Renewable Energy 196 (2022) 405–421

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Supply chain optimization and GHG emissions in biofuel production from forestry residues in Sweden

Flavia Basile [a], Lorenzo Pilotti [a], Marco Ugolini [b], Giovanni Lozza [a], Giampaolo Manzolini [a, *]

[a] Department of Energy, Politecnico di Milano, Italy
[b] CA.RE. FOR. Engineering, Italy

ARTICLE INFO

*Article history:*
Received 27 October 2021
Received in revised form
20 May 2022
Accepted 18 June 2022
Available online 4 July 2022

*Keywords:*
Residual biomass
GHG emissions
Advanced biofuels
Supply chain design
Biomethanol
Optimization

ABSTRACT

This paper applies an innovative optimization methodology to the supply chain of biomethanol production starting from forestry residues in Sweden. The model accounts for the collection of the biomass, the transport to the biorefinery including intermediate storages and the biodiesel plant. Particular attention is devoted to the characterization from economic and environmental point of view of the transport by truck and trains, the impact of the drying process as well as the size of the biorefinery plant. Results show that the forestry residues collection is limited by the size of the biodiesel plants. The calculated cost of the fuel is around 525 €/t being the biorefinery the major cost. The equivalent $CO_2$ emissions are around 10.4 $g_{CO2}/MJ_{MeOH}$ thanks to the low carbon intensity of the Swedish electricity. A sensitivity analysis showed that the supply chain does not vary significantly assuming higher prices of biomethanol.


## 1. Introduction

The EU Member States set the ambitious target to improve the share of renewable energy within the final consumption of energy in road and rail transportation sectors with at least 14% by 2030 [1]. Several restrictions were imposed by the EU commission upon the biofuels produced from food, feed crops and with high indirect land-use [1]. This was expressed in an increasing sub-target of '*Advanced Biofuels*' production, namely the ones produced by residual biomasses listed in Part A of Annex IX in Ref. [2], which shall contribute by at least 3.5% by 2030 to the use of renewable energy in the transport sector target.

The residual biomass is a versatile key renewable energy source (RES) from which advanced liquid biofuels can be generated.

In this framework, forestry is already playing a key role as residual biomass source in the transition towards a low-carbon, sustainable, and circular biomass-based economy [3,4]. In addition, residues from forest logging shall be used while maintaining forests' capacity to provide ecosystem services [5,6].

An increase in biomass utilization for biofuel production will increase the complexity of the supply chain (SC) [7] and also the carbon footprint of the biomass supply. The SC is "*the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer*" [8].

This paper focuses on the optimization of the SC of biofuel production using forest residues. This was carried out within the European project CONVERGE, which develops an innovative process for methanol production from residual biomasses (biomethanol) [9].

The optimization of the SC can reduce the cost of the biofuels, which are not yet competitive against conventional fuels [10], without the necessity of technology development [11].

Numerous methodologies based on conventional mathematical optimization techniques have been developed to optimize the performance of bioenergy SC with different objectives and functions (e.g., profitability, carbon footprint, etc.).

Some scientific contributions, related to the optimal allocation of biomass, have been based on the geographic information system (GIS).

Möller and Nielsen [12] identified transportation as one of the

* Corresponding author.
*E-mail address:* giampaolo.manzolini@polimi.it (G. Manzolini).

https://doi.org/10.1016/j.renene.2022.06.095

## Nomenclature

*Acronyms*

ABSC Advanced Biofuel Supply Chain
AIC Annualized Investment Costs
AOC Annual Operating Costs
CGE Cold Gas Efficiency
EU European Union
LCB Lignocellulosic Biomass
LCOF Levelized Cost Of Fuel
LHV Lower Heating Value
LR Residues from forest logging or logging residues
MC Moisture Content
MILP Mixed Integer Linear Programming
O&M Operations and Maintenance
OF Objective Function
PNS Process Network Synthesis
PFF Primary forest fuel
R Revenues
RED Renewables Energy Directive
RES renewable energy sources
SC Supply chain
RME Rapeseed Methyl Ester
SCM Supply chain management
ST Small-diameter trees
TAC Total Annual Cost
TME Tallow Methyl Ester

*Sets*

$\mathscr{B}$ Set of all biomass feedstock varieties
$\mathscr{B}^{AR} \subset \mathscr{B}$ Set of biomass as received
$\mathscr{B}^{I} \subset \mathscr{B}$ Set of biomass primary residue
$\mathscr{B}^{II} \subset \mathscr{B}$ Set of biomass secondary residue
$\mathscr{B}^{P1} \subset \mathscr{B}$ Set of biomass dried up to 25% MC
$\mathscr{B}^{P2} \subset \mathscr{B}$ Set of biomass dried up to 18% MC
$\mathscr{B}^{P3} \subset \mathscr{B}$ Set of biomass densified and dried up to 15% MC
$\mathscr{D}$ Set of candidate sites for intermediate depots and pre-processing facilities
$\mathscr{I}$ Set of biomass origin sites
$\mathscr{K}$ Set of candidate sites for biomass conversion plants
$\mathscr{M}$ Set of destination points – upgrading and blending facilities
$\mathscr{N}$ Set of all nodes in the ABSC superstructure
$\mathscr{R}$ Set of freight terminals
$\mathscr{S}$ Set of the four seasons
$\mathscr{T}$ Set of weekly time periods
$\mathscr{T}_s \subset \mathscr{T}$ Set of timesteps occurring during season $s$

***Parameters [u.m.]***

$\tilde{\gamma}_{el_b}$ Ratio between the requested electricity by the plant and biomass b LHV input $\left[\frac{MWh}{MJ}\right]$
$\tilde{C}_n^{driver}$ Annual cost of driver decided according to the served point n $\left[\frac{€}{n.driver}\right]$
$\tilde{C}_n^{truck}$ Annual cost of truck decided according to the served point n $\left[\frac{€}{n.driver}\right]$
$\tilde{C}_{n,n'}^{fixed}$ Fixed costs due to load and unload the truck used between n and n' $\left[\frac{€}{expedition}\right]$
$\tilde{C}_{n,n'}^{km}$ Variable cost due to fuel consumption, maintenance, oil. etc of truck used between n and n' $\left[\frac{€}{km}\right]$
$\tilde{C}_{r,r'}^{train}$ Cost counting both fixed part and variable one already multiplied with the rail distance between r and r' $\left[\frac{€}{expedition}\right]$
$\tilde{c}_b$ Biomass type $b$ purchasing cost [€]
$\widetilde{CCF}$ Capital charging factor [%]
$\widetilde{CGE}_b$ Conversion plant cold gas efficiency, variable with biomass feedstock type $b$ [%]
$\tilde{d}_{n,n'}$ Distance from node $n$ to node $n'$ $[km]$
$\tilde{e}_{others}^{p}$ Emissions connected to other processes different from the use of methanol during the processing step $\left[\frac{gr_{CO_2}}{MJ_{FAME}}\right]$
$\tilde{e}^{x}$ Emissions connected to process x $\left[\frac{gr_{CO_2}}{MJ_{FAME}}\right]$
$\widetilde{\Delta t}$ Discretization period $[days]$
$\tilde{E}_{meth}$ Methanol employed to produce FAME biodiesel $\left[\frac{MJ}{MJ_{FAME}}\right]$
$\tilde{E}_{cons_{r,r'}}$ Specific energy consumption by train $\left[\frac{kWh}{t \cdot km}\right]$
$\widetilde{fuel}_{load}^{cons}$ Diesel consumption to load the truck $\left[\frac{kg}{expedition}\right]$
$\widetilde{fuel}_{unload}^{cons}$ Diesel consumption to travel $\left[\frac{kg}{km}\right]$
$\widetilde{fuel}_{travel}^{cons}$ Diesel consumption to unload the truck
$\tilde{G}_{b,i,t}$ Yearly availability of biomass secondary residue "as received" $b$ at origin point $i$ $[t_{wet}]$
$\widetilde{GHG}^{el}$ Average carbon intensity of electricity from the grid $\left[\frac{gr_{CO_{2,eq}}}{MWh}\right]$
$\tilde{h}^{driver}$ Working hours of driver during the time period t $[h]$
$\tilde{h}^{truck}$ Working hours of truck during the time period t $[h]$
$\widetilde{INVf}^{dryer}$ Fixed investment cost of industrial dryer [€]
$\widetilde{INVv}^{dryer}$ Variable investment cost of industrial dryer $\left[\frac{€}{kg_{H_2O}/s}\right]$
$\widetilde{LHV}_b$ Lower heating value of biomass feedstock type $b$ $\left[\frac{MJ}{t_{dry}}\right]$
$\widetilde{LHV}^{fuel}$ Methanol lower heating value $\left[\frac{MJ}{t}\right]$
$\widetilde{MF}_b$ Mass factor $\left(\frac{1}{(1-\widetilde{MC}_b)}\right)$ of biomass type $b$ $\left[\frac{t_{wet}}{t_{dry}}\right]$
$\tilde{M}_b^{water}$ Conversion factor of biomass b on weight dry basis into the equivalent water to be evaporated achieving the required moisture of 10% at inlet of the gasifier $\left[\frac{t_{H_2O}}{t_{dry}}\right]$
$\widetilde{MAX}_m^{fuel}$ Maximum quantity required of biomethanol from biodiesel plant m $\left[\frac{t_{fuel}}{y}\right]$
$\tilde{p}^{fuel}$ Biomethanol selling price $\left[\frac{€}{t_{fuel}}\right]$
$\tilde{\rho}_b$ Bulk density of biomass type b $\left[\frac{t}{m^3}\right]$
$\widetilde{tep}_b$ Techno-economical potential of biomass b [%]
$\tilde{t}_a^{load}$ Time to load truck of type $a = arcs_{n,n'}$ $[h]$
$\tilde{t}_a^{unload}$ Time to unload truck of type $a = arcs_{n,n'}$ $[h]$
$\tilde{t}^{wait}$ Time to wait before the departure $[h]$
$\tilde{v}_a$ Average velocity of truck type $a$ $[m/s]$
$\tilde{V}^{tanker}$ Maximum tanker volume capacity $[m^3]$
$\tilde{V}^{train}$ Maximum train wagon volume capacity $[m^3]$
$\tilde{V}^{truck}$ Maximum truck volume capacity $[m^3]$
$\tilde{\nu}_{fuel}$ Methanol density $\left[\frac{m^3}{t}\right]$

$\tilde{W}^{train}$ Maximum train wagon weight capacity $[t_{wet}]$
$\tilde{W}^{truck}_{1,2,3}$ Maximum truck weight capacity according to the arc number $[t_{wet}]$

***Continuous Variables [u.m.]***

AIC Investments costs annualized according to their expected lifetime and to a discount rate [€]
AOC Total annual operating costs accounting for storages and conversion plants operating costs, biomass purchasing costs, and transportation costs [€]
$E^{rail}_{tot}$ Consumed electricity by rail transport $\left[\frac{kWh}{y}\right]$
$elec_k$ Consumed electricity from the grid by biorefinery k $\left[\frac{MWh}{y}\right]$
$gsf_{b,k,t}$ Useful convertible biomass type $b$ converted at conversion facility $k$ in each timestep $t$ $[t_{dry}]$
$G_{i,b,t}$ Mass of primary residue type $b$ harvested from site $i$ at time $t$ $[t_{dry}]$
$INVdryer^{bio}_k$ Investment cost of dryer at biorefinery k [€]
OF Objective function [€]
$OPEX_{biorefinery}$ Operative costs regarding biorefinery working, including the electricity $\left[\frac{€}{y}\right]$
$OPEX_{storage}$ Operative costs regarding management, maintenance and eventual pre-processing of biomass into storages $\left[\frac{€}{y}\right]$
R Revenues from methanol sales [€]
$TC_{n,n'}$ Annual cost of transporting biomass or biofuel from node $n$ to node $n'$ [€]
$tr_{t,b,n,n'}$ Transported biomass (in dry ton) or biofuel b from point n to n' during period t $\left[\frac{t_{dry}}{week}\right]$
$t^{road}_{t,n,n'}$ Total time required to be spent during the operation of truck transport from point n to n' during period t $\left[\frac{h}{week}\right]$
$V^h$ Total volume of harvested residues in one year $\left[\frac{Mm^3}{y}\right]$
$ytot^{biomass}$ Total yearly quantity of biomass exploited by the supply chain $\left[\frac{ton}{y}\right]$
$ytot^{fuel}$ Total yearly quantity of biomethanol produced by the supply chain $\left[\frac{ton}{y}\right]$

***Binary Variables [u.m.]***

$z^{bio}_k$ Selection of biorefinery site k $[-]$

***Integer Variables [u.m.]***

$N^{exp}_{t,n,n'}$ Number of expeditions necessary to transport the mass $tr_{t,b,n,n'}$ $[-]$
$N^{drivers}_n$ Number of drivers assigned at point n, required to transport biomass from that point to the others and then to return to it $[-]$
$N^{trucks}_n$ Number of trucks assigned at point n, required to transport biomass from that point to the others and then to return to it $[-]$

major contributors to the delivered costs of wood chips. They presented a method based on continuous cost surface mapping using raster-based geographical information systems (GISs) to minimize the transportation costs of the wood.

Sultana and Kumar [13] used the GIS to determine optimal locations, sizes and number of bio-energy facilities (pellet plants) in Alberta (Canada), while optimizing the transportation cost.

Another methodology is based on Process graph (P-graph) which is a systematic approach to the design of networks with the aid of graph-theoretic tools. Unlike the conventional mathematical optimization techniques, this method offers the capability to identify both optimal and near-optimal solutions.

Hassim et al. in Ref. [14] presented an approach to the planning of bioenergy SCs, taking into account both total cost minimization and risk reduction via P-graph. The SC risk is accounted for transportation fatalities computed in an actuarial manner.

Vance et al. [15] proposed a multi-objective P-graph approach to enable Pareto optimal solutions to be identified.

Wolfsmayr and Rauch [16] investigated Multimodal Primary Forest Fuel (PFF) transport using the railroad. They assess barriers and drivers for the modal shift from truck to train using the concept of Quality Function Deployment, an approach that has not been used in forest management before.

Furthermore, short transport distances, flexibility and low average PFF volume per logging site, as well as the low demand for small and medium-scale heating plants, make unimodal road transport advantageous [17]. For longer transport distances, multimodal transport is possible, where the initial haulage by truck is followed by the main haulage on a train.

Mixed Integer Linear Programming (MILP), which is the one adopted in this work, was adopted by Gunnarsson, Rönnqvist, and Lundgren [18] to study the SC problem of heating plants in Sweden focusing on the supply procurement decisions.

Shastri et al. [19] formulated a MILP optimization model (e.g., BioFeed) to analyze the cost reduction obtained by the implementation of distributed storage and pre-processing at satellite storage locations to maximize the profit of the system (i.e., Miscanthus production and provision system). The same authors in Ref. [20] applied a similar MILP-based optimization approach to design a SC able to provide the Miscanthus feedstock for large-scale ethanol production in Illinois. Finally, Leduc et al. [21] studied the implementation of a biomass to methanol SC in the north of Sweden, starting from woody biomass by a linear programming optimization approach.

This paper presents an optimization tool for the SC of biofuel production that covers the gaps in the literature:

- the model performs the optimization over a typical year of operation, with weekly temporal resolution;
- the supply chain model is not stationary but considers an evolving time horizon in commitment and scheduling decisions, according to biomass availability which can be different from season to season;
- the model accounts for multi-feedstock biomass collection, seasonal biomass availability, multi-modal and inter-modal transportation. It includes the sizing of pre-processing facilities to modify the physical parameters of the biomass, such as specific volume and moisture content (MC), which affect transportation, storage, and conversion activities.

The model improves a previous version [22] in the accuracy of the description of transportations and of the physical parameters variation in the preprocessing facilities as well as conversion facilities performance.

The model is tested for a case study in southern Sweden to produce biodiesel using residual biomasses bioeconomic potential broken down at regional level in compliance with RED-II directive [1]: the complexity of this allows the optimization of a high number of variables and simultaneously accounts for actual constraints in a dynamic time scenario(limited production capacity of the already existing biodiesel plants, transports, available sites for storages and conversion facilities, time to wait for drying residues).

The paper is organized as follows: the approach to the problem is described in Section 2, the SC structure and the considered components are presented in Section 3. The detailed mathematical formulation of the MILP model is in Section 4. All the case study assumptions, numerical results are shown in Section 5 and Section 6 respectively, while the main findings are drawn in Section 7.

## 2. Biofuel supply chain description

The conceptual architecture of the SC for biofuel production can be simplified into three main parts [23]:

- *Upstream*: includes all the stages from the harvesting/collection of biomass to the biorefineries;
- *Midstream*: accounts for the conversion process itself taking place at the biorefineries;
- *Downstream*: covers the storage of the biofuel and its own distribution to the biodiesel plant.

The *upstream* step corresponds to the SC of primary forest residues that show complex logistics due to the involvement of different contractors, the intrinsic characteristics of the feedstock, and their dependence on other SCs (e.g. roundwood) [24]. Forest primary residues procurement involves several, interconnected, upstream operations: harvest (cutting), forwarding (extraction), storage, comminution and transportation, all of which affect the production costs of forest woodchips [25,26]. The storage, or intermediate depot, is where the residues can be gathered from distinct points of extraction and stacked for the time required allowing the correct operation of the biorefinery. This is a fundamental entity for the seasonal biomasses from agricultural crops and it could be a viable option for the non-seasonal harvested year-round ones (as forest wood) for their drying. An alternative consists of exploiting an industrial dryer at the biorefinery, which is the quickest drying process but implies higher operational costs. The storage is not a mandatory step as the biomass could be transported directly to the biorefinery, adopting a just-in-time (pull) strategy rather than a push strategy.

The pre-treatment improves biomass properties in terms of preservation (reducing dry matter losses) achieving the requirements for storage [23] (MC < 20–25%), and then for the thermochemical process (MC equal to 10%). Pre-treatment options are (i) comminution/chipping, (ii) pre-drying and (iii) densification.

The explored pre-drying processes are: natural drying and forced drying. The high operative costs and the energy consumption that regard forced drying are not trivial limiting the selection of this process.

In the *midstream* step, the secondary biomass is converted into biomethanol through thermochemical processes in the biorefineries as developed within the CONVERGE project [9]. The biomass is firstly gasified then the methane in the syngas is converted into hydrogen and $CO_2$ which is separated in a Sorption Enhanced Reforming. The $H_2$ is compressed in the Electrochemical Hydrogen compressor and then converted into methanol in a membrane reactor.

The *downstream* step accounts for the utilization of biomethanol for biodiesel production in the conventional transesterification process (about 0.2 l of methanol and 1 l of oil, produce 1 l of biodiesel) or in the chemical industry or as gasoline additive. In this work, biomethanol is considered only for biodiesel production. Eventual surplus respect to the biodiesel demand goes to international trade through commercial interports (intended as final destination for this analysis and included in one single group referred as purchasers).

## 3. Model structure

The SC structure implemented in the optimization model is shown in Fig. 1 and considers the biomethanol production from forestry residues in Sweden. The nodes of the network are grouped in $\mathscr{I}$ set of biomass origin sites, $J$ for storages, $\mathscr{R}$ the rail terminals, $\mathscr{K}$ biorefinery sites and $\mathscr{M}$ biomethanol users (i.e. biodiesel production).

The model optimizes the SC from economic point of view and selects short and long-term decisions as reported in Table 1:

The objective function of the model is the minimization of the Total Annual Costs (TAC in Equation (1)) which includes three main contributions: the Annualized Investment Costs (AIC), the Annual Operating Costs (AOC) and the Revenues (R). AIC is the investment expenditures (i.e. the storages and biorefineries installation, the trucks fleet purchase), AOC is the operational cost (i.e. biomass purchase and transport, management and maintenance of storages and biorefineries) and R are the revenues from the selling of the biomethanol.

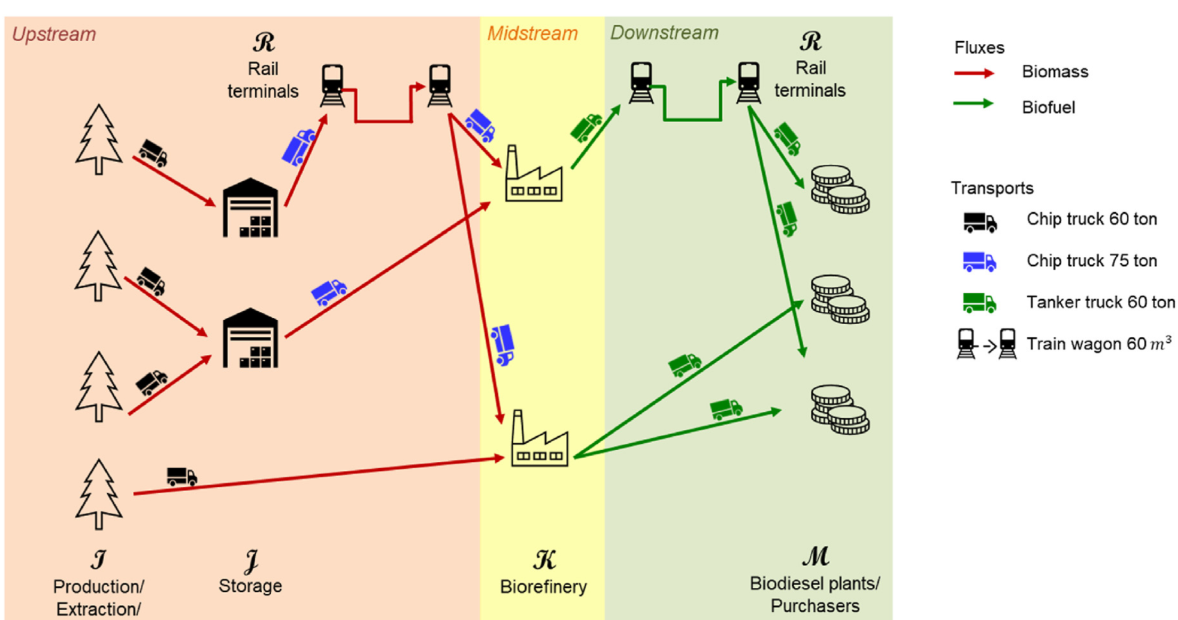


**Fig. 1.** Structure of the model adopted in this work for the production of biomethanol in Sweden.

**Table 1**
Model input and output in terms of short and long terms decisions.

| Input | Strategic output (Long term, design) | Tactical output (Short term, operation) |
|---|---|---|
| 1. Coordinates of all network nodes (including all potential locations for collection, storage, biorefineries and biodiesel plant) and relevant intra-node distances;<br>2. Biomass characteristic as Moisture content (%), Density and bulk density ($t/m^3$), chemical characterization (%), Physical state and Lower Heating Value on a dry basis ($MJ/kg_{dry}$);<br>3. Biomass availability profile throughout the year for each origin site;<br>4. Biomass purchasing costs, constant along the year;<br>5. Biofuel selling price, constant along the year<br>6. Specific capital costs and operating costs for all types of conversion and storage facilities;<br>7. Characterization of all transportation means (transportation capacities, connections distances, transportation fares). | 1. Site selection for collection, storages, biorefinery and biodiesel plant;<br>2. Storage maximum area;<br>3. Pre-treatments types;<br>4. Biorefinery size;<br>5. Dryer size;<br>6. Transportation modes;<br>7. Transport fleet size; | 1. Number of journeys by truck and train;<br>2. Biorefinery operation: on-off status and load capacity;<br>3. Amount of pre-treated biomass;<br>4. Biomasses characteristic approaching the biorefinery;<br>5. Amount of biomass transformed and biomethanol production;<br>6. Amount of electricity purchased;<br>7. Amount of biomasses/ biomethanol transported between nodes;<br>8. Amount of biomethanol purchased from the biodiesel plants;<br>9. Time required for the truck operations between nodes;<br>10. Biorefinery operation: on-off status and load capacity. |

$$TAC = AIC + AOC - R \tag{1}$$

The model optimizes the schedule and operation of the SC for the selected period, as well as the entire superstructure. Examples of decisions made are the selection between the different options available of the number of storages and location, the number and location of the biorefineries with the corresponding sizes, the transportation capacity (the number of trucks/drivers) at each node and all the pre-processing steps to be executed or storage point.

Once optimized the SC with corresponding costs, the levelized cost of fuel (LCOF) can be calculated as:

$$LCOF = \frac{AIC + AOC - R}{m_{fuel}} \tag{2a}$$

where $m_{fuel}$ [t] is the amount of biomethanol produced in a year.

The LCOF allows the comparison between the cost of biomethanol with the one produced using fossil fuels or other non-conventional routes. The AIC is calculated assuming a weighted average cost of capital equal to 12% which corresponds to a plant lifetime of 25 years and a net discount rate of 11%.

### 3.1. SC modeling assumptions

#### 3.1.1. Residual biomass

The first block of the SC is includes the characterization of the biomass in terms of physical characteristics, costs, and availability. In this work, forest logging and collection of the biomass are considered as a unique block. They are defined by:

- yearly producibility in $t/y$;
- purchasing price at the harvesting/extraction point;
- availability period of biomass for the collection.

#### 3.1.2. Storage facilities and biomass pre-treatments

Indoor storages are considered as the open-air type leads to remoisten the already dried biomass as well as significant volatile losses; both are relevant issues for thermochemical processes [22]. The indoor storage minimizes the drying matter losses which cannot be entirely avoided. This aspect is accounted in the model as function of the MC.

Input of the storage are:

- the maximum height;
- bulk density;
- operative costs, connected to the biomass management (called inventory carrying cost).

For solid biomasses with high MC (≥50%), two pre-treatment phases with different moisture content levels can be adopted: the model can optimize the drying configuration by selecting one or more storages accounting for energy and storage footprint. In the case of drying, waste heat from the gasification process is adopted. If additional heat is needed, this is obtained by syngas combustion. Then, the biomass that satisfy the maximum value of MC requested of 17–18% can be densified by pelletization reducing the volume occupancy. This process is usually related to a comminution process that occurs before the densification.

#### 3.1.3. Biomass and biomethanol transport

Three different types of trucks have been identified:

- 60 ton chip truck (60 CT) transports the biomass from the collection point to the storage or directly to the biorefinery [27];
- 75 ton chip truck (75 CP) transports the biomass from the storages to the biorefineries or to the rail terminals, otherwise from the rail terminal to the biorefineries [27];

**Table 2**
Matrix for the type of transportation. Letters refer to the model structure reported in Fig. 1.

| From \ To | Collection points (I) | Storage (J) | Rail terminals (R) | Biorefineries (K) | Biodiesel plants (M) |
|---|---|---|---|---|---|
| Collection (I) | – | 60 CT | – | 60 CT | – |
| Storage (J) | – | – | 75 CP | 75 CP | – |
| Rail terminals (R) | – | – | TR | 75 CP | 60 TT- |
| Biorefinery (K) | – | – | 60 TT | – | 60 TT |
| Biodiesel (M) | – | – | – | – | – |

- 60 ton tanker truck (60 TT), transports bio-methanol from the biorefineries to the biodiesel plants or rail terminals, otherwise from the rail terminal to the biodiesel/ship terminal.

The appropriate type of trucks and trains (TR) connecting two nodes of the SC are summarized in Table 2.

The cost of the truck, as well as the driver, are considered: the drivers of tanker trucks have a higher salary than the drivers of the chip trucks [28]. The lifetime of the trucks has been assumed equal to 7 years and a salvage value is assigned for each category of truck according to Ref. [27].

The estimation of the number of drivers and trucks is set according to the time required (h) for the operations (loading, unloading, driving, waiting), which is limited by the number of weekly working hours of every single truck and driver. The truck can work every day of the year $16h/d$, while a driver works $207d/$ y for $8\frac{h}{d}$ [27].

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 a train (TR), which has a maximum capacity of 60 $m^3$.

The distances between the different possible nodes are determined as rail distances and road distances.

### 3.1.4. Biorefineries and biodiesel plants

The biorefinery converts the biomass into biomethanol. It is modelled as a black box described by the total conversion efficiency (TCE) which is the ratio of methanol energy content and the one of the entering biomass:

$$TCE[\%] = \frac{(\dot{m} \cdot LHV)_{methanol}}{(\dot{m} \cdot LHV)_{biomass}} \tag{2b}$$

where $\dot{m}$ is the mass flow rate and LHV the Low Heating Value.

The presence of the moisture penalizes the conversion efficiency; therefore, the model can select the presence and size of the dryer with corresponding heat duty.

Preliminary AspenPlus [29] simulations of the CONVERGE technology were carried to assess the heat duty as function of the MC. For MC below 35%, all the steam produced on site is used for drying and covering the process demands penalizing the electricity production with corresponding costs. The electric energy demand is described by the electric ratio defined as:

$$\gamma_{el}[\%] = \frac{P_{el,tot}}{(\dot{m} \cdot LHV)_{biom}} \tag{2c}$$

where $P_{el,tot}$ is the balance between the demanded power by the auxiliaries (negative sign) and the one produced by the steam cycle (positive sign).

When the MC is above 35%, in addition to the electric penalty, a part of the biomass is diverted from methanol production and used to supply the required steam, penalizing the TCE.

The cost of the industrial dryer is reported in Fig. 2 as function of the evaporated moisture:

The overall investment cost of the biorefinery without dryer is known for three different sizes (10, 100, 300 MWth) [30]. The cost for intermediate sizes is determined using a piece-wise linear interpolation (as shown in Fig. 2).

The biorefinery size has been limited between 10 and 300 MWth of biomass in input for the reliability of the costs estimate. Moreover, the plant can operate between 60% and 100% of the established plant size [22].

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) [30].

Finally, the biorefinery should operate for a minimum of four consecutive weeks (Minimum Up-Time) and can be out of operation for at least two consecutive weeks (Minimum Down-Time), necessary for the starting up [22].

In the biodiesel plant, the biomethanol replaces the commercial methanol produced by fossil fuels keeping the same ratio with the oil: 0.0818 MJ of methanol is required for 1 MJ of biodiesel.

A maximum capacity for biodiesel plant is set. In cases the producible quantity of biomethanol is larger than the one exploitable by the local biodiesel plants, the excess is sold through international ship ports.

### 3.1.5. Emission calculation

A very relevant aspect is the assessment of the greenhouse gas (GHG) emissions related to the biomethanol production process including the SC.

The GHG are calculated according to the EU Directive 2018/2001, Annex V, part C (RED II) [1], which gives the general formula for the estimation of the $CO_{2_{eq}}$ for a common biofuel. This considers the whole produced emissions of anthropogenic type, starting from the collection phase to the distribution of the biomethanol towards the final

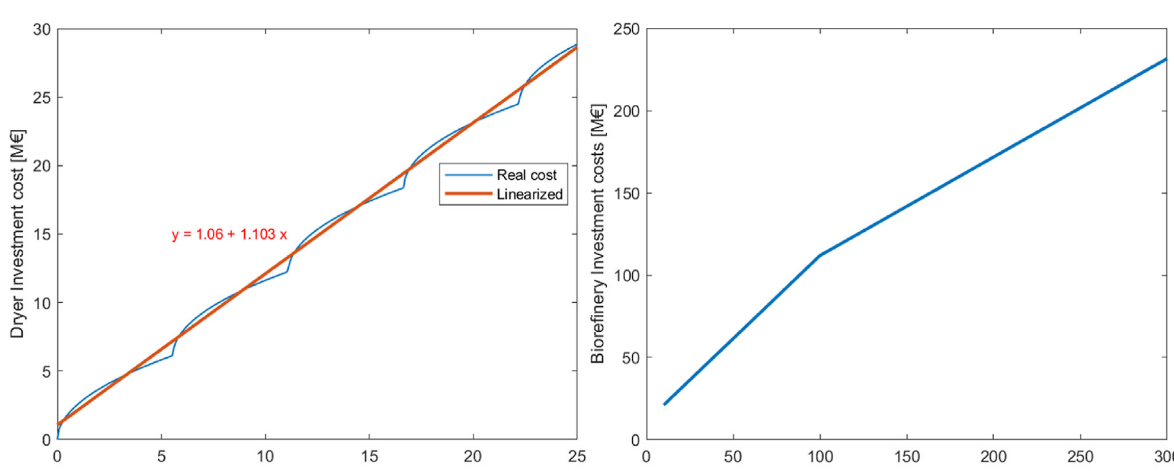


**Fig. 2.** - *Dryer investment cost as a function of the amount of water evaporated (left side) and investment cost of biorefinery based on CONVERGE technology as function of the biomass input, excluding the dryer investment (right side)* [30].

consumers. The Global Warming Potential (GWP) is the parameter adopted to compare the impact of the SC on the final product.

This topic is relevant because a consistent comparison between the different production systems, end-uses and corresponding lifecycle GHG emissions of advanced biofuels is missing.

Although numerous LCA studies have considered advanced biofuels reductions in life cycle GHG emissions by estimating their impact on climate change, they often differ in methodology regarding goal & scope, functional unit and their findings are often conflicting, with a wide variation in the estimates [31].

## 4. Mathematical optimization model and emission calculation

### 4.1. Mathematical model

The model presented above is formulated as a deterministic MILP (Mixed-Integer Linear Program), a widespread and effective methodology extensively applied for biomass SC optimization [32]. The model is implemented in the Matlab toolbox YALMIP [33] and solved using the commercial solver CPLEX v12.10.

The adopted approach is based on a multiperiod description of the year with time period discretization of two weeks: this discretization is accurate enough to provide a fair description of the mono-feedstock SC constituted by non-seasonal biomass, without penalizing excessively the modelling of the operation strategy of the conversion plant. Detailed mathematical insight regarding the formulation of the original MILP model can be found in Ref. [22].

To account for the different means of transport (i.e. trucks, tankers and trains), nodes have to be distinguished according to the type of transport along the arc connecting them. Therefore, the constraint on the number of journeys ($Nj^{exp}_{t,n,n'}$) performed in period t from node n to n' is written as (2) if the arc is connected by truck, as (3) if it is connected by train.

$$tr_{t,b,n,n'} \cdot \widetilde{MF}_b \leq Nj^{exp}_{t,n,n'} \cdot \tilde{W}^{truck}_a \quad \forall t \varepsilon \mathscr{T}, b \varepsilon \mathscr{B}, n, n' \varepsilon \mathscr{N} \backslash \mathscr{R} \tag{2d}$$

$$tr_{t,b,r,r'} \cdot MF_b \big/ \rho_b \leq Nj^{exp}_{t,r,r'} \cdot \tilde{V}^{train} \quad \forall t \ \varepsilon \ \mathscr{T}, b \ \varepsilon \ \mathscr{B}, r \varepsilon \ \mathscr{R} \tag{3}$$

The duration of a single journey does not consider only the traveling time, which is distance-dependent, but it has also to account for the time spent in the operations of loading, unloading and waiting, as shown in Equation (4), that always occur when the product departs/arrives from/to a destination.

$$t^{road}_{t,n,n'} = \left(\tilde{t}^{load}_a + \tilde{t}^{unload}_a + \tilde{t}^{wait} + \left(\tilde{d}_{n,n'} \cdot 2\right) \big/ \tilde{v}_a\right) \cdot Nj^{exp}_{t,n,n'} \quad \forall t \varepsilon \mathscr{T}, \ n \varepsilon \mathscr{N} \backslash \mathscr{R}, n' \varepsilon \mathscr{N} \backslash \mathscr{R} \tag{4}$$

Once time spent in each arc is known ($t^{road}_{t,n,n'}$) as the working hours of each driver and truck ($\tilde{h}^{driver}$, $\tilde{h}^{truck}$) are input parameters, Equations (5) and (6) determine the number of drivers ($N^{driver}_n$) and trucks ($N^{truck}_n$) required to transport the biomass or the biofuel at each node of the SC.

$$\sum_{n' \varepsilon N} t^{road}_{t,n,n'} \leq N^{driver}_n \cdot \tilde{h}^{driver} \quad \forall t \ \varepsilon \ \mathscr{T}, \ n \ \varepsilon \ \mathscr{N} \tag{5}$$

$$\sum_{n' \varepsilon N} t^{road}_{t,n,n'} \leq N^{truck}_n \cdot \tilde{h}^{truck} \quad \forall t \ \varepsilon \ \mathscr{T}, \ n \ \varepsilon \ \mathscr{N} \tag{6}$$

Finally, constraint (7) limits the maximum yearly quantity of methanol that each biodiesel plant $m \in \mathscr{M}$ that can be processed.

$$\sum_{t \varepsilon \mathscr{T}} \sum_{rm \varepsilon \mathscr{R} \cup \mathscr{M}} tr_{t,b,rm,m} \leq \widetilde{MAX}^{fuel}_m \quad \forall b \in fuel, \ m \in \mathscr{M} \tag{7}$$

At the biorefinery, an industrial dryer can be installed to evaporate some of the water in the incoming biomass, to comply with the MC optimal range. The maximum quantity of water evaporated by the drier ($water_k$), expressed in $[kg/s]$ is defined according to Equation (8).

$$\sum_{b \varepsilon \mathscr{B}} \sum_{idr \varepsilon \mathscr{I} \cup \mathscr{D} \cup \mathscr{R}} tr_{t,b,ijr,k} \cdot \tilde{M}^{water}_b \cdot \frac{1000}{\widetilde{\Delta T} \cdot 24 \cdot 3600} \leq water_k \ \forall t \in \mathscr{T}, \ k \in \mathscr{K} \tag{8}$$

Then, the investment cost of the dryer is computed as a linear function of the maximum water flow processed plus a constant term (see Equation (9)), which goes to zero if the dryer is not selected.

$$INVdryer^{bio}_k = \widetilde{INVv}^{dryer} \cdot water_k + \widetilde{INVf}^{dryer} \cdot z^{bio}_k \ \forall \ k \in \mathscr{K} \tag{9}$$

### 4.2. Emission calculation

Starting from the optimization results, an estimation of the $CO_2$ emissions from the designed SC is computed. Three main phases can be identified: (i) the collection phase (if present), (ii) the biomass processing and transformation into biomethanol and (iii) the transport and distribution of biomass/biomethanol along the SC. These quantities can be determined from the results of the optimization as the volume of extracted biomass, the quantity of purchased electricity, the transported quantities, the number of journeys and the distance connecting each node.

$$e_x \left[\frac{gr_{CO_{2,eq}}}{MJ}\right] = \frac{CO_{2_{eq,x}} \left[\frac{ton}{y}\right]}{ytot^{fuel} \left[\frac{ton}{y}\right] \cdot LHV^{fuel} \left[\frac{MJ}{kg}\right]} \cdot 10^3 \tag{10}$$

For each phase ($x$), the specific $CO_{2_{eq}}$ are defined according to Equation (10). The emission for the phase of collection ($e_{ec}$), processing ($e_p$) and transport ($e_{td}$) are estimated in (12), (13) and (14) respectively to compute the total emission for the biomethanol production (11).

$$e_{fuel} = e_{ec} + e_p + e_{td} \tag{11}$$

$$CO_{2_{eq,ec}} \left[\frac{ton}{y}\right] = \left(CO_2 \left[\frac{ton}{Mm^3}\right] \cdot GWP_{CO_2} + NO_x \left[\frac{ton}{Mm^3}\right] \cdot GWP_{NO_x} + CO \left[\frac{ton}{Mm^3}\right] \cdot GWP_{CO}\right) \cdot V^h \left[\frac{Mm^3}{y}\right] \tag{12}$$

$$CO_{2_{eq,p}} \left[\frac{ton}{y}\right] = \widetilde{GHG}^{el} \cdot \sum_{k \varepsilon \mathscr{K}} elec_k \tag{13}$$

$$CO_{2_{eq,td}} \left[\frac{ton}{y}\right] = \left(CO_2 \left[\frac{ton}{kg_{fuel}}\right] \cdot GWP_{CO_2} + NO_x \left[\frac{ton}{kg_{fuel}}\right] \cdot GWP_{NO_x} + CO \left[\frac{ton}{kg_{fuel}}\right] \cdot GWP_{CO}\right) \cdot fuel^{cons}_{tot} + \widetilde{GHG}^{el} \cdot E^{rail}_{tot} \tag{14}$$

The processing phase accounts only for the electricity consumption (biorefinery). For the transport phase, the emissions related to the fuel consumptions of the diesel trucks [34] take into account also the load and unloading operations (15), while the electricity consumed by the train transport is a function of the transported quantities and distance and is estimated according to Equation (16).

$$fuel^{cons}_{tot}\left[\frac{kg}{y}\right] = N^{exp}_{t,n,n'} \cdot \left[\widetilde{fuel}^{cons}_{load} + \widetilde{fuel}^{cons}_{unload} + \left(\widetilde{fuel}^{cons}_{travel} \cdot \tilde{d}_{n,n'}\right) \times\right] \ \forall n, n' \varepsilon \mathscr{N}, t \varepsilon \mathscr{T} \tag{15}$$

$$E^{rail}_{tot}\left[\frac{kWh}{y}\right] = \sum_{r\varepsilon\mathscr{R}}\sum_{r'\varepsilon\mathscr{R}}\sum_{t\varepsilon\mathscr{T}}\sum_{b\varepsilon\mathscr{B}} tr_{t,b,r,r'} \cdot \widetilde{MF}_b \cdot \tilde{d}_{r,r'} \cdot \tilde{E}_{cons_{r,r'}} \tag{16}$$

Finally, the value of remaining emissions related to the biodiesel production process (i.e. bio-oil) is mainly taken from literature. The overall emissions for the biodiesel are calculated as in Equation (17), where the emissions related to biomethanol ($\tilde{E}_{meth} \bullet e_{fuel}$) are taken from previous equations.

$$e_p\left[gr_{CO_{2,eq}} \middle/ MJ_{biodiesel}\right] = \tilde{e}_{others} + \left(\tilde{E}_{meth} \bullet e_{fuel}\right) \tag{17}$$

## 5. Swedish case study and assumptions

The model described above is applied to the Swedish case which is relevant because of the large residual biomasses bioeconomic potentials assessed in the CONVERGE project. This is also demonstrated by the ambitious plans in Sweden to use residual woody biomass in biorefining processes [35–37].

Scandinavia is one of the EU districts with the highest biomass bioeconomic potentials allowing mono-feedstock supply chains and relatively high capacity of the CONVERGE technology (beyond 200 MWth) [38].

The model virtually refers to the association Mellanskog - Skogsagama a Forest Owner's Association that owns 1,7 million hectares of forest land in Svealand, a region of central-southern Sweden, between Norrland and Götaland.

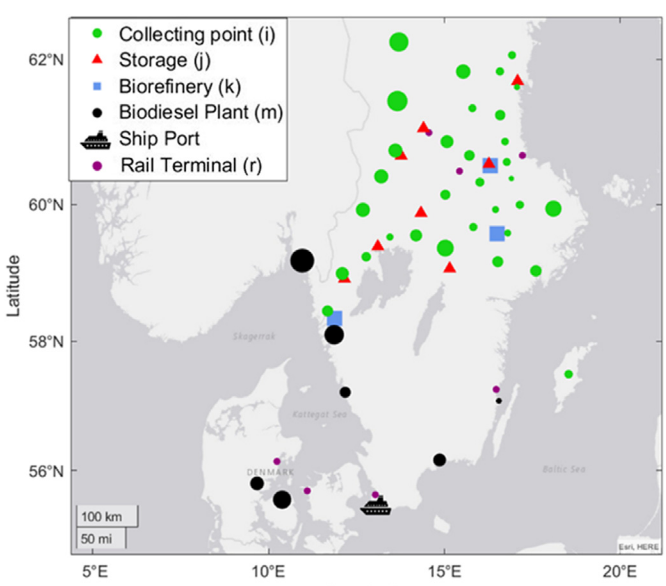


**Fig. 3.** Location of the collecting points, storages, terminals, biorefineries and biodiesel plants for the considered cases study.

**Table 3**
Assumptions on the characteristics of the collected biomass.

| | | |
|---|---|---|
| Price wood chips | 55 | €/ton |
| MC wood chips purchased | 35 | % |
| Max biomass collected | 80% | of total |
| Min. roadside storage | 24 | weeks |
| Weekly dry matter losses roadside | | |
| • summer/spring | 0.05% | |
| • autumn/winter | 0.1% | |
| Time to dry biomass from MC 35→25% | 6 | weeks |
| Time to dry biomass from MC 25→17.3% | 4 | weeks |
| height stored woodchips | 5 | m |

**Table 4**
Biomass characteristics as a function of the MC.

| MC | Weekly dry matter losses | LHV [MJ/kg] | TCE | Electric ratio |
|---|---|---|---|---|
| 35% | 0.125% | 11.54 | 57.71% | −6.85% |
| 25% | 0.05% | 13.7 | 57.00% | −6.41% |
| 17.3% | 0% | 15.4 | 56.10% | −6.04% |
| 15% | 0% | 15.9 | 55.85% | −5.94% |

**Table 5**
Emissions during the extraction and logging phases in Sweden.

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

Forest is composed of tree species distribution of 39% Scots pine (*Pinus sylvestris* L.), 41% Norway spruce (*Picea abies* (L.) Karst), and 20% broadleaf, mainly birch (*Betula* spp.).

Forest residues from forest logging are harvested and extracted year-round and stored in collecting point roadside. They consist of the early phases that compose the residues from forest logging SC.

The SC nodes of the case study are 32 collection points, 8 storages, 12 rail terminals, 3 biorefineries, 8 biodiesel plants and a ship port. The location of the nodes is reported in Fig. 3.

Considering the harvested forest residues technically available on the ground, it is assumed to exploit only 80% of this. Swedish Forest Agency recommends leaving at least 20%[1] of residues on the ground of a clear-felled area to maintain the soil carbon balance and soil fertility and its own regeneration [39].

Maximizing natural drying and minimizing re-moistening are essential elements of MC management [40]. The dried-stacked method allows a first drying step so to achieve a decrease in MC to 35%–40% from 50 to 55% of the fresh wood in the Swedish forests [41–43].

After a roadside chipping, the residues are ready to be purchased and transported to the other points. In Sweden, the average trucking distance for primary forest fuels is 63 km [44]. Efficient long-distance transport is thus needed to increase the use of residual forest biomass [45]. Trucks are the dominant means of transportation for distances below 100 km, while rail and ships dominate for longer distances. The accessibility of the resource can

[1] Other studies indicated more conservative numbers: Mellström and Thörnlind 1981, Hakkila [55] reported that in certain cases up to 50% of logging residues cannot be gathered. Nurmi [56] showed that the 60%–80% of the logging residues can be extracted after harvest.

**Table 6**
– *Emissions related to biodiesel production process taken from Biograce-II tool* [52].

| *All results in* *gram $CO_{2,eq}/MJ_{biodiesel}$* | Non- allocated Results | Allocation factor | Allocated results | Total |
|---|---|---|---|---|
| **Cultivation $e_{ec}$** | | | | **28.7** |
| Cultivation of rapeseed | 48.35 | 58.6% | **28.3** | |
| Rapeseed drying | 0.72 | 58.6% | **0.4** | |
| **Processing $e_p$** | | | | **21.6** |
| Extraction of oil | 6.50 | 58.6% | **3.8** | |
| Refining of vegetable oil | 1.06 | 95.7% | **1.0** | |
| Esterification | 17.51 | 95.7% | **16.7** | |
| **Transport $e_{td}$** | | | | **1.4** |
| Transport of rapeseed | 0.30 | 58.6% | **0.17** | |
| Transport of rapeseed oil | 0.00 | 95.7% | **0.00** | |
| Transport of refined vegetable oil | 0.00 | 95.7% | **0.00** | |
| Transport of biodiesel to depot | 0.47 | 100.0% | **0.47** | |
| Transport to filling station | 0.80 | 100.0% | **0.80** | |
| **Land use change $e_l$** | **0.0** | 58.6% | **0.0** | **0.0** |
| **Bonus or $e_{sca}$** | **0.0** | 100.0% | **0.0** | **0.0** |
| **$e_{ccr} + e_{ccs}$** | **0.0** | 100.0% | **0.0** | **0.0** |
| **Total** | **75.7** | | | **51.7** |

also vary over the year because the access to the forest roads may be limited during freeze-thaw melting periods or heavy rains.

The average price of woodchips considered for the analysis was assumed equal to 55€/*ton*.[2] The production cost of the woodchips is not estimated, as the precise phases with the relative costs are out of scope. The characteristics of the collected biomass are reported in Table 3.

The storage sites have been chosen uniformly spread between the collecting points and they represent realistic purchasable lands with prices between 0.43 and 13.5 $€/m^2$ according to the area and its geographical location [46]. In this case, it could be experienced the exploitation of the storage as a pre-treatment place. Once it is achieved the MC of 17% (seeTable 3), the biomass could be densified. This could present great advantages upon the occupied volume, hence reducing the transport costs. The characteristics of the biomass and corresponding conversion process as function of the MC are reported in Table 4.

The ideal annual demand of biomethanol from the biodiesel plants is 350 kt/y and is equal to their real annual production of biodiesel reported in Ref. [47].

The biomethanol economic value is equal to 600 €/t: this price is higher than the one made by fossil fuels. The local biodiesel plants, which perform the esterification, are reported in Appendix Table A with their corresponding annual production capacity.

Moreover, it has been chosen a very large capacity shipping port sited in Malmoe of about 421,000 t/y of bio-methanol. This is accounted as a demand point because the biofuel passes through it to reach other oversea plants.

The relative costs of the transport system considered by default for a common advanced biomass SC applied into Sweden are also reported in Appendix.

The assumed emission factors for Sweden relative to collection phase are reported in Table 5 [48], the carbon intensity of electricity ($\widetilde{GHG}^{el}$) as of 2018 is 13 $\frac{gr_{co_2}}{kWh}$ [49]. The average carbon intensity of the EU is equal to 282. $\frac{gr_{co_2}}{kWh}$.

The allocation of the greenhouse gas emissions for the woodchips was based on RED-II and being forestry residual biomass, no methane emissions are accounted. About the different pollutants emitted from the trucks, they are determined from heavy-duty cycle vehicles, which reflects the trucks involved in this analysis [50]. The values are CO 6.8 $g/kg_{fuel}$, NOx 32.1 $g/kg_{fuel}$, $CH_4$ 1.56 $g/kg_{fuel}$, $CO_2$ from lubricant and fuels equal to 2.32 $g/kg_{fuel}$ and 3.17 $kg/kg_{fuel}$.

About train transport, the emissions are calculated according to the quantity of electricity consumed as function of the train size [51].

All these assumptions are used to assess the carbon footprint of the biomethanol produced in the biorefinery. Then, the biomethanol impact on the biodiesel production using conventional transesterification process is calculated using vegetable oil made by rapeseed (RSE), commonly used in Sweden (see Table 6). For the esterification process, the quantity of methanol requested to produce 1 MJ of biodiesel is exactly 0.082 MJ ($\tilde{E}_{meth}$) [52] and the heat demand is covered by a Natural Gas boiler [52], whose emissions are accounted for.

The considered emissions, excluding the part regarding the methanol production process (which results from the optimization of the SC, see $e_p$ Eq. (17)), are assumed according to the Biograce-II tool [52]:

The purpose of the analysis is not to provide a detailed and accurate analysis of the GHG emissions related to the biodiesel production route, but to give a general idea of the produced emissions in the different parts of the production process.

## 6. Results

This section summarizes the results of the SC optimization for the Swedish case. Starting from the base Scenario (**Scenario 0,** S0) with the assumptions reported in Section 5, five additional Scenarios (Sensitivity analysis) are evaluated to assess the impact of the boundary conditions on the optimal solution compared to S0.

Specifically, the scenarios are defined by the following additional constraints compared to S0:

- **Scenario 1** (S1) the biodiesel plants have infinite capacity which is the ideal case;
- **Scenario 2** (S2) higher biorefinery plant capacity without considering the effect of the limited demand;

[2] The reference is: UNECE/FAO price series [57]. The Price Database (last updated July 2021) reports the price for Sweden and the average price for wood chips and particle at 2020 (Q4), the most up-to-date value, is 183 SEK/MWh. Applying the currency conversion value SEK/€ and the caloric value for wood chips of mixed wood with MC 35 % the estimated price for the wood chips for industry was 55,6 €/t, rounded to 55 €/t.

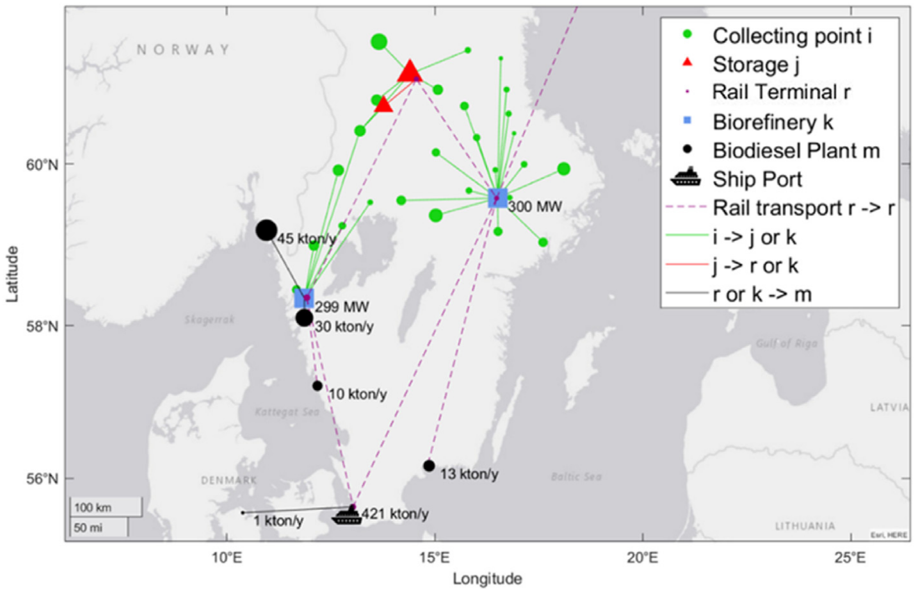


**Fig. 4.** Supply chain layout of Scenario 0.

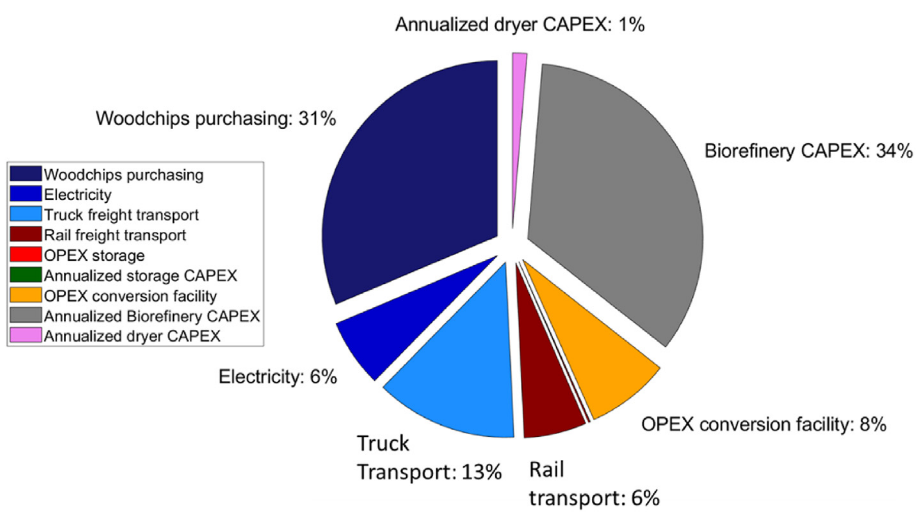


**Fig. 5.** Costs share for production of biomethanol in scenario S.0.

- **Scenario 3** (S3) higher biomethanol price (650 €/*ton*);
- **Scenario 4** (S4), lower the biomethanol price (550 €/*ton*);
- **Scenario 5** (S5) increases the biodiesel plant capacity by 50%.

These scenarios were selected to identify the factors that drive the sizing and the operation of the considered SC focusing on the limitation of the demand, on the maximum biorefinery capacity and the biomethanol price.

**Table 7**
*GHG emission of bio-methanol compared with the fossil one for S.0.* [51].

| | Fossil methanol $\left[\frac{g_{CO_{2,eq}}}{MJ_{MeOH}}\right]$ | EU Biomethanol $\left[\frac{g_{CO_{2,eq}}}{MJ_{MeOH}}\right]$ | SE Biomethanol $\left[\frac{g_{CO_{2,eq}}}{MJ_{MeOH}}\right]$ |
|---|---|---|---|
| **Collection** | – | 5.82 | 5.82 |
| **Conversion** | – | 9.12 | 0.42 |
| **Transport/Truck** | – | 4.07 | 4.07 |
| **Transport/Rail** | – | 0.39 | 0.02 |
| **TOT** | **99.57** | **19.4** | **10.4** |

### 6.1. Reference scenario (S0)

#### 6.1.1. Biomass supply and biomethanol distribution

Scenario 0 depicts the *Base case*, with limitation on demand of the biodiesel plants and the option to exploit an international commercial port based in Malmoe. The overall SC layout is reported in Fig. 4.

Trains and trucks are both selected by the optimization for Scenario 0: train is advantageous for the long distances and used to transport almost the whole biomethanol produced to southern Sweden, where biodiesel plants and commercial ports are concentrated. Between the three biorefinery facilities available, two are selected, achieving almost the maximum size equal to 300 MWth of biomass input. The biomass utilization of the exploitable amount is about 77%.

The upstream part of the SC is controlled by the demand of the biodiesel plants, which limits the total utilization of the biomass. Storages, whose amount of biomass is almost constant along the year, are used in proximity to the rail terminals for short terms storage to make sure that each train is full without any purpose of drying woodchips. Therefore, they can be open-air type, a more economical solution, with limited impact on the biomethanol production cost. Drying is performed directly at the conversion facility exploiting wasted heat and a bit of syngas.

This base case is suitable for the applied road transport modeling, as the covered distances are high and they are difficult to be managed by a central transport system with one point of reference.

Other quantities, which give an idea of the large dimensions of this SC, are the number of drivers 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 (as reported in table).

The LCOF is equal to 524.27 $€/t_{MeOH}$ is very close to the selling price suggesting that the exploited biomass is the economically profitable one (see Fig. 5).

The major contribution is covered by the capital costs of the biorefineries, as it can be intuitive, but also the woodchips purchasing has a great impact. Moreover, optimization of the transport is relevant as it accounts for 19% of overall costs.

#### 6.1.2. Emissions

In terms of environmental impact, the produced biomethanol has a lower carbon intensity with respect to the fossil one (see Table 7). This occurs assuming both the average European (EU) and Swedish (SE) carbon intensities of electricity. Moreover, it is highlighted how a scenario with greener electricity (as Swedish one) can reduce even more the GHG emissions of the produced biodiesel:

The major emitting part in the EU scenario is played by the electricity consumption from the biorefineries, however, when Swedish electricity mix is considers, this become the lowest. The emissions due to rail transport are very low consistently with the assumptions made.

In the Swedish scenario, the most emitting phase is the collection step, but its estimation is purely indicative and dependent on the technology available. However, it still involves fossil fuels due to the impossibility to use electricity in remote places (forests) and, therefore, its contribution should not be underestimated.

As a term of comparison, other works assess lower emissions for biomethanol from forest residues $\left(5.03\ \frac{g_{CO_{2,eq}}}{MJ_{MeOH}}\right)$[53] than the ones calculated in this work. From the emissions of green methanol, the new impact of biodiesel produced can be calculated, by estimating the emissions due to the usage of methanol at the esterification level, which amount to 0.85 $\frac{g_{CO_{2,eq}}}{MJ_{biodiesel}}$ instead of 8.15 $\frac{g_{CO_{2,eq}}}{MJ_{biodiesel}}$.

The specific emissions of biodiesels are reduced thanks to the replacement of grey methanol, but the emissions involved into the other categories are still too high in some biodiesel categories: for Rapeseed Methyl Esterification (RME) biodiesel emissions due to cultivation are the most relevant. On the other hand, when considering biodiesel from animal or oils waste (TME), the GHG decrease is relevant in relative terms (see Table 8).

### 6.2. Sensitivity analysis

#### 6.2.1. Scenario 1

This case is representative of the impact of the demand constraint in terms of problem complexity. The resulting optimal SC layout for the case without the limitation on the annual capacities of the biodiesel plants is reported in Fig. 6:

The biomethanol merges towards the closest point available and the number of biorefineries is increased from 2 to 3 with different sizes.

The biomass usage is increased to 98.8% of the exploitable amount and a very small percentage of biomass is dried in advance at storage sites (this didn't occur in S0).

The cost of biomethanol production is increased by 5 $\frac{€}{t}$. The most significant increase regards the investments on the biorefineries and consequently the relative OPEX. Moreover, as in Fig. 7, the truck transport costs are higher, while the rail ones reduce, because the northern biorefinery is not very well connected by railway.

#### 6.2.2. Scenario 2

When larger biorefinery plants are adopted and no limitation on biomethanol demand, the optimized SC adopts two biorefineries at the maximum size to exploit the scale cost effect. The overall capacity of this scenario (700 MW) is lower than S1 (768 MW) leading to a lower quantity of sold biomethanol as the installation of another biorefinery would be too expensive with limited advantages in the additional biodiesel production.

The SC layout changes considerably as reported in Fig. 8:

The resulting LCOF is reduced to 515 $\frac{€}{t}$ consequence of 13 $\frac{€}{t}$ lower biorefinery CAPEX, 9 $\frac{€}{t}$, reduction in truck transport and an increase by 11 $\frac{€}{t}$, in rail transport.

In this case, the higher transport cost does not correspond to an increase of the GHG emissions, as mentioned by Ref. [54], because the transport is moved from road to railway.

It is more convenient to centralize the biomass conversion in the biorefineries and to exploit the economies of scale, but this brings about very large plant sizes. Indeed, such biomethanol plants of 350 *MWth* do no exists (the largest programmed one is Vaermlands in Sweden with a maximum available capacity of 111 *MWth*).

#### 6.2.3. Scenario 3–4

In these scenarios, the SC network and biomass utilization do not change with respect to the *S0* as consequence of the constraint on biorefinery capacities. Similarly, the LCOF remains the same. The only remarkable difference is on revenues, because when price of

**Table 8**
*GHG emission of RME and TME biodiesel production routes with fossil methanol, EU biomethanol and SE biomethanol.*

| | Biodiesel with Fossil methanol $\left[\frac{g_{CO_{2,eq}}}{MJ_{biodiesel}}\right]$ | Biodiesel with EU Biomethanol $\left[\frac{g_{CO_{2,eq}}}{MJ_{biodiesel}}\right]$ | Reduction [%] | Biodiesel with SE Biomethanol $\left[\frac{g_{CO_{2,eq}}}{MJ_{biodiesel}}\right]$ | reduction [%] |
|---|---|---|---|---|---|
| RME | 51.7 | 45.4 | −12% | 44.7 | −13.5% |
| TME | 21.3 | 15.6 | −26.8% | 15.0 | −30% |

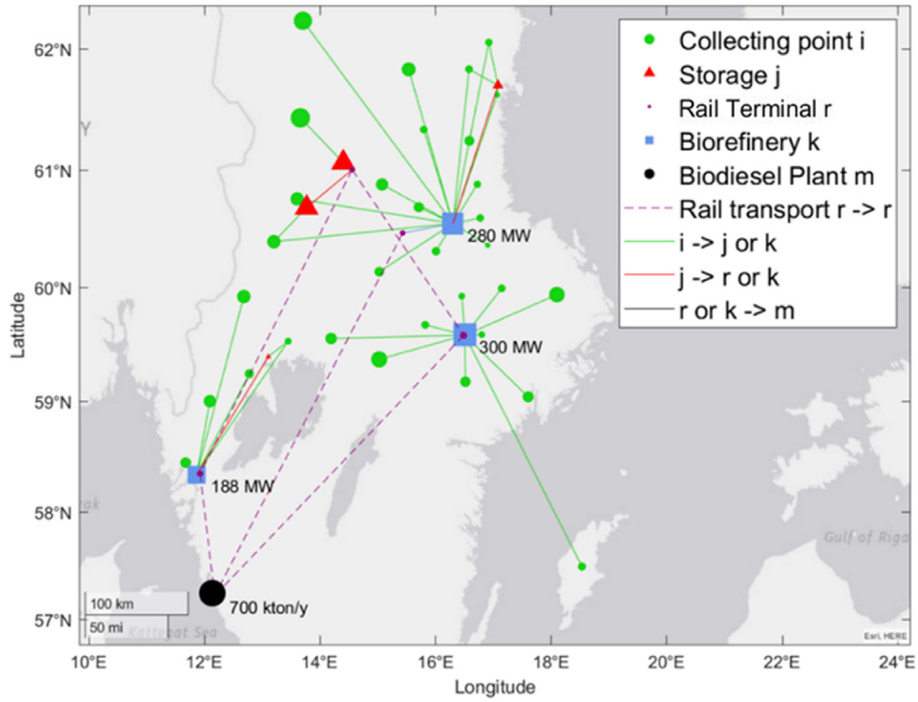


**Fig. 6.** Overall supply chain layout of Scenario 1.

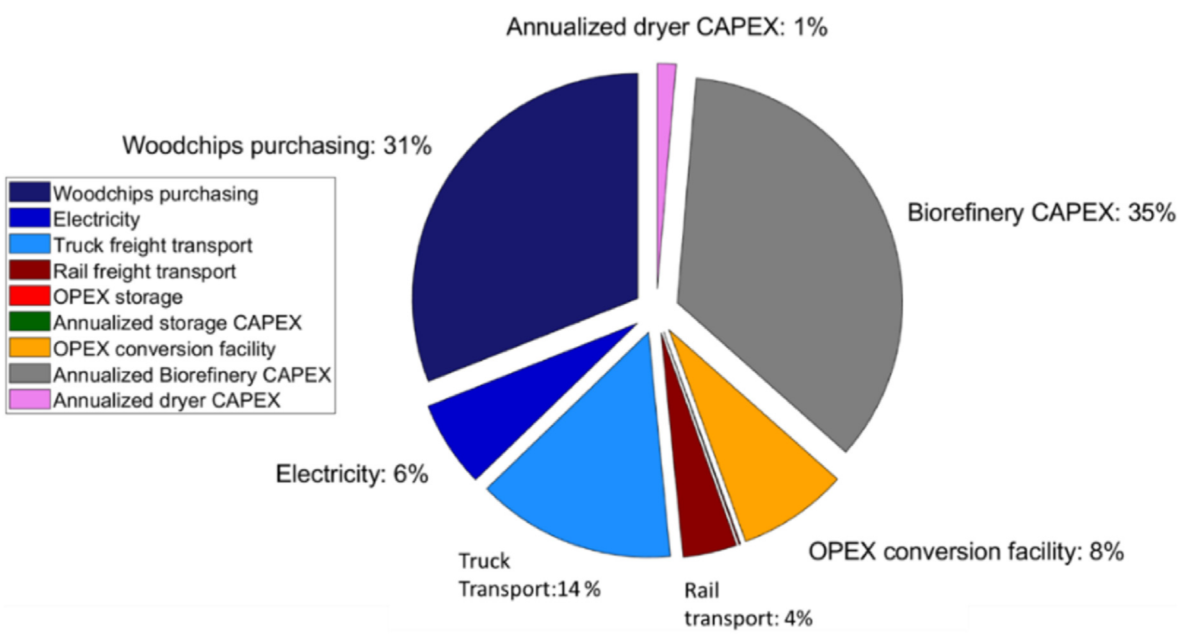


**Fig. 7.** Costs share for production of bio-methanol in scenario S.1.

biomethanol is higher, its marginal profit on sold one is 125 $\frac{€}{t}$, whereas, when it is lower, it achieves about 26 $\frac{€}{t}$. The discrepancy is evident and the selling price is crucial for the profit of the supply system.

Therefore, it can be stated that the price oscillations do not affect significantly the Swedish SC layout.

### 6.2.4. Scenario 5

In this scenario, it was increased the yearly demand of each biodiesel plant by 50%. As reported in Fig. 9, no particular changes occur respect to the S0, as the real limited local demand is too small for the producible quantity of biomethanol.

Therefore, even increasing it, it is not capable to face the large availability of biomethanol; the only solution is to sell it to the foreign market with the associated evaluation of the additional emissions.

## 6.3. Discussion

By comparing the solutions identified in all the scenarios (see

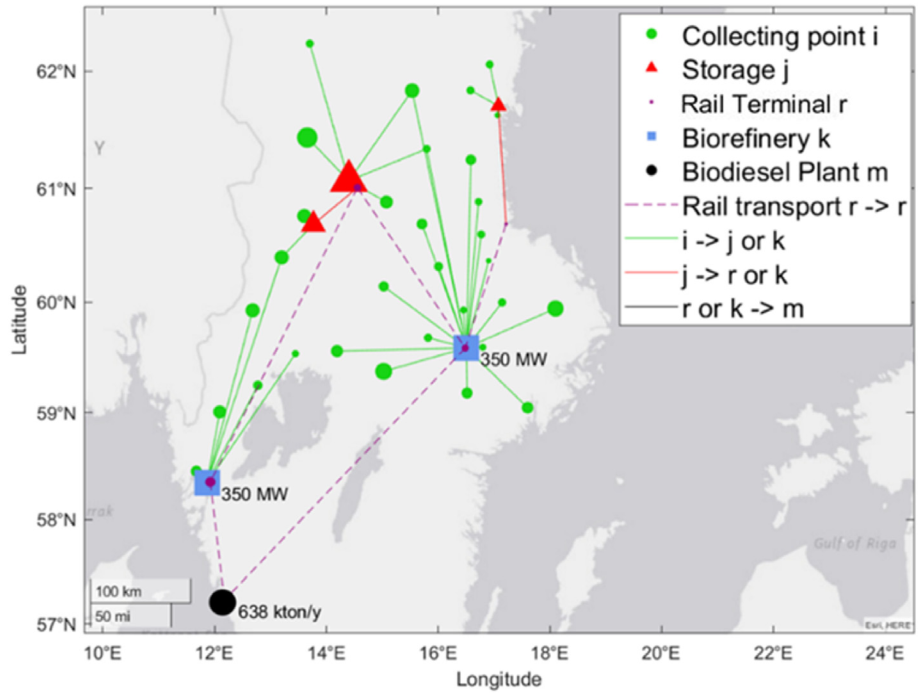


Fig. 8. Overall supply chain layout of S.2.

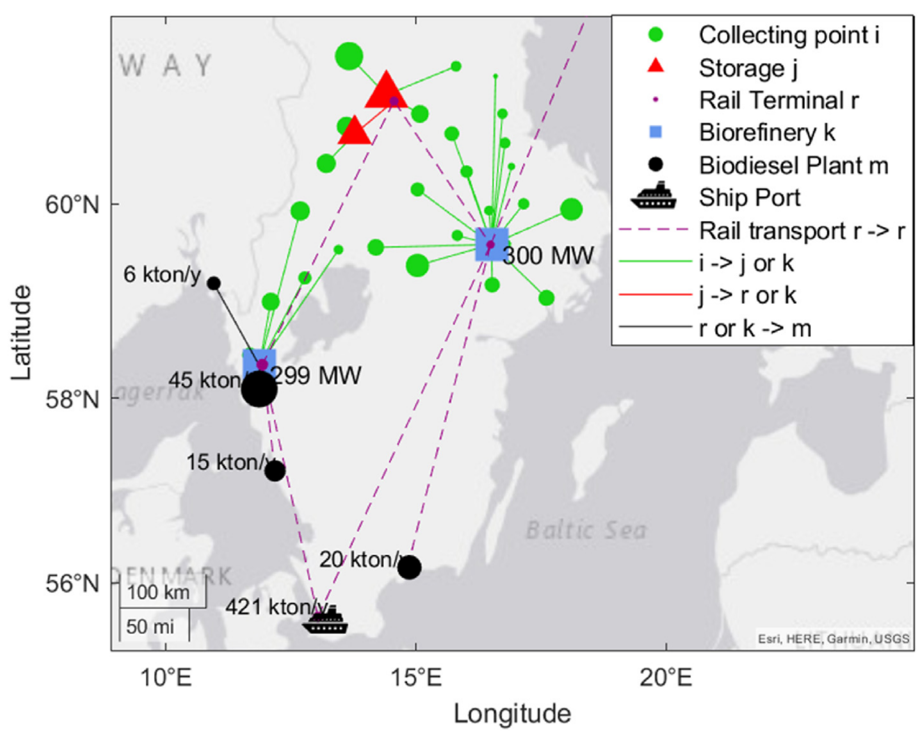


Fig. 9. Overall supply chain layout of scenario S.5.

Table 9), it is possible to draw some general conclusions on the optimal SC configuration and the relative importance of specific modeling features included in the formulation:

- It is not convenient to exploit all the biomass with maximum conversion facilities size of 300 MWth; In particular, the optimization tool limits the number of collecting points to 26 out of 32;
- Biomass pretreatment is not considered as the natural drying process is the most preferred option;
- The selling price of biomethanol does not affect the SC but only the marginal profits;

**Table 9**
Scenarios results of Swedish case (N.F. not foreseen).

| Numerical results | | S.0 | S.1 | S.2 | S.3 | S.4 | S.5 |
|---|---|---|---|---|---|---|---|
| **Annual profit** [M€/y] | | 41.367 | 49.033 | 53.82 | 68.181 | 14.169 | 41.805 |
| **Bio-methanol production** [kt/y] | | 546.3 | 699.6 | 638.1 | 543.6 | 545 | 546.2 |
| **Plants size** [MWth] | | 300<br>299 | 280<br>300<br>188 | 350<br>350 | 296.6<br>299.72 | 299.7<br>298.4 | 299.5<br>299.7 |
| **LCOF** [€/t] | | 524.3 | 529.9 | 515.7 | 524.6 | 524.0 | 523.5 |
| **Marginal profit** [€/t] | | 75.7 | 70.1 | 84.3 | 125 | 26 | 76.54 |
| **Biomass potential** [kt/y] | | 2124 | 2124 | 2124 | 2124 | 2124 | 2124 |
| **Biomass use** [%] | | 76.9% | 98.4% | 89.8% | 76.5% | 76.7% | 76.9% |
| **N. sites selected** collection points | | 26/32 | 32/32 | 31/32 | 25/32 | 26/32 | 26/32 |
| storages | | 2/8 | 4/8 | 3/8 | 3/8 | 3/8 | 2/8 |
| terminals | | 9/12 | 7/12 | 7/12 | 9/12 | 9/12 | 9/12 |
| biorefineries | | 2/3 | 3/3 | 2/3 | 2/3 | 2/3 | 2/3 |
| demand | | 7/9 | 1/9 | 1/9 | 7/9 | 6/9 | 6/9 |
| **Area storage** [$m^2$] | | 7912 | 6882 | 11248 | 7841 | 7904 | 7797 |
| **Cost transports** [M€] | | 54.1 | 67.4 | 62.2 | 53.9 | 53.8 | 53.7 |
| **Pre-treated biomass** (% of total) | | 1.9% | 1.7% | 1.7% | 2% | 2% | 1.9% |
| **Saturated demand sites** | | 6/9 | N.F. | N.F. | 6/9 | 6/9 | 6/9 |
| **Transport features** | È< | 189 | 261 | 211 | 192 | 187 | 189 |
| | **N. trucks** | 63 | 86 | 72 | 65 | 64 | 64 |
| | **N. journeys by train in one year** | 1104 | 1107 | 1566 | 1086 | 1093 | 1128 |
| **Mathematical model implementation** | | | | | | | |
| **N. constraints** | | 50833 | 49498 | 49498 | 50833 | 50833 | 50833 |
| **N. variables** | **Binary** | 116 | 116 | 116 | 116 | 116 | 116 |
| | **Continuous** | 71449 | 70123 | 70123 | 71449 | 71449 | 71449 |
| **Gap** [%] | | 3% | 3% | 3% | 3% | 5% | 3% |
| **Computational time [s]** | | 31292 | 8596 | 26368 | 14288 | 86526 | 31292 |
| **System** | | Polimi's computer 16 GB RAM Intel Core i7-2600 CPU 3.4 GHz | | | | | |

- The LCOF is only slightly affected by the optimization boundary conditions as its variation is below 5%.

## 7. Conclusions

This work focused on the optimization of the supply chain for the production of biodiesel using forest residues as feedstock for methanol production. The optimization tool based on MILP started from a previous work was adapted and applied to the Swedish case.

The definition of the biofuel supply chain required the development of specific features to account for the alternative transport options: different types of trucks are considered as well as rail transportation. Particular attention was devoted to the biorefineries as they strongly affect the design of the supply chain. In addition, the model was improved to fully characterize the feedstock (energy and moisture content) and the impact of the storages on the characteristics.

The final topic examined in this study regards the evaluation of emissions produced during the biodiesel production process with particular attention to the biomethanol step.

Results show that not all the available biomass is exploited (around 80% of the exploitable one) because of size limits of the biorefinery plants. Moreover, the optimized supply chain adopts the largest size of the biorefinery plants to limit their impact on the cost taking advantage of the scale effect costs. A sensitivity analysis showed that changing the size of the biorefinery and biodiesel plants will significantly modify the supply chain optimization increasing the biodiesel production from around 550 kt/y to 700 kt/y. On the contrary, changing the cost of the biodiesel does not significantly affect the optimization result.

One of the main outcomes of this work is the complexity of the supply chain for the production of the biofuels where all the steps can significantly affect the conversion process cost and efficiency. Every decision to promote of biofuel production and utilization, as subsidies, shall include all the supply chain elements to make sure that they are effective in the increasing share of biofuels utilization. Future works will focus on further improvements of the optimization tool in particular focusing on (i) the improvement of the assignation of trucks and drivers for the upstream part, which is the only one that could have an important variation along the year, (ii) inclusion of a residues supplying system for the biodiesel plants to further decrease the emissions at the heating boiler level, (iii) arrangement of a distribution system for the biodiesel produced and (iv) inclusion of the open-air storages option and improved economic data on the pre-treatment machines, (v) integration with a dynamic model for calculating lifecycle GHG emissions of the lignocellulosic biomass supply chains for advanced biofuels for road transportation markets, based on the calculation rules of the Revised Renewable Energy Directive (RED-II).

## Author credits

Pilotti L – Conceptualization, Methodology, Software, Validation, Writing original draft.
Basile F - Resources, Software, Validation, writing original draft.
Lozza G - Writing-review and editing.
Ugolini M. - resources, methodology writing original draft.
Manzolini G – Conceptualization, Writing-review and editing, Supervision, Funding Acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This paper is part of the CONVERGE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 818135.

## Appendix

**Table A.1**
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 |

**Table A.2**
road transportation assumptions

| | Chip Truck 60 ton | Chip Truck 75 ton | Tanker Truck 60 ton | |
|---|---|---|---|---|
| **Annual truck fixed costs** | 47258,25 | 70881,342 | 60925,09 | €/y*N.truck |
| **Variable costs with km** (fuel, maintenance) | 5.4 | 6.088 | 5.4 | €/km |
| **Fixed cost of loading and unloading** | 34,92 | 41,5 | 90 | €/n. journeys |
| **Annual driver cost** | 41186,36 | 41186,362 | 43721 | €/n.drivers |
| **Payload** | 37 | 49 | 35 | ton |
| **t load** | 22,2 | 29,5 | 50 | min |
| **t unload** | 16,6 | 16,6 | 50 | min |
| **Average truck velocity** | 43 | 64 | 50 | km/h |

**Table A.3**
Rail transportation assumptions

| Train | | |
|---|---|---|
| **Wagon fixed cost** | 160 | €/wagon |
| **Wagon variable cost** | 0,89 | €/km*wagon |
| **Fixed cost of loading and unloading** | 16,24 | €/journey*wagon |

*Table A.4. Economic assumptions for the plant and drying process*

| Storage | | | |
|---|---|---|---|
| CAPEX | | | |
| Fixed storage | 70000 | € | |
| Tensile struct | 68 | €/mq | |
| Land | Variable | €/mq | |
| Fixed forced drying | 250000 | € | |
| Variable densification | 10 | €/tonmax/week | |
| **OPEX** | | | |
| C natural drying | 1 | €/ton | |
| C forced drying | 15 | €/ton | |
| C densification | 20 | €/ton | |
| Inventory carrying cost | | | |
| | MC 35% | 0.882 | €/t |
| | MC 25% | 0.868 | €/t |
| | MC 17.3% | 0.868 | €/t |
| | MC 15% | 1.148 | €/t |
| **Biorefinery costs** | | | |
| **Dryer investment** | | | |
| Fixed | 1,06 | M€ | |
| Variable | 1103 | M€/$kg_{evap}$/s | |
| | | | |
| installation costs | 30% | | |
| indirect costs | 22% | | |
| contingency | 20% | | |
| Interest during construction, fraction of TOC | 5% | | |
| O&M, fraction total investment costs | 4,60% | | |
| price purchase/selling electricity | 50 | €/MWh | |

## References


[1] EU Science HUB, Renewable Energy – Recast to 2030 (RED II) | EU Science Hub, EU Sci. Hub, 2019, pp. 1–4. Accessed: Aug. 25, 2021. [Online]. Available: https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii.

[2] E. Parliament, Council, "EUR-Lex - 32018L2001 - EN - EUR-Lex, Official Journal of the European Union, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC#d1e32-147-1. ccessed Oct. 05, 2021.

[3] P.J. Verkerk, et al., Spatial distribution of the potential forest biomass availability in europe, For. Ecosyst 6 (1) (2019), https://doi.org/10.1186/s40663-019-0163-5.

[4] G. Winkel, Towards a Sustainable European Forest-Based Bioeconomy – Assessment and the Way Forward, What Science Can Tell Us, 2017. Accessed: Aug. 29, 2021. [Online]. Available: https://www.efi.int/publication-bank/towards-sustainable-european-forest-based-bioeconomy-assessment-and-way-forward.

[5] D. De Rigo, et al., Forest resources in Europe : an integrated perspective on ecosystem services , disturbances and threats, Eur. Atlas For. Tree Species (2016) 8–19. https://archive.is/aoYxd.

[6] P.J. Verkerk, R. Mavsar, M. Giergiczny, M. Lindner, D. Edwards, M.J. Schelhaas, Assessing impacts of intensified biomass production and biodiversity protection on ecosystem services provided by European forests, Ecosyst. Serv. 9 (Sep. 2014) 155–165, https://doi.org/10.1016/j.ecoser.2014.06.004.

[7] H.L. Lam, P.S. Varbanov, J.J. Klemeš, Regional renewable energy and resource planning, Appl. Energy 88 (2) (2011) 545–550, https://doi.org/10.1016/j.apenergy.2010.05.019.

[8] M. Christopher, Logistics & Supply Chain Management, fourth ed., Financial Times Prentice Hall, 2011.

[9] Home - converge H2020 project." https://www.converge-h2020.eu/(accessed Aug. 25, 2021).

[10] G. Festel, M. Würmseher, C. Rammer, E. Boles, M. Bellof, Modelling production cost scenarios for biofuels and fossil fuels in Europe, J. Clean. Prod. 66 (2014) 242–253, https://doi.org/10.1016/j.jclepro.2013.10.038.

[11] C. Kanzian, F. Holzleitner, K. Stampfer, S. A. Kanzian, and K. & Ashton, "Regional energy wood logistics-optimizing local fuel supply," Accessed: Aug. 25, 2021. [Online]. Available: http://www.metla.fi/silvafennica/full/sf43/sf431113.pdf.

[12] B. Möller, P.S. Nielsen, Analysing transport costs of Danish forest wood chip resources by means of continuous cost surfaces, Biomass Bioenergy 31 (5) (2007) 291–298, https://doi.org/10.1016/j.biombioe.2007.01.018.

[13] A. Sultana, A. Kumar, Optimal siting and size of bioenergy facilities using geographic information system, Appl. Energy 94 (Jun. 2012) 192–201, https://doi.org/10.1016/j.apenergy.2012.01.052.

[14] R.T.L. Ng, R.R. Tan, M.H. Hassim, P-graph methodology for Bi-objective optimisation of bioenergy supply chains: economic and safety perspectives, Chem. Eng. Trans. 45 (2015) 1357–1362, https://doi.org/10.3303/CET1545227.

[15] L. Vance, I. Heckl, B. Bertok, H. Cabezas, F. Friedler, Designing sustainable energy supply chains by the P-graph method for minimal cost, environmental burden, energy resources input, J. Clean. Prod. 94 (2015) 144–154, https://doi.org/10.1016/j.jclepro.2015.02.011.

[16] U.J. Wolfsmayr, P. Rauch, The primary forest fuel supply chain: a literature review, Biomass Bioenergy 60 (Jan. 2014) 203–221, https://doi.org/10.1016/J.BIOMBIOE.2013.10.025.

[17] C.N. Hamelinck, R.A.A. Suurs, A.P.C. Faaij, International bioenergy transport costs and energy balance, Biomass and Bioenergy 29 (2) (2005) 114–134, https://doi.org/10.1016/J.BIOMBIOE.2005.04.002.

[18] H. Gunnarsson, M. Rönnqvist, J.T. Lundgren, Supply chain modelling of forest fuel, Eur. J. Oper. Res. 158 (1) (Oct. 2004) 103–123, https://doi.org/10.1016/S0377-2217(03)00354-0.

[19] Y.N. Shastri, L.F. Rodriguez, A.C. Hansen, K.C. Ting, Impact of distributed storage and pre-processing on Miscanthus production and provision systems, Biofuels, Bioprod. Bioref 6 (1) (Jan. 2012) 21–31, https://doi.org/10.1002/BBB.326.

[20] T. Lin, L.F. Rodríguez, Y.N. Shastri, A.C. Hansen, K.C. Ting, GIS-enabled biomass-ethanol supply chain optimization: model development and Miscanthus application, Biofuels, Bioprod. Bioref 7 (3) (May 2013) 314–333, https://doi.org/10.1002/BBB.1394.

[21] S. Leduc, J. Lundgren, O. Franklin, E. Dotzauer, Location of a biomass based methanol production plant: a dynamic problem in northern Sweden, Appl. Energy 87 (1) (Jan. 2010) 68–75, https://doi.org/10.1016/j.apenergy.2009.02.009.

[22] L. Moretti, M. Milani, G.G. Lozza, G. Manzolini, A detailed MILP formulation for the optimal design of advanced biofuel supply chains, Renew. Energy 171 (Jun. 2021) 159–175, https://doi.org/10.1016/j.renene.2021.02.043.

[23] A.A. Rentizelas, Biomass storage, Biomass Supply Chain. Bioenergy Biorefining (Jan. 2016) 127–146, https://doi.org/10.1016/B978-1-78242-366-9.00006-X.

[24] T. Sowlati, Modeling of forest and wood residues supply chains for bioenergy and biofuel production, Biomass Supply Chain. Bioenergy Biorefining (Jan. 2016) 167–190, https://doi.org/10.1016/B978-1-78242-366-9.00008-3.

[25] M. Aalto, K.C. Raghu, O.J. Korpinen, K. Karttunen, T. Ranta, Modeling of biomass supply system by combining computational methods – a review article, Appl. Energy 243 (2019) 145–154, https://doi.org/10.1016/j.apenergy.2019.03.201.

[26] K. Karttunen, Added-value innovation of forest biomass supply chains, Diss. For. (186) (2015), https://doi.org/10.14214/df.186.

[27] S. Berg, D. Athanassiadis, The cost of closed terminals in the supply chain for a potential biorefinery in northern Sweden, 35, no. 3-4, pp. 165-176, https://doi.org/10.1080/02827581.2020.1751268, May 2020, 10.1080/02827581.2020.1751268.

[28] Ministero delle Infrastrutture e dei Trasporti, "Autotrasporto merci conto di terzi, valori indicativi di riferimento dei costi di esercizio dell'impresa | mit." https://www.mit.gov.it/documentazione/autotrasporto-merci-conto-di-terzi-valori-indicativi-di-riferimento-dei-costi-di (accessed May 16, 2022).

[29] Aspen Plus | Leading Process Simulation Software | AspenTech." https://www.aspentech.com/en/products/engineering/aspen-plus (accessed May 21, 2021).

[30] G. Manzolini, Converge Project. D5.2 – Techno-Economic Assessment for the Base Case and the Reference Case, 2020.

[31] H.K. Jeswani, A. Chilvers, A. Azapagic, Environmental sustainability of biofuels: a review, Proc. R. Soc. A 476 (2243) (2020), https://doi.org/10.1098/RSPA.2020.0351.

[32] L.J.R. Nunes, T.P. Causer, D. Ciolkosz, Biomass for energy: a review on supply chain management models, Renew. Sustain. Energy Rev. 120 (2020), 109658, https://doi.org/10.1016/j.rser.2019.109658.

[33] J. Lofberg, YALMIP : a toolbox for modeling and optimization in MATLAB, in: 2004 IEEE Int. Conf. Comput. Aided Control Syst. Des., 2004, pp. 284–289, https://doi.org/10.1109/CACSD.2004.1393890.

[34] N.-O. Nylund, K. Erkkilä, Heavy-duty Truck Emission and Fuel Consumption: Simulating Real-World Driving in Laboratory Conditions, Proceeding 2005 DEER Conf, 2005, pp. 1–23.

[35] Questions and Answers about the Biorefinery - SCA." https://www.sca.com/en/energy/Project-and-development/biorefinery/questions-and-answers-about-the-biorefinery/(accessed Aug. 29, 2021).

[36] Lulea University of Technology." https://www.ltu.se/org/tvm/Avdelningar/LTU-Green-Fuels/Forskare-vill-testflyga-svenskt-biobransle-2021-1.181623?l=en (accessed Aug. 29, 2021).

[37] A./S. Niras, Sustainable Jet Fuel for Aviation. Nordic Perspectives on the Use of Advanced Sustainable Jet Fuel for Aviation, 2020. Accessed: Aug. 29, 2021. [Online]. Available: https://www.nordicenergy.org/wp-content/uploads/2020/01/Sustainable-Jet-Fuel-Update-FinalNER.pdf.

[38] M. Ugolini, L. Recchia, N. Migliorini, G. Manzolini, G. Guandalini, M. Milani, European regions suitability for advanced biofuel production. Cases scenarios for residual biomass supply chains, in: European Biomass Conference and Exhibition Proceedings, 2020, pp. 22–29. Accessed: Aug. 29, 2021. [Online]. Available: https://re.public.polimi.it/handle/11311/1161271.

[39] B. Nilsson, Extraction of Logging Residues for Bioenergy-Effects of Operational Methods on Fuel Quality and Biomass Losses, the forest linnaeus university press, 2016, pp. 1–122. Accessed: Aug. 25, 2021. [Online]. Available: http://lnu.diva-portal.org/smash/get/diva2:1049815/FULLTEXT01.pdf.

[40] J. Routa, M. Kolström, J. Ruotsalainen, L. Sikanen, Validation of prediction models for estimating the moisture content of small diameter stem wood, Croat. J. For. Eng. J. Theory Appl. For. Eng. 36 (2) (Oct. 2015) 283–291.

[41] P. Lehtikangas, R. Jirjis, Vältlagring Av Avverkningsrester Från Barrträd under Varierande Omständigheter [Windrow Storage of Logging Residues from Softwood under Variable Conditions], 1993. Uppsala, Sweden, https://agris.fao.org/agris-search/search.do?recordID=US201300729416.

[42] A. Eriksson, L. Eliasson, P.-A. Hansson, R. Jirjis, Effects of supply chain strategy on stump fuel cost: a simulation approach, Int. J. For. Res. (2014) 1–11, https://doi.org/10.1155/2014/984395, 2014.

[43] B. Nilsson, D. Nilsson, T. Thörnqvist, Distributions and losses of logging residues at clear-felled areas during extraction for bioenergy: comparing dried-and fresh-stacked method, Forests 6 (11) (2015) 4212–4227, https://doi.org/10.3390/f6114212.

[44] A. Davidsson, V. Asmoarp, Skogsbrukets Vägtransporter 2016. En Nulägesbeskrivning Av Flöden Av Biomassa Från Skog till Industri [Forestry Road Transports 2016. Current Situation Regarding the Flow of Biomass from Forest to Industry, 2019 [Online]. Available: https://www.skogforsk.se/cd_20190307161827/contentassets/cabd68ec0e91487783a4ad2c60e08829/arbetsrapport-1007-2019.pdf.

[45] J. Routa, A. Asikainen, R. Björheden, J. Laitila, D. Röser, Forest energy procurement: state of the art in Finland and Sweden, Wiley Interdiscip. Rev. Energy Environ. 2 (6) (Nov. 2013) 602–613, https://doi.org/10.1002/wene.24.

[46] Booli - bostadssajten med flest hus och lägenheter till salu." https://www.booli.se/(accessed Aug. 25, 2021).

[47] Institute of environmental sustainability biodiesel labs teacher manual with student documents, Accessed: Aug. 25, 2021. [Online]. Available: www.luc.edu/biodiesel, 2017.

[48] S. Berg, T. Karjalainen, Comparison of greenhouse gas emissions from forest operations in Finland and Sweden, For. An Int. J. For. Res. 76 (3) (Jan. 2003) 271–284, https://doi.org/10.1093/FORESTRY/76.3.271.

[49] EEA greenhouse gases - data viewer — European Environment Agency." https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (accessed Aug. 25, 2021).

[50] EEA, EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019, European Environment Agency," *European Environment Agency*, 2019. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019. (Accessed 25 August 2021).

[51] EcoTransIT world - emission calculator." https://www.ecotransit.org/en/

emissioncalculator/(accessed Aug. 25, 2021).
[52] BioGrace, The BioGrace GHG calculation tool: a recognised voluntary scheme. https://www.biograce.net/home, 2014. (Accessed 25 August 2021).
[53] J. Pucker, A. Kraft, Improving the Sustainability of Fatty Acid Methyl Esters (Fame-Biodiesel)-Assessment of Options for Industry and Agriculture Reliable Bio-Based Refinery Intermediates (BioMates) View Project, EU-PEARLS View project, 2016, https://doi.org/10.5071/24thEUBCE2016-ICV.1.74.
[54] A. De Meyer, D. Cattrysse, J. Van Orshoven, A mixed integer linear programming model for the strategic optimisation of biomass-for-bioenergy supply chains, in: European Biomass Conference and Exhibition, 2013, pp. 276–283, 2.
[55] P. Hakkila, Utilization of Residual Forest Biomass, 1989, pp. 352–477, https://doi.org/10.1007/978-3-642-74072-5_8.
[56] J. Nurmi, Recovery of logging residues for energy from spruce (Pices abies) dominated stands, Biomass Bioenergy 31 (6) (Jun. 2007) 375–380, https://doi.org/10.1016/j.biombioe.2007.01.011.
[57] UNECE, UNECE, Prices, 2019. https://unece.org/forests/prices. (Accessed 16 May 2022).