Chemical Looping Gasification for Sustainable Production of Biofuels

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Environmental risk assessment

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1 Introduction

The overall objective of WP6 is the assessment of risks related to health, safety, environment, society, technology and economics for the full biomass-to-end-use chain using technologies developed in the CLARA project and to propose actions for risk mitigation. Within WP6, TU Vienna is responsible for the environmental risk study (Task 6.2). The aim of T 6.2 is to identify and analyse some of the most relevant environmental risks that would be expected in relation to biomass pre-treatment and the chemical looping gasification of biomass for the production of Fischer-Tropsch (FT) Diesel.

Through an interactive process of iteration together with the CLARA consortium members, the scope of the risk analysis was narrowed down to render it relevant to the CLARA project's specifications and design. The environmental risk analysis consists of two main parts: the first part being a literature analysis on the likelihood, severity and mitigation practices for all environmental risks that form the scope of this analysis and the second part being the summary of an interactive workshop that was held with the CLARA consortium. While the first part is to provide relevant insights from literature, the second part reflects the project consortium's critical discussions on the various potential environmental risks, what preventative measures are already being taken and which practices are suggested to be implemented as further mitigation.

2 Disclaimer

The content of this deliverable reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

3 Scope of this study

There are a total of 14 risks that make up the scope of this environmental risk analysis. The iterative process that defined the scope of this study and took place in consultation with the project consortium is described in sub-section 2.1. The final scope of this study is described in more detailed in sub-section 2.2.

3.1 Process of iteration

The definition of the scope of this study was an iterative process that involved multiple feedback rounds, as well as an interactive workshop with the CLARA project consortium members . In order to exemplify the iterative process, all 19 risks that were initially considered as part of this analysis, together with the reasons for being excluded of the final scope of this study (where applicable), are listed in **Table 1**.

Table 1: Summary of all risks initially considered & their categorization

Risk	Part of final scope	Explanation (if applicable)
Soil preparation	**N**	Potential risks related to soil preparation are not relevant for the CLARA project, as only agricultural and forest residues are being utilized for biomass conversion processes.
Harvesting	**Y**	
Soil contamination	**N**	Potential soil contamination is not expected to pose a significant risk in case of the CLARA project, as the environmental burden of farm activities is predominantly related to wheat grain harvesting (and not the harvesting of straw residuals). It is also not relevant to the harvesting of forest residues.
Pre-treatment	**Y**	
Feedstock & fuel transport	**Y**	
Release of toxic gas washing solutions to the atmosphere	**Y**	
Land use	**N**	Potential risks associated to land use changes are not relevant because exclusively biomass residues are being harvested for the production of biofuels in the CLARA project.

Hazardous potential of gaseous components	**Y**	
Effects of Oxygen Carrier material acquisition and disposal	**Y**	
Effects of down-stream utilization/ deposition of residual solids and liquids	**Y**	
Effects of energy consumption of BtL plant	**Y**	
Emission of fine solid particles from fluidization equipment	**Y**	
Dust	**Y**	
Noise	**Y**	
Waste water	**Y**	
Tar	**Y**	
Effects of other utilities	**Y**	
Fire hazards	**N**	Will be covered in detail in health & safety assessment (Task 6.1)
Explosion	**N**	Will be covered in detail in health & safety assessment (Task 6.1)

The main reasons why certain environmental risks that may be otherwise relevant for an environmental risk study of a biomass gasification plant are not being included in this study is due to the fact that the CLARA project exclusively makes use of biomass residues and thus does not require any changes of land use, nor is it directly related to any fertilization/cultivation practices of biomass.

For instance, soil preparation involving intensive ploughing and other methods to increase the productivity of agricultural land that can lead to soil degradation (e.g. loss of soil moisture, soil erosion, damage to soil structure etc.) is not deemed to be relevant for the CLARA project. Another environmental risk that may normally be considered as part of such a study but has been deemed irrelevant to the CLARA project is the overly intensive use of fertilizer and pesticides - a common practice in conventional agriculture that leads to soil acidification, the reduction of organic matter and increased pest growth. Similarly, environmental risks associated with the conversion of natural and semi-natural ecosystems to non-food bioenergy crops (e.g. negative impacts on biodiversity and the loss of stored carbon) have also not been considered, as changes of land use are not foreseen by the CLARA project. Finally, the risk of fire during starting up, shutting down or the intermittent operation of pre-treatment and/or gasification plant, as well as the risk of explosion as a result of gas leakages into the atmosphere have also been excluded from this analysis, as they are not deemed to be exclusively of environmental nature, but general safety topics and will thus be handled in detail in the health & safety assessment (Task 6.1).

3.2 Risks under consideration

The final scope of the environmental risk analysis, together with brief descriptions of each risk, has been summarized below in **Table 2.**

Table 2: Summary and description of environmental risks included in scope of this analysis

Risk	Description
Harvesting	• Intensive harvest of leaves and needles from forest residues may lead to nutrient depletion • Use of heavy machinery may cause soil complications, e.g. soil compaction (limited ability of plants to take up nutrients and water due to increased soil density)
Pre-treatment	• Pre-treatment facilities for feedstock preparation need additional resources and energy input (may cause additional environmental burden locally) • Heat for evaporation of water and electricity input for pelletization cause additional emissions in the entire process chain
Feedstock & fuel transport	• CO2 & NOx emissions occur when feedstock is transported to pre-treatment facilities & gasification plants
Release of toxic gas washing solutions to the atmosphere	• Toxic gases could be released released and dissolved into the air by accident and have a short-term harmful effect on local ecosystems
Hazardous potential of gaseous components	• Contribution to global warming by the release of GHG due to operation failure
Effects of Oxygen Carrier material acquisition and disposal	• The demand of several CLARA plants for ilmenite oxygen carriers could lead to increased global ilmenite production and associated environmental issues, such as groundwater pollution due mining activities
Effects of down-stream utilization/ deposition of residual solids and liquids	• Environmental risks related to down-stream utilization and/or deposition of residual solids (e.g. fly ash) and liquids (e.g. used biodiesel) • Fly ash can contain toxic substances due to adsorption of chemicals and its dispersion can have negative impacts on agriculture, ecosystems and its animal population

Effects of energy consumption of BtL plant	• BtL plant is not self-powered, i.e. net electricity supply needed • Emissions of GHG gases and other air pollutants, contribution to GHG effect
Emission of fine solid particles from fluidization equipment	• Emission of fine particles & trace elements from fluidization equipment can have negative impacts on agriculture, local ecosystem
Dust	• Dust originating from improper disposal of fly-ash removal may be toxic due to adsorption of chemical substances and may lead to soil/ groundwater contamination if released into the environment
Noise	• Negative effect of noise by the operation of the pre-treatment, gasification plants and transport activities on local animal populations, e.g. bird populations
Waste water	• Waste water resulting from gas cleaning of raw syngas can contain carcinogenic monocyclic and polycyclic hydrocarbons, which can pose a lethal risk to animal and plant populations if leaked
Tar	• Tar is a viscous mixture of different hydrocarbons and is a byproduct of biomass conversion into syngas/ gasification process • They pose a risk for the environment due to containing mutagenic and/or toxic substances (higher adverse effects when disposed into water than into soil)
Effects of other utilities	• Discharge of cooling water into rivers, lakes may have temperature altering effects, threatening endemic species and algal biomass • Release of nitrates is expected to accelerate eutrophication of water bodies

It should be noted that the risk descriptions above are meant to be short explanations and that a more detailed analysis of each individual risk will be given in chapter 4 (literature research & analysis).

4 Framework & scales of analysis

Each of the 14 risks that were identified as relevant for this study have been ranked according to likelihood and severity on a scale from 1 to 5, with the intersection of both values representing a particular risk's overall risk potential. The overall risk potentials of each risk have been subsequently visualized on a matrix, categorizing each into acceptable, as low as reasonably practicable (ALARP) and unacceptable. In a final step, mitigation strategies were proposed for the analyzed risks.

The rating, visualization via the risk matrix, as well as the proposition of mitigation strategies for each individual risk has been done in two separate parts: the first part consisted of a comprehensive literature research and analysis on the identified risks and the second part was held in the form of an interactive workshop with the CLARA consortium members. This sub-chapter aims to give a more detailed description of the framework and scales of analysis that have been used for this environmental risk study. The results of the literature research & analysis, as well as the workshop will be given in subsequent chapters.

4.1 Risk likelihood ranking

Table 3: Definition of risk likelihood ratings from 1 to 5

Rating	Notation	Description	Frequency range
1	Extremely unlikely	No recorded incidence	$< 10^{-6}$ per year
2	Very unlikely	Very few recorded or known incidents	10^{-6} to 10^{-4} per year
3	Unlikely	Occur infrequently. Possibility exists.	10^{-4} to 10^{-2} per year
4	Improbable	Incidents occur regularly with medium frequency.	10^{-2} to 1 per year
5	Probable	Frequent incidents and strong likelihood for re-occurrence.	> 1 per year

4.2 Risk severity ranking

Table 4: Definition of severity ratings from 1 to 5

CONSEQUENCES					
Category	Minor	Significant	Severe	Major	Catastrophic
Rating	1	2	3	4	5
Description	Temporary, short term damage	Long lasting, slightly increased emissions	Severe pollution	Widespread damage	Catastrophic damage

4.3 Risk Matrix

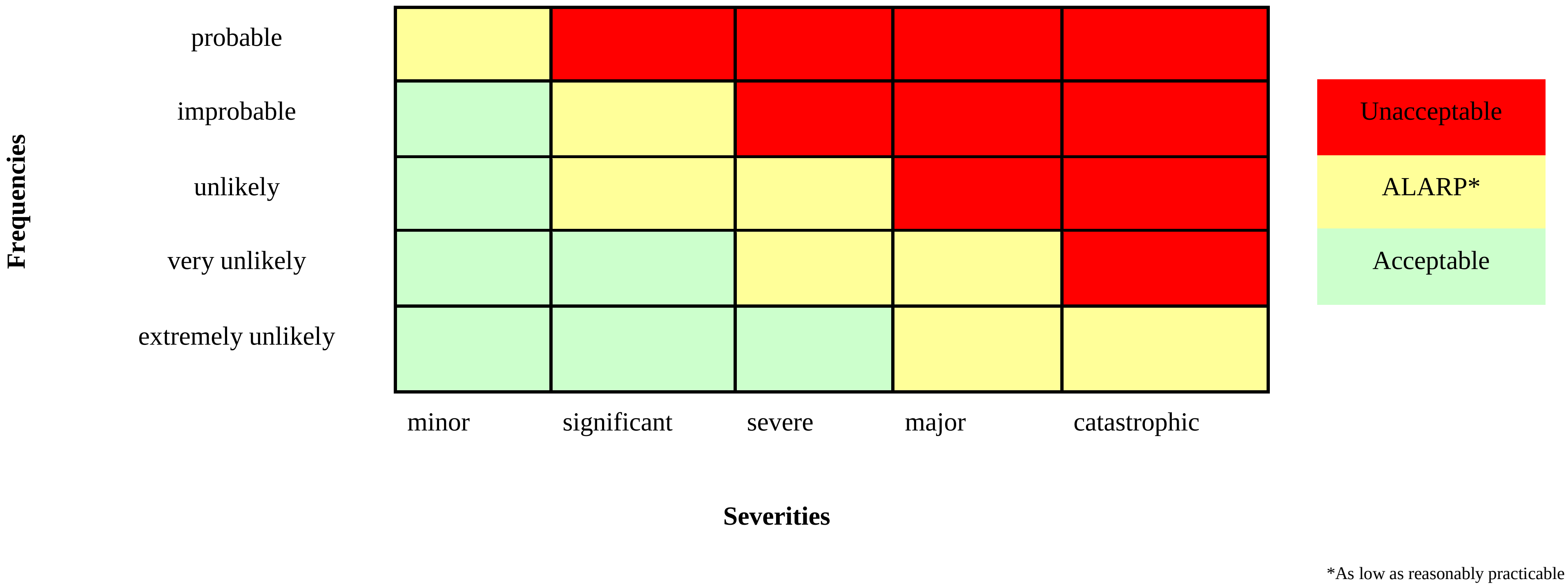

Figure 1: Risk matrix for the characterization and visualization of risk potentials (Hillary Kasedde 2009)

5 Literature Research & Analysis

The results of the literature survey regarding the likelihood, severity/impact and mitigation for each risk are summarized in form of a table in sub-section 4.1 and subsequently selected risks are analyzed in more detail in sub-section 4.2. Finally, the overall classification of all risks are visualized via a risk matrix in sub-section 4.3.

5.1 Summary of risk analysis: <u>literature survey</u>

The following table is to give a summary of the literature survey that has been carried out to classify the environmental risks within the scope of this study from a qualitative and quantitative perspective. Possible mitigation options are also mentioned briefly, again based on literature.

For more detailed descriptions of each risk, please refer to table 2 in sub-section 2.2. In some cases, a range for likelihood and/or severity is given due to differing viewpoints in literature.

Table 5: Summary of literature survey on likelihood, severity and mitigation for selected risks

Risks (related to)	Likelihood	Severity (qualitative)	Severity/impact (quantitative)	Mitigation
Harvesting	**1** Extremely unlikely (**Forest residues**) **4** Improbable (**Wheat straw residues**)	**2** Significant (**Forest residues**) **1** Minor (**Wheat straw residues**)	The utilization of heavy machines in agriculture and forestry can cause soil compaction (Ampoorter et al. 2012), however harvesting contributed only 6% to the environmental impact in terms of global warming potential (GWP) (Ampoorter et al. 2012; Busari et al. 2015; Labelle et al. 2022).	Machine modifications such as distribution of machine's weight on a larger number of tires or increasing individual tire dimensions. Leaves and needles of harvested biomass should remain in the forest (Ampoorter et al. 2012; Busari et al. 2015; Labelle et al. 2022).
Pre-treatment	**5** Probable	**1** Minor	The additional resources and energy input, such as heat for the evaporation of water and electricity for pelletization, required for the reduction of forest residue's initial moisture content from ~40% to ~ 10% cause additional emissions in the entire process chain. The same applies for the drying for wheat straw, however it has been reported to be less energy intense due to lower initial moisture content (Schipfer und Kranzl 2019).	Optimization of the pre-treatment process according to the type of biomass feedstock is expected to lead to a decrease of economic and environmental inefficiencies (Schipfer und Kranzl 2019).
Feedstock & fuel transport	**5** Probable	**1** Minor	CO_2 emissions resulting from fossil fuel dependent transport of	Decrease of GHG emissions caused by

			raw & processed feedstock, as well as FT-crude, pose an environmental burden. Since trucks are mainly powered by diesel, NO_x emissions are an issue as well.	feedstock & fuel transport through the use of alternative vehicle types that generate reduced emissions (i.e.hybrid, electrical) or run on alternative fuels (biofuels). Further, a reduction of transport distances, optimized transport routes and strategically engineered proximities of raw-material sources, pre-treatment and gasification facilities would decrease the environmental burden due to feedstock & fuel transport.
Release of toxic gas washing solutions to the atmosphere	**2** Very unlikely	**1** Minor	Toxic gases could be released into the air by accident and have a short-term harmful effect on local ecosystems ((Greenaction & GAIA 2006).	The probability of the release of toxic gas washing solutions into the atmosphere has been classified as highly unlikely, given suitable disposal techniques are applied according to EU norms. In the rare case of an accidental release, a short-term effect on local ecosystems is expected rather than posing a major environmental risk. (Greenaction & GAIA 2006)
Hazardous potential of gaseous components	**3** Unlikely	**2** Significant	In the unlikely case that CO_2, CO or methane are released into the environment due to operation failure in the pre-treatment or gasification plant, the consequences are expected to be negligible, because these GHG are of biological origin and since most of them are used in CCU, there would be no contribution to the atmospheric GHG concentrations ((A. Rollinson 2018).	The utilization of a CO_2 capture unit in would be expected to neutralize any contribution to global warming caused by GHG release and could even lead to negative emissions (A. Rollinson 2018, 2018).
Effects of Oxygen Carrier material acquisition and disposal	**1-2** Extremely to very unlikely	**2** Significant	Ilmenite extraction through the mining of titanium oxide is associated with pollution of groundwater resources, deforestation and natural ecosystem decline through dredging operations in fragile coastal areas. Improper disposal may lead to leaching to groundwater resources. Elevated	Any potential, adverse environmental effects related to ilmenite extraction could be minimized through recycling or reuse of the material, if possible. An alternative mitigation option would be to use a different material for

			radiation hazards are associated with mineral-sand loading and storage facilities. (Farjana und Huda 2021; Andrén)	the oxygen carrier, e.g. LD slag.(Hildor et al. 2019)
Effects of down-stream utilization/ deposition of residual solids and liquids	**2** Very unlikely	**2** Significant	The dispersion of fly ash, a form of particulate matter that can contain toxic substances due to adsorption of chemicals, may have negative impacts on local agriculture, ecosystems and animal populations. (Thapa et al. 2019)	For safety reasons and in order to minimize its potential environmental risks, fly ash should be stored wet. However, this leads to the extracted water becoming contaminated and needing further treatment, as the contaminants should not leak into ground water (Kasedde, 2009). Wet scrubbers are effective in the removal of contaminants, but cause the generation of large amounts of waste sludge. In biomass gasification plants it is usually standard practice that liquid residuals from scrubbers are treated according to relevant, pre-defined safety standards. (Thapa et al. 2019)
Effects of energy consumption of BtL plant	**5** Probable	**1** Minor	As the BtL plant is not self-powered, the required external electricity supply is expected to cause the emission of GHG gases and other air pollutants. The extent of these emissions, and thus a BtL plant's contribution to the GHG effect, are dependent on specific countries' electricity mixes.(Schipfer und Kranzl 2019)	It is not realistic to expect to mitigate emissions caused by electricity consumption entirely, however the mandates of the EU Green Deal will lead to increased shares of renewables (e.g. off- & on-shore wind, PV) in the electricity generation and thus a decrease of GHG emissions. (Schipfer und Kranzl 2019)
Emission of fine solid particles from fluidization equipment	**2** Very unlikely	**3** Severe	In the unlikely case that particulate matter escapes, it could contribute to environmental pollution and in severe cases lead to e.g. the acidification of nearby water bodies and an increase in drought occurrences.(Eutrophierung und Versauerung - LfU Bayern 2022)	The emission of solid particles from fluidization equipment has been classified as unlikely in literature, given the following mitigation practices are applied: • sound engineering practices in relation to equipment design

				• periodic control and proper handling of equipment • proper equipment isolation according to EU norms • proper implementation of HAZOP study (Eutrophierung und Versauerung - LfU Bayern 2022)
Dust	**2 – 3** Very unlikely to unlikely	**3** Severe	Improper disposal of fly-ash and its leakage into the environment may be toxic due its heavy metal content and, in extreme cases, may lead to soil and groundwater contamination. (Pitman et al. 2006)	Mitigation options reported in literature include the installation of particulate filters in relevant sections of the plants and the proper disposal of waste according to EU normative/ existing best practices. (Pitman 2006)
Noise	**5** Probable	**1** Minor	Noise pollution may have negative effects on local animal populations, e.g. bird populations and could impact the quality of life of nearby residents.(Donnison et al. 2021)	The strategic positioning of biomass pre-treatment and gasification plants in close vicinity of biomass rich land, the utilization of equipment with improved noise isolation and intermittent use of machinery should contribute to sufficiently manage this risk (Donnison et al. 2021).
Waste water	**2** Very unlikely	**3** Severe	Waste water resulting from gas cleaning of raw syngas may contain carcinogenic monocyclic and polycyclic hydrocarbons, which can pose a lethal risk to animal and plant populations, if leaked.(Donnison et al. 2021; Calì et al. 2020; Goswami et al. 2020)	Literature suggests a number of effective waste water treatment methods in case of contamination (Perruci et al., 2019(Michael Vendrup und Terkel C Christensen 2018; Calì et al. 2020; Goswami et al. 2020), however it is expected that this risk can be effectively mitigated by standard engineering practices and equipment that are mandatory for biomass gasification plants within the EU.
Tar	**2** Very unlikely	**3** Severe	Tar, a viscous mixture of different hydrocarbons and a by-product of biomass conversion into syngas/gasification process, poses a risk for the environment	Standard engineering equipment and techniques required and applied in biomass gasification plants (e.g.

			due to containing mutagenic and/or toxic substances (higher adverse effects when disposed into water than soil).(Thapa et al. 2019; Chidikofan et al. 2017)	scrubbers to strip tars from syngas) should suffice to mitigate this risk (i.e. prevent tar from being disposed into nearby land and water). It has been reported that tar removal rates of more than 98% can be reached (Thapa et al. 2019).
Effects of other utilities (e.g. cooling water, nitrogen)	**2** Very unlikely	**3** Severe	The accidental discharge of cooling water into rivers and lakes may have temperature altering effects, threatening endemic species and algal biomass. The release of nitrates could contribute to the eutrophication of water bodies.(International Atomic Energy Agency (IAEA) 1980; Calì et al. 2020; Michael Vendrup und Terkel C Christensen 2018)	Close monitoring and application of EU guidelines for the utilities in question (e.g. parameters and pre-treatment/ storage requirements for cooling water) should suffice to mitigate this risk. (International Atomic Energy Agency (IAEA) 1980; Calì et al. 2020; Michael Vendrup und Terkel C Christensen 2018)

5.2 Extended analysis of selected environmental risks

In this section, selected risks are analyzed and described in more detail including but not limited to their likelihood, severity/impact and possible mitigation strategies, as suggested in selected literature.

1) Harvesting

Environmental issues related to harvesting that are frequently cited in literature include soil disturbances caused by heavy machines and nutrient depletion caused by the withdrawal of leaves/ needles from forests (Labelle et al. 2022). Various mitigation strategies have been reported in literature (Labelle et al. 2022), such as taking into account terrain-related factors, operational planning, machine modifications and amendments, i.e. the distribution of machine's weight on larger number of tires or increasing individual dimensions. More concretely, this could be achieved i.e. through the use of high flotation tires, an extra bogie axle, lower inflation pressure of tires and the use of steel flexible tracks. Two further main amendments to machinery that are mentioned by Labelle et al. are brush mats and mulch cover to reduce the pressure on the soil. It has been also mentioned that when collecting forest residues, needles and leaves should remain in the forests for minimal invasion into the ecosystem. The environmental risks commonly associated with the harvesting of wheat straw residues are also expected to be in an acceptable range for the CLARA project, as any potential soil disturbances are usually short term and the soil productivity is being maintained by the application of fertilizers. The likelihood of soil compaction and disturbance has been rated as 1 (extremely unlikely) for forest residues and 4 (improbable) for wheat straw and the severity can be estimated to be 2 (significant) for forest residues and 1 (minor) for wheat straw.

Assuming that at least some of the mentioned mitigation strategies are put to practice and the fact that predominantly residues that can be collected minimally invasive are utilized in the CLARA project render the risk of long lasting soil disturbances through harvest activities rather low.

2) Energy consumption and GHG emissions resulting from pre-treatment

Pre-treatment of feedstock has the purpose to reduce transport cost and to improve biomass characteristics for chemical looping gasification (CLG) – rendering it important from an economic viewpoint. The two selected feedstocks for the CLARA project, wheat straw (agricultural residue) and pine forest residues (forest residue), have different initial moisture contents (MC). While wheat straw's MC is reported to be ~15%, pine forest residues possess a MC of around ~40%. Therefore, any required thermal input for the pre-treatment of wheat straw was neglected in this study, due to the already relatively low MC. On the other hand, pine forest residues require heat for drying before pelletization due to their higher MC. However, as the residual powder from feedstock pelletization is burned and utilized as heat source, fossil fuels are not necessary to dry the feedstock and hence it was concluded that no additional GHG emissions would result due to the pre-treatment of pine forest residues. An optimization of the pre-treatment process according to the type of biomass feedstock would be expected to lead to a decrease of economic and environmental inefficiencies.

For the pelletization of the selected feedstocks, however, electricity is required and a literature survey has been conducted to gain a better understanding on the energy consumption and GHG emissions resulting from it. In case of straw pellets, it was found that the specific electricity consumption per kWh of straw pellets is negligible compared to the energy content, because the consumed electricity accounts to approximately 1% of the feedstock's energy content. Energy input for the pine forest residues, however, has been reported to be higher, accounting for around 11% of the feedstock's energy content.
Currently, fossil fuels are part of countries' electricity mixes to varying degrees (depending on a specific country's energy system), however, the installed capacity of renewables in Europe is expected to increase further in the next years, mainly driven by additional solar and wind capacities. The capacity of renewables in the EU has been forecasted to grow until 2030 on an average of 40 GW per year (IAE, 2021) and it is likely that the 2030 target of 32% share of renewables in the primary energy consumption could be increased up to 40%. While in some European countries the share of renewables is already responsible for the majority of electricity generation, as e.g. in Sweden with 75% in 2021 (Energy use in Sweden 2021) the share of renewables in the overall electricity of Germany accounted for only 40% in 2021 (Umweltbundesamt 2022). This too, however, is expected to increase in the near future due ambitious goal of achieving a net-zero emission system by 2050 in the EU. Generally speaking it can be said that GHG emissions will occur due to the pre-treatment of biomass, but that the overall environmental burden is expected to stay within well-manageable limits and a downward trend is expected to occur in the coming years. The likelihood has been rated as 5 (probable), because emissions will occur for electricity consumption, but the severity is only 1 (minor).

3) GHG emissions from transport

The transport sector is one of the major sources for GHG emissions in the EU, as it is mainly dependent on fossil fuels. According to the European Environment Agency (EEA), the EU average emissions increased by around 25% from 1990 to 2019 (EEA 2020).

In case of the CLARA project, GHG emissions result from the transportation of feedstock to the pelletization and CLG plants. These emissions can be reduced by using local biomass (as proposed in the CLARA project), optimizing/ lowering transportation distances and strategically engineering proximities of raw-material sources, pre-treatment and gasification facilities, as well as the use of alternative vehicle types that generate reduced emissions (i.e.hybrid, electrical) or run on alternative fuels (biofuels). Further, it is expected that the application of the CLG technology will compensate for this environmental risk over time as FT-products replace fossil fuels in the transport sector and therefore contribute to a decrease of GHG emissions. The likelihood of this risk has been classified as 5 (probable), as the transport of feedstock is unavoidable, but the severity is only 1 (minor).

6) Effects of oxygen carrier acquisition

The oxygen carrier material chosen for the CLARA project is Ilmenite. In 2020, the amount of globally mined ilmenite was around 6.2 million tonnes/a (Abbas and Andrén 2021), with the main reserves being reported to be in China, South Africa and Australia. The main purpose of ilmenite mining is to produce TiO_2, which is used as a pigment, i.e. in paints. Around 95% of the annually mined ilmenite is used for the TiO_2 industry. Regarding its use as oxygen carrier, the amounts used in a 200 MW CLG plant are expected to be low compared to the global consumption. Experiments conducted within the CLARA project assumed amounts of a single 200 MW CLG plant will account for approximately 0.05-0.1% of the global production. Therefore, a single plant is extremely unlikely to have detrimental environmental effects that would otherwise be associated with the extraction of ilmenite through the mining of titanium oxide (i.e. pollution of groundwater resources, deforestation, natural ecosystem decline, groundwater contamination).

The environmental effects of ilmenite usage may be further reduced by recycling or reuse of the material if possible. Another mitigation option would be to use a different oxygen carrier, for example LD slag.

7) Effects of down-stream utilization/ deposition of residual solids and liquids

The raw syngas from biomass gasification contains substances that are harmful for utilized catalysts and undesirable for the fuel synthesis. Therefore, a gas cleaning step is unavoidable in the whole process chain. Ash, sulfur components and tars need to be removed before the fuel synthesis. Scrubbers are very effective in gas cleaning, but can create large quantities of residual liquids (Roddy and Manson-Whitton 2012). These need to be handled e.g. by waste water treatment facilities. For a detailed description on risks related to fly ash and liquid residuals, refer to "risk 11 – fly ash" and "risk 13 – wastewater", respectively.

8) Effect of energy consumption (electricity) of BtL plant on the environment

As the BtL plant is not self-powered, the required external electricity supply is expected to cause the emission of GHG gases and other air pollutants. The extent of these emissions is dependent on specific countries' electricity mixes; for a more detailed description on electricity sources, see "risk 2 – energy consumption and GHG emissions resulting from pre-treatment".

Besides the electricity consumption, biomass is used as fuel in the combustion reactor to provide heat for the gasification reactor, through which CO_2 and other GHG are emitted. However, the CO_2 released by combustion is seen as carbon neutral, because it was formerly bound by plants during photosynthesis. It is possible to apply carbon capture and storage to reach negative emissions and to offset the fossil energy consumption in the process chain of the BtL plant. Therefore, the likelihood is classified as 5 (probable), but the severity as 1 (minor).

11) Dust originating from improper disposal of fly-ash

Literature has shown that the landfilling of ashes is a commonly practiced method for the disposing of fly-ash, which is not unexpected in light of the relatively low cost of landfilling compared to the cost of the development of new technologies. In some cases, it has also been reported that the heavy metal content of ashes may prevent the effective development and later application of other disposal techniques.

Another practiced policy for the proper disposal and utilization of fly-ash is to return ashes of forest origin back to the forest as a mitigation strategy against acidification. However, upon studying literature it has been found that not all countries, as e.g. Austria, Italy and the Netherlands, have regulations for the use of biomass ash or wood ash in forestry, in which case it would have to be qualified as illegal dispersion of waste. Sweden and Canada (on a province by province level), on the other hand, has been reported to have specific regulations and policies to return ashes from forest origin back to the forest - if not contaminated. A commonality between the regulations related to the proper disposal of fly-ash in Sweden and Canada is the focus on the technical quality of fly-ash, such as lime and nutrient contents, as well as the environmental quality, i.e. trace elements.

A major drawback of releasing ashes back into the environment has been reported to be the solubility and reactivity of the ashes, which may have a negative effect on vegetation and soil life. In order to mitigate and reduce the instantaneous release of soluble components from ashes, fly-ash can be pelletized with binders, thus causing a slower release of nutrients, as already done in Sweden (NMI, 2018). It has been reported that heavy metal content of fly-ash that has been pelletized with binders is not expected to burden the environment.

Generally, the use of incentives to discourage landfilling may favor the development of economically competitive and ecologically favorable alternative disposal methods. Finally, an improved convergence of nationally defined regulations may further support the development of improved practices for the environmentally safe disposal of fly-ash.

13) Improper disposal of waste water

Waste water sludge resulting from the cleaning through wet scrubbers (i.e. removal of toxic and undesirable substances) of the raw syngas can be classified as hazardous waste when containing high heavy metal contents (Vendrup and Christensen 2018). In literature, several effective waste water treatment methods that can reduce i.e. organic fractions such as polycyclic aromatic hydrocarbons almost to zero have been mentioned (Perucci et al. 2019). Solid substance removal by sedimentation and desulfurization have been cited among standard methods.

Except in the case of a leakage, it is very unlikely that environmentally hazardous substances will be emitted into the environment through waste water. This risk is expected to be well manageable by standard engineering techniques that are required for and common practice in biomass gasification systems in the EU, therefore the likelihood can be estimated as 2 (very unlikely) and the consequences depend on the location, but might be severe (3) due to potentially exposing an ecosystem to harmful chemicals.

14) Tar emission to the environment

Tar is a viscous mixture of different hydrocarbons and a by-product of biomass gasification as a consequence of the dual bed gasifier (DFB) design utilized in the CLARA project. Tars pose a risk for the environment due to containing mutagenic and/or toxic substances. It should be mentioned that literature cites higher adverse effects when disposed into water than soil.

Tar emission into the environment (i.e. tar being disposed into nearby land and water) can be prevented through the application of standard engineering equipment and techniques (i.e. scrubbers to strip tars from syngas) that are common practice in biomass gasification plants within the EU. Literature cites a considerably high efficiency of tar removal rates of more than 98% with wet scrubbers (Thapa et al. 2019).

To reduce the tar overall amount of tar formation during gasification, a modification of the gasifier design would be necessary. It has been mentioned in literature that i.e. the tar formation has been observed to be generally lower with entrained flow gasification, which is however not deemed suitable for the CLARA project.

5.3 Risk Matrix

probable	Pre-treatment, Feedstock & Fuel transport, Effects of energy consumption of BtL plant, Noise						
improbable	Harvesting (wheat straw residues)						Unacceptable
unlikely		Hazardous potential of gaseous components					ALARP*
very unlikely	Release of toxic gas washing solutions into atmosphere	Effects of Oxygen Carrier acquisition & disposal, Effects of down-stream utilization/ deposition of residual solids and liquids	Emission of fine solid particles from fluidization equipment, Dust, Waste water, Tar, Effects of other utilities (e.g. cooling water, nitrogen)				Acceptable
extremely unlikely		Harvesting (forest residues)					
	minor	significant	severe	major	catastrophic		

Figure 2: Risk matrix depicting likelihood & severity of each risk

6 Workshop results & feedback

6.1 Public perception of likelihood, severity & mitigation of selected risks

As part of this environmental risk analysis, a workshop with CLARA consortium members was conducted in addition to the literature research that was outlined in chapter 4. The main motivation behind this workshop was to gain an understanding about what a non-expert, public perception on the selected environmental risks related to biomass gasification plants could look like. Thus, the results of this workshop do not represent the opinion of the author(s), nor do they reflect information conveyed in literature.

The workshop was held virtually via an interactive survey and brainstorming tool. There were 13 participants from the CLARA consortium and the interactive survey consisted of two parts. In the first part, each participant was asked about how they would rate the likelihood as well as the severity of each of the 14 risks that form the scope of this analysis. For the sake of rendering the rating of the risks more straightforward, the workshop participants were asked to rate each risk as either low (1), medium (2) and high (3) for both severity and likelihood. The results are of the workshop's first part are summarized in table 6 below.

It should be noted that not all 13 participants answered every single question (due to e.g. technical difficulties such as intermittent internet connection and/or some participants not being available for the entire duration of the workshop). Therefore, the total number of answers is indicated for each risk, together with the individual number of votes. This should not be an issue as the workshop's objective was to gain a general understanding of the public perception as a relative estimate. The prevalent answers for likelihood and severity are highlighted in bold for each risk.

For a detailed description of each risk, please refer to table 2 in sub-section 2.2.

Table 6: Summary of workshop on likelihood & severity of risks

Risks (related to)	Likelihood *votes*	Severity (qualitative) *votes*
Harvesting	• High: 2 • **Medium: 7** • Low: 4 (Total votes: 13)	• High: 1 • **Medium: 9** • Low: 2 (Total votes: 12)
Pre-treatment	• High: 4 • **Medium: 5** • Low: 3 (Total votes: 12)	• High: 1 • **Medium: 6** • **Low: 6** (Total votes: 13)
Feedstock & fuel transport	• **High: 7** • Medium: 5 • Low: 1 (Total votes: 13)	• High: 0 • **Medium: 9** • Low: 4 (Total votes: 13)
Release of toxic gas washing solutions to the atmosphere	• High: 3 • Medium: 4 • **Low: 6**	• High: 4 • **Medium: 7** • Low: 2

	(Total votes: 13)	(Total votes: 13)
Hazardous potential of gaseous components	• High: 2 • Medium: 3 • **Low: 8** (Total votes: 13)	• High: 1 • **Medium: 7** • Low: 5 (Total votes: 13)
Effects of Oxygen Carrier material acquisition and disposal	• High: 2 • Medium: 4 • **Low: 7** (Total votes: 13)	• High: 1 • Medium: 4 • **Low: 7** (Total votes: 12)
Effects of down-stream utilization/ deposition of residual solids and liquids	• High: 0 • Medium: 5 • **Low: 7** (Total votes: 12)	• High: 3 • **Medium: 6** • Low: 4 (Total votes: 13)
Effects of energy consumption of BtL plant	• **High: 7** • Medium: 4 • Low: 2 (Total votes: 13)	• High: 0 • Medium: 5 • **Low: 7** (Total votes: 12)
Emission of fine solid particles from fluidization equipment	• High: 0 • Medium: 1 • **Low: 11** (Total votes: 12)	• High: 0 • **Medium: 8** • Low: 4 (Total votes: 12)
Dust	• High: 0 • Medium: 2 • **Low: 10** (Total votes: 12)	• High: 1 • **Medium: 5** • Low: 4 (Total votes: 10)
Noise	• High: 1 • Medium: 3 • **Low: 6** (Total votes: 10)	• High: 0 • Medium: 1 • **Low: 9** (Total votes: 10)
Waste water	• High: 1 • Medium: 1 • **Low: 9** (Total votes: 11)	• **High: 5** • Medium: 4 • Low: 2 (Total votes: 11)
Tar	• High: 1 • Medium: 2 • **Low: 8** (Total votes: 11)	• High: 2 • **Medium: 6** • Low: 3 (Total votes: 11)
Effects of other utilities **(e.g. cooling water, nitrogen)**	• High: 0 • Medium: 0 • **Low: 11** (Total votes: 11)	• High: 2 • **Medium: 6** • Low: 2 (Total votes: 10)

6.2 Proposed mitigation strategies

In the second part of the workshop, the participants were asked to brainstorm and come up with potential mitigation strategies for the individual risks. The results of the second part of the workshop are summarized in table 7.

For a detailed description of each risk, please refer to table 2 in sub-section 2.2.

Table 7: Summary of mitigation strategies proposed during Workshop

Risks (related to)	**Mitigation strategies** (*proposed during WS*)
Harvesting	• Returning ash back to soil if it does not contain any toxic substances • Application of proven best practices/ soil quality management practices • Revision (modernization) of machinery and chemical soil nutrient analysis/control according to EU normative • Deployment of ASTM & ESN norms
Pre-treatment	• Utilizing renewable energy sources • Optimized hours of operation • Heat integration & utilization of waste/process heat • Integration into plants with an overcapacity of heat/power (CHP), if locally available
Feedstock & fuel transport	• Utilization of electric vehicles and/or vehicles fueled by advanced biofuels/ renewable fuels for transport • Optimization of logistics, evaluation of locations/ short distances between feedstock sources & plants • Sourcing of local feedstock with close proximity to the plant, preferably from within the EU • Considering transport by train • Improvement of feedstock compactness (to enable transportation of larger quantities)
Release of toxic gas washing solutions to the atmosphere	• Use suitable disposal, according to EU norms (to prevent toxic gases being released/dissolved into the air by accident and have a short-term harmful effect on local ecosystems)
Hazardous potential of gaseous components	• Optimization of CO_2 usage by integrating external and green hydrogen • Smaller plant size (200MW) • CO_2 capture and/or re-use in plant • Adsorbents: installation of an extra unit for adsorption, if low amounts of toxic gases are expected • Improvement of conversion efficiency
Effects of Oxygen Carrier material acquisition and disposal	• Recovery/ re-utilization of Ilmenite as Oxygen Carrier (also in other processes), if possible • Considering other OC materials that are environmentally more friendly • Usage of OC material sourced exclusively from existing sources and experienced & already existing suppliers • Cooperation with suppliers that have rigid environmental standards

Effects of down-stream utilization/ deposition of residual solids and liquids	• Re-utilization of fly ash in other processes instead of disposal (e.g. road construction)
	• Utilization of fly ash according to its content
	    ○ Use in agriculture/release into surrounding ecosystem in case of absence of Arsenic (As) and other heavy metals
	    ○ If classified as dangerous solid, store according to EU norms

	(For an already optimized plant, it is only possible to add one extra unit dedicated to the burning of ashes or other materials)
Effects of energy consumption of BtL plant	• Utilization of renewable electricity and waste heat from the gasification process for drying • Strategic location of plant with close proximity to wind energy & buying local, renewable energy • Optimization of plant operation hours • Optimization of power/heat use by integrating use of excess heat for power generation through detailed engineering
Emission of fine solid particles from fluidization equipment	• Proper implementation of HAZOP study • Deployment of sound engineering practice (in relation to equipment design, periodic control & proper handling) • Properly isolated system according to EU norms
Dust	• Use suitable wastewater cleaning step, according to EU norms (in order to prevent dust originating from improper disposal of toxic fly-ash removal to contaminate groundwater if released into the environment)
Noise	• Building plant away from urban centers, ideally surrounded by land rich in biomass • Utilization of newest technology in equipment (high energy efficiency, reduced noise/improved noise isolation)
Waste water	• Recycling/ re-use of waste water within plant • Linkage to a plant in which water is treated and reused • A proper disposal regime, according to EU norms • Utilization of less toxic sorbents
Tar	• If the process will be optimized, no problems. In other case, the tar can be used to produce carbon and gases, with the use of adsorption of sulfur and nitrogen compounds, etc... similar to refinery • Upgrading & removal of tar through tar cracking via POX (partial oxidation) • Proper disposal, recycling / treatment • Proper collection and offer for professional utilization in relevant industries • Repurpose within plant & processes, where/if possible
Effects of other utilities **(e.g. cooling water, nitrogen)**	• Recycling/re-use of cooling water within plant • Optimization of cooling system, use of air cooling • Application of best practices & engineering practices of power plants already in use (regarding e.g. filters, heat changer etc.)

6.3 Mitigation action already taken by CLARA

In addition to an interactive workshop on their perception of the likelihood and severity of the risks that form the scope of this study, as well as potential mitigation strategies for the latter, CLARA consortium members were asked to provide feedback regarding what already has been done within the CLARA project in order to mitigate the mentioned risks. This lead to a valuable discussion that can be seen as an extension of section 5.1 and 5.2. Table 8 provides a summary of concrete mitigation actions already put into practice by the CLARA project, as well as other, relevant comments by the project partners regarding what should be considered regarding each risk.

Table 8: Summary of mitigation strategies already put into place

Risks (related to)	Mitigation strategies ***(already put into practice by CLARA project)***
Harvesting	• Strict focus on biomass residues, no dedicated harvest of any biomass • As the biomass that is being utilized is not explicitly produced for CLARA, but are biomass residues from already existing activities, the collection of those is already optimized. A complete de-mechanization of the biomass collection process is unrealistic and so is simply leaving all residues in the forest/fields (as this would render processes utilizing biomass impossible). • CO_2 emissions from harvesting and agriculture in total should be taken into consideration
Pre-treatment	• As direct feeding of raw material into the gasifier is not possible, a certain pre-treatment is necessary. Within CLARA, pre-treatment efforts are minimized by e.g. excluding chemical additives. • Heat required for pellet production is produced on-site (internal usage) and electrical energy derived from renewable resources ○ in order to avoid the use of natural gas for biomass drying, a fraction of the fine residues (powder) from pelleting is derived to a combustion chamber in to produce the required heat for the drying • Energetic optimization is always an issue and depends on plant location as well as the possibility of integration into other energy systems
Feedstock & fuel transport	• Transport itself is not in the engineering scope of CLARA. Ideally, it would be optimal to generally resort to CO_2 lean transport media (e.g. trains instead of trucks, powered by Green H_2 or Green Diesel) but this may not be applicable for a CLARA plant that is to be operated in the near future (as some of the mentioned CO_2 lean transport media have not reached market maturity yet).
Release of toxic gas washing solutions to the atmosphere	• Plant is engineered according to existing best practices to restrict potential release of substances to an absolute minimum. • Avoiding leakages to the ground is a general engineering topic and requires safe handling of the inventories by installing retention basins under all relevant plant sections. • As the CLARA project is currently in the pre-engineering and not in the detail engineering phase, this has not been mentioned in the equipment list or other documents within CLARA yet. • There are certain typical risks of failures associated to gas washing solution leakages that are, however, not very probable. See the general Health & Safety deliverable for a more detailed analysis.
Hazardous potential of gaseous components	• The CLARA plant is engineered to be equipped with flare systems for emergency cases and according to existing best practices (as per EU normative) to restrict potential release of substances to an absolute minimum, as there would be no operation permit for a plant emitting toxic gases during normal operation in amounts high enough to have the potential environmental effects considered. • It needs to be considered that leakages can happen and should always be avoided through sound engineering practice. • The use of complete input in the synthesis section through recycling leads to minimum CO_2 emissions by the process itself. Zero CO_2 is technically impossible, but as biomasses is used CO_2 emissions are "green".
Effects of Oxygen Carrier material acquisition and disposal	• A question that should be considered in relation to the OC material in use in the CLARA project, is whether ilmenite is also a residue / side product of an already existing business (TiO_2 production). If so, the environmental effect is already given. • Potential re-usage of waste material from CLG for down-stream utilization • A mitigation measure taken by the CLARA project could be a switch to another OC material with superior environmental performance.

Effects of down-stream utilization/ deposition of residual solids and liquids	• All residuals are removed or disposed according to existing best practices. • It is highly unlikely that fly ash will be dispersed into the environment to the extent that it would lead to the mentioned consequences • In general, it is an engineering topic for later phases of the project • Leakages should be avoided through re-utilization of certain waste streams
Effects of energy consumption of BtL plant	• Only electrical energy needed (no external heat provision is required) • The possibility to use green energy – which should be encouraged - and to which extent, depends on the system existing at the plant site once the project enters the realization phase • There is no direct influence of the CLARA project consortium at this stage of the project on the energy mix that will be utilized by the BtL plant.
Emission of fine solid particles from fluidization equipment	• The emission of particles to an extent that it would lead to e.g. acid rain/ weather changing effects is highly unlikely • All units are equipped with particulate filters and sensory equipment to detect potential leakages
Dust	• The emission of particles to an extent that it would lead to e.g. acid rain/ weather changing effects is highly unlikely • All units are equipped with particulate filters and sensory equipment to detect potential leakages • Waste material is removed/disposed according to existing best practices
Noise	• As mitigation practice noise encapsulation/insulation and the use of silent machines are foreseen
Waste water	• Risk of formation of carcinogenic compounds such as nitrosamines is very little compared to the formation of tar • Mitigation: proper treatment of wastewater / disposal or re-use according to existing best practices • No emission of waste water to surroundings during normal operation expected
Tar	• No emission of tar species to surroundings expected during normal operation • Waste material is removed/disposed according to existing best practices • Recycling of tars to gasifier
Effects of other utilities (e.g. cooling water, nitrogen)	• All sub-units are energy-pinched to minimize cooling water demands • Nitrogen is largely emitted in gaseous form • During the detailed engineering phase of the plant the discharge of cooling water into the surrounding/rivers will be technically minimized (e. g. by air cooling/ re-cooling of cooling water). • The release of nitrate is not expected

Potential environmental risks related to

- the down-stream utilization/ deposition of residual solids and liquids,
- other utilities (e.g. cooling water, nitrogen),
- the emission of fine solid particles from fluidization equipment,
- dust resulting from fly-ash removal,
- noise and
- waste water (resulting from raw syngas cleaning)

are considered to be general engineering topics and are to be handled with sound engineering practices to avoid leakages, minimize energy and utility use, as well as to also to minimize costs. The potential leakage of tar into the environment could theoretically also be mitigated by using a different gasification technology, such as e.g. entrained flow, in which tar formation does not occur. However, this is not what is intended in the CLARA project, its main objective is to study the deployment and upscaling of Chemical Looping Gasification (CLG) of biomass residues for the production of FT-Diesel.

Overall, it is also important to differentiate between risks that do not originate from the CLARA concept but are typical technical risks that are to be generally expected in relation to biomass processing and gasification, as they will be minimized by sound engineering practice (e.g. avoiding of leakages, retaining of liquids, treating and/or disposing waste in accordance with EU norms). The focus should rather be on risks that cannot be avoided in a CLG plant such as CO_2 emissions originating from the combustion of a certain portion of recycled gases.

7 Conclusion

It should be pointed out that this study came to the conclusion that there do not seem to be any potential environmental risks related to the CLARA project that are expected to be deemed "unacceptable", i.e. pose a serious, irreversible threat to the environment and surrounding ecosystem. According to both the literature analysis and the interactive workshop with consortium members, most risks under study were in the acceptable range and a few, select risks were deemed to be in the "as low as reasonably practicable" (ALARP) range, i.e. classified as tolerable risks.

According to the literature survey that has been carried out as part of this study, potential environmental risks related to biomass pre-treatment, feedstock & fuel transport, effects of energy consumption of the BtL plant and noise pollution were all risks that were deemed to be highly likely but were also expected to have an insignificant effect on the environment. It is important to keep in mind that high likelihood does not equal high severity (and vice versa) and that there will naturally be risks related to the pre-treatment and gasification of biomass that are unavoidable but pose a reasonably insignificant environmental threat – thus it can be concluded that they should not be the focus of mitigation efforts, but rather should be kept to a minimum through existing best practices.

Potential environmental risks related to the emissions of fine solid particles from fluidization equipment, dust, waste water, tar and the effects of other utilities (e.g. cooling water, nitrogen) were deemed to be very unlikely but their potential effect was classified as severe. In case of these risks it is important to point out that literature has stressed their low likelihood, given proper engineering practices and the strict implementation of EU norms.

The similarity of the workshop results to the literature survey suggests that the public perception of a CLARA plant may be expected to be a relatively realistic estimation and that no overly pronounced resistance to such a plant may be expected from the local community.

8 Bibliography

A. Rollinson (2018): Fire, explosion and chemical toxicity hazards of gasification waste. In: *Journal of Loss Prevention in the Process Industries*.

Ampoorter, Evy; an de Schrijver; van Nevel, Lotte; Hermy, Martin; Verheyen, Kris (2012): Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. In: *Annals of Forest Science* 69 (5), S. 533–542. DOI: 10.1007/s13595-012-0199-y.

Andrén, James: Environmental impact of ilmenite from mines to product, Abbas, Andren. Online verfügbar unter https://odr.chalmers.se/bitstream/20.500.12380/303559/1/Environmental%20impact%20of%20ilmenite%20from%20mines%20to%20product%2c%20Abbas%2c%20Andren.pdf, zuletzt geprüft am 06.05.2022.

Busari, Mutiu Abolanle; Kukal, Surinder Singh; Kaur, Amanpreet; Bhatt, Rajan; Dulazi, Ashura Ally (2015): Conservation tillage impacts on soil, crop and the environment. In: *International Soil and Water Conservation Research* 3 (2), S. 119–129. DOI: 10.1016/j.iswcr.2015.05.002.

Calì, Gabriele; Deiana, Paolo; Bassano, Claudia; Meloni, Simone; Maggio, Enrico; Mascia, Michele; Pettinau, Alberto (2020): Syngas Production, Clean-Up and Wastewater Management in a Demo-Scale Fixed-Bed Updraft Biomass Gasification Unit. In: *Energies* 13 (10), S. 2594. DOI: 10.3390/en13102594.

Chidikofan, G.; Benoist, A.; Sawadogo, M.; Volle, G.; Valette, J.; Coulibaly, Y. et al. (2017): Assessment of Environmental Impacts of Tar Releases from a Biomass Gasifier Power Plant for Decentralized Electricity Generation. In: *Energy Procedia* 118, S. 158–163. DOI: 10.1016/j.egypro.2017.07.034.

Donnison et al. (2021): Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. In: *Environmental Research Letters*.

EEA (2020): EU GHG Emissions by aggregated sector.

Energy use in Sweden (2021). In: *Swedish Institute*, 14.07.2021. Online verfügbar unter https://sweden.se/climate/sustainability/energy-use-in-sweden, zuletzt geprüft am 10.05.2022.

Eutrophierung und Versauerung - LfU Bayern (2022). Online verfügbar unter https://www.lfu.bayern.de/luft/schadstoffe_luft/eutrophierung_versauerung/index.htm, zuletzt aktualisiert am 14.03.2022, zuletzt geprüft am 14.03.2022.

Farjana; Huda (2021): Life cyle Assessment of Ilmenite and Rutile Production in Australia. In: *Science Direct-Elsevier*.

Goswami, Lalit; Pakshirajan, Kannan; Pugazhenthi, G. (2020): Biological treatment of biomass gasification wastewater using hydrocarbonoclastic bacterium Rhodococcus opacus in an up-flow packed bed bioreactor with a novel waste-derived nano-biochar based bio-support material. In: *Journal of Cleaner Production* 256, S. 120253. DOI: 10.1016/j.jclepro.2020.120253.

Greenaction & GAIA (2006): Incinerators in Disguise. Case Studies of Gasification, Pyrolysis, and Plasma in Europe, Asia, and the United States.

Hildor, Fredrik; Mattisson, Tobias; Leion, Henrik; Linderholm, Carl; Rydén, Magnus (2019): Steel converter slag as an oxygen carrier in a 12 MWth CFB boiler – Ash interaction and material evolution. In: *International Journal of Greenhouse Gas Control* 88, S. 321–331. DOI: 10.1016/j.ijggc.2019.06.019.

Hillary Kasedde (2009): Hazard and Safety Evaluation of Gasifier Installations in Uganda. MSc Thesis Report. Royal Institute of Technology, Stockholm, Sweden.

International Atomic Energy Agency (IAEA) (Hg.) (1980): Environmental Effects of Cooling Systems. Technical Reports Series No. 202. IAEA.

Labelle, Eric R.; Hansson, Linnea; Högbom, Lars; Jourgholami, Meghdad; Laschi, Andrea (2022): Strategies to Mitigate the Effects of Soil Physical Disturbances Caused by Forest Machinery: a Comprehensive Review. In: *Curr Forestry Rep* 8 (1), S. 20–37. DOI: 10.1007/s40725-021-00155-6.

Michael Vendrup; Terkel C Christensen (2018): TREATMENT OF WASTEWATER FROM FLUE GAS CLEANING. In:. Veolia Power Conference 2016. Online verfügbar unter https://www.researchgate.net/publication/329218808_TREATMENT_OF_WASTEWATER_FROM_FLUE_GAS_CLEANING.

Schipfer, Fabian; Kranzl, Lukas (2019): Techno-economic evaluation of biomass-to-end-use chains based on densified bioenergy carriers (dBECs). In: *Applied Energy* 239, S. 715–724. DOI: 10.1016/j.apenergy.2019.01.219.

Thapa, Sunil; Indrawan, Natarianto; Bhoi, Prakashbhai R.; Kumar, Ajay; Huhnke, Raymond L. (2019): Tar reduction in biomass syngas using heat exchanger and vegetable oil bubbler. In: *Energy* 175, S. 402–409. DOI: 10.1016/j.energy.2019.03.045.

Umweltbundesamt (2022): Erneuerbare Energien in Zahlen. Online verfügbar unter https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#strom, zuletzt aktualisiert am 10.05.2022, zuletzt geprüft am 10.05.2022.

Rona M. Pitman, Wood ash use in forestry – a review of the environmental impacts, Forestry: An International Journal of Forest Research, Volume 79, Issue 5, December 2006,

IAE, Renewables 2021 Analysis and forecast