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A detailed MILP formulation for the optimal design of advanced biofuel supply chains

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ABSTRACT

The optimal design of a biomass supply chain is a complex problem, which must take into account multiple interrelated factors (i.e the spatial distribution of the network nodes, the efficient planning of logistics activities, etc.). Mixed Integer Linear Programming has proven to be an effective mathematical tool for the optimization of the design and the management strategy of Advanced Biofuel Supply Chains (ABSC). This work presents a MILP formulation of the economical optimization of ABSC design, comprising the definition of the associated weekly management plan. A general modeling approach is proposed with a network structure comprising two intermediate echelons (storage and conversion facilities) and accounts for train and truck freight transport. The model is declined for the case of a multi-feedstock ABSC for green methanol production tested on the Italian case study. Residual biomass feedstocks considered are woodchips from primary forestry residues, grape pomace, and exhausted olive pomace. The calculated cost of methanol is equal to 418.7 €/t with conversion facility cost accounting for 50% of the fuel cost share while transportation and storage costs for around 15%. When considering only woodchips the price of methanol increases to 433.4 €/t outlining the advantages of multi-feedstock approach.

1. Introduction

The European Strategy for low-emission mobility identifies the deployment of advanced biofuels as part of the necessary measures to promote a transition towards a decarbonized transport system, and support at the same time the creation of new jobs, investment opportunities, and innovation [1]. According to the Renewables Energy Directive RED II 2018/2001 [2], the contribution of advanced biofuels in terms of share of final energy consumption in the transport sector shall be at least 0,2% in 2022, 1% in 2025 and 3,5% in 2030. Advanced biofuels can be defined as second-generation liquid biofuels [3], based on the conversion of residual lignocellulosic biomass (LCB), which is a renewable, non-food competitive resource [4]. The RED II directive specifies a list of eligible feedstocks for the production of advanced biofuel0F[1] which includes mainly primary agricultural residues, primary forestry residues, and agro-forestry industrial residues/wastes (secondary residues). Residues and wastes are an abundant unused potential resource to be converted into biofuels [5]. Moreover, since it is not the main product, but it is the result of other activities, residual biomass is typically an appealing resource for its low cost. However, the types of biomass feedstock relevant for the production of advanced biofuels are typically seasonal, geographically scattered and low-quality resource. As a consequence, the effective design and management of Advanced Biomass Supply Chains (ABSC) is a necessary step towards improving the market up-take of sustainable advanced biofuels and increasing their share in the transport sector as an alternative to fossil fuels [6].

Due to the broad interest in this topic, numerous optimization models have been developed in the literature to identify the best ABSC configuration to reduce the total logistics cost and to improve the supply chain performance [7]. In this work, we will restrict the attention to the production of second-generation liquid biofuels from LCB (residual and non-residual) through thermochemical processes. Even considering this specific conversion route, reference models are numerous and quite different from each other. General reviews on the optimal design and operation of the process

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[1] The RED II Directive (EU) 2018/2001 at the art.2, gives the following definition of advanced biofuel: biofuels that are produced from the feedstock listed in Part A of Annex IX.

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Nomenclature

Acronyms

ABSC	Advanced Biofuel Supply Chain
AIC	Annualized Investment Costs
AOC	Annual Operating Costs
CAPEX	Capital Expenditures
CGE	Cold Gas Efficiency
DFC	Distance Fixed Cost
DVC	Distance Variable Costs
EU	European Union
FTL	Full Truckload
INV	Investments
LCB	Lignocellulosic Biomass
LHV	Lower Heating Value
MC	Moisture Content
MILP	Mixed Integer Linear Programming
O&M	Operations and Maintenance
OF	Objective Function
R	Revenues
RED	Renewables Energy Directive

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.]

$\tilde{A}_d^{max}$	Maximum available space of each intermediate depot *d* $[m^2]$
$\tilde{C}^{INVdens}$	Investment cost of installing a densification machine, proportional to its size $\left[\frac{€}{ton_{dry}}\right]$
$\tilde{C}_d^{fix}$	Fixed investment cost of installing an intermediate depot at location *d* [€]
$\tilde{C}_d^{var}$	Investment cost of installing an intermediate depot at location *d* proportional to occupied area A_d $\left[\frac{€}{m^2}\right]$
$\tilde{c}^{OPEXdens}$	Densification operating expenses $\left[\frac{€}{ton_{dry}}\right]$
$\tilde{c}_b$	Biomass type *b* purchasing cost [€]
$\tilde{c}_d^{dry}$	Operating expenses relative to the biomass drying process at intermediate depot *d* $\left[\frac{€}{ton_{dry}}\right]$
$\widetilde{icc}_b$	Inventory carrying cost of biomass type *b* stored at intermediate depots $\left[\frac{€}{ton_{dry}}\right]$
$\widetilde{CGE}_b$	Conversion plant cold gas efficiency, variable with biomass feedstock type *b* [%]
$\tilde{d}_{n,n'}$	Distance from node *n* to node *n*' [*km*]
$\widetilde{DFC}_{n,n'}$	Transportation cost from node *n* to node *n*', proportional to the required number of expeditions $\left[\frac{€}{expedion}\right]$
$\widetilde{dml}_{b,s}^{rs}$	Weekly dry mass percentage loss in roadside storages for biomass type *b* during season *s* [%]
$\widetilde{dml}_b$	Weekly dry mass percentage loss at intermediate depots for biomass type *b* [%]
$\tilde{dr}$	Discount rate [%]
$\widetilde{dry}_b^{\%}$	Percentage of feedstock type *b* with an MC higher than the acceptable threshold (25%) that must be burned at conversion facility in order to operate properly [%]
$\widetilde{DVC}_{n,n'}$	Transportation cost from node *n* to node *n*', proportional to the transported mass and the length of the journey $\left[\frac{€}{ton_{dry} \cdot km}\right]$
$\tilde{f}_{b,i,s}$	Fraction of $\tilde{H}_{b,i}^{tot}$ that can be harvested at most during season *s* [%]
$\tilde{G}_{b,i,t}$	Weekly availability profile of biomass secondary residue “as received” *b* at origin point *i* $[ton_{wet}]$
$\tilde{H}_{b,i}^{tot}$	Yearly availability profile of biomass primary residue “as received” *b* at origin point *i* $[ton_{dry}]$
$\widetilde{LHV}_b$	Lower heating value of biomass feedstock type *b* $\left[\frac{MJ}{ton_{dry}}\right]$
$\widetilde{LHV}_b^{ref}$	Reference lower heating values for the biomass feedstock type *b* $\left[\frac{MJ}{ton_{dry}}\right]$
$\widetilde{LHV}^{fuel}$	Methanol lower heating value $\left[\frac{MJ}{ton}\right]$
$\widetilde{LT}$	Project life time [*years*]
$\widetilde{MF}_b$	Mass factor $\left(\frac{1}{(1-\widetilde{MC}_b)}\right)$ of biomass type *b* $\left[\frac{ton_{wet}}{ton_{dry}}\right]$
$\tilde{P}^{max}$	Maximum size of conversion facility *k* [*MW*]
$\tilde{P}^{min}$	Minimum size of conversion facility *k* [*MW*]
$\tilde{rf}_b$	Room factor of biomass type *b* $\left[\frac{ton_{dry}}{m^2}\right]$
$\tilde{T}_b^{dry,1}$	Minimum drying period at intermediate depots required by the biomass type *b* to reach 25% MC [*weeks*]
$\tilde{T}_b^{dry,2}$	Minimum drying period at intermediate depots required by the biomass type *b* to reach 18% MC [*weeks*]
$\tilde{T}_b^{dry,rs}$	Minimum drying period at roadside storage required by the biomass type *b* to reach an MC adequate for collection [*weeks*]

$\tilde{V}^{tanker}$	Maximum tanker volume capacity $[m^3]$
$\tilde{V}^{train}$	Maximum train wagon volume capacity $[m^3]$
$\tilde{V}^{truck}$	Maximum truck volume capacity $[m^3]$
$\tilde{v}_b$	Volume occupation factor of biomass type b $\left[\frac{m^3}{ton_{dry}}\right]$
$\tilde{v}_{fuel}$	Methanol density $\left[\frac{m^3}{ton}\right]$
$\tilde{W}^{tanker}$	Maximum tanker weight capacity $[ton]$
$\tilde{W}^{train}$	Maximum train wagon weight capacity $[ton_{wet}]$
$\tilde{W}^{truck}$	Maximum truck weight capacity $[ton_{wet}]$

Continuous Variables[u.m.]

A_d	Area covered by intermediate depot d $[m^2]$
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 [€]
c_d^{opex}	Annual operating and maintenance cost for intermediate depot d [€]
c_i^{feed}	Annual cost of purchasing biomass from origin point i [€]
$c_j^{O\&M}$	Total annual operating and maintenance cost for depots and conversion plants j [€]
$cons_{d,b,b',t}$	Amount of biomass type b converted in another biomass type b' at intermediate depot d in each timestep t $[ton_{dry}]$
D_d	Maximum capacity of densification machine installed at intermediate depot d $[ton_{dry}]$
$gas_{b,k,t}$	Useful convertible biomass type b converted at conversion facility k in each timestep t $[ton_{dry}]$
$G_{i,b,t}$	Mass of primary residue type b harvested from site i at time t $[ton_{dry}]$
INV_d	Capital investment for intermediate depot d [€]
INV	Total capital investment for conversion plant k, intermediate depot d and relative equipment [€]
OF	Objective function [€]
P_k^{nom}	Design capacity of conversion facility k $[MW]$
$prod_{d,b',b,t}$	Amount of biomass type b' generated from conversion of biomass type b at intermediate depot d in each timestep t $[ton_{dry}]$
R	Revenues from methanol sales [€]
$S_{b,d,t}$	Amount of biomass type b stored at intermediate depot d in each timestep t $[ton_{dry}]$
$S_{b,i,t}^{rs}$	Amount of biomass type b roadside stored at site i in each timestep t $[ton_{dry}]$
$tr_{k,m,t}^{fuel}$	Amount of biofuel transported from conversion facility k to blending facility m at time t $[ton]$
$TC_{n,n'}$	Annual cost of transporting biomass or biofuel from node n to node n' [€]
$tr_{b,n,n',t}$	Mass of biomass feedstock (or biofuel) type b transported from node n to node n' at time t $[ton_{dry}]$

Binary Variables[u.m.]

z_d^{st}	1 if the intermediate depot d is to be established, 0 otherwise [–]
z^{cf}	1 if the conversion facility k is to be established, 0 otherwise [–]
$z_{k,t}^{op}$	1 if the conversion facility k is in operation at time t, 0 otherwise [–]

Integer Variables[u.m.]

$N_{n,n',t}^{exp}$	Number of expeditions necessary to transport the mass $tr_{b,n,n',t}$ [–]

supply chain were presented by several authors [8]: provide an overview of the literature on biomass supply chain optimization [9]; reviewed papers focusing on feedstock varieties and transportation means [7]; focused their attention on logistics activities and operations [10]; is the most recent review on the literature state of the art. Overall, Mixed Integer Linear Programming (MILP) is identified as the most widely adopted optimization technique, in virtue of its suitability to large-scale complex problems and to its capacity of providing a global certificate of optimality for the identified solution. Some of the most cited and relevant papers resorting to the MILP methodology are reviewed below.

Kim et al. [11] propose a MILP model for the optimal design of biomass supply chain networks. The algorithm yields design decisions based on aggregate yearly balances without accounting for logistics planning and feedstock storage. This simplified approach, developed also in Refs. [12,13], focuses on the location-allocation problem, identifying the location of each network node and the annual flow directed towards/from it neglecting the temporal distribution of transport streams.

Dal-Mas et al. [14] formulate a stochastic multi-year capacity planning MILP model for an ethanol supply network, addressing the uncertainty on biomass and biofuel prices. Strategic design decisions are optimized over a 10-years horizon, with a temporal resolution of two years, to limit the computational complexity.

You and Wang [15] perform the life-cycle optimization of a biomass-to-liquid supply chain, minimizing the total annualized cost and the greenhouse gas emissions over a 12-months planning horizon. The work compares distributed and centralized configurations of the processing network for biomass conversion and liquid fuel production.Zhang et al. [16] propose a MILP model to design an efficient bioethanol supply chain. They restrict their attention to a specific feedstock type (switchgrass), and include all major steps of the biomass switchgrass-to- bioethanol conversion chain.

Zhu et al. [17] propose a dynamic MILP model for the optimization of tactical and strategical decisions in the switchgrass-to-biofuel supply chain, considering both truck and train transport. The model has been later extended to address multi-feedstock supply chains [18]. The results of the study demonstrate how a multi feedstock strategy is crucial for a steady and sufficient supply of biomass [9] and is fundamental to tackle biomass seasonal availability, resulting in a relevant increase in total annual profit.

The literature review highlights how the models presented often neglect to include the optimization of logistics operations, with a monthly or even lower temporal discretization. This is essential to determine meaningful and efficient design decisions based on an optimized intra-annual management strategy. Biomass transportation and storage is furthermore significantly affected by the physical characteristics of feedstock, which must be carefully considered when characterizing logistic activities. The pre-processing of the feedstock in different supply chain nodes can be very relevant on overall costs, but the optimal integration of pre-

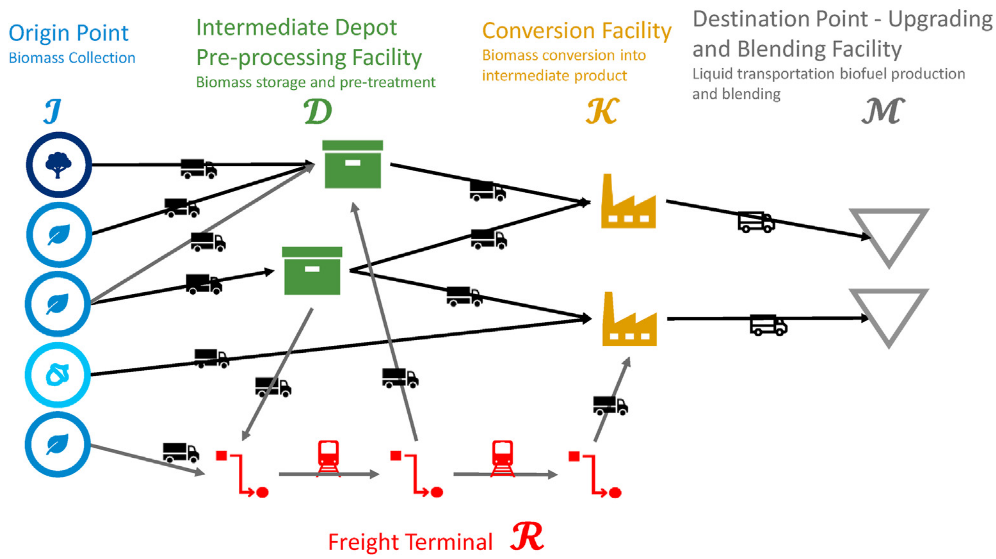


Fig. 1. ABSC superstructure.

processing facilities has been barely considered in the literature [7]. Finally, most of the studies consider only truck shipments, as analysis of large-scale biomass collection and transportation chains are very few. Few papers focus on rail transportation due to the limited need for long-distance biomass handling. In logistic network modeling, especially in large-scale networks, is crucial to include the possibility of exploiting multimodal transportation so to assess the potential benefits.

This work aims at addressing the identified limitations of existing models, developing and testing a general MILP formulation for the concurrent optimization of the biofuel supply network design and its efficient logistic management. The optimization problem is defined over a typical year of operation, with weekly temporal resolution. The proposed model sets the basis for a comprehensive and detailed supply chain optimization, addressing the highlighted gaps in the literature. Specifically, the model accounts for multi-feedstock biomass harvesting, seasonal biomass availability, multi-modal and inter-modal transportation, and includes the sizing of pre-processing facilities to modify key physical parameters of the biomass, such as specific volume and moisture content, which can affect transportation, storage, and conversion activities.

The approach is finally tested on the Italian case study, focusing on methanol production from woodchips, grape pomace, and exhausted olive pomace through a gasification-based plant. Starting from the solution of a reference scenario, a sensitivity analysis explores the effectiveness of the model and the importance of the innovative elements introduced. The paper is organized as follows: the supply chain structure and the components considered are presented in Section 2, Section 3 discusses the detailed mathematical formulation of the MILP model, while Section 4 details all the case study assumptions. Numerical results are finally shown in Section 5 and the main conclusions are drawn in Section 6.

2. Problem statement

The first step towards the mathematical optimization of the design and the management strategy of an ABSC is the definition of a superstructure representing the complexity of the system. The conceptual schematization considered in this work is depicted in Fig. 1. The proposed network structure comprises two intermediate echelons (storage and conversion facilities) and accounts for train and truck freight transport. The nodes of the network can be categorized in the following sets:

- The set of biomass origin sites ($\mathscr{I}$), where different varieties of raw feedstock are produced and collected;
- The set of candidate sites for intermediate depots ($\mathscr{D}$), where biomass can be stored and, in some cases, pre-processed;
- The set of candidate sites for biomass conversion plants ($\mathscr{K}$), where feedstock can be transformed into the target product (e.g. green methanol);
- The set of destination points ($\mathscr{M}$), to which the final product is delivered;
- The set of freight terminals ($\mathscr{R}$), where it is possible to shift from a mode of transportation to another.

It is assumed that most of the optional pre-processing activities are performed in the intermediate depots where centralized processing facilities can be adopted.

The depicted superstructure has been devised based on the production pathway envisioned in the CONVERGE Project [19], studying the production of methanol via biomass gasification plants. The aim of this European research is to develop an efficient supply chain to produce green methanol from residual biomass at costs competitive to the fossil alternative. The green methanol can be used for different purposes, which are not explored in detail and are just represented by the destination points $\mathscr{M}$. The multiple conversion steps can nevertheless be included in the formulation by adding additional echelons analogous to the set of nodes $\mathscr{K}$. The specificity of the conversion process is thus intrinsic in the constraints defining the conversion nodes, as will be discussed in Section 3.5.

Starting from the following inputs:

i. Coordinates of all network nodes (including all potential locations for storage and conversion facilities) and relevant intra-node distances
ii. Biomass availability profile throughout the year for each origin site
iii. Biomass purchasing costs and biofuel selling price

iv. Specific capital costs and operating costs for all types of conversion and storage facilities
v. Characterization of all transportation means (transportation capacities, connections distances, transportation fares)

With respect to the described supply chain superstructure, the optimization problem that minimizes the combination of annualized investments and yearly operating costs aims at determining:

i. The optimal location (among the set of available sites) for the storage and conversion structures, and their optimal size
ii. The optimal weekly schedule of logistic and conversion activities.

The problem variables to be optimized are:

i. The biomass harvesting and shipping schedule for each origin point
ii. The number, geographical location and size of all conversion facilities, and their operating schedule
iii. The number, geographical location and size of biomass intermediate depots, and their inventory level at the end of each week
iv. The selection of pre-processing activities, and the location and size of the associated facilities
v. The biomass and biofuel transportation schedule across nodes

2.1. ABSC modeling assumptions

2.1.1. Harvesting and collection of residual biomass

Harvesting is the act of moving raw material from the growing site to a more secure location, for processing, collection, or storage. Collection is the process of getting residues from that location and carry them to the other supply chain nodes. Harvesting and collection are assumed in this work to be both performed at the biomass origin sites $\mathscr{I}$.

Harvesting is necessary for biomass types such as agricultural and forestry residues. Planning the collection of forest residues may not include harvest planning, since logs harvesting is commonly decoupled from biomass collection [7]. In this work, it is assumed that after forest pruning, wood residues are stored in piles at roadside landing. This is generally done for two main reasons: (i) biomass at the roadside can be preliminarily dried and pre-treated (chipped) and, (ii) roadside landing is accessible also during winter, when snow and hard weather conditions can conversely prevent from accessing the forest and disrupt harvesting operations.

According to Ref. [7], only primary residues (e.g. forestry residues) are typically stored at the roadside after harvesting, and then collected when needed (demand-driven collection). Conversely, the collection of secondary industrial residues (such as pomace) is supply-driven: these wastes must be removed continuously from their origin point not having storage capacity: as soon as they are produced, they must be collected and sent to other nodes of the network, or discarded.

2.1.2. Storage facilities

Biomass storage can be either performed outdoor or in covered storage facilities. Outdoor storage is widely used for primary residues, as the harvested material is generally piled on-field or at the first available roadside nearby the harvesting area [20]. In this storage configuration, the stored biomass is exposed to meteorological conditions, therefore characterized by a high Moisture Content (MC), which is the parameter that mostly affects the rate of material loss and quality degradation. Conversely, covered storage requires the installation of sophisticated tensile structures or covered facilities with walls. Therefore, it is more expensive than outdoor storage, but it offers better protection and control of handled inventories. The covered storage configuration is normally adopted when erecting a dedicated storage facility, to reduce the negative effects of weather on biomass dry matter loss and quality. In this work, roadside storage is allowed for forestry residues without the need of building a dedicated facility, whereas all intermediate depots (which can be used to store any type of feedstock) are always assumed to be covered type. Storage typology selection is therefore not included in the present work, although it is compatible with the developed methodology and might be considered as part of future works.

2.1.3. Biomass pre-treatments

The thermochemical processes involved in the most common biomass-to-biofuel conversion routes typically impose requirements on the maximum feedstock MC. As a consequence, biomass drying is generally a necessary pre-process. Natural drying can be performed both at the roadside and in the intermediate depots, although it requires a long time and it is slower for open-air storages. Quicker forced drying can be performed through dedicated facilities either at the conversion plants, where waste heat can generally be exploited, or at the intermediate depots, taking into account corresponding capital and operating costs.

Other biomass pre-processes (e.g. chipping, densification, grinding) may be required or attractive to modify some physical characteristics of the biomass feedstock (e.g. shape, size, bulk density) and attain an economical benefit. In this work, we consider the options of residual wood natural drying and chipping at origin points, biomass drying (both natural and forced) at intermediate depots, eventually followed by densification process, and feedstock forced drying at conversion plant.

2.1.4. Biomass and biofuel transport

Freight transport and relevant material handling activities (e.g. loading and unloading) can account for a significant fraction of the total logistics cost since biomass has a low energy density (MJ/m^3). In this work, freight transport is assumed to be carried out trough for-hire services. Outsourcing transportation activities to a third-party logistics service provider is a common practice, especially in rail transportation.

Transportation fares comprise two contributions: a component variable with the traveled distance (Distance Variable Costs, DVC [€/(ton$_{dry}$ km)]), and a fixed component proportional to the number of journeys (Distance Fixed Cost, DFC [€/expedition [13,21]]) that accounts for material handling, loading, and unloading. Road freight transport is characterized by relatively low DFC and high DVC. Nevertheless, trucks have the enormous advantage of 'door-to-door' delivery. On the contrary, rail freight transport is characterized by high DFC and low DVC. For long distances (typically higher than 250 km) transportation by train is considered more convenient than road freight transport [22]. However, the rail infrastructure is not as capillary as the road system. Therefore, rail transportation typically requires the integration of truck hauling to and from freight terminals. When freight terminals have qualified assets, intermodal transportation1F[2] is possible. This allows a significant reduction of DFC (handling costs) compared to multimodal transportation adopted in freight terminals where is instead necessary to unload the biomass from each container and load it

[2] Intermodal transport consists of moving the entire biomass container from one means of transport to the other.

onto a different vehicle.

Since the transported volumes are high, and material handling cost is elevated, just full truckload (FTL) shipment is examined: the trucks pick up the biomass from a single node and deliver it to a unique destination, without intermediate stops in other nodes.

2.1.5. Conversion facilities

In this work, the innovative green methanol production pathway of CONVERGE Project [19] is taken as reference, because precise information about investment and operating expenditures are available. Theoretically, the product gas obtained from biomass gasification has a composition that strongly depends on the characteristics of the feedstock. Here, it is assumed that the conversion plant has the flexibility necessary to process different feedstock types since precise data about reaction stoichiometry are available just for woodchips case. Whenever available, the effect of biomass chemical characteristics on gasification reaction may be included in the model.

The Cold Gas Efficiency (CGE) variation with plant size and feedstock type is neglected. Therefore, the lower unitary cost of large-scale plants is mainly due to the economy of scale factor for the investment costs.

On the contrary, it is important to include in the analysis the CGE variation with feedstock moisture content. Biomass feedstocks with excessive moisture content reduces gasification efficiency as significant amount of energy is supplied for the water evaporation. Therefore, the biomass drying process is strongly advised and beneficial for the CGE. At the gasification plant, the feedstock is always dried through a tube bundle drier fed with saturated steam. Generally, the steam can be produced exploiting the waste heat from other processes. Nevertheless, whenever the MC of the biomass feedstock delivered to the gasification plant is particularly high (above 25%), a more intense drying process is required. In this work, it is assumed that the additional heat for drying is provided by burning some of the received biomass.

The proposed modeling approach, which is declined in the specific case of biomass gasification for methanol production, can be adapted to other types of conversion processes by adopting the correct parameters and without changing the overall ABSC structure.

2.1.6. Blending facilities

For simplicity, in this work, a definite biofuel demand profile from upgrading and blending facilities is not considered. It is assumed that upgrading and blending facilities have an infinite uptake capacity, which means that the entire biofuel production can be readily processed. This seems a reasonable assumption, since the need for liquid fuels is year-round and the quantity of biofuel produced by the ABSC is only a small fraction of the total market demand. Moreover, for this kind of plant, it can be assumed that the operating hours are as high as possible minimizing the number of stops.

Alternative approaches accounting for a demand profile, or an upper bound on the uptake capacity of the blending facility may be easily included in the model.

3. Mathematical optimization model

Mixed Integer Linear Programming (MILP) is the most used optimization technique in the literature, mainly because it can provide a certificate of global optimality for the identified solution [21]. Furthermore, for this class of formulations advanced commercial solvers, which can effectively tackle very large problems, are available. Both features are extremely important when dealing with the complex and interconnected ABSC optimal design problem, which might require to account for a very large number of nodes and transport routes [8]. However, resorting to the MILP formalization implies a limit in the system modeling, as non-linear constraints cannot be directly introduced. Nevertheless, when necessary, piecewise linear functions can be used to approximate non-linear relations, at the cost of a significant increase in computational complexity.

This section describes the proposed MILP formulation of the ABSC design optimization model. The objective function and the main constraints characterizing the nodes (harvesting point, storages, biorefineries, etc.) and the arcs (transport connections) are described. Input data defining the problem instance are included as parameters, identified with a tilde (~) to distinguish them from the optimization variables. The variables representing the mass of transported feedstocks are always expressed on a dry basis, to decouple mass balances from the drying processes. The effect of moisture is implemented by pre-defined sets of physical properties (specific to dry mass) for the various forms of biomass, according to their specific MC.

3.1. Objective function - OF

The optimization aims at minimizing the fuel production costs as combination of Annualized Investment Costs (AIC) and Annual Operating Costs (AOC), accounting also for the Revenues (R) from methanol selling (negative sign):

$$\mathrm{OF} = \min(\mathrm{AIC} + \mathrm{AOC} - \mathrm{R}) \tag{1}$$

Investments (INV) accounts for intermediate depots and conversion facilities CAPEX.

$$\mathrm{INV} = \sum_{j \in \mathscr{D} \cup \mathscr{K}} \mathrm{INV}_j \tag{2}$$

Investments are annualized according to their expected lifetime and to a discount rate, as shown in Ref. [23]:

$$\mathrm{AIC} = \frac{\tilde{dr}}{1 - \left(1 + \tilde{dr}\right)^{-\tilde{LT}}} \cdot \mathrm{INV} \tag{3}$$

where $\tilde{dr}$ is the discount rate (assumed to be 10%) and $\tilde{LT}$ is the investment lifetime (assumed to be 20 years for all investments).

AOC comprises operating costs for storages and biorefineries, biomass purchasing costs, and transportation costs.

$$\mathrm{AOC} = \sum_{j \in \mathscr{D} \cup \mathscr{K}} c_j^{O\&M} + \sum_{i \in \mathscr{I}} c_i^{feed} + \sum_{n \in \mathscr{N}} \sum_{n' \in \mathscr{N}} \mathrm{TC}_{n,n'} \tag{4}$$

Specifically, for each active arc in the ABSC superstructure and for each timestep, the Transportation Cost (TC) is computed as the sum of two contributions: a Distance Variable Cost (DVC) proportional to the transported mass and the length of the journey, and a Distance Fixed Cost (DFC) proportional to the required number of expeditions, accounting for the capacity of the considered transportation means:

$$\mathrm{TC}_{n,n'} = \sum_t \left(\sum_b \mathrm{tr}_{b,n,n',t} \cdot \tilde{d}_{n,n'} \cdot \tilde{DVC}_{n,n'} + N^{exp}_{n,n',t} \cdot \tilde{DFC}_{n,n'} \right) \quad \forall n, n' \in \mathscr{N} \tag{5}$$

where: $\mathrm{tr}_{b,n,n',t}$ is the mass of feedstock (or biofuel) *b* transported from node *n* to node *n*' at time *t*; $\tilde{d}_{n,n'}$ is the road distance (or equivalent) between nodes *n* and *n*'; $\tilde{DVC}_{n,n'}$ and $\tilde{DFC}_{n,n'}$ are the

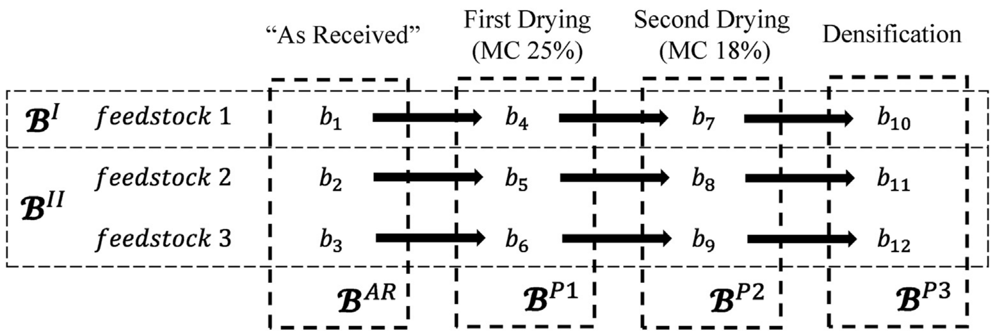


Fig. 2. Partitions of the set of biomass feedstock varieties **B**.

variable and fixed cost components for the connection between *n* and *n*'; $N^{exp}_{n,n',t}$ is the number of expeditions necessary to transport the mass $tr_{b,n,n',t}$; $\mathcal{N}$ is the set of all nodes in the ABSC superstructure. It is important to notice that each combination of *n* and *n*' implicitly determines the transportation means used to travel that arc, as any pair of nodes in the superstructure is always connected by a single means of transport (Fig. 1). Pair of nodes that are not interconnected by any transportation means are associated with infinite (very high) transportation costs $D\tilde{V}C_{n,n'}$ and $D\tilde{F}C_{n,n'}$.

$D\tilde{V}C_{n,n'}$ [€/(ton$_{dry}$ km)] is proportional to the transported mass on a dry basis, as generally done in the literature. $D\tilde{F}C_{n,n'}$ is expressed directly in [€/expedition], and accounts for the material handling. In several papers, DFC is instead expressed in [€/(ton$_{dry}$)] [9]. This choice is debatable, as the continuous adaptability of the cost item does not capture the economic incentive of saturating the transport capacity. On the contrary, the choice adopted in this work pushes towards the saturation of each shipment, and allows for the economical selection of pre-treatments that modify the physical properties of the transported biomass so as to use fewer containers and reduce handling costs.

Revenues are computed by multiplying the total methanol delivery to the consumption points by the selling price of methanol:

$$R = \sum_{t\in\mathcal{T}}\sum_{k\in\mathcal{K}}\sum_{m\in\mathcal{M}} tr^{fuel}_{k,m,t}\tilde{c}^{methanol} \tag{6}$$

3.2. Biomass pre-treatments

As mentioned, biomass feedstocks can be preprocessed before the actual conversion to biofuel at the conversion facility, to modify specific physical parameters and attain advantages in the transport or conversion activities. Some preprocessing activities, as feedstock drying, are continuous processes, meaning that the physical property progressively changes in time. Nevertheless, accounting for continuously variable MC (or in general for any variable feedstock property) would make the problem formulation non-linear. Therefore, all pre-treatments (including drying) are modeled considering discrete property variation between the pre- and post-processing feedstock conditions. In the specific case of drying, different stages are identified for each feedstock, progressively reaching lower MC thresholds. Processed biomass is modeled as an independent feedstock type, characterized by a new set of physical parameters, and generated in the nodes where the pre-treatment takes place, by consuming the original feedstock. Fig. 2 depicts how the set of all feedstock varieties $\mathcal{B}$ can be partitioned to identify the various states of a given feedstock type, and which are the available conversion routes associated with the pre-treatments.

3.3. Origin point - $\mathcal{I}$

Origin points are the nodes where the biomass is harvested and collected. Biomass availability is represented by the generation term $G_{i,b,t}$ of biomass b *"as received"* that becomes available for collection from node i in each timestep t. Origin points are modeled differently according to whether the originated biomass is a primary ($\mathcal{B}^{I}$) or a secondary ($\mathcal{B}^{II}$) residue.

As mentioned, the production of secondary residues depends on the associated agricultural processes, which planning is exogenous to the ABSC management problem. Therefore, the availability profile $\tilde{G}_{b,i,t}$ for all secondary residues *"as received"* is an input of the problem. As a given quantity of secondary residues is available it must be immediately disposed of, either by collecting it or by discarding it, without the possibility of on-site storage:

$$\sum_{n\in\mathcal{N}} tr_{b,i,n,t}\cdot \tilde{MF}_b \le \tilde{G}_{b,i,t} \qquad \forall i\in\mathcal{I}, b\in\mathcal{B}^{II}\cap\mathcal{B}^{AR}, t\in\mathcal{T} \tag{7}$$

The inequality allows collecting only a fraction of the available biomass production based on the overall profitability, while the rest is discarded.

Conversely, harvesting operations for primary forestry residues can be more flexible. Starting from the yearly availability $\tilde{H}^{tot}_{b,i}$, which represents the total mass of secondary residue *b* that can be harvested from site *i*, it is possible to define a seasonal availability that depends on the effect of weather conditions on harvesting operations.

$$\sum_{t\in\mathcal{T}_s} G_{b,i,t} \le \tilde{f}_{b,i,s}\cdot\tilde{H}^{tot}_{b,i} \qquad \forall i\in\mathcal{I}, b\in\mathcal{B}^{I}\cap\mathcal{B}^{AR}, s\in\mathcal{S} \tag{8}$$

$$\sum_{t\in\mathcal{T}} G_{b,i,t} \le \tilde{H}^{tot}_{b,i} \qquad \forall i\in\mathcal{I}, b\in\mathcal{B}^{I}\cap\mathcal{B}^{AR}$$

where $G_{b,i,t}$ is the mass of residue b harvested from site i at time t, $\tilde{f}_{b,i,s}$ the fraction of $\tilde{H}^{year}_{b,i}$ that can be harvested at most during season *s*, $\mathcal{S}$ is the set of the four seasons, and $\mathcal{T}_s$ is the set of timesteps occurring during season s. Primary forestry residues are typically produced during all months except summer. Since a precise generation profile is not available, a constraint on the maximum seasonal production is assumed. In this work, a value of 70% is assumed.

After cutting operations, wood and primary residues are left at the roadside for a preliminary drying. Biomass can be kept there for a longer period, at little expenses, providing additional flexibility for the planning of shipping operations. The amount $S^{rs}_{b,i,t}$ of biomass *b* stored at site i in each timestep t ***d***epends on harvesting and shipping operations:

$$S^{rs}_{b,i,t+1} = S^{rs}_{b,i,t} \cdot \left(1 - \tilde{dml}^{rs}_{b,s}\right) + G_{b,i,t} - \sum_{n \in \mathcal{N}} tr_{b,i,n,t} \quad \forall i \in \mathcal{I}, b \in \mathcal{B}^{I} \cap \mathcal{B}^{AR}, s \in \mathcal{S}, t \in \mathcal{T}_s \tag{9}$$

where $\tilde{dml}^{rs}_{b,s}$ ***i***s the weekly dry mass percentage loss in roadside storages for biomass type b during season *s*. $\tilde{dml}^{rs}_{b,s}$ is lower during summer and spring than during autumn and winter.

The drying period $\tilde{T}^{dry,rs}_{b}$ required by the biomass to reach an adequate MC for collection imposes a minimum delay between biomass harvesting and its collection for shipping. During the drying period, the biomass will be subject to dry mass loss. The collection delay can be imposed by limiting the maximum output from each site at time *t* based on the roadside storage content at time $t - \tilde{T}^{dry,rs}_{b}$, accounting also for the potential shipping of already dried biomass in the elapsed time:

$$S^{rs}_{b,i,t-\tilde{T}^{dry,rs}_{b}} \geq \sum_{\tau = t - \tilde{T}^{dry,rs}_{b}}^{t} \sum_{n \in \mathcal{N}} tr_{b,i,n,t} \cdot \left(1 - \tilde{dml}_{b,s}{}^{rs}\right)^{\tilde{T}^{dry,rs}_{b}} \quad \forall i \in \mathcal{I}, b \in \mathcal{B}^{I} \cap \mathcal{B}^{AR}, t \in \mathcal{T} \tag{10}$$

In this work, we assume that residues must station at the roadside landing for at least 10 weeks to reach a 30% MC. The effect of a longer stationing on moisture content is neglected.

All biomass "as received" ($b \in \mathcal{B}^{AR}$) is purchased at a biomass-specific price $\tilde{c}_b$:

$$c^{feed}_{i} = \sum_{t \in \mathcal{T}} \sum_{b \in \mathcal{B}^{AR}} \sum_{n \in \mathcal{N}} tr_{b,i,n,t} \cdot \tilde{c}_b \quad \forall i \in \mathcal{I} \tag{11}$$

Before collection, wood residues are always chipped for better handling and transportation. The purchasing price of primary residues is therefore comprehensive of the cost of chipping.

3.4. Intermediate depot -$\mathcal{D}$

Intermediate depots can store all varieties of biomass, to decouple collection from conversion. Furthermore, stationing in the storage can affect some of the feedstock's physical properties, either because of natural processes that occur over time (e.g. drying) or because the depot is equipped with pre-processing facilities, that can alter the physical nature of the biomass. A dry mass balance describes the dynamic evolution of the stored quantity in the intermediate storage *d* for each biomass type *b*:

$$S_{b,d,t+1} = S_{b,d,t} \cdot \left(1 - \tilde{dml}_b\right) + \sum_{n} tr_{b,n,d,t} - \sum_{n} tr_{b,d,n,t} - \sum_{b'} cons_{d,b,b',t} + \sum_{b'} prod_{d,b',b,t} \quad \forall d \in \mathcal{D}, b \in \mathcal{B}, t \in \mathcal{T} \tag{12}$$

The terms cons and prod account for the possibility to perform on-site biomass pre-processing, converting part of the feedstock into a new physical form. Both terms are non-negative, and the consumption variable $cons_{d,b,b',t}$ for the biomass *b* to be converted in biomass *b*′ corresponds to a generation term $prod_{d,b',b,t}$ for the processed biomass *b*′:

$$cons_{d,b,b',t} = prod_{d,b',b,t} \quad \forall d \in \mathcal{D}, b, b' \in \mathcal{B}, t \in \mathcal{T} \tag{13}$$

The compatible couples *b* and *b*′ which are connected by a pre-process are shown in Fig. 2: partitions of the set of biomass feedstock varieties **B**. For all other couples, the conversion variables are forced to zero. More complicated pre-processing schemes can be represented by properly constraining the conversion variables.

Three pre-processes can be performed in the storage sites: (i) natural drying from the initial MC down to 25%, (ii) natural drying from 25% to 18, and (iii) densification (to 0.7 ton/m^3). Similarly to what done for roadside storages, drying times $\tilde{T}^{dry,1}_{b}$ and $\tilde{T}^{dry,2}_{b}$ are defined for each drying step respectively, and each biomass type. Densification involves biomass compression, increasing its bulk density, and additionally resulting in further biomass drying up to MC 15%. The three processes are hierarchical, meaning that the completion of a pre-processing step is necessary to proceed with the following. While drying can be performed by simply stationing the biomass in the storage for a given period, densification can be performed within a timestep but requires the installation of dedicated equipment, with its associate costs.

Biomass with high MC can therefore either be shipped directly or, if subject to drying, must station in the storage until the drying period required to reach the target MC has passed. The intermediate drying threshold (MC 25%) is selected because it matches the feedstock requirements imposed by the conversion plant, so to assess whether it is more convenient natural drying at the intermediate storage or forced drying at the conversion plant. Further drying has the effect of improving biomass conversion efficiency to biofuel (paragraph 3.5), and to facilitate transport (paragraph 3.7).

Drying processes are modeled in the same way as shown for roadside storage. The required minimum residence time and the effect of dry matter loss are accounted for by imposing a limitation on the maximum converted quantity in each timestep.

$$S_{b,d,t-\tilde{T}^{dry,1}_{b}} \cdot \left(1 - \tilde{dml}_b\right)^{\tilde{T}^{dry,1}_{b}} \geq \sum_{\tau = t - \tilde{T}^{dry,1}_{b}}^{t} \sum_{b' \in \mathcal{B}^{P1}} cons_{d,b,b',\tau} \cdot \left(1 - \tilde{dml}_b\right)^{t-\tau} \quad \forall d \in \mathcal{D}, b \in \mathcal{B}^{AR}, t \in \mathcal{T} \tag{14}$$

$$S_{b,d,t-\tilde{T}^{dry,2}_{b}} \cdot \left(1 - \tilde{dml}_b\right)^{\tilde{T}^{dry,2}_{b}} \geq \sum_{\tau = t - \tilde{T}^{dry,2}_{b}}^{t} \sum_{b' \in \mathcal{B}^{P2}} cons_{d,b,b',\tau} \cdot \left(1 - \tilde{dml}_b\right)^{t-\tau} \quad \forall d \in \mathcal{D}, b \in \mathcal{B}^{P1}, t \in \mathcal{T} \tag{15}$$

$$\sum_{b' \in \mathcal{B}^{P3}} cons_{d,b,b',t} \leq S_{b,d,t} \quad \forall t \in \mathcal{T}, b \in \mathcal{B}^{P2}, d \in \mathcal{D} \tag{16}$$

The densification process can be performed in one timestep, provided that the densification facility D_d is opportunely sized:

$$\sum_{b \in \mathcal{B}^{P2}} \sum_{b' \in \mathcal{B}^{P3}} cons_{d,b,b',t} \leq D_d \quad \forall d \in \mathcal{D}, t \in \mathcal{T} \tag{17}$$

The major intermediate depot cost driver is the area necessary to store the biomass. The total area required is computed according to a room factor $\tilde{rf}_b$ that, considering the dry bulk density of each biomass species *b* and a stockpile height of 5 m [24], converts storage mass capacity [ton] in the occupied area A_d [m^2].

$$\sum_{b} \frac{S_{b,d,t}}{\tilde{rf}_b} \leq A_d \quad \forall d \in \mathcal{D}, t \in \mathcal{T} \tag{18}$$

The selection of storage sites in the available locations is controlled with binary variables (z_d^{st}). Each location is furthermore characterized by a site-specific limitation on the maximum available space.

$$0 \le A_d \le z_d^{st} \cdot \tilde{A}_d^{max} \quad \forall d \in \mathcal{D} \tag{19}$$

Investment costs comprise a fixed quota (comprehensive of paving access road, anti-fire system, etc), a quota proportional to the area, comprehensive of land and tensile structure, and the cost for possible in-site pre-treatment facilities (such as pelletizer machine for densification process):

$$INV_d = z_d^{st} \cdot \tilde{C}_d^{fix} + A_d \cdot \tilde{C}_d^{var} + D_d \cdot \tilde{C}^{INVdens} \quad \forall d \in \mathcal{D}, t \in \mathcal{T} \tag{20}$$

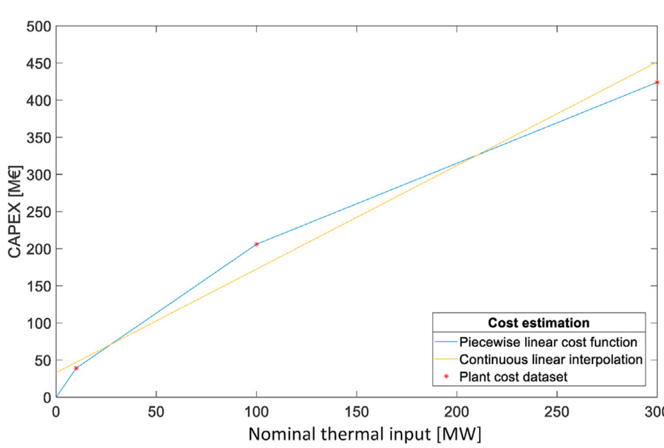
The fixed cost term $\tilde{C}_d^{fix}$ (€) is activated by the binary variable z_d^{st}, which indicates the selection of the storage site. Both the fixed $\tilde{C}_d^{fix}$ (€) and the variable cost term $\tilde{C}_d^{var}$(€/m^2) strongly depend on site geographical location. The densification machine investment cost is modeled in a simplified manner, and is obtained by multiplying the machine size (D_d) for a cost parameter $\tilde{C}^{INVdens}$ (€/ton).

Operating expenses comprise inventory carrying costs and possible payments for performing pre-treatments:

$$c_d^{opex} = \sum_{b \in \mathcal{B}} \sum_{t \in \mathcal{T}} S_{b,d,t} \cdot \tilde{icc}_b + \sum_{b \in \mathcal{B}^{P1}} \sum_{b' \in \mathcal{B}^{P2}} \sum_{t \in \mathcal{T}} cons_{d,b,b',t} \cdot \tilde{c}_d^{dry} + \sum_{b \in \mathcal{B}^{P2}} \sum_{b' \in \mathcal{B}^{P3}} \sum_{t \in \mathcal{T}} cons_{d,b,b',t} \cdot \tilde{c}^{OPEXdens} \quad \forall d \in \mathcal{D} \tag{21}$$

Inventory carrying costs ($\tilde{icc}_b$) depend on biomass type. The higher the moisture content, the higher the risk of obsolescence, the higher the need for control, the higher the inventory charge. The term $\tilde{c}_d^{dry}$ can vary site by site, and accounts for the modest O&M expenses relative to the drying process. Densification operating expenses ($\tilde{c}^{OPEXdens}$) mainly consider machine energy consumption and material handling.

In the proposed conceptual modeling, intermediate depots constitute a different layer of the supply chain compared to the conversion plants. However, in practice, some of the available sites for storage might be adjacent to the conversion plants. For these sites, moving material from the storage to the conversion plant does not require trucks, and the cost of material handling is considered only proportional to the wet mass moved. This cost component is conceptually the equivalent of DFC in arcs connected by truck or rail but is considerably lower in numerical terms since at conversion plant operations are supposed to be automated with a conveyor or a crane.



Nominal thermal input	[MW]	10	100	300
Total capital investment	[M€]	39.1	206	424

Fig. 3. Conversion plant cost estimation curves and break-point coordinates.

3.5. Conversion facility – $\mathcal{K}$

Conversion facilities produce biofuel, by consuming feedstock. As mentioned, in this work we consider a gasification plant in line with the methanol production process studied in the CONVERGE project, although alternative processes could be considered in a similar way. To operate correctly, the plant requires a feedstock with an MC lower than the acceptable threshold for processing (25%). Feedstock types that are characterized by a higher MC must be sharp dried on-site. We assume that the drying is performed by burning a fraction $burn_b$ of the received biomass, to identify the useful convertible biomass $gas_{b,k,t}$:

$$gas_{b,k,t} = \sum_n tr_{b,n,k,t} \cdot \left(1 - \tilde{dry}_b^{\%}\right) \quad \forall\ k \in \mathcal{K}, t \in \mathcal{T} \tag{22}$$

$burn_b$ is computed according to an energy balance considering the feedstock LHV and the energy necessary to evaporate the amount of water required to reach the target MC. For all biomass feedstocks that present a moisture content lower than 25% sharp drying is not required, and the parameter $\tilde{dry}_b^{\%}$ is set equal to zero.

An energy balance based on the Cold Gas Efficiency (CGE) of the conversion plant links feedstock consumption and biofuel production. As already discussed, the CGE varies depending on the MC of the biomass feedstock. Each biomass type *b* is therefore associated with a specific $\tilde{CGE}_b$, and the overall process efficiency is obtained as an averaged sum of all isolated conversion processes. The CGE value available from CONVERGE is taken as a reference and is then adjusted for each biomass type (including processed feedstock) based on the corresponding MC, according to Ref. [25].

$$\sum_b \sum_n gas_{b,k,t} \cdot \tilde{LHV}_b \cdot \tilde{CGE}_b = \sum_m tr_{k,m,t}^{fuel} \cdot \tilde{LHV}^{fuel} \quad \forall\ k \in \mathcal{K}, t \in \mathcal{T} \tag{23}$$

The conversion plant nominal capacity P_k^{nom} can be defined in terms of maximum energy input processed by the plant at full-load in one week, considering the reference heating values $\tilde{LHV}_b^{ref}$ (on a dry basis) for the biomass feedstocks $b \in \mathcal{B}$ (16).

$$\sum_b \sum_n gas_{b,k,t} \cdot \tilde{LHV}_b^{ref} \le P_k^{nom} \quad \forall\ k \in \mathcal{K}, t \in \mathcal{T} \tag{24}$$

A maximum and minimum size for each gasification plant is enforced based on the information available from the CONVERGE project. The selection of the site for the conversion plant is once more controlled by a binary variable:

$$z^{cf} \cdot \tilde{P}^{min} \le P_k^{nom} \le z^{cf} \cdot \tilde{P}^{max} \quad \forall\ k \in \mathcal{K}, t \in \mathcal{T} \tag{25}$$

When in operation, the load of the conversion plant should be between 60% and 100% of its design capacity. By including a binary operation variable $z_{k,t}^{op}$ the plant is allowed to shut down in given timesteps, to allow considering an intermittent operation.

Table 1
Biomass feedstock characteristics (as received).

	 Woodchips (from primary forestry residues)	 Grape pomace	 Olive pomace
Area of origin	Tuscany	Tuscany	Apulia
Annual biomass availability	390	19	125
[kton] (wet basis)	autumn-winter-spring	January–February	January–March
390 19 125			
Seasonality			
Energy content	11.9	8.9	24
LHV [MJ/kg] (wet basis)			
MC [%] (wt% as rec.)	35	55	12
Bulk density [kg/m3] (wet basis)	300	220	550
Purchasing cost [€/ton]	55	22	25

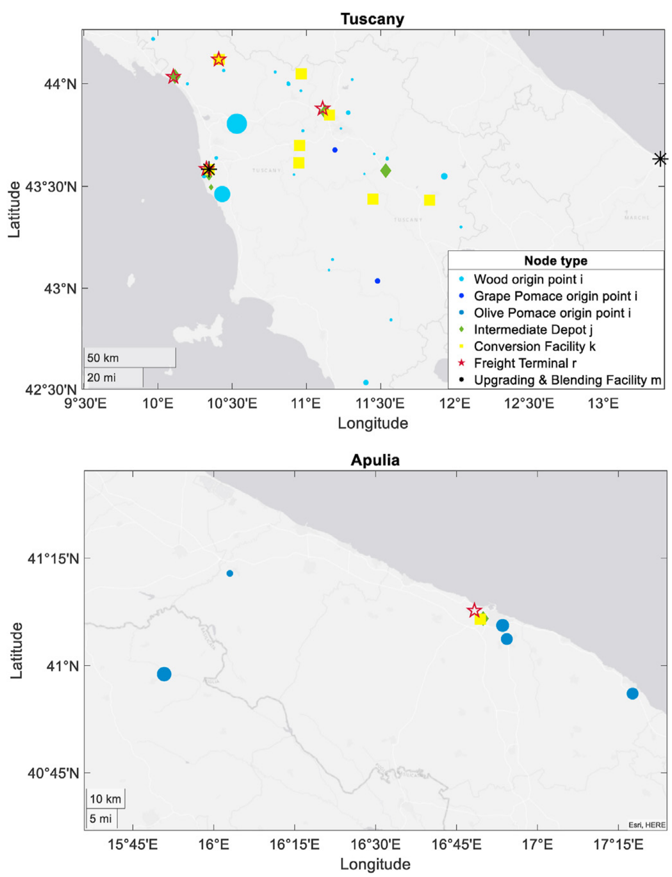


Fig. 4. Geographical distribution of nodes in Tuscany (top) and Apulia (bottom). The distance of the main cities of Tuscany (Florence, (Lat 43°43′N, Long 11°19′ E)) and Apulia (Bari, Lat 41° N, Long 17°20′E) is around 700 km both on roads and railroads.

$$P^{nom}_{k} \cdot 0.6 - \left(1 - z^{op}_{k,t}\right)\tilde{P}^{max} \leq \sum_{b}\sum_{n} gas_{b,k,t} \cdot \tilde{LHV}^{ref}_{b} \leq z^{op}_{k,t}\tilde{P}^{max} \quad \forall\ k \in \mathcal{K}, t \in \mathcal{T} \tag{26}$$

Minimum up/down times are enforced after start-up/shut down, to ensure meaningful operation profiles.

The economies of scale on the investment cost of the conversion facility is extremely relevant. Fig. 3 shows the investment cost indicated in the CONVERGE report for different sizes of conversion facilities. The specific investment cost decreases with size, introducing a non-linear effect on the plant cost (Plant cost dataset). A piecewise linear cost function is enforced to accurately evaluate the effect of economies of scale on the specific installation cost of the biorefineries, as this investment cost is a major cost item in the objective function and its incorrect characterization can substantially alter the optimal configuration identified.

The impact of different cost function approximations is discussed in Section 5.

Annual O&M are computed according to a piecewise linear cost function representing the effect of economies of scale. This piecewise curve is characterized by the same nominal capacity breakpoints as the facility investment cost curve.

3.6. Freight terminals – $\mathscr{R}$

Freight terminals are characterized by a simple dry mass balance between inbound and outbound transport fluxes:

$$\sum_{n} tr_{b,n,r,t} = \sum_{n} tr_{b,r,n,t} \quad \forall r \in \mathscr{R}, b \in \mathscr{B}, t \in \mathcal{T} \tag{27}$$

Some of the freight terminals can be enabled for intermodal transportation, meaning that the containers can be directly moved from the trucks to the trains without the need for loading/unloading biomass. Mass balance equations are the same, but handling costs are considerably lower.

3.7. Transportation – arcs

Transport equations compute the number of expeditions (and in turn the cost of transport) required for moving a given mass of feedstock or biofuel, accounting for the volume $\tilde{V}$ and weight $\tilde{W}$ capacity of each transportation means: trucks (28), tankers (trucks dedicated to biofuel transportation) (29), and train wagons (30).

$$\sum_{b \in \mathscr{B}} \left(tr_{b,n,n',t} \cdot \tilde{v}_{b}\right) \leq N^{exp}_{n,n',t} \cdot \tilde{V}^{truck} \quad \sum_{b \in \mathscr{B}} \left(tr_{b,n,n',t} \cdot \tilde{MF}_{b}\right) \leq N^{exp}_{n,n',t} \cdot \tilde{W}^{truck} \quad \forall n.n' \in \mathcal{N}, t \in \mathcal{T} \tag{28}$$

$$\sum_{b \in \mathscr{B}} \left(tr_{b,r,r',} \cdot \tilde{v}_{b}\right) \leq N^{exp}_{r,r',t} \cdot \tilde{V}^{train} \quad \sum_{b \in \mathscr{B}} \left(tr_{b,r,r',t} \cdot \tilde{MF}_{b}\right) \leq N^{exp}_{r,r',t} \cdot \tilde{W}^{train} \quad \forall\ r, r' \in\ \mathscr{R}, t \in \mathcal{T} \tag{29}$$

$$tr^{fuel}_{k,m,t}\tilde{v}_{fuel} \leq N^{exp}_{k,m,t} \cdot \tilde{V}^{tanker} tr^{fuel}_{k,m,t} \leq N^{exp}_{k,m,t} \cdot \tilde{W}^{tanker} \quad \forall\ k \in \mathcal{K}, m \in \mathscr{M}, t \in \mathcal{T} \tag{30}$$

Table 2
Economic assumption adopted within the Italian case study considered in this work. Figures are provided by Care.For.Engineering within the CONVERGE project.

Trucks		
	Variable costs	Fixed costs
Truck	0.14 [€/(km·t)] (Eq. (5))	Archs I→ J, I→ K, I→ R 110 [€/t] (Eq. (5)) Archs J↔K, J↔R 95 [€/t] (Eq. (5))
Tanker	0.12 [€/(km·t)] (Eq. (5))	120 [€/t] (Eq. (5))
Train		
Intermodal	–	250 [€/t] (Eq. (5))
Multimodal	–	350 [€/t] (Eq. (5))
Storage		
Structure	tensile structure 68 €/m^2 (Eq. (20)) purchase of land 200 €/m^2 (Eq. (20))	70000 € (Eq. (20))
Biomass treatment		
Natural drying	1 €/t (Eq. (20))	
Forced drying	15 €/t (Eq. (20))	25000 €/storage (Eq. (20))
Densification	20 €/t (Eq. (21))	10 €/t (Eq. (20))

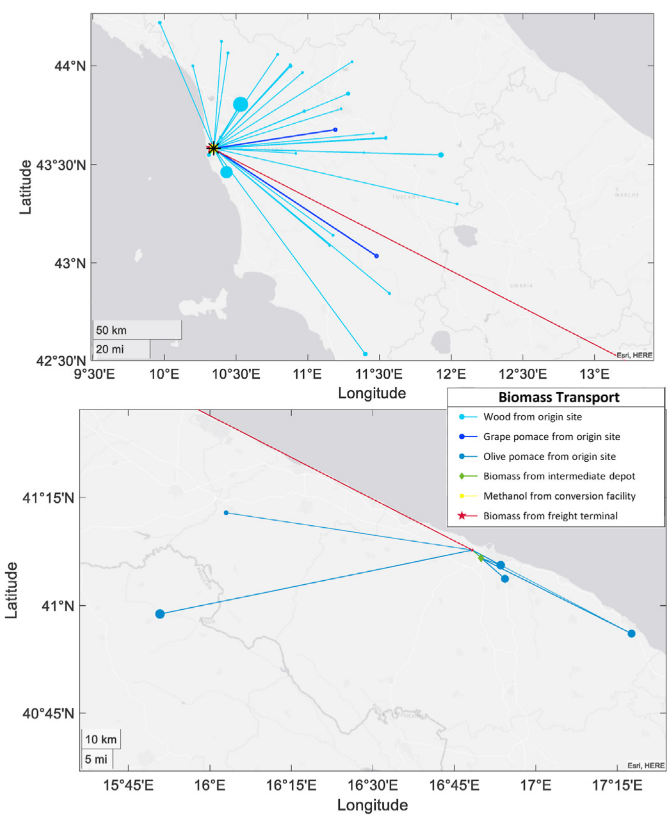


Fig. 5. Active connections in Tuscany (top) and Apulia (bottom) – S0. Distance traveled between Apulia (Bari, Lat 41° N, Long 17°20′E) and Tuscany (Livorno, Lat 43°30′N, Long 10°25′ E) by train is around 800 km.

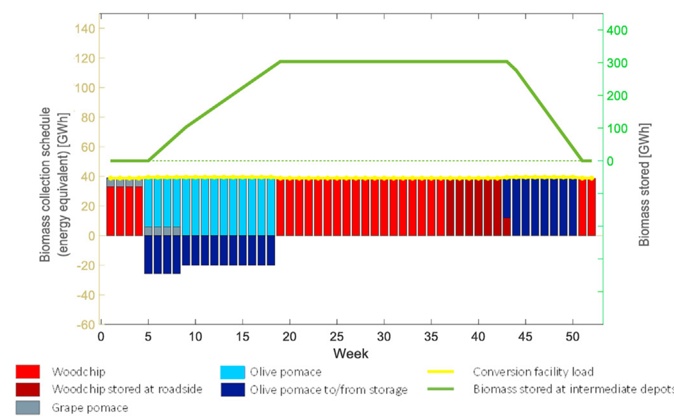


Fig. 6. Biomass weekly collection schedule. Positive bars are transported to the conversion facility and transformed in biofuel, whereas negative bars are sent to intermediate storage. The weekly load of the conversion facility (yellow line) and the profile of stored biomass energy (equivalent/green line) are also shown.

Trucks (and in first approximation train wagons too) can generally bear up to 28 ton, with an available volume of 80 m^3. Every time bulk density is lower than 'optimal' value (350 kg/m^3), less than 28 tons are transported.

4. Model application: the Italian case study

The proposed model is applied to the production of green methanol from biomass gasification, a technology under development in the CONVERGE project [26]. Nevertheless, it must be stressed that the proposed formulation can potentially be used to study the production of any type of biofuel in any geographical region, provided that the ABSC is characterized by a structure similar to the one depicted in Fig. 1.

The proposed model is applied to the optimization of a hypothetical ABSC for green methanol production in Italy. The biomass sources relevant to the Italian application are:

- residual woodchip (primary residue)
- grape pomace (secondary residue)
- exhaust olive pomace (secondary residue)

Their availability for biofuel production is particularly significant in the regions of Apulia and Tuscany: therefore, all the locations of interest for the Italian ABSC nodes are distributed in these two areas. Biomass can be transported from one region to the other by means of the available connections (railroads and highways). The accurate geographical and seasonal availability of feedstocks has been characterized through databases [27], atlases [28], and direct feedback from national stakeholders, collected through questionnaires and interviews by the Care For Engineering association [29]. The feedstocks selected for the study and their main characteristics are summarized in Table 1. The differences in physical and economical parameters, as well as the different seasonal availability of feedstocks, are the key drivers that allow exploring different aspects of the proposed modeling approach and to assess the advantages of a multi-feedstock approach to the optimal ABSC design and management.

In the two mentioned Italian regions, it is also available a

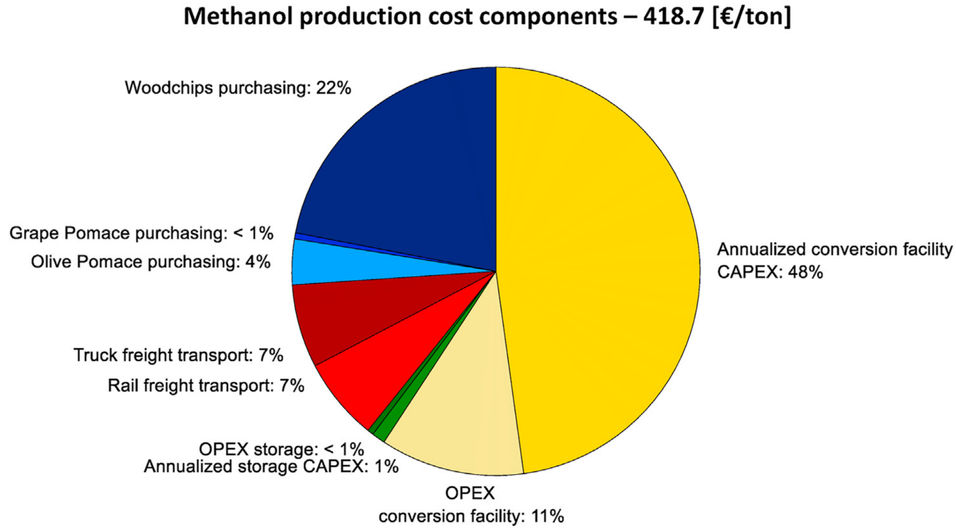


Fig. 7. Methanol production cost components – S0.

consolidated traditional fuel distribution infrastructure, constituted by upgrading and blending facilities already in operation (which can serve as destination points), and an articulated multi-modal transport system that can be used for industrial purposes2F.[3] This can facilitate the creation of the ABSC as a part of a wider system.

Fig. 4 shows the geographical location of the nodes defining the ABSC superstructure, providing the spatial complexity of the problem. The dimension of the blue dots (origin points) is proportional to their annual biomass availability. Eleven candidate locations are considered as conversion facilities (yellow squares), while six candidate locations have been identified as intermediate depots (green diamonds). The candidate sites have been selected from existing industrial districts, according to considerations on the presence of other chemical and petrochemical industries as well as on land availability.

The following input assumptions relevant to the case study are also made:

i. The optimization problem is defined over a horizon of 1 year, considered representative of the typical system operating conditions, with weekly temporal resolution;
ii. Registered offices of companies selling biomass assumed as biomass origin points;
iii. Residual wood harvesting and chipping costs are included in raw material purchasing price;
iv. Storage and pre-processing input parameters have been assumed considering previous European projects [24,30], literature references [31], experts and stakeholders publications [32] and surveys;
v. Road distances are computed using HERE maps API [33], whereas train distances are taken from documents relative to the specific railway considered (e.g. Ref. [34])
vi. The green methanol market price is assumed constant and equal to 600 €/ton.
vii. The CGE of the conversion facility is assumed equal to 57% for biomass with 25% MC, which means that 1 kg of woodchip will be converted into 0.39 kg of methanol.

[3] The high velocity high capacity railway line Trans-European Transport Network (TEN-T) [39] will swiftly connect Apulia and Tuscany by 2023.

About the cost of transportation and storage assumed in this work, they are summarized in Table 2. All these costs have been provided by Care.For.Engineering within the CONVERGE project.

5. Numerical results

Starting from the general definition of the Italian case study, the study is divided into two stages. The optimization is firstly solved considering the full set of assumptions, available sites, and transportation modes introduced (**Scenario 0,** S0). Then, a set of additional Scenarios are explored, enforcing variations in specific boundary conditions of the study to assess the impact on the optimal solution compared to S0. The model is implemented in the Matlab toolbox YALMIP [35], and solved using the commercial solver CPLEX v12.10 on a computer with Intel i7-6700HQ @ 2.60 GHz processor and 16 GB memory.

5.1. Reference scenario (S0)

The optimal solution of S0 pushes towards centralizing the biofuel production, installing one large conversion plant in Livorno (Lat 43°30′N, Long 10°25′ E, Tuscany) where all feedstocks conveyed. The conversion plant is designed to operate continuously at its nominal load throughout the year, converting all available feedstock. The seasonal availability of secondary residues is handled by installing two intermediate storages, one in Bari (Lat 41° N, Long 17°20′E, Apulia region) and one in the proximity of the conversion plant. Roadside storages and harvesting planning are instead sufficient to manage the availability of forestry residues, which are never shipped to intermediate storages despite the higher dry mass losses. The active transportation routes throughout the year are shown in Fig. 5. Connections are represented with the color of the starting node (ref. to nodes legend of Fig. 4). Cartesian distances between nodes are plotted, but actual road/rail distances have been considered in the optimization for all scenarios. Furthermore, it is important to remark that the optimization is based on a weekly analysis of the transportation fluxes, that allows a dynamic characterization of the conversion plant operating load and of the storages mass content evolution.

Fig. 6 shows the weekly biomass collection schedule, in terms of equivalent energy content, for each biomass feedstock. Positive bars indicate that the biomass is transported to the conversion facility and converted in methanol, whereas negative bars indicate that the biomass is sent to intermediate storage before being transferred to the conversion facility. The dynamic evolution of the biomass stored in intermediate depots (in terms of equivalent energy content) is represented by the green line. Primary forestry residues that are stationed at the roadside for a period longer than the required drying period are depicted with a darker color.

Since the investment for the conversion facility is the main cost item of the objective function, the optimal solution pushes towards the centralization of conversion activities, to exploit as much as possible economies of scale. The specific investment cost reduction outbalances the additional costs due to biomass transportation, especially since a train connection (considerably cheaper than trucks for long distances) can be used to convey pomace from Apulia directly to the site selected for the conversion plant in Tuscany (Livorno, Lat 43°30′N, Long 10°25′ E, Fig. 5). Furthermore, the majority of the available feedstock is constituted by woodchips (70% of total feedstock mass), which harvesting points are located in a relatively small area. Grape pomace only counts for a minor fraction of total biomass availability, as it is collected from two distilleries in Tuscany and directly transported to the conversion plant in the first eight weeks of the year. Olive pomace is instead collected in Apulia, and transported to Tuscany through the railroad connection to Livorno. An intermediate storage is installed in Apulia, to manage the seasonal availability of olive pomace which is collected during the weeks of low woodchips availability (end of winter) at a rate exceeding the conversion plant nominal load. A fraction of the olive pomace collected from olive mills (negative bars) is therefore stored (green upper line) during winter and early Spring. It is then used to supply the plant in late Fall when the availability of woodchips is reduced.

Since woodchip is always transported directly to the conversion plant without being stored in an intermediate storage, on-site sharp drying by burning a fraction of the feedstock is always necessary to attain the target MC. This behavior is due to two main reasons:

- This type of feedstock has a high MC and a low bulk density. To store woodchips in an intermediate depot would, therefore, be costly, due to the required vast storage area, and their drying process takes long.
- Direct shipment is cheaper than splitting transport to the conversion plant into two steps (from the origin site to storage and then from storage to conversion facility) because handling costs (loading and unloading) are relevant and would be paid twice. More precisely, for the case of residual wood as received, handling costs are about 5 €/ton, while sharp drying at conversion plant costs approximately 1.3 €/ton (since it is accomplished burning 2.3% in mass of wood as received, which is purchased at 55 €/ton).

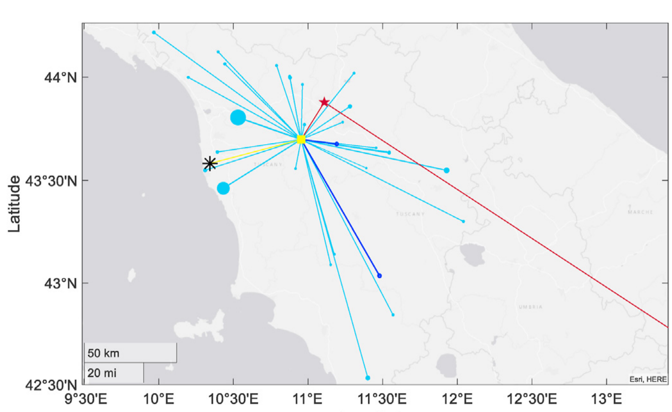


Fig. 8. Active connections – S1.

Conversely, feedstock with a relatively high bulk density such as pomace is easier and cheaper to be stored in an intermediate depot compared to wood. Moreover, its low moisture content (less than 15%), makes dry matter loss negligible.

The optimal solution tends to collect all available feedstock. In the case of woodchip, the percentage of the collected feedstock is reduced by the dry mass loss at the roadside storages. The largest fraction of this biomass loss (about 10%) occurs during the mandatory preliminary drying period, whereas the rest is due to the longer stationing of a fraction of the woodchip in the roadside storage to smooth the biomass collection profile.

Fig. 7 finally shows the impact of each cost item on the final methanol production cost, which is equal to 418 €/t. Even though this cost is very specific to the considered case, previous similar studies determined comparable methanol production costs, between 0.34 €/l (425 €/ton) [36] and 0.4 €/l (500 €/ton) [37]; moreover green methanol market price is around 600 €/ton [38]. The annualized investment cost of the conversion plant plus its operating expenditures represents the dominant component of the methanol production cost. However, it must be noted that if all available feedstock were processed in a centralized conversion facility, this cost item would be independent of the optimization process. Conversely, nearly 40% of the methanol production cost is related to the biomass supply activities, comprising purchasing, transportation, pre-treatment, and storage costs. Specifically, transportation expenditures account for nearly 37% of the total biomass supply costs, constituting the main driver for positioning the conversion plant in Livorno (Lat 43°30′N, Long 10°25′ E). As a matter of fact, Livorno is in a strategic geographical position, being close to a freight terminal and a blending facility, as well as to the largest origin points of woodchips. It is nevertheless important to highlight once again that most biomass supply cost components are strongly interconnected, and that it is not generally straightforward to identify the optimal configuration. Drying and densifying woodchips at intermediate storage may result in a reduction of required expeditions from the depots to the conversion plant as well as in an advantage in conversion efficiency that limits the need for in-site biomass burning. Finally, in a situation where the availability of biomass is geographically sparser, it might not be optimal to collect and convert all available feedstock.

5.2. Sensitivity analysis

The five scenarios explored in the sensitivity analysis introduce differential modifications with respect to the reference scenario S0, aiming at exploring the impact of changes in the boundary conditions of the study Specifically, the scenarios are defined by the following additional constraints compared to S0:

- **Scenario 1** (S1) forbids the selection of the optimal conversion plant site determined in S0 (Livorno)
- **Scenario 2** (S2) and **Scenario 3** (S3) neglect the multi-feedstock assumption, limiting the feedstock availability to woodchips (S2) and secondary residues from agro-food industries (S3)
- **Scenario 4** (S4) forbids biomass transportation by train
- **Scenario 5** (S5) forbids train transportation as S4, and additionally implements a less accurate conversion plant cost function corresponding to a continuous linear interpolation of the available dataset

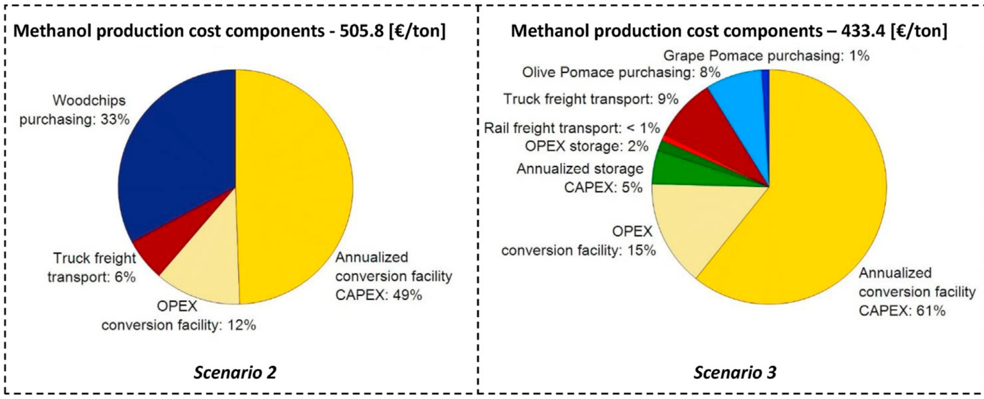


Fig. 9. Methanol production cost components – S2 (left) and S3 (right).

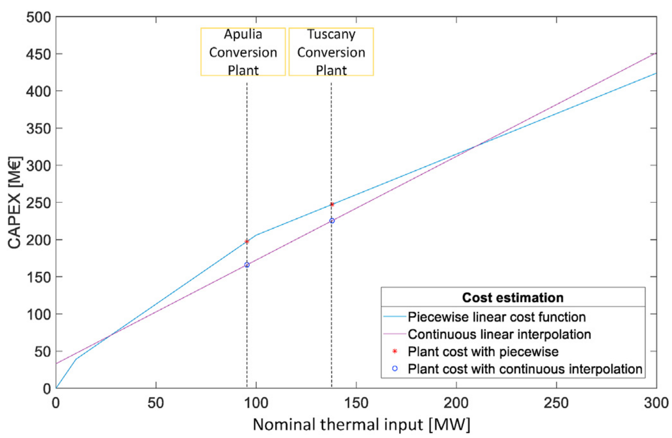


Fig. 10. Conversion facility cost curves.

The analysis of the described scenarios aims at answering the following questions:

- How does the optimal configuration change when some decisions are constrained? For instance, what happens if one of the identified sites is not available (S1) or if rail transportation is not possible (S4)? What is the impact on the methanol production cost?
- What is the value of the proposed multi-feedstock approach, compared to separately addressing the management of different feedstocks (S2 and S3)?
- What can be the impact on decisions and cost estimates of a simplified formulation of the conversion plant cost function (S5)?

5.2.1. Scenario 1

Compared to S0, S1 does not present significant changes to the study assumptions, introducing only the limitation that the optimal conversion site of Livorno cannot be selected. The optimization, therefore, converges towards an alternative solution, slightly more expensive than the reference solution S0 but based on the same general strategy: complete centralization of conversion activities in Tuscany, transportation by train of the olive pomace from Apulia to the north, full exploitation of all feedstocks availability. The optimal location alternative to Livorno is Pozzale, (Lat 43°40′N, Long 11°36′ E, around 60 km N-E of Livorno), which represents a compromise between the proximity to a freight terminal located in Florence (Lat 43°43′N, Long 11°19′ E) and to the largest woodchip origin sites (Fig. 8). The methanol is then once again delivered to the fuel upgrading and blending facility in Livorno.

Table 3
Sensitivity analysis results summary.

FEEDSTOCK MANAGEMENT		S0	S1	S2	S3	S4	S5
Biomass utilization [%]	Woodchips	89%	89%	87%	/	89%	87%
	Olive pomace	100%	100%	/	100%	100%	100%
	Grape pomace	100%	100%	/	100%	100%	100%
Biomass stationing in intermediate depots [%]	Woodchips	0%	0%	0%	/	0%	0%
	Olive pomace	36%	36%	/	74%	36%	73%
	Grape pomace	0%	0%	/	0%	0%	0%
Woodchips stored at roadside [%]		21%	21%	25%	/	21%	25%
Gasification plant capacity [MW]		234.9	234.9	132.7	100.6	234.9	Plant 1: 137.9 Plant 2: 95.4
Intermediate storage area [m^2]		28600	28600	0	58400	28600	57400
ECONOMIC ANALYSIS							
Annual revenues [M€]		12.4	12.4	6.8	5.5	12.4	12.3
Total annualized costs [M€]		8.67	8.94	5.74	4.01	9.16	*8.9* (9.4[a])
Annual biomass purchasing costs [M€]		2.26	2.26	1.88	0.36	2.26	2.24
Annual freight transport costs [M€]		1.14	1.41	0.34	0.38	1.63	0.65
Annualized intermediate depot costs [M€]		0.13	0.13	0	0.25	0.13	0.24
Annualized conversion facility costs [M€]		5.14	5.14	3.52	3.02	5.14	*5.77* (6.3[a])
Methanol production cost [€/ton]		**418.7**	**431.5**	**505.8**	**433.4**	**442.2**	***432.5*** **(462.8[a])**
Computational time [s]		104459	100376	39800	22273	7406	654

[a] Recalculated with non-linear cost function.

The seasonal biomass management strategy is analogous to what shown for S0: the olive pomace availability exceeding the nominal conversion plant capacity is stored in intermediate depots and used in late Fall to operate the conversion facility at nominal load throughout the year, whereas the seasonality of woodchips is managed through harvesting planning and roadside storages.

The methanol production cost in this scenario increases from 419 €/ton (S0) to 431 €/ton, mainly as a result of an increase in transportation costs. As can be seen in Table 2, annual freight transport cost increases from 1.14 M€ (S0) to 1.41 M€ (S1). This increase is essentially entirely due to road transport expenditures, which increases by almost 45% (from 0.57 M€ in S0 to 0.84 M€ in S1). Forcing the selection of a different conversion site, therefore, leads to an overall 2.9% cost increase, but the model is still able to identify a performing alternative configuration.

5.2.2. Scenarios 2 - 3

S2 and S3 aim at assessing the value of the multi-feedstock approach to the ABSC design and management, compared to the separate management of different feedstocks. Specifically, S2 accounts only for the presence of primary forestry residues (woodchips), whereas S3 considers only agricultural secondary residues (grapes and olives pomace).

The optimal configuration for both scenarios suggests a single conversion plant working continuously at nominal capacity throughout the year, sized to process all available feedstock. The choice of centralizing conversion activities is made easier by the regional geographical distribution of the feedstocks, with woodchips being located in Tuscany and olive pomace in Apulia. The small fraction of grape pomace produced in Tuscany is transported to Apulia by train. Feedstock seasonality is managed as seen for the other scenarios, without the need for intermediate storages to manage woodchips. The intermediate storage area for S3 is nevertheless remarkably higher than what seen in the previous scenarios, as the collection of olive pomace is concentrated in the three months of availability, but its conversion rate is constant throughout the year. Both conversion plants are smaller than in S0 due to the lower biomass availability and therefore they present higher specific investment costs, particularly so for S3 since pomaces alone account for only 30% of total biomass availability (mass fraction). The conversion facility CAPEX thus has an even higher impact on the production cost (Fig. 9) leading to higher cost of fuel than S0 for both scenarios. Specifically, the methanol production cost accounting only for woodchips (S2) is 20.8% higher than the multi-feedstock scenario.

In scenario S2, roadside storage is more broadly exploited to guarantee that the conversion plant works constantly at its nominal capacity all year round. However, storing large quantities of wood at roadside for long periods leads to the fact that in this scenario an additional 2% (respect to S0) of dry mass purchased is lost due to natural degradation. This is the case with the lowest percentage of exploitation of biomass available.

5.2.3. Scenario 4 - 5

Both S4 and S5 explore the hypothesis that rail freight transport is not available, and only truck transport is considered. This constitutes an obstacle to conversion centralization, as it is more difficult to convey to the same location the woodchip (originated in Tuscany) and the olive pomace (originated in Apulia).

Despite this additional limitation on transport, the optimal solution of S4 still adopts the same general ABSC configuration and the same feedstock management philosophy of S0 (Table 2). The optimal location selected for the single conversion plant is still Livorno due to its proximity with a blending facility, which allows to drastically cut the cost of methanol transport. However, transporting biomass from Apulia to Tuscany by truck has a significant impact on the annual freight transport expenditures (+43%), and consequently on the methanol production cost (+23.5 €/t).

Conversely, if the conversion facility cost function is modified (S5), the optimal solution shifts towards the installation of two conversion plants, one processing feedstocks from Tuscany and the other processing the olive pomace generated in Apulia. This is due to the underestimation of investment cost for low-scale plants caused by the simpler modeling of the non-linear conversion plant cost curve (Fig. 10), leading to a completely different configuration of the ABSC.

5.3. Comparative analysis

By comparing the optimal solutions identified in the various scenarios of the sensitivity analysis, it is possible to draw some general conclusions on the optimal ABSC configuration and the relative importance of specific modeling features included in the formulation. Table 3 summarizes the results detailed in the previous paragraphs, separating feedstock management decisions and associated economic performance.

As expected, the reference scenario S0 is characterized by the lowest cost, being the less constrained problem.

The increase in cost for S1 can be associated to higher transportation costs, while the overall management strategy is not affected. All the scenario with multi-feedstock centralized management (S0, S1, S4) shows the same storage dynamics, both for what concerns the intermediate depot and the percentage of woodchips stored at the roadside.

The separated management of primary and secondary residues (S2 and S3 respectively) has a significant impact on total annualized costs, mainly due to the reduced exploitation of economies of scale for the conversion facilities. The total annual revenues of case 2 and 3 lead to the same earnings of scenario 0 (this is due also to the assumption of neglecting CGE variation with plant size), while the overall cost of building two different plants and manage two separate chains is higher than base scenario since plant economies of scale are not exploited.

6. Conclusions

The objective of this paper is to define a methodology to perform the regional optimization of an Advanced Biomass Supply Chain (ABSC). The conceptual schematization of the ABSC is articulated in four echelons: biomass harvesting point, intermediate storages, conversion plants, and consumption points. Starting from the geographical availability of biomass, and from the identification of suitable sites for the installation of storage and conversion facilities, the objective of the optimization is the minimization of the fuel production costs which is the sum of operating and annualized investment costs by defining the location and size of all involved processing points, as well as the weekly schedule of biomass transportation and processing. The optimization is performed formulating a Mixed Integer Linear Programming (MILP) model, which can be effectively tackled by commercial solvers yielding the global optimal solution. The formulation accounts for the presence of multiple varieties of biomass feedstock, different means of transport, and potential feedstock pre-processing. Conversion plants are modeled based on the information available from the CONVERGE European project, studying facilities for the production of green methanol from secondary biomass. Nevertheless, the proposed optimization methodology can be easily modified to account for a different conversion process and final product.

The proposed formulation is tested on the Italian case study, for which the availability of woodchip, grape pomace, and olive pomace are characterized in the regions of Tuscany and Apulia. Despite the geographical sparsity of the biomass feedstock, the optimal solution in the reference scenario S0 pushes toward the centralization of conversion activities, installing one large plant in Tuscany which is operated continuously at maximum load throughout the year. This is due to the fact the investment and operating costs of the conversion facility account for the majority (about 60%) of the methanol production cost, and significantly benefit from economies of scales. Intermediate storages are installed only to handle the strong seasonal availability of industrial secondary residues (olive and grape pomaces), whereas the combination of harvesting planning and roadside storage grants sufficient flexibility to distribute the availability of woodchip throughout most part of the year. For the feedstocks with high Moisture Content (e.g. woodchip) sharp drying at the conversion plants results to be more convenient than natural drying in intermediate storages, since the latter would require significantly longer times, higher logistical costs, and larger storage areas. The resulting production cost for green methanol is of 418.7 €/ton.

A sensitivity analysis is then performed, defining five scenarios characterized by differential modifications to the assumptions considered in the reference scenario. The analysis allows to draw the following conclusions:

- The optimal ABSC design solution proves to be stable to perturbances, and the model allows to define an alternative near-optimal configuration even when the optimal site for the conversion plant determined in the reference scenario is made unavailable (Scenario 1).
- Synergies derived from the multi-feedstock approach significantly contribute to lower the methanol production cost, mainly exploiting the advantages related to the centralization of conversion activities. Specifically, the summation of total costs determined in Scenarios 2 and 3, which respectively account only for the presence of woodchips and pomaces, is 12.5% higher than the multi-feedstock reference scenario.
- Intermodal transportation is significantly profitable when journey distances are high. If railroad transport is forbidden (Scenario 4), the methanol production cost increases by 5% compared to the reference scenario. Conversely, for low-distances, road freight transport is always the most economical option, mainly because it allows ‘door-to-door’ delivery.
- Nonlinear cost curves, such as plant scale economies, must be reproduced by means of piece-wise linear approximations in the MILP formulation, accepting a higher computational burden. A less accurate linear representation of the investment cost function for the conversion plants (as considered in Scenario 5) reduces the computational time by one order of magnitude but leads to a suboptimal architecture for the ABSC (centralized vs decentralized). In turn, this causes an increase of 8.7% in the total costs with respect to the reference scenario once the nonlinear cost function is used to accurately evaluate the actual costs.

Future developments work will focus on overcoming the deterministic nature of the study, which assumes perfect knowledge of the biomass availability profiles. This is essential to increase the robustness of the design solution, against potential misrepresentations of the typical year of operation for the ABSC. Furthermore, the technological representation of the ABSC nodes, as well as of the available biomass pre-processes, is important to broaden the applicability of the method, and to increase the technical soundness of the design decisions. On the other hand, an increase in the complexity of the model must be followed by the adoption of advanced solution techniques for the MILP formulation, which already presents a significant computational burden for off-the-shelf commercial solvers. Finally, more case studies will be explored with the presented model.

CRediT authorship contribution statement

Luca Moretti: Conceptualization, Methodology, Software, Validation, Writing - original draft. **Mario Milani:** Resources, Software, Validation, Writing - original draft. **Giovanni Gustavo Lozza:** Writing - review & editing. **Giampaolo Manzolini:** Conceptualization, Writing - review & 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.

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