Phytoremediation driven energy crops production on heavy metal degraded areas as local energy carrier

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# Report on cost effectiveness and environmental benefits of phytoremediation driven energy crops production

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| B | Bytom (Polish site) |
| Cd | cadmium |
| d.w. | dry weight |
| HM | heavy metal(s) |
| HMC | heavy metal contaminated |
| L | Leipzig (German site) |
| *MG* | *Miscanthus giganteus* |
| Pb | lead |
| *PV* | *Panicum virgatum* |
| SD | standard deviation |
| *SH* | *Sida hermaphrodita* |
| *SP* | *Spartina pectinata* |
| Zn | zinc |

# Report on cost effectiveness and environmental benefits of phytoremediation driven energy crops production

## OVERVIEW OF THE TECHNICAL DOCUMENT

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This deliverable includes an overview about results produced by IETU and VITA 34 after 3 growing seasons for biomass yield and heavy metal extraction implemented under the Phyto2Energy project. They allow to lead to a recommendation for full scale remediation scenario incl. cost analysis. Recommendation refers to heavy metal contaminated (HMC) sites comparable to tested sites in Poland and Germany. Further the document provides information about further plant species applicable for phytoremediation of HMC sites.

## INTRODUCTION

Heavy metal (HM) exposure to the environment is a serious problem, as HM are non-biodegradable and potentially accumulating in the food chain, with a significant impact on human health.
The cultivation of HMC sites for growing of foodstuffs is officially permitted by law. In view of the increased demand of land by humans and additional loss of fertile soil as a result of climate change, the reintroduction of HMC sites into the agricultural production cycle is to be pursued.
For the rehabilitation of HMC sites soil exchange is a common and widely used tool. The process is indeed very effective but also very complex, whereby the treatment and dumping of the soil is very cost-intensive. For treatment of soil chemical processes are applied commonly (e.g. soil washing by high pressure method) that provide wastes, which are very expensive to dispose of. A mere dumping of the contaminated soil does not correspond to the principles of a responsibly rehabilitation strategy, but instead transfers the contamination to another site.
In contrast to conventional remediation strategies like soil exchange, an environmentally friendly and at the same time cost-effective remediation strategy is gaining importance increasingly - phytoremediation. Thereby plants are cultivated on contaminated soils for extraction and/or stabilization of pollutants.
In the project Phyto2Erergy, the use of four selected plants for the rehabilitation of HMC soils at two sites were tested. One site was located in Bytom in Poland and poses a typical post industrial site. The other site was located in Germany close to the city of Leipzig that was used formerly as a sewage dewatering plant. On both sites two identical field trials were installed whereon *Miscanthus x gigantheus* (MG), *Panicum virgatum* (switchgrass, PV), *Spartina pectinata* (cordgras, SP) and *Sida hermaphrodita* (Virginia mallow, SH) were tested for HM extraction (Pb, Cd, Zn) and biomass yield. Plants were tested in their original state, but also treated with NPK and a special inoculum, promoting HM uptake of plants by stimulating microbial consortia in soil.
Within the project the plants potential as local energy carriers were investigated. Thus, farmers will have the opportunity to achieve a financial benefit through the production of energy during rehabilitation of HCM sites.

## OVERVIEW OF PROJECTS RESULTS

### Establishment of field experiment by IETU and VITA 34

For establishment of field experiment a trial on Polish and on German site was established respectively by IETU and VITA 34 in 2014. The Polish test site was located in the peripheral area of Bytom, close to Katowice, in the vicinity to a former lead/zinc/cadmium works comprising ore mining, enriching and smelting facilities. The metallurgical complex was in operation for more than 100 years and contributed significantly to pollution of local soils. Since the last 30 years the land is used for agriculture, cultivating grain crops, especially wheat.

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The German test site was located close to the city Leipzig and was used as a sewage dewatering plant between 1952 and 1990. Sewage from a waste water treatment plant of Leipzig was there disposed for dewatering resulting in a contamination inter alia with HM. After the closure of the dewatering plant about 650,000 t of sewage sludge remained in several basins. After 1990 remediation of the facility was started using phytoremediation techniques. Nowadays the remediation process poses one of the most extensive and best monitored phytoremediation project in Europe.

The field trials were installed in spring 2014. In the following, the installation is exemplarily presented for the German side. At first the field trial was demarcated and staked out (figure 1). Afterwards weed control was conducted by spraying 60 - 80 ml/m² of the product “Round up” (figure 2). Subsequent plants were mowed and plant material was disposed. The bare soil was then tilled with a small mill cutter (figure 3). The preparation of plant beds was accomplished by second spraying of “Round up” in the same dose as described above (figure 4).

**Figure 1:** demarcation and staking out of field experiment

**Figure 2:** weed control

**Figure 3:** tilling by mill cutter

**Figure 4:** accomplished plant beds after second weed control

On plots with 16 m² each pre-cultivated seedlings of MG, PV, SH and SP were planted. Each plot (specie) depicted either control, or was treated with NPK fertilizer or with an inoculum. The plots were harvested after every vegetation season in winter for chemical analysis and gasification tests of plant material. Additionally, several soil samples and individual samples of plants were taken during experiment for analysis.

## Results after three years of field experiment

For coping with entire value added chain not only HM extraction but biomass yield is of basic interest as harvested biomass is projected for gasification and energy production.

Within three years of experiment biomass yield increased continuously for each vegetation season. On Polish site highest yields were obtained in winter 2017 for *Miscanthus x gigantheus* and *Spartina pectinata*. On German site yields were significantly lower in winter 2017, whereas *Miscanthus x gigantheus* and *Sida hermaphrodita* provided highest yields.

Based on the results of HM uptake by plants and yield of biomass, the extraction of HM per hectare was calculated. Results between Polish and German site differed significantly, as uptake of Pb on Polish site is in front. Reasons therefore could be ascribed to differences in bioavailability of Pb in soil and plant growth, as Polish plants achieved higher biomass yield.

Maximum Pb extraction was accomplished on Polsi site for *Spartina pectinata* treated with NPK and on control plot. On German site maximum Pb extraction was also calculated for *Spartina pectinata* treated with NPK and with inoculum I.

Polish uptake of Cd is significantly higher compared to German site, whereas highest extraction was calculated for second vegetation season with maximum for *Sida hermaphrodita* treated with inoculum I. On German site *Miscanthus x gigantheus* provided highest extraction of Cd when plants were treated with inoculum I.

After second vegetation season extraction of Zn is almost equal distributed on both sites. Thereby *Miscanthus x gigantheus* treated with inoculum I provided highest extraction of Zn.

## Recommendation on full scale remediation

After three years of experience the project team is now able to recommend on sure remediation strategies for HMC sites that are comparable to the tested site in Poland and Germany. The recommendations base on both, high biomass yield and high HM extraction.
For the Polish HMC site (and a comparable to Polish site) a full scale remediation with *Spartina pectinata* treated with NPK fertilizer and/or with *Miscanthus x giganteus* treated with inoculum is recommended. Yields and calculated MH extraction per year is included in table 1.

Table 1: recommendation on full scale remediation for Polish site with yield and HM extraction

| HM | species, treatment | yield [t/ha*a] | HM extraction [kg/ha*a] |
|---|---|---|---|
| Lead | *Spartina pectinata*, NPK | 33.9 | 1.05 |
| Cadmium | *Miscanthus x giganteus*, inoculum I | 33.3 | 0.02 |
| Zinc | | | 3.51 |

For Pb contaminated site a planting of *Spartina pectinata* treated with NPK would lead to a yield of 33.9 t/ha*a with a Pb extraction of 1.05 kg/ha*a. By planting *Miscanthus x giganteus* treated with inoculum on Cd and Zn contaminated area a yield of 33.3 t/ha*a was calculated for each plant specie. This will lead to a Cd extraction of 0.02 kg/ha*a and a Zn extraction of 3.51 kg/ha*a.

In table 2 full scale remediation scenario for the German HMC site (and a comparable to German site) is included. Thus, project results led to conclusion that a cultivation of *Miscanthus x giganteus* treated with inoculum will reach to 17.7 t/ha*a biomass. Thereby 0.02 kg/ha*a Pb, 0.01 kg/ha*a Cd and 2.36 kg/ha*a Cd will be extracted from HMC soil.

Table 2: recommendation on full scale remediation for German site with yield and HM extraction

| HM | species, treatment | yield [t/ha*a] | HM extraction [kg/ha*a] |
|---|---|---|---|
| Lead | *Miscanthus x giganteus*, inoculum I | 17.7 | 0.02 |
| Cadmium | | | 0.01 |

| Zinc | | | 2.36 |
|---|---|---|---|

The reasons for differences in yield and HM extraction between both sites arose from variable site conditions. Soil properties and climatic conditions affect significantly on plant growth and performance in view to HM extraction. For this reason an eligible and comprehensive project management for successful planning of full scale remediation projects for further HMC sites is indispensable.

## Assessment of the environmental added value

In table 3 a rating based on several criteria between the applied environmental technology `phytoextraction` and relevant alternatives, like physical/chemical processes and off site treatments, are represented to compare all usual methods. An environmental technology is defined as a technology, which provides an environmental added value compared to relevant alternatives and therefore, each item of information will be 'scored' on the following basis:

- Major negative differences in comparison to the relevant alternative (--)
- Significant negative differences in comparison to the relevant alternative (-)
- No significant differences in comparison to the relevant alternative (0)
- Significant positive differences in comparison to the relevant alternative (+)
- Major positive differences in comparison to the relevant alternative (++)

Issues that should be taken into consideration are included, but are not limited to:

- the degree of risk posed to human health, the environment and environmental values and whether actual or potential harm is occurring;
- the nature and extent of contamination and the potential for further contaminant migration (for example, is a groundwater plume increasing, stable or contracting in extent?);
- the results and reliability of contaminant fate and transport modelling;
- the acceptability of time frames to stakeholders, particularly the owners of affected sites; and
- intergenerational equity (remediation should be completed in a time frame that ensures the polluter bears the cost rather than future generations).

For a final overview all positive and negative factors are sum up and best variant will be evaluated.

Table 3: Comparison of environmental technology "Phytoextraction" as the applied method to three different alternatives to assess the environmental added value

| | Applied method | Relevant alternatives | | |
|---|---|---|---|---|
| | ***in situ* Phytoextraction** | *on site* physical/chemical process (soil washing) | *on site* by consolidation and isolation with a barrier | *off site* treatment of excavated soil |
| Emission of pollutants to air | + | - | | |
| | 0 | | 0 | |
| | + | | | - |
| Emission of pollutants to water | + | - | | |
| | - | | 0 | |
| | - | | | 0 |
| Emission of pollutants to soil | ++ | - | | |
| | 0 | | -- | |
| | - | | | 0 |

| | | | | |
|---|---|---|---|---|
| Consumption of natural resources | 0 | - | | |
| | - | | 0 | |
| | ++ | | | -- |
| Energy consumption | ++ | - | | |
| | + | | 0 | |
| | ++ | | | - |
| Water consumption and related processes | - | -- | | |
| | - | | ++ | |
| | - | | | 0 |
| “Production” of non-hazardous waste | + | -- | | |
| | - | | 0 | |
| | + | | | - |
| “Production“ of hazardous waste | + | -- | | |
| | + | | -- | |
| | + | | | -- |
| „Production“ efficiency–productivity | + | - | | |
| | + | | - | |
| | ++ | | | -- |
| „Production“ efficiency–final quality | + | 0 | | |
| | ++ | | -- | |
| | + | | | + |
| Total positiv difference in comparison to relevant alternatives | 10 | 0 | | |
| | 5 | | 2 | |
| | 10 | | | 1 |

**Hierarchy of options for remediation**

The preferred hierarchy of options for site clean-up and/or management can be outlined as follows:

- on-site treatment of the contamination so that it is destroyed or the associated risk is reduced to an acceptable level

and

- off-site treatment of excavated soil, so that the contamination is destroyed or the associated risk is reduced to an acceptable level, after which soil is returned to the site

or, if the above options are not practicable:

- consolidation and isolation of the soil on site by containment with a properly designed barrier and

- removal of contaminated material to an approved site or facility, followed, where necessary, by replacement with appropriate material

or

- where the assessment indicates remediation would have no net environmental benefit or would have a net adverse environmental effect, implementation of an appropriate management strategy

When deciding which option to choose, the sustainability (environmental, economic and social) of each option should be considered, in terms of achieving an appropriate balance between the benefits and effects of undertaking the option.
In cases where no readily available or economically feasible method is available for remediation, it may be possible to adopt appropriate regulatory controls or develop other forms of remediation.

**Comparison between conventional and phytoremediation driven energy crop production using corn as an example**

Corn is an annual plant of the family of grass and is a so-called C4 plant. For this reason, corn can exploit solar energy very effectively and it has lower water and nutrient requirements than many other crops. In Germany corn is cultivated on about 2.5 million hectares (20% of the total arable area). In total, 80% of maize cultivation amounts to silage maize and 20% are used as grain maize. The production of animal feed has the largest share, but also biogas plants has increased significantly from 2005 to 2012. However, increasing cultivation of corn has also resulted in an increasingly negative discussion in public. Points of criticism are unilateral crop rotations, erosion risk, humus removal and reduction of biodiversity. By changing legal framework the corn acreage for biogas production has not substantially increased since 2012. Therefore, using corn additionally for phytoremediation will lead to more debates concerning biodiversity in public. Another critical fact is using feed and/or food for subsequent destruction, which has also to be considered very carefully. Nevertheless, field studies from 2003 suggest, that phytoextraction with maize, in comparison to common thermal and chemical methods for heavy metal decontamination, is an ecologically sensible, cost-effective alternative that contributes to the purification of cadmium-contaminated soils up to 25 ppm total content in the topsoil over a manageable time frame of up to 20 years and low material costs of € 20 per ton of soil is feasible (Haensler, 2003, University of Duesseldorf). Another advantage of maize is the high tolerance to Pb, Cd and Cu in contaminated soil. For example, sunflower, which is also a biofuel crop, showed higher accumulation rates than maize in greenhouse experiments with low concentrated heavy metal contaminated soil, but had poor tolerance to heavy metals under high contamination level (0.1mol/l) of Pb, Cu and Cd (Oh et al., IJESD, Vol.4, No.2, 2013). When using annual plants like maize for phytoremediation, cultivation is always associated with annual efforts in new planting. More practical in temperate zones is it to use hardy plant species for long term effects in soil restoration.

## Cost estimation

Costs for full scale remediation of 1 ha HMC land are calculated representatively for *Miscanthus x giganteus*.
The plant species is a permanent crop that can be cultivated for 15 years with moderate requirement for nutrients and soil. Waterlogged soils as well as wind and frost exposed sites should be excluded for MG cultivation.

Estimated costs for full scale remediation of 1 ha HMC area consist of one-off (table 4) and annual costs (table 5). Thereby one-off costs are usually planned for the beginning of the project.
One-off costs comprise land preparation as well as cultivation and planting of plants. For land preparation weed control has to be carried out optionally before plowing and plant bed preparation. Therefore about 150 EUR have to be calculated.
For planting 1 ha with MG about 10,000 rhizomes have to be purchased with about 20 cent per rhizome. They are planted usually be machine, whereas loss of plants within the first year of about 15% has to be calculated.

Lost plants have to be replaced. If necessary weed control is to be done. For all works about 2,850 EUR are estimated, leading to one-off costs of about 3,000 EUR.

Table 4: estimation of one-off costs for full scale remediation of HMC sites

| **one-off costs** | **costs[1] [EUR/ha]** |
|---|---:|
| **land preparation** | |
| weed control (optional) | 50.00 |
| plowing | 80.00 |
| plant bed preparation | 20.00 |
| **subtotal Land preparation** | **150.00** |
| **cultivation and planting** | |
| rhizomes (0.20 EUR per plant; 10,000 plants/ha) | 2,000.00 |
| planting by machine | 450.00 |
| weed control | 50.00 |
| additional planting for losses (15% of total rhizomes planted assumed, labor and material costs) | 250.00 |
| fertilization (NPK) | 100.00 |
| **subtotal Cultivation and planting** | **2,850.00** |
| **TOTAL** | **3,000.00** |

[1] German price level, exemplarily for *Miscanthus x gigantheus*; sources: Ministry for Environment, Agriculture and Geology of Saxony (www.publications.sachsen.de), Service Center Rural Area (DLR) Eifel (www.dlr-eifel.rlp.de)

Annual costs (table 4) consist of harvest and transport of biomass as well as storage of biomass. If the application of the inoculum is desired, additional costs amount to 2,330 EUR. Thereby for 1 ha demand of 500 L was calculated. The price for inoculum (EmFarma Plus™ by ProBiotics™ Polska, http://www.probiotics.pl/probio-emy/dla-gleby-i-roslin/emfarma-plus.html) is 4.46 EUR/L. Hence, total annual costs were estimated to 3,300 EUR.

Table 5: estimation of annual costs for full scale remediation of HMC sites

| **annual costs** | **costs[1] [EUR/ha]** |
|---|---:|
| harvest and transport of biomass (labor costs) | 650.00 |
| storage of biomass (fixed costs for building) | 350.00 |
| application of inoculum (purchasing inoculum (4.46 EUR/L; 500 L/ha) 2.230 EUR/ha, application 100 EUR) | 2,330.00 |
| **TOTAL** | **3,330.00** |

[1] German price level, exemplarily for *Miscanthus x gigantheus*; sources: Ministry for Environment, Agriculture and Geology of Saxony (www.publications.sachsen.de), Service Center Rural Area (DLR) Eifel (www.dlr-eifel.rlp.de)

Calculating estimated one-off and annual costs for a period of 10 years about 36,300 EUR have to be invested for remediation of 1 ha HMC land (table 6). Therein not included are costs for leasing agricultural land, if applicable, and costs for project management. The latter comprise all management activities for planning of full scale remediation, monitoring and consulting.

Further a return of investment considering the revenues for energy production is not considered. Nevertheless, comparing 36,300 EUR to investment costs for conventional soil remediation techniques like e.g. soil excavation, the cost advantage is clearly on the part of the Phyto2Energy approach.

Table 6: estimation of one-off and annual costs for full scale remediation of HMC sites

| **total costs** | **costs[1] [EUR/ha]** |
|---|---:|
| one-off costs | 3,000.00 |
| annual costs for about 10 years | 33,300.00 |
| **TOTAL** | **36,300.00** |

[1] German price level, exemplarily for *Miscanthus x gigantheus*; sources: Ministry for Environment, Agriculture and Geology of Saxony (www.publications.sachsen.de), Service Center Rural Area (DLR) Eifel (www.dlr-eifel.rlp.de)

## FURTHER PLANTS SPECIES FEASABLE FOR PHYTOREMEDIATION

For the rehabilitation of HMC areas, further plants are also suitable beside the investigated species within the Phyto2Energy project.
In general, plantation of plants on HMC sites counteract the leachate water formation largely and the transport of pollutants by wind. Due to the metabolic processes in the root area of the plants a continuous pollutant removal by the plants (phytoremediation) is achieved. The heavy metals are taken up with the pore water via the roots in the plants and accumulated in the plant biomass (root, shoot). Through the annual harvest and thermal utilization of the above-ground plant mass after the end of the vegetation period, the heavy metals are removed from the soil.

## SUMMARY & RECOMMENDATION

After three growing seasons the project team is now able to recommend on sure remediation strategies for HMC sites that are comparable to the tested site in Poland and Germany. The recommendations base on both, high biomass yield and high HM extraction. For the Polish HMC site (and a comparable to Polish site) a full scale remediation with *Spartina pectinata* treated with NPK fertilizer and/or with *Miscanthus x giganteus* treated with inoculum is recommended:

- For Pb contaminated site a planting of *Spartina pectinata* treated with NPK would lead to a yield of 33.9 t/ha*a with a Pb extraction of 1.05 kg/ha*a.
- For Cd and ZN contaminated site a planting of *Miscanthus x giganteus* treated with inoculum I would lead to a yield of 33.3 t/ha*a. This enables a Cd extraction of 0.02 kg/ha*a and a Zn extraction of 3.51 kg/ha*a.

For a full scale remediation scenario for the German HMC site (and a comparable to German site) the project results lead to the following recommendation:

- Cultivation of *Miscanthus x giganteus* treated with inoculum would reach 17.7 t/ha*a biomass. Thereby 0.02 kg/ha*a Pb, 0.01 kg/ha*a Cd and 2.36 kg/ha*a Cd will be extracted from HMC soil.

The reasons for differences in yield and HM extraction between both sites arose from variable site conditions. Soil properties and climatic conditions affect significantly on plant growth and performance in view to HM extraction. For this reason an eligible and comprehensive project management for successful planning of full scale remediation projects for further HMC sites is indispensable.

Finally, financial aspects have to be taken into account. Therefore, costs for full scale remediation of a 1 ha HMC site are calculated representatively for the species *Miscanthus x giganteus* (German price level, exemplarily for *Miscanthus x gigantheus*; sources: Ministry for Environment, Agriculture and Geology of Saxony (www.publications.sachsen.de), Service Center Rural Area (DLR) Eifel (www.dlr-eifel.rlp.de)). The plant species is a permanent crop that can be cultivated for 15 years with moderate requirement for nutrients and soil. Waterlogged soils as well as wind and frost exposed sites should be excluded for MG cultivation. Estimated costs for full scale remediation of a 1 ha HMC site consist of one-off and annual costs. Thereby one-off costs are usually planned for the beginning of the project. One-off costs comprise land preparation as well as cultivation and planting of plants. For land preparation weed control has to be carried out optionally before plowing and plant bed preparation. Therefore about 150 EUR have to be calculated. For planting 1 ha with MG about 10,000 rhizomes have to be purchased with about 20 cent per rhizome. Rhizomes are planted by machine and loss of plants within the first year of about 15% has to be calculated. Lost plants have to be replaced. If necessary weed control has to be done. In sum about 2,850 EUR are estimated, leading to one-off costs of about 3,000 EUR.

Annual costs consist of harvest and transport of biomass (650€) as well as storage of biomass (350€). If the application of the inoculum is desired, additional costs for inoculation amount to 2,330 EUR. For 1 ha a demand of 500 L was calculated. The price for inoculum (EmFarma Plus™ by ProBiotics™ Polska, http://www.probiotics.pl/probio-emy/dla-gleby-i-roslin/emfarma-plus.html) is 4.46 EUR/L. Hence, total annual costs were estimated to 3,330 EUR.

Calculating estimated one-off and annual costs for a period of 10 years about 36,300 EUR have to be invested for remediation of 1 ha HMC land. Not included are costs for leasing agricultural land, if applicable, and costs for project management. The latter comprise all management activities for planning of full scale remediation, monitoring and consulting. Further a return of investment considering the revenues for energy production is not considered. Nevertheless, comparing 36,300 EUR to investment costs for conventional soil remediation techniques like e.g. soil excavation, the cost advantage is clearly on the part of the Phyto2Energy approach. Thus, the Phyto2Energy project provides instructions for a direct and financially beneficial application of research results in the agricultural/industrial sector.