PHYTOREMEDIATION OF CONTAMINATED SITES TO PRODUCE FEEDSTOCK FOR SUSTAINABLE BIOFUELS

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ABSTRACT:Biomass can play a higher role for energy availability and security in the context of decarbonisation; but land scarcity is a critical and limiting factor for the global biofuel production from energy crops. At the same time, soil pollution is widespread all over Europe, where a significant area of land is contaminated and therefore unusable for any purpose. The overall objective of the H2020 Phy2Climate project is to build the bridge between the phytoremediation of contaminated sites with the production of clean drop-in biofuels. Phytoremediation consists of employing plants in soil decontamination and its effectiveness depends on the plants ability to absorb, transfer, stabilize, concentrate and/or degrade contaminants. As the project aims for the production of high-quality drop-in biofuels like marine fuels (ISO 8217), gasoline (EN 228) and diesel (EN 590), a biorefinery concept is employed and the biorefinery processing of biomassharvested from four contaminated pilot sites in different regions of Europe and South-America is based on the Thermo-Catalytic Reforming (TCR®) technology, which combines an intermediate pyrolysis process with a subsequently catalytic reforming of the pyrolysis productsThe produced biofuels will present no Land Use Change risks, thus, the phytoremediation will decontaminate lands from a vast variety of pollutants and make the restored lands available for agriculture, while improving the overall sustainability, legal framework, and economics of the process.
Keywords: phytoremediation, energy crops, biofuel, biochar, Thermo-Catalytic Reforming (TCR®), sustainability.

1 INTRODUCTION TO PHY2CLIMATE PROJECT

The overall objective of the H2020 Phy2Climate project is to build the bridge between the phytoremediation of contaminated sites with the production of clean drop-in biofuels. These biofuels will present no Land Use Change risks, thus, the phytoremediation will decontaminate lands from a vast variety of pollutants and make the restored lands available for agriculture, while improving the overall sustainability, legal framework, and economics of the process. In this way, Phy2Climate aims at significantly contributing to the Mission Innovation Challenge for sustainable biofuel production and to almost all UN Sustainable Development Goals, as well as to the EU Biodiversity Strategy for 2030, that is part of the European Green Deal, and to the new EU Soil Strategy for 2030 adopted in 2021.

On the one hand, it is unquestionable that there is a growing demand for land, which increases tensions among the different groups of users. Land is a finite resource, and the main competitors are Feed, Food & Fuel. From the available worldwide arable land, about 71% is dedicated to animal feed, about 18% to food and only about 4% to biofuels (another 7% is for material use of crops). The multiple uttered food vs fuel debate is, actually, a food vs feed debate. However, the increasing demand for biofuels and biobased products also contributes to this tension, but in a much smaller dimension. The increasing land demand for energy crops leads to direct and indirect Land Use Change (iLUC), causing deforestation, soil erosion, loss of biodiversity and vital water resources.

On the other hand, there is a significant area of land which is contaminated and, therefore, unusable for any purpose. Even worse, the investigation, registration as "contaminated site", as well as the remediation and management of such areas are very cost-intensive, adding even more fuel to the fire.

Soil pollution degrades major ecosystem services provided by soils, which directly affects human and environmental health, and reduces food and water safety. Soil pollution is omnipresent and, according to several studies and available official numbers, a large number of contaminated sites are existing. Almost 70% of soil ecosystems in the EU are considered unhealthy and it is estimated that almost 400,000 sites will require remediation to make them safe to use. In the USA, it is estimated that contaminated sites cover about 9 Mio hectare and in China between 13 to 20 Mio.

2 PHY2CLIMATE PROJECT APPROACH AND FEATURES

Phy2Climate is a H2020 project with title “A global approach for recovery of arable land through improved phytoremediation coupled with advanced liquid biofuel production and climate friendly copper smelting process”.

In line with the EU strategy for international cooperation in research and innovation, the Phy2Climate approach synergistically interlinks the remediation of contaminated soil with the production of added value products.

Crops grown on 4 pilot sites in different regions of Europe and South America will be tested as feedstock for biomass thermo-chemical conversion through thermo-catalytic reforming (TCR®). This is an innovative technology that can produce different types of biofuels for road and shipping transport, as well as bio-coke for the metallurgical industry. In case of heavy metal contamination of the soil, the extracted metals and metalloids will be also valorised in the metal smelting process.

The overall regulatory framework for phytoremediation and drop-in biofuels conversion has also been mapped out, unfolding a series of policy and legal areas of intervention that need further scrutiny throughout the above Phy2Climate value chain.

Greenhouse Gas (GHG) reduction will be achieved by substituting fossil fuels and pet-coke, as well as by enhancing the organic carbon content in the soil (Figure1, Phy2Climate concept). The approach has a significant potential to provide a sustainable and economic solution to lower the pressure in the land-use competition.

Cultivation of energy crops on contaminated land could produce up to 137 million m^3 of drop-in liquid biofuel per year worldwide, while remediating 22 million ha of land. Additionally, such an approach wouldprovidesustainable and economic solutions to lower the pressure in land-use competition, andcontributeto GHG reduction through replacing fossil fuels with green energy and storing carbon in soils.

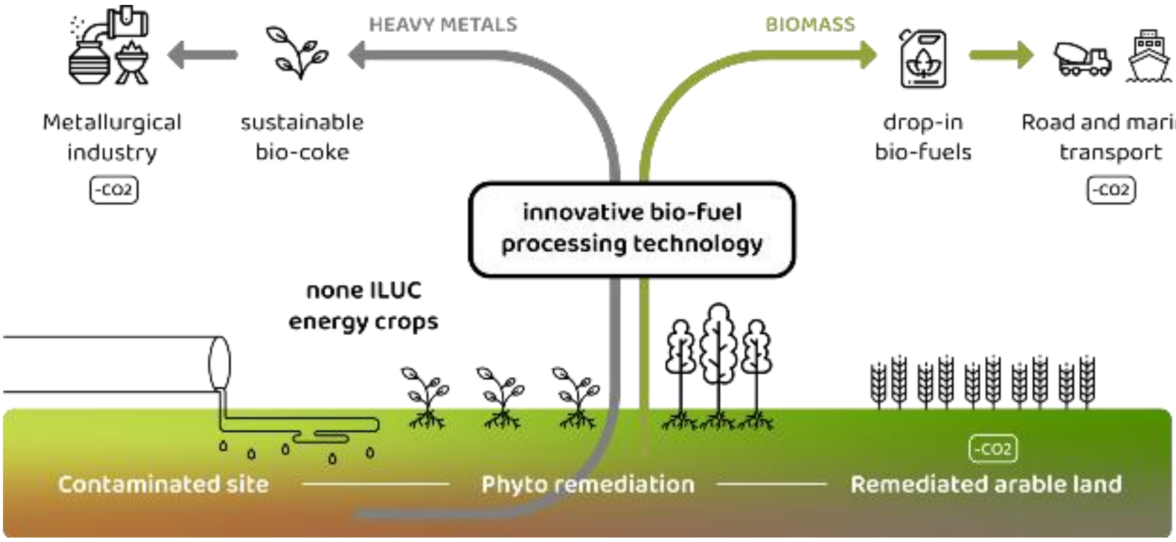

Figure 1: Phy2Climate concept. Credit: Phy2Climate project.

The project consortium has put together 16 partners from 9 countries with long-term expertise in soil remediation, phytoremediation, biofuel technologies and energy processes, environmental and social sustainability, legislative analysis, communication and dissemination, as well as business development for innovative technologies. Phy2Climate project is coordinated by ITS-Förderberatung GmbH (Austria).

Partners include: Fraunhofer UMSICHT, Aurubis AG, Pro Umwelt, TrägervereinUmwelttechnologie-Cluster Bayern e.V. (Germany), Leitat Technological Center, Litoclean, Exolum (Spain), Institute of field and Vegetable Crops - National Institute of the Republic of Serbia, University of Novi Sad Faculty of Sciences, Public Water Management Company VodeVojvodine (Serbia), Silesian University of Technology (Poland), ETA-Florence Renewable Energies (Italy), Hasselt University - Centre for Government and Law (Belgium), Instituto Nacional de TecnologíaAgropecuaria (Argentina), Biovala (Lithuania).

3 BIOMASS PRODUCTION FROM PILOT SITES

As reported by the EC JRC [1], soil contamination is the occurrence of pollutants in soil above a certainlevel causing a deterioration or loss of one or more soil functions. Also, soil contaminationcan be considered as the presence of man-made chemicals or other alteration in the naturalsoil environment. This type of contamination typically arises from the rupture of undergroundstorage tanks, application of pesticides, percolation of contaminated surface water to subsurfacestrata, leaching of wastes from landfills or direct discharge of industrial wastes to the soil.

The most common chemicals involved are petroleum hydrocarbons, solvents, pesticides, leadand other heavy metals. The occurrence of this phenomenon is correlated with the degree ofindustrialization and intensity of chemical usage.

The use of energy crops as phytoremediation species is an incipient approach that is gaininginterest in

Europe,and worldwide, as an option to valorise the harvest. A high number of energycrop species that show a good phytoremediation capacity have been identified.

The phytoremediation technology development will be driven by the leaders of each of thefour phytoremediation pilot sites in Spain (South Europe), in Serbia (Balkan region), in Lithuania(Baltic region), and in Argentina (South America). In order to guarantee awholesome approach, the pilot sites will cover different types of contaminants, climate regionsin four latitudes, different political contexts, financial and regulation schemes.

The pilot sites have carried out preliminary pot tests with the aim of optimizing the phytoremediation strategy to be applied in situ, according to each specific condition (clime, contamination source/s, and soil).

First, a harmonized pot tests experimental plan, defining a common framework in which pot tests had to be performed, was agreed upon. It provides sampling (including type and frequency of sampling and storing procedure for both soil and energy crops) and monitoring (including soil and energy crop characterisation) procedures and defines the main parameters of the experimental design such as controls, number of replicates and the duration of the experiments.

To meet the main and specific objectives, each pilot site has defined its own experimental plan to perform pot trials, based on the agreed common framework in which to conduct phytoremediation actions.

Then, the differences between pot tests in greenhouse conditions and follow-up field trials at the contaminated sites have been analysed.

In Spain, Serbia and Lithuania, the first cycle of field trials has been completed. Due to different climatic conditions, the field tests in Argentina are slightly late.

Field trials were implemented in the second year of the Phy2Climate based on the results from the pot-experiments. The implementation of field trials includes landscape and soil preparation activities, seeding and planting, setting up monitoring programme, harvesting and pelletizing.

The objective of each pilot site is to produce >40kg (dry weight) of energy crops per growing season and remediate the contaminated sites in a rate that results in <20 years for complete site remediation and its transition as arable land.

3.1 Lithuanian pilot site

The contaminated site is in mid-Lithuania in the city of Siauliai, which is contaminated with petroleum hydrocarbons (TPH). In the Soviet era, this site served as an oil base, and it was abandoned after 1990, although the last oil tanks were only removed in 2009. Since then, the site has been left unused. A primary eco-geological survey carried out in 2014 showed that the concentration of TPH in the soil samples varied from 1,566 mg kg^{-1} to 17,760 mg kg^{-1}, which, according to Lithuanian and EU legislation, exceeds the limit values up to 22 times.

Today, the territory of the former oil base falls in the water intake sanitary protection zone of Siauliai (a city with about 104,000 inhabitants as of 2023). Industrial activities in this zone are prohibited to protect the water from chemical, biological, or physical contamination. The nearest artesian well is only about 55 m away from the site, and the groundwater plate lays below the territory, at a depth of 1.1-2.2 m. Up until today, no remediation activities have been carried out at the site.

The area of the contaminated site is about 2400 m^2. Initial soil characterization was carried out in 2021. Based on the level and depth of the contamination, the site was subdivided into 3 experimental parcels. The parcel (P1) with the most shallow contamination (0-40 cm) was intended for Jerusalem artichoke (parcel size—870 m^2); the parcel (P2) with a deeper laying contamination (0-60 cm) was intended for amaranth (parcel size—310 m^2); and the parcel (P3) with the deepest contamination (up to 100 cm) was intended for the herbaceous plant mix (parcel size—1230 m^2).

The selection of plant species was based on the literature review, where it was stated that the dense and fibrous root system and the rapid growth of the selected plant species can be utilized for efficient degradation/removal of TPHs. These plant species are known to be tolerant in soil of poor quality. In addition, Jerusalem artichoke, amaranth, and the selected herbaceous plant species are common in Lithuania, so the agrotechnical means to cultivate them are also well established.

The biomass obtained during the field trials was collected, dried out, pelletized, and forwarded to one of the “Phy2Climate” partners to be further utilized in biofuel production.

Further description and data are available in the paper “Expectations and Reality of Upscaled Phytoremediation Field-Trials”.

3.2 Spanish pilot site

Spanish pilot site is located inTarragona (Cataluña), the north-eastern part of Spain, in an 800 m^2 unpaved area Exolum company installations, formerly known as Compañía Logística de Hidrocarburos S.A. (CLH).

Locally, it is based at an industrial park, next to the Francolí river and Mediterranean Sea. The land use in the study area is industrial, surrounded by other industrial facilities, roads, highways, and the railway. The site belongs to the Spanish oil pipelines´network, and it has been used to store fuel hydrocarbons and petroleum products since 1927, occupying a total surface of 100,000 m^2.

The potentially polluting substances at the site belong to the Total Petroleum Hydrocarbons (TPH). Although, currently, there is no reported active contamination source, the historical pollution detected in the subsoil derives from leakages in buried pipes (at least two registered in 1996 and 2002), accidental spills, and spills from the wagons of the old railway.

Several environmental characterizations have been carried out at the site since 1995, in which boreholes were executed and remained installed as piezometers, and soil and groundwater samples were analyzed for potentially polluting substances. Contamination by TPH was detected in both soils and groundwater, being benzene, toluene, ethylbenzene, xylenes (hereinafter, BTEX), MTBE and ETBE the major contributors. Additionally, light non-aqueous phase liquid (LNAPL) was detected in the subsoil at several areas of the site.

In the unpaved area, soil contamination by TPH presented an average concentration of 2,400 mg/kg back in 2014, when the last soil monitoring event took place. In this case, most of the hydrocarbons detected were in the diesel-range organics (C10-C28).

Initial characterization was conducted selecting 4 sampling points. Higher concentrations of Total Petroleum Hydrocarbons (TPH) were found to be P4 at the greatest depth. Accordingly, 5,486 mg TPH/kg of soil were detected during the initial characterization. P4 was followed by P2 and P3, in which concentrations between 500 and 700 mg TPH /kg of soil were found to be present in the first meter of depth. Polyaromatic hydrocarbons (PAH) were also measured and were found to be the highest at the surface of P2. Metals such as Mo, Cd, As and Zn, were found to be under the limit of detection in all SP except for P3, in which concentrations of around 170 mg/kg were detected at depths from 0.2 to 2.5 m. Unexpectedly, Pb was found to be present in all samples, regardless of the SP and depth. On the other side, S and B were rarely found.

Pilot area (800 m^2)was divided into several control (200m^2), and experimental plots (600 m^2). A rotation of two plant species was selected as phytoremediation strategy (considered bibliography and the preliminary pot test essays), using as amendments Biochar, Compost and PGPR.

A rotational crop was established in the area using Sorghum and Rapeseed, plant species. The biomass produced for the first Sorghum crop season, has exceeded the production target. Biomass was collected, reaching in the control plots, and plots with low/intermediate pollution luxuriant specimens. Total TPHs concentration in experimental plots, has been reduced by the establishment of the phytoremediation technique. In general, Polycyclic aromatic hydrocarbons have also shown a decrease in their concentration. Achieving TPH removal values of up to 86% efficiency.

Biomass was dried and pelletized. Pellets has been sent to be characterized and tested for biofuel production by WP3 partners.

3.3 Serbian pilot site

The Serbian pilot site is situated along Begej canal near Serbian-Romanian border where app. 5.900 m^3 of sediments from Begej canal is placed in a confined area. The pilot site has a total area of app. 3.800 m^2. For the Phy2Climate project the site is divided in two sections – Landfill 1 and Landfill 2 – each of approximately 1,200 m2.

Sediment that was dredged during 2017 and was moved to Landfill 1 by Public Water Management Company VodeVojvodinePWMCVV. Landfill 2 was prepared to accommodate fresh canal sediments by PWMCVV.

By 2020 the area was completely overgrown with vegetation. In February 2021 reeds and other vegetation were first removed from the site. Dredged material was transferred to Landfill 1 and then soil was slowed and levelled by the PWMCVV.

Dredging of fresh sediments from canal was finalised by the end of 2021. The pilot site was treated with herbicide (glyphosate) at the beginning of June 2021 to prevent common reed from growing. After that, pilot site was treated with triclopyr to prevent broadleaf weeds from growing (pre-sowing treatment).

For the purpose of initial monitoring Landfill 1 will be divided into 10 experimental (1-10) and 2 control (11,12) sections.

The area is contaminated mainly by metals (Cr, Cu, Zn, Pb, Cd), with high heterogeneity in soils. Organic pollutants (TPH and PAH) are present at significant level instudy area. Trace level of PCBs and some organochlorine pesticides were also detected.

Based on the results of the initial characterization and on the results of preliminary pot tests a specific phytoremediation strategy was established to be investigated in field. The selection of the most suitable plants for growing on the pilot site was done on the basis of the pot test results.

Rapeseed (*Brassica napus*) winter variety Zlatana owned by Institute of Field and Vegetable Crops was selected for seeding at the pilot site at Landfill 1 for the first growing season. Sowing of rapeseed was performed in September 2021.

At the end of the field experiment, the most intensive remediation effect occurred in the most contaminated areas. The concentration of the metal in the energy crop is generally higher in the contaminated soil, compared to the control parcel. As expected, there is no significant change in the total concentration of observed heavy metals in soil.

Generally, Bioaccumulation Factors (BAF) for Cr of the belowground biomass has significantly higher, and correspondingly Translocation Factors (TF) was <1 which indicate that the main mechanism of the Cr removal is phytostabilisation and not phytoextraction. For Cu, Zn, Pb and Cd BAF is approximately at the same level in above- and belowground biomass which is in line with TF obtained. TF decreased in the 38 weeks of sampling; however, this is mostly due the removal of seeds and fallen off leaves in the last phase of rapeseed growth. For Cu, and Zn TF > 1 is reached. For Pb and Cd TF were close to 1.The concentration of the metals in the seeds is presented at low level.

Possible leaching of contaminants to the groundwaters was achieved by the installation of piezometers upstream and downstream. Indicating that there is no current impact of the sediment landfill to the groundwater. Heavy metals have been detected at the low levels, only the arsenic contamination in the one upstream and downstream sample has exceeded the remediation threshold. However, this can be attributed to the natural geochemistry. Regarding the organic contaminants, a few polycyclic aromatic hydrocarbons and trifluralin have been detected, but at low concentrations which were below the remediation threshold level.

At the end of the field experiment, PAHs removal was about 95%. During the experiment, the concentration of all PAHs decreased. The percentage of TPH removal was in the range of 15-38% for the experimental section.

The aim to produce >40 kg (dry basis) of energy crops per growing season was achieved and exceeded (530 kg of seeds and 2,500 kg of harvest residues). Fresh biomass was spread, dried and pelletized.

3.4 Argentinian pilot site

The study area it is a relevant mining zone, exploited until the early 1970’s, located in La Planta (31º10’24,38” S, 67º52’57,26” W), San Juan, Argentina. In an arid environment which corresponds to the "Monte" phytogeographic province. Regarding geomorphology, the area is located in an extensive alluvial plain of the Bermejo River. Primary and secondary streams are often dry and only have water during certain seasons.

This area presents the appearance of an open forest in which species such as "black carob" (*Prosopis flexuosa*) and "broom" (*Bulnesia retama*) predominate.

In a first step, soil samples were taken from two sites: contaminated (Site 1) and reference site (Site 2). Main pollutants are heavy metal(loid)s. Site 1 presents a heterogenic distribution of metal(loids) in soil.

Regarding sub-plot division, two 504 m^2-plots with different contamination degree were built in the most contaminated site.

For the execution of the remediation tasks, two soil amendments were selected to be applied: compost (organic amendment) and dolomite (inorganic amendment). Compost is produced from municipal and agro-industrial waste in the city of San Juan, Argentina. It is a mixture of pruning remains, industrial tomato waste, garlic husk, cow and poultry manure, and mature compost. Dolomite is composed of 62% calcium carbonate and 26% magnesium carbonate.

Based on results obtained in pot tests, 5% compost and 18% dolomite were added in Plot 1, and only 5% compost was added in Plot 2.

The preliminary pot test was carried out exposing a variety of quinoa (“Morrillos”) to contaminated soil with amendments (compost and dolomite) and a control group (reference soil) for 45 days.

A reduction of 55.6% in seed yield (panicle size) was observed in the plants exposed to the contaminated soil with amendments. Panicle formation started before the expected time for this species, which is 65 d under normal conditions.

To stablish in field trials, five plant species were selected by their metal(loid) bioaccumulation capacity. The four native shrubs and trees selected were *Plectrocarpa tetracantha*, *Bulnesia retama*, *Larrea cuneifolia* and *Prosopis flexuosa*; and the quinoa crop (*Chenopodium quinoa*) has been used as an herbaceous annual plant to increase the phytoextraction rate of metal(loids).

According to the monitoring results, an increase in the main stem height of the species of shrubs and trees was observed. During a period of 149 d, *Bulnesia retama*, *Larrea coneifolia*, *Prosopis flexuosa* and *Plectrocarpa tetracantha* increased their size by 17.44, 19.73, 10.92 and 11.89%, respectively.

Chenopodium quinoa was sown manually in August 2022 after minimum temperatures exceeded zero degrees Celsius. Quinoa crop was monitored and harvested at the end of December 2022. Overall, there are a total of 134 plants of shrubs and trees, and 7,200 plants of the quinoa crop growing in the Argentinian Pilot Site.

The global goal of the Phy2Climate project to achieve 40 kg of dry biomass was achieved in the first growing cycle of quinoa crop (*Chenopodium quinoa*). In addition, the shrubs and trees (*Bulnesia retama*, *Larrea coneifolia*, *Prosopis flexuosa* and *Plectrocarpa tetracantha*) that were planted in early 2022, they continue growing in both plots.
As the main findings, highlight that three varieties of quinoa crop were sown in the plots in order to test their yield under field conditions. In August 2022, quinoa crop was established on soil amended with compost and dolomite. Plant height (cm) and biomass production (kg/ha) were compared between the results obtained in the experimental plots and a control field located close to the Pilot Site.

The difference in plant height and biomass production between experimental plots and control was for the differents quinoa varieties Morrillos (-37% plant heigh and -61% biomass production); Hornillos (-65% plant height and -51% biomass production); and 252 (-58% plant height and -91% biomass production).

After the first harvest, plants developed on the polluted plots showed worse growth, but they reached the biomass amount needed for the WP3 demand. All the varieties presented a reduction of 37-65% in plant height and 51-91% in biomass production.

Regarding the native shrubs and trees, they have been monitored since planting in early 2022, Plants present good growth rate and look healthy. All the plant species from Plot 2 are taller than those growing in Plot 1.

4 BIOMASS CONVERSIONAND BIOFUEL REFINEMENT

One of the biggest hurdles to produce biofuels from phytoremediation energy crops is the handling of the contaminated biomass. Fermentation processes for 1st and 2nd generation bioethanol and biogas production present the problem of contaminant spreading in high volume by-product streams such as fermentation residues or vinasse. Similarly, in state-of-the-art 1G biodiesel, the contaminants can also end up in the products and by-products such as glycerine and press cake. Otherwise, the 5hermos-chemical processes offer a better alternative to handle the contaminants present in the energy crops. By using technologies such as pyrolysis or gasification, most of the organic contaminants will be cracked and converted into simpler less hazardous or more useful molecules. As the Phy2Climate project aims for the production of high-quality biofuels like marine fuels (ISO 8217), gasoline (EN 228) and diesel (EN 590), a biorefinery concept is employed with the Thermo-catalytic process (TCR®) developed at the Fraunhofer Institute UMSICHT in Sulzbach-Rosenberg, Germany at its centre.

The TCR®-technology comprises out of an enhanced intermediate pyrolysis screw reactor combined with a subsequent reforming process[2] [3]. The principalfunction of the technology is schematically shown in the figure2.

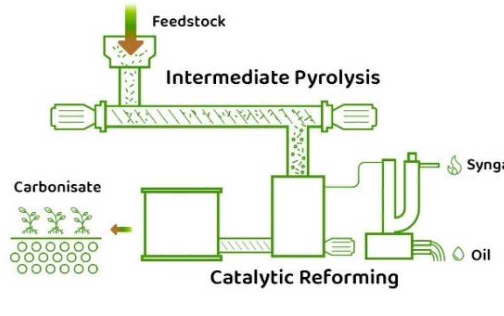

Figure 2: Schematic principle of the Thermo-Catalytic Reforming TCR®: A Platform Technology to use residues and to produce sustainable and storable energy carriers.
Credit: Fraunhofer UMSICHT.

At present, there are several TCR® plants available, ranching from lab-scale with a feed capacity of 2 kg/h until pilot scalewith a feed capacity of 500 kg/h [4]. Within the Phy2Climate project, the TCR®2 lab-scale unit shown in figure 3 is used for the conversion of the pelletized and dried biomass collected from the pilot sites (activities of WP3).

Figure 3: The lab-scale plant TCR®2 at the Fraunhofer Institute UMSICHT.
Credit: Fraunhofer UMSICHT.

The pyrolysis step occurs at moderate temperatures between 400−500 °C and a reasonable heating rate of 200−300 °C/min. As products of this pyrolysis step volatile gases and a carbon-rich fraction (further referred as carbonizate and bio-coke) are formed. Successive to the pyrolysis process, the produced volatile gases and the carbonizate are directed into a second unit, called the postreformer. Within this unit, an intensive contact between the pyrolysis gases and the carbonizate is ensured at temperatures of 500−700 °C. In this temperature regime, the carbonizate from the pyrolysis process acts as a catalyst, further refining the pyrolysis gases as well as significantly reducing tars and increasing the hydrogen content within the gas. The products of the TCR® process are therefore bio-coke containing heavy metals originating from the biomass of sites with heavy metal contamination, a condensate consisting of a bio crude oil and an aqueous phase and a hydrogen-rich syngas.

Subsequent to the conversion of the pre-treated biomass to bio-coke, bio crude oil and hydrogen-rich syngas, these intermediate products are further upgraded to high-quality energy carriers like marine fuels (ISO 8217), gasoline (EN 228) and diesel (EN 590). For this, further refinement steps are employed. The bio crude oil is refined by means of a distillation step yielding a light, a medium and a heavy oil fraction, which are thereafter evaluated for direct use as marine fuels according to ISO 8217. The aqueous phase of the TCR® process is purified using an innovative electrooxidation step while at the same time producing hydrogen [5]. The non-condensable gases of the TCR®-process serve together with the produced hydrogen from the electrooxidation of the aqueous phase as feed for a Gas-to-Liquid (GtL) process in order to produce liquid hydrocarbons. In a further step, the produced hydrocarbons from the GtL plant are separated based on their boiling point yielding a gasoline and a diesel fraction. These fractions are eventually analysed with regards to their chemical properties and compared to international diesel and gasoline standards. The produced bio-coke is evaluated for the substitution of petroleum-based coke in the copper smelting industry without further refinement. The whole biorefinery concept as it is employed in the Phy2Climate project is summarized in figure 4.

Further description and data are available in the paper “Development and Commissioning of an Innovative Biorefinery for the Conversion of Contaminated Biomass Into High-quality Energy Carriers”.

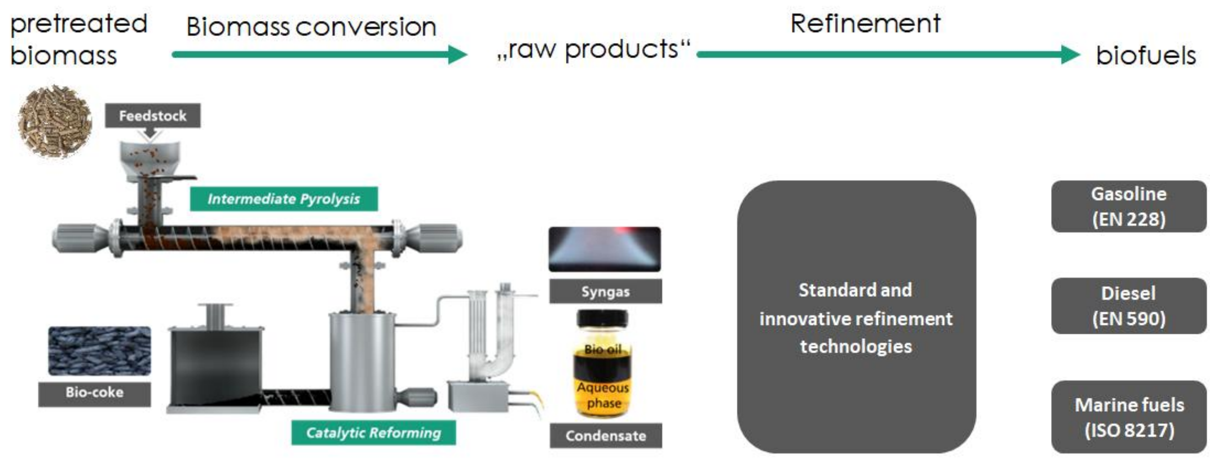

Figure 4: Concept of biorefinery within the Phy2Climateproject.
Credit: Fraunhofer UMSICHT.

5 ENVIRONMENTAL IMPACT

The Phy2Climate approach aims at becoming anenvironmental impact role model by combining different complementing processes with apositive environmental effect. The phytoremediation of contaminated sites in 4 regions all overthe world is combined with innovative biomass processing technologies to produce clean drop-inbiofuels for the road and shipping transport as well as bio-coke as substitution of petroleumcoke (pet-coke) in the metallurgical industry. GHG reduction should be achievedby substituting fossil fuels and pet-coke as well as by enhancing the organic carbon contentin the soil. This overall picture of Phy2Climate approach seems very promising, but to be ableto fully and independently judge the sustainability of the technology, its environmental impacthas to be analysed in terms of the whole life cycle.

To be able to judge the sustainability aspects of the technology, its environmental impact has to be analyzed in terms of the whole life cycle. The Life Cycle Assessment(LCA) is a standardizedtool, however, each technology deserves an individual approach. The analysis of a multi-effectsystem with variable feedstock scenarios is, indeed, a complex and challenging task. The SilesianUniversity of Technology (SUT) prepared the methodology applied for the purpose of Life Cycle Assessment and the preliminary results of the Life Cycle Inventory phase. The whole process has to be disassembled into factors and the whole LCA frameworkfor this case has to be built. First steps, now undergoing, are to initially define the goal andscope, system boundaries, functional units, process and reference flows, and data collection rules.LCA is an iterative process and the assumptions can be, luckily, continuously revised the moredata appears.

Primary data are being collected from four pilot phytoremediation sites and from a biorefinery. In cases when the primary data turns out to be insufficient, it will be supplemented with secondary data.

6 SOCIAL SUSTAINABILITY

In order to prove that the technology meets the sustainability principles, it is inevitable to find a balance between environmental, economic and social aspects. It is widely acknowledged that the new energy technologyproject does not depend on technological advances and favourable economic conditions alone. It is important to recognize the perceptions of social acceptance of new energy technologies in order to better implement and develop suchprojects.

One of the aims of the Phy2Climate project is to develop a practical toolbox for project managers to deal with societal acceptance issues in the development of a new approach. How does societal acceptance emerge (or does not) in new energy projects and what are the underlying mechanisms? In this project, the social acceptance of the Phy2Climate approach is discussed based on three different dimensions of social acceptance – socio-political, community, and market acceptance. All three are sometimes interdependent categories of social acceptance. SUT-team is now preparing the methodology by defining the target groups and survey thematic fields.In the socio-political dimension, opinion of general public, stakeholder, and policy makers are being considered. The aspects of public acceptance with focus on policy makers will be analysed relying on expertise of the Work Package (WP) 6 leader, Hasselt University, while the stakeholders are recognized by the WP5 leader, ITS. The second dimension of social acceptance – community acceptance will deal with controversies at the local level. Three main factors have revealed for community acceptance, namely, procedural justice, distributional justice and community trust on information. The final aspect of social acceptance is the market acceptance that refers to the adoption of a new technology in a market or the process by which market parties adopt and support the energy innovation. The market acceptance aspects will be revealed with a close cooperation with the WP5 leader, ITS.

7 REGULATORY ISSUESAND OPPORTUNITIES FORPHYTOREMEDIATIONANDRECOVERY OF OUTPUTMATERIALS IN THE EU

The complex and innovative processes deployed by Phy2Climate brings about several importantlegal and regulatory issues that arise on every step down the chain. Thus, Phy2Climate isdeveloping legal expertise in order to allow for a smooth realization of the overall project and informfuture policy-making in the EU and elsewhere. WP6 appraises all legal bottlenecks arisingthroughout the implementation of the project by, first, cataloguing potential legal and regulatoryissues throughout the entire value-chain in different legal systems (within and outside theEU in a selection of countries), and by mapping potential edges de lege lata and de lege ferenda.

The project will, thus, analyse the interplays among the identified relevant fields of law to pinpointthe relevant legal issues arising in connection to every step of the value chain, while enshriningalso potential legal and regulatory best practices and solutions as implemented in thedomestic legal setups analysed.

Phy2Climate aims to significantly contribute to several flagship EU policies under the European Green Deal(EGD) and to implement up to 16 UN 2030 Sustainable Development Goals.

The Phy2Climate innovative value chain can be analytically broken down into at least six key elements, which flowfrom the preparation and implementation of phytoremediation strategies in contaminated sites (Steps 1-3) to theconversion of the phytoremediation output materials into advanced biofuels (Steps 4-6) as represented in figure 5.

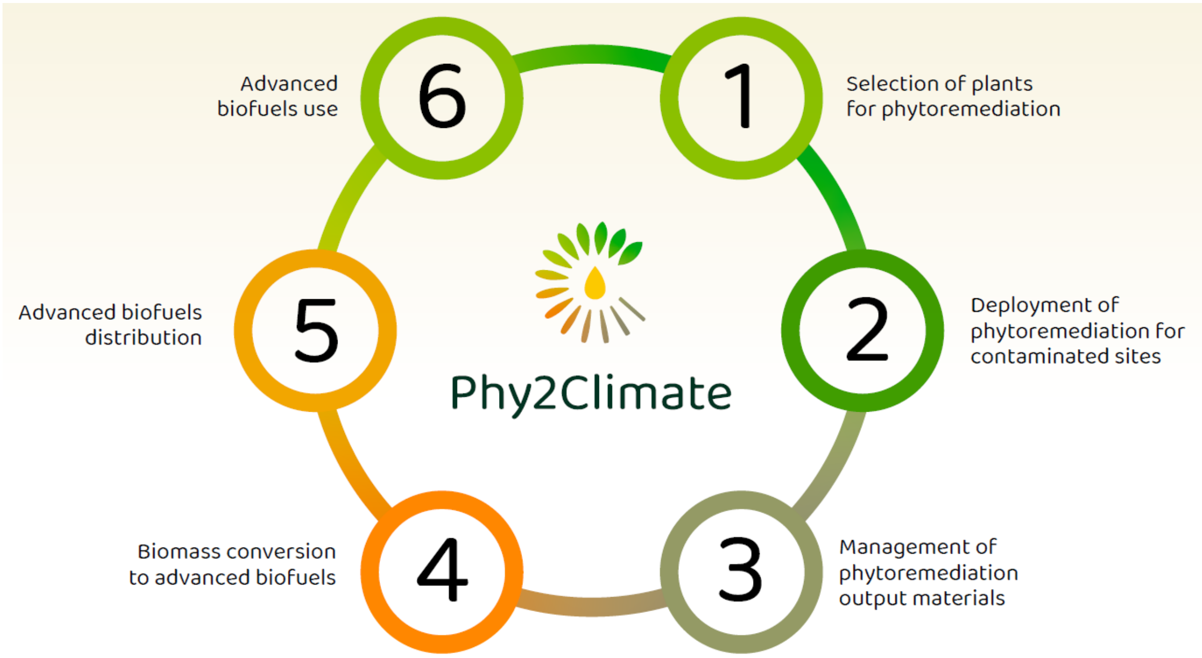

Figure 5: The Phy2Climate innovative value chain can be analytically broken down into at least six key elements. Credit: Phy2Climate project.

Every step across the above value chain, however, faces specific legal roadblocks related to either the institutionalfragmentation, the lack of comprehensive legal frameworks, silos-thinking and policy-making, or technical barriersin the regulatory framework.

A stakeholder survey conducted for the purposes of the project has highlighted the following main legal roadblocksthroughout the uptake of the above value chain. Stakeholders were requested to rank different legal barriersbased on the following expected magnitude:

Major barrier: A remarkable legal roadblock that must be overcome in the short-term and requires pointedintervention by national and/or EU legislator. “Lack of harmonised EU legislation on soil managementand remediation, including soil quality standard andremediation targets” was the most ranked barrier.

Moderate barrier: A relevant legal issue that requiresfurther attention as it could hamper the sound deployment
of phytoremediation or production of advanced biofuels. “Lack of proper inclusion of social and environmental benefits in EU’s sustainability criteria for biofuelswith regard to indirect Land Use Change (iLUC)” was the most ranked barrier.

Minor barrier: A legal pitfall that nevertheless does not impinge on the viability of the value chain and can beovercome without far-reaching regulatory interventions.“Regulatory limitations to the use of certain fertilizers to harvest plants for phytoremediation” and “Legal limitations (or bans) to the use of GMO for soil remediation” were the most ranked barriers.

Within the above-mentioned areas of law that provide relevant legal framework for the Phy2Climate approach, wehave pinpointed specific legal issues, which require further investigation and, eventually, a regulatory interventionat the EU and Member States domestic level.

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9 ACKNOWLEDGEMENTS

Phy2Climate project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°101006912.

10 LOGO SPACE