Implementing a Storage Infrastructure in a Phyto-remediated Biomass-to-biofuels Value Chain: Analysis of Benefits and Costs

IMPLEMENTING A STORAGE INFRASTRUCTURE IN A PHYTO-REMEDIATED BIOMASS-TO-BIOFUELS VALUE CHAIN: ANALYSIS OF BENEFITS AND COSTS

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ABSTRACT: Soil pollution, particularly by heavy metals, poses a significant threat in Europe, often rendering traditional remediation methods unfeasible due to the sheer volume of contaminated soil. Phytoremediation, or phytostabilization, offers an effective alternative for low-to-moderate pollution levels. The GOLD project aims to enhance this by cultivating high-yielding lignocellulosic energy crops on such soils, using the harvested biomass as feedstock for a two-step conversion pathway to produce biofuels and alcohol-based coproducts, while also collecting densified heavy metal pollutants in ashes and slags. A key challenge is securing constant feedstock for conversion plants, especially given the variable availability of polluted biomass. This study modelled the impact of a storage infrastructure on value chain logistics, examining scenarios with and without a long-term storage capacity. Results from the Italian case study demonstrated that storage significantly increases the utilization of polluted biomass and enables four times increase in pollutant recovery (from 2.24 t/yr to 8.9 t/yr). However, storage facility deployment comes at a substantial additional cost of 22-24 €/t of biomass. Despite these costs, the broader social and environmental benefits of phytoremediation, highlight the need for targeted policy measures like capital support or subsidies to enhance economic feasibility.
Keywords: biochar, bioethanol, polluted soil, supply chain, storage, value chain modelling.

1 INTRODUCTION

1.1 Phyto-stabilization as a support to EU soil pollution

Soil pollution represents one of the most pressing threats to soil resources both in Europe and globally. Approximately 2.5 million major contaminated sites are estimated to be located in the EU [1]. Among these sites, contamination by heavy metals and metalloids accounts for over 37% of cases, while it has been reported that around 6% of EU agricultural land —137,000 km²— exceeds allowable concentrations of metal(loid)s, necessitating urgent remediation efforts. Traditional soil remediation methods, like the dig-and-dump approach, are not always suitable to deal with the polluted areas due to the sheer volume of soil to be treated. An alternative strategy is the use of phytoremediation or phytostabilization of soil, which can be effective in cases where the pressure on land to be used for other purposes and/or pollution levels are low to moderate but still in excess of i.e. agricultural advisory levels. Beyond soil decontamination, cultivating crops on such polluted soils can help mitigate environmental impacts by reducing leaching and emissions of dust, which can affect nearby communities.

1.2 The GOLD project: an overview

The GOLD project aims to further enhance the phytoremediation benefits by choosing the most suitable high-yielding lignocellulosic energy crop (among Sorghum, Miscanthus, Hemp and Switchgrass) for each investigated polluted soil type and using it as a feedstock to produce biofuels. Five different test fields were investigated, from different agro-ecological zones (as reported in Figure 1) and with different types and level of contaminants in the soil.

The harvested biomass is then considered as the input for a two-step conversion pathway, that involve a first step where three alternative process pathways are considered for the production of an intermediate bioenergy carrier (IBC) - as biochar from Slow Pyrolysis [2] (SP), or torrefied pellet from torrefaction [3], [4], or Torwashed biomass from Torwash process [5], [6]. The IBC is then fed to the second process that involve Gasification and Syngas Fermentation (GSF). The final objective is two-fold: production of bioethanol and a range of alcohol-based coproducts from low ILUC feedstocks cultivated on 'degraded' lands and collection of the densified heavy metal pollutants in the ashes and slags.

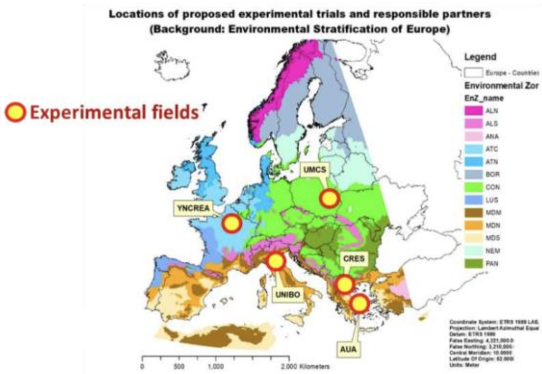

Figure 1: GOLD experimental test fields

The combination of the 5 test fields, 4 crops (and 6 different tested crop treatments) and 3 conversion pathways leads to more than 100 different Value Chains (VCs). Only 15 VC have been modeled and evaluated by Work Package 3, considering only the best-performing crop for each test field and all the three alternative conversion pathways. A comprehensive VC model was developed, including all the steps from cultivation to conversion process; an *ad-hoc* logistics model was specifically developed to cope with the two-steps conversion pathway and with the complexity of the upstream phase regarding the collection and transport of the polluted biomass.

1.3 Scope of the work

One of the main goals for the operation of a biomass conversion plant regards securing a constant feedstock input across the year; this would usually require selecting a specific mix of biomasses that would maximize their overall calendar availability. The additional constraint of optimizing pollutants uptake, posed by GOLD phytoremediation activities, requires to stick to a specific type of biomass; whenever the polluted biomass from phyto-remediation activities is unavailable, it is then necessary to use biomass from the market (e.g., agricultural residues or energy crops) as a substitute. This would guarantee operation continuity, but on the other hand would reduce the amount of phyto-stabilized/phyto-remediated land. Thus, a properly sized storage infrastructure was modelled to guarantee the use of the highest share of polluted biomass during plant operations. The current literature provides limited data on the influence of storage infrastructure on the logistics costs within a biomass-to-biofuel VC. This gap is even more pronounced in VCs that integrate phytoremediation activities: they inherently present greater logistical complexity due to the need to identify and access contaminated sites across a region, increasing the challenges of planning and cost management. To address these issues, there is a pressing need for a VC model capable of optimizing the utilization of biomass derived from polluted soils. This model would need to balance the dual objectives of maximizing the use of the polluted biomass from phyto-remediated soils while minimizing the costs associated with its collection, transport and storage, thereby supporting the involved stakeholders in achieving economic and environmental sustainability. This work builds upon prior research carried out by the authors as part of the GOLD project, offering a foundation for developing practical solutions to these challenges.

2 MATERIALS AND METHODS

The primary goal of the analysis is to ensure the operational continuity of the biomass conversion pathway, focusing specifically on a slow pyrolysis plant producing biochar as feedstock for the GSF plant. Whenever the polluted biomass is unavailable, it is assumed that biomass from the market (e.g., agricultural residues or energy crops) will be used as a substitute.

The study examines two scenarios: one with a long-term biomass storage infrastructure (approximately six months of buffer capacity) located near the slow pyrolysis plant and one without it. The VC logistics model is accounting for the density of polluted areas in the region, the calendar availability of biomass, the type of conversion plants, and their spatial distribution. Two different cases are considered for the latter: a centralized system, with the two plants located in the same industrial area, and a decentralized system, with one or more SP plants distributed regionally and a barycentrically-positioned GSF plant (see Figure 2 below).

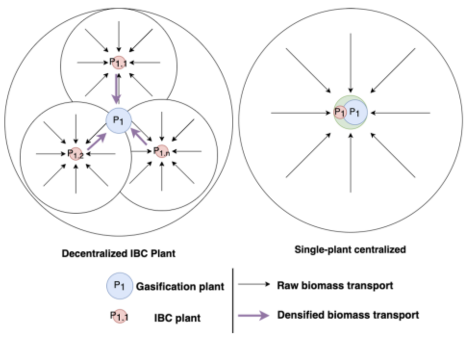

Figure 2: Centralized and decentralized scenario cases

The logistics costs structure considers loading and unloading time at the farm and at the plant, plus transport time; harvesting and baling costs are considered as part of the agricultural phase (thus not included here). Table I summarizes the main assumptions.

Table I: Main parameters used for the logistics model

Mean of transportation	truck	
Payload	25	t
Average Speed	30	km/h
Energy consumption (empty)	12	km/l
Energy consumption (full)	10	km/l
Diesel cost	1.8	€/l
Driver/machine cost	60	€/h

A storage infrastructure sizing module was implemented to calculate the Levelized Cost of Storage (LCoS) in €/t_biomass, determined by setting the Net Present Value (NPV) to zero at the end of the infrastructure's lifecycle (30 years). Three different storage sizes were considered; the logistics model defines the optimal combination for each VC. Table II reports the main techno-economical parameters used in the calculation for each storage size.

Table II: Main Techno-economical parameters of the storage infrastructure used in the model

	Small	Medium	Large
Net internal volume (m^3)	3,207	5,146	7,732
CAPEX (€/m^3)	38.9	34.2	31.9
OPEX (€/yr)		<1% CAPEX	
Lifetime		30 yrs	

The study aims to assess the benefits associated to the use of storage in terms of increased polluted biomass conversion and pollutant removal, comparing these gains to the associated cost increases. The model outputs include information on the extent of phyto-remediated areas covered by the conversion plants, the share of the annual biomass needs of the SP plant covered by polluted biomass in both scenarios (with and without storage infrastructure), as well as the logistics cost, including transportation costs for both biomass and IBCs (the latter only in the decentralized case) and LCoS (for the scenario with the storage infrastructure deployed). Literature data were collected to define the size of the storage modules and the associated costs (CAPEX and OPEX – historical inflation trends were applied to the original values) [7].

3 RESULTS

The logistics model has been applied to one of the 17 VCs studied in GOLD project: the cultivation of sorghum in polluted soils (best-performing crop both in terms of yield and pollutants uptake) in the areas of the Italian Case Study, to feed the SP+GSF conversion pathway. The two logistics schemes (Centralized and Decentralized, already described above) were considered, impacting on the travel distances and thus on the cost of logistics; the effects of the storage infrastructure were evaluated for both schemes.

Table III: Main parameters of the Italian Case Study

	Centralized	Decentralized	
Slow Pyrolysis Plants	1	7	n.
Biomass input (SP)	34.2	5.0	kt/yr
Biochar output	11.7	1.6	kt/yr
Gasifier size (input)	9.5		MW
EtOH output	3.28		kt/yr

The decentralized case sees 7 Slow Pyrolysis plants serving the GSF plant. The SP-GSF plants distance ranges between 24 km and 39 km for the no storage and the storage case, while the average radius of the area covered by a single SP plant is 8 km in the no storage case and 13 km in the storage one. The phytoremediated area increased because the storage infrastructure allows to use a 4-times higher polluted biomass quantity as input to the plant, as reported in Figure 3. This in turns allows to recover 4 times more pollutants from the soil, from 2.24 t/yr to 8.9 t/yr.

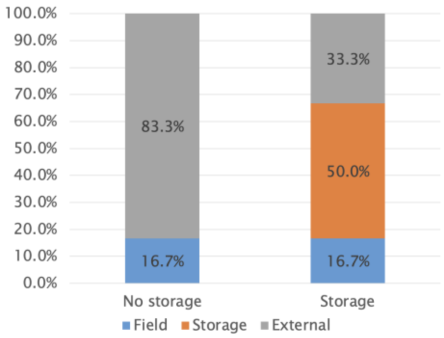

Figure 3: Centralized and decentralized scenario cases

The figures regarding biomass mix and pollutants uptake are maintained also in the Centralized Case; the average radius of the covered area is 21 km in the no storage case and 34 km in the storage one.

Figure 4 reports on the calculated logistics efforts in t/km; the lower efforts resulting for the no storage cases are related to the small biomass collection basin (only 16% of total plant needs, when compared to the 67% unlocked by the use of the storage facility). In the storage cases it can be appreciated the reduced effort related to the decentralized localization of the SP plants.

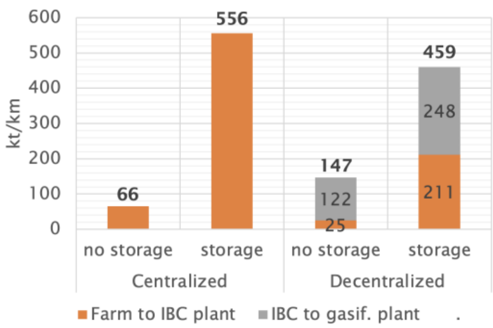

Figure 4: Centralized and decentralized scenario cases

Finally, Figure 5 reports on the cost figures for the four cases analyzed, broken down between biomass and IBC transport cost and the LCoS.

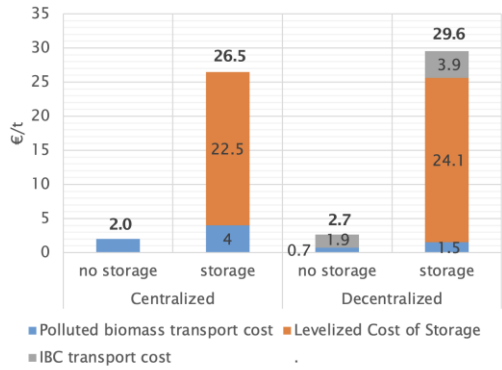

Figure 5: Centralized and decentralized scenario cases

It can be noticed that, under the assumptions made, the Centralized case is always the best performing one, even if just slightly. While the really small collection basins are the main reason in the centralized case, loading/unloading times (and related costs) may play a role in the decentralized cases. It is also evident that the increase of the polluted biomass share in the plant mix and the corresponding increase in pollutants uptake allowed by the use of the storage infrastructure comes at a quite high cost (22-24 €/t of biomass). When evaluating the price increase, additional benefits should also be considered, such as the series of social and ecosystemic benefits that phytoremediation can enable. Moreover, the market price for the externally purchased biomass should be considered as well; whenever the price difference would be higher than the LCoS, the proposed solution would be less expensive as well.

4 CONCLUSIONS

Implementing high levels of biomass utilization from phytoremediation activities involves additional costs, primarily related to the development of logistics systems including substantial storage infrastructures. The cost of storage, estimated between 22 and 24 €/t of biomass, is considerable.

However, these costs can be offset by their broader social and environmental benefits, such as reducing the extent of marginal lands and contributing to the decarbonization of the EU transport sector. Indeed, the analysed Italian Case Study shown that a storage facility would unlock significantly higher biomass availability, leading to a four-fold increase in both polluted biomass utilization and pollutant recovery (from 2.24 t/yr to 8.9 t/yr).

To support these initiatives, targeted policy measures are needed; proposed interventions include capital support for the construction of storage infrastructure, or subsidies for the procurement of polluted biomass, either partially or fully covering its purchase cost. These measures would enhance the economic feasibility of integrating phytoremediation into biomass-to-biofuel value chains, driving progress toward both environmental restoration and sustainable energy production goals.

Future optimization could involve utilizing a biomass mix to increase seasonal availability and potentially reducing storage costs, though this might decrease total heavy metal uptake.

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