimum shares referred to in the first and fourth subparagraphs of Article 25(1) may be considered to be twice their energy content:

(a) Algae if cultivated on land in ponds or photobioreactors;

(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC;

(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;

(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex;

(e) Straw;

(f) Animal manure and sewage sludge;

(g) Palm oil mill effluent and empty palm fruit bunches;

(h) Tall oil pitch;

(i) Crude glycerine;

(j) Bagasse;

(k) Grape marcs and wine lees;

(l) Nut shells;

(m) Husks;

(n) Cobs cleaned of kernels of corn;

(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre-commercial thinnings, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;

(p) Other non-food cellulosic material;

(q) Other ligno-cellulosic material except saw logs and veneer logs.

Part B. Feedstocks for the production of biofuels and biogas for transport, the contribution of which towards the minimum share established in the first subparagraph of Article 25(1) shall be limited and may be considered to be twice their energy content:

(a) Used cooking oil;

(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.