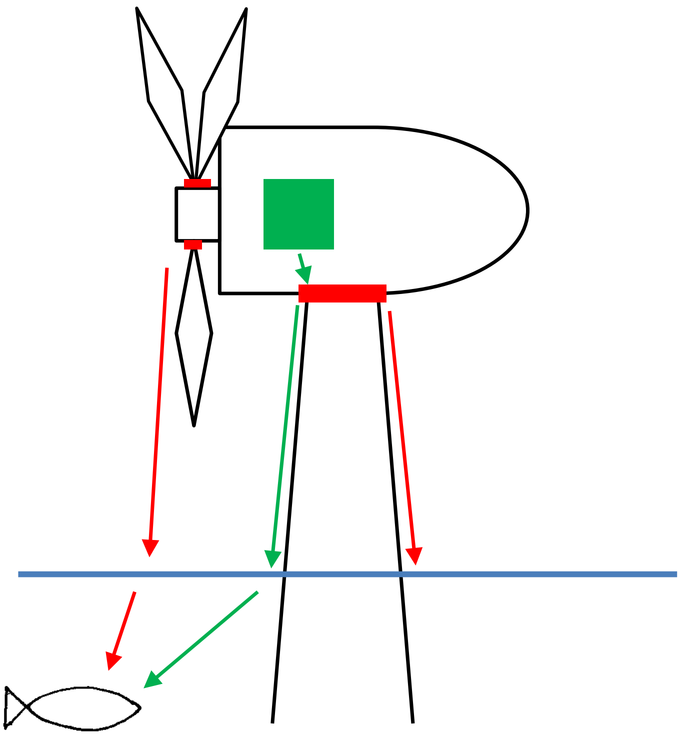

Screening Environmental Risk Assessment of Grease and Oil Emissions from Off-Shore Wind Power Plants

RICKARD ARVIDSSON AND SVERKER MOLANDER

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Abstract

This report constitutes a generic environmental risk assessment of emissions of grease and oil from off-shore wind power plants. In this context, risk is defined as an exposure of a stressor high enough to cause adverse effects on a certain endpoint. The stressors considered are alkanes, phosphate isodecyl/phenyl compounds and zinc alkyl dithiophosphate. The endpoints considered are the aquatic organisms fish, *Daphnia magna*, algae and aquatic bacteria. A screening risk assessment method is applied, assuming one-time releases of lubricant and gear oil. Although this should be seen as an early screening study, it indicates that the stressors included constitute risks to aquatic organisms given the setup of this study. A one-by-one parameter sensitivity analysis is performed to investigate the impact of different emissions, evaporation and biodegradation on the results. Even with low emissions, high evaporation and high biodegradation, the results show that the organisms living close to the wind power plant are subject to risk. The implications of these results if taken into account that some off-shore wind power plants may not occur one-by-one but rather be part of parks containing tens of plants together are discussed. Recommendations to reduce the risk are given. A technical risk reduction measure is to use less toxic, biodegradable lubricants. An organizational risk reduction measure is to increase maintenance and thereby reducing the likelihood of emissions occurring.

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1 Introduction

There are clear indications that wind power may be an important energy source in the future. In a study by Jacobson and Deluchi (2009) they suggested how a fossil free energy system can be achieved in 2030. According to that scenario, wind power could provide 51 percent of the world's energy in the form of 3.8 million wind turbines. Lu et al. (2009) estimated that 2.5 MW turbines operating on 20 percent of their capacity could still provide more than 40 times the total current electricity production, and more than 5 times the total current energy production. In the review of technical solutions to global warming, air pollution and energy security, Jacobson (2009) concluded that wind power technologies are the highest ranked solutions. Currently, about 1.5 TWh of wind power electricity is produced in Sweden (Swedish Energy Agency 2008). However, more wind power parks are planned, both on land and off shore (Swedish EPA 2010), and 10 TWh is planned for 2015 (Swedish Energy Agency 2008). Thus, in the light of the potential expansion, adverse environmental impacts from wind power must be investigated, assessed and managed.

1.1 Background

Chemical pollution constitutes one of the major environmental problems. In a study by Rockström et al. (2009) attempts were made to estimate nature's limits to some environmental problems such as global warming, biodiversity, the nitrogen and phosphorous cycles and chemical pollution. However, they were not able to estimate how much chemical pollution nature could sustain, nor how the environmental problem of chemical pollution was to be measured.

In Sweden, there are 16 environmental objectives, one being "a none-toxic environment". The responsible authority is the Swedish Chemicals Agency and the definition of the goal is "The environment must be free from man-made or extracted compounds and metals that represent a threat to human health or biological diversity. This objective is intended to be achieved within one generation." The Environmental Objectives Council estimate the current state of this environmental objective is as follows: "This objective will be very difficult or not possible to achieve by 2020, even if further action is taken" (Swedish Environmental Objectives Council 2009).

The environmental impact of wind power is often discussed, both regarding life cycle impact from carbon dioxide and other emissions (Vattenfall 2005) and effects on the local ecosystem (Swedish EPA 2010). It is however seldom that the use of chemicals in wind power plants is addressed. All wind power plants need lubricants in order to lubricate gears and bearings which are needed to increase the efficiency of moving parts. During the operation of wind power plants the lubrication of these bearings is a key factor. It has been reported that leakage of lubricants may occur, see the photos in Appendix 1.

1.2 Aim of the study

The purpose of this study is to make an initial assessment of possible environmental effects of chemicals used in wind power plants by applying environmental risk assessment (ERA). ERA is a common framework to address the problem of toxic chemicals (EEA and UNEP 1998; van Leeuwen and Vermeire 2007). This study assesses the environmental risk of gear oil and bearing grease in off-shore wind power plants.

It should be noted that, as is often the case in environmental systems analysis studies, lack of data has been a problem in this study. Thus this report should be seen as a screening ERA and as a starting point of a discussion regarding emissions of chemicals from wind power plants. To our knowledge, no such study has been conducted, although similar ERA studies with other sources and stressors have been performed, see for instance Einarsson (2009). As has been recommended below, further studies are needed to investigate this topic more thoroughly. We would finally like to clarify that this study does not compare wind power to other energy sources, and that using of this study as argument for choosing other energy sources is thus not accurate.

2 Method

The ERA procedure is quite standardized. Although slight differences between different descriptions exist, the similarities are more numerous and are well described in a number of books and reports, see for instance Suter et al. (1993), US EPA (1998), van Leeuwen and Vermeire (2007) and Burgman (2005) or Figure 1. The first part of an ERA is often some kind of *problem formulation*. In that stage, *hazard identification* is performed, thus identifying potential risks such as the use of chemicals known to be toxic. A *conceptual model* is developed in order to understand how the hazard may cause adverse effects. In ERA a conceptual model usually includes the identification of (1) the source of the hazard, (2) the stressor, which is the agent able to cause harm (typically a chemical substance), (3) pathways by which the stressor may reach the receptor, and (4) receptors or endpoints, which is the value at stake that the stressor may harm. Typically, the receptors are living organisms such as fish or humans.

The second part of an ERA normally includes conducting an *exposure assessment* and an *effect assessment*, also referred to as *dose-response assessment*. The exposure assessment includes environmental modeling or measurements to determine the dose to which the receptor is exposed. That dose or concentration is referred to as the *predicted environmental concentration* (PEC). The effect assessment includes using toxicological data to determine the highest dose or concentration at which it is certain that there will be no adverse effects to a certain receptor. This concentration is referred to as the *predicted no effect concentration* (PNEC), and is typically derived from toxicological dose-response curves. Such results are often expressed as the concentration at which half of the organisms died (LC50, where L stands for lethal and C for concentration) or where it was possible to see an effect on half of the organisms (EC50, where E stands for effect). Then these concentrations must be divided by a security/uncertainty/application factor to obtain a reliable PNEC. If the toxicological studies have measured a so called no effect concentration or level (NOEC or NOEL), this can be applied directly. However, if the toxicological measurements were not conducted on the exact species that one is interested in, or if there are very few studies that differ considerable in their results, then again security factors may be applied.

In the *risk characterization* the PEC and PNEC are compared. If the PEC is higher than the PNEC, i.e. if the ratio PEC/PNEC is higher than one, it indicates risk. If not, there may be no risk. The PEC and PNEC may also be expressed not as single numbers but as ranges or even probability distributions in order to conduct a more detailed characterization. The latter is the case when performing Monte Carlo simulations. In order to estimate the uncertainties of the results, a sensitivity analysis is often conducted. The last part of an ERA includes communication the results to different stakeholders and give recommendations for future studies, monitoring of the risks and other actions. This is often referred as *risk management* or *risk reduction*. In this study the ERA framework is applied almost directly. For specific considerations regarding exposure and effect assessments, see these two chapters below.

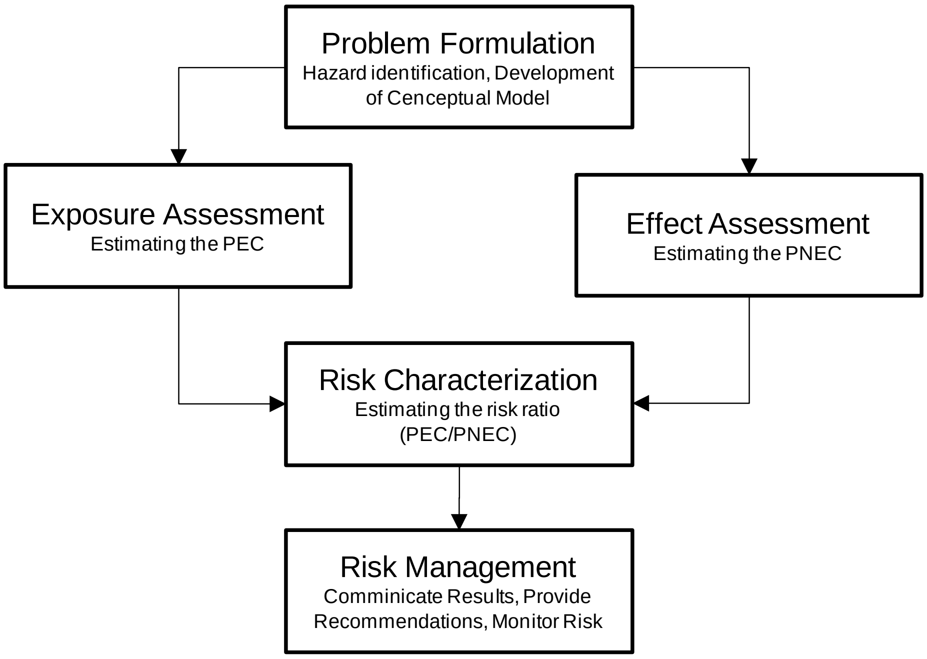

Figure 1. The ERA framework obtained from van Leeuwen and Vermeire (2007).

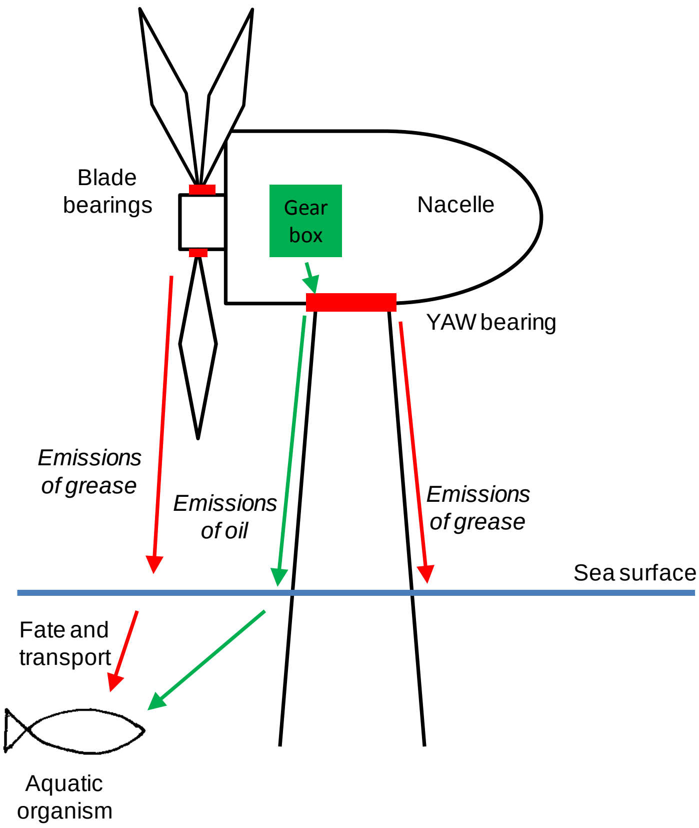

Figure 2. Conceptual model showing the emissions considered in this report.

3 Problem formulation

There are primarily four sources of chemical emissions (and thus potential stressors) used in wind power plants. These are grease for lubrication of bearings, gear box oil, hydraulic oil and chemicals used for cleaning of the plants. Neither the hydraulic oil nor cleaning chemicals has been included in this study. For grease, only that which is applied in bearings located in connection to the outside of the wind power plant has been considered: the grease on the YAW bearing and blade bearing[1]. The blade bearings allow for the blades to change angle, and the YAW bearing allows for the nacelle to turn horizontally. See Figure 2 for a rough conceptual model. The chemical products included in this ERA have thus been grease used in YAW and blade bearings and gear box oil. Leakage of these chemical products from wind power plants is a debated topic. Many of the experts, mainly industry representatives that have been contacted, suggest that no leakages occur. These include experts from Swedish Wind Energy, Svensk Vindkraftförening (Eng. Swedish Windpower Association) and the Vattenfall. An environmental impact assessment of the wind power park in Ulvatorp in Sweden clearly state that emissions occurring within the wind power plant cannot reach the outside of the wind power plant (Gothia Vind AB and Airtricity 2009). However, the photos in Appendix 1 indicate that leakages may occur. Also, studies performed confirm that oil spills from wind power plants do occur, often because of structural failures, operation failures or oil transfers (Etkin 2006). Finally, maintenance personnel have also confirmed emissions. Often it is the task of maintenance personnel to wipe off the inside of the nacelle from oil which has leaked out, and they made complaints about filthiness and slipperiness due to oil and grease leakages. This wiping off is believed to prevent emissions of oil and grease, but since maintenance often takes place one time per year only, at which time much oil and grease normally has leaked out, is would seem dubious if this risk prevention is sufficient to completely prevent emissions.

Seals are used in bearing applications to keep the lubricant inside the bearing as well as to prevent dirt and moisture from entering the bearing. In dynamic sealing at least one side of the sealing is in motion, and thus the seal has to be designed to allow for sliding. This in turn implies that the sealing function cannot be 100 percent since that would require no motion. There is thereby a tradeoff between friction and the sealing function. The required tightness of a seal is determined by the indented application of the bearing. In wind power applications the requirement from the turbine manufacturers is in general that the seal should be “tight”. The exact definition of tight is not specified further. Tight could imply no visible leaks, which could mean leakages of 1-5 percent. The major consequence of a leak for the wind power plant owner’s point of view is that the bearing is not lubricated sufficiently which might result in a break-down. This is the major concern related to seals leakages from a maintenance point of view, since it requires additional visits to the wind power plant. Reasons for additional seal leakages could be, for instance, wrong dimensions on the housing that the seal is mounted on, inaccurate surface properties on the running surface, assembly and mounting errors such

[1] Blade bearings are sometimes referred to as pitch bearings.

as damage to the seal edge, mounting of the seals with the wrong side towards the lubricant and mounting of bended seal borders. Over time the seal edge can be worn down. There is also a risk that the seal pop out which would cause a major leak.

The sealing of the blade bearings is critical as the weight load on these bearings is changing during the turn of the rotor hub and deformation is relatively high. The seal thereby has to balance heavy deformations. In addition, the positioning of the bearing leaves little space for the seal. The YAW bearings are also exposed to high deformation forces but deformation occurs less frequently compared to the blade bearings. The sealing of the gearbox is exposed to less deformation than the blade and blade bearings, and the movement of the bearings is continuous and sealing is exposed to less deformation.

3.1 Emission scenarios

Only little information about the magnitude of the leakages has been found. As stated above, many actors involved in the wind power sector would suggest that there are no emissions. Some revealed that it is often stated in environmental impact assessments of wind power plants that there will be no emissions, but that this statement is seldom further motivated. It is unclear whether the photos in Appendix 1 show an accidental, one time oil spill or a continuous leakage. For a 2 MW wind power plant, the amount of grease used for these bearings is 25 kg grease/year and 10 kg of these are tapped of during maintenance (Gothia Vind AB and Airtricity 2009). This implies that 15 kg of grease is emitted annually. According to several experts in the field, 25-30 percent of the grease is emitted. Since these bearings are positioned outside the nacelle, they are likely emitted to the environment. These figures are similar to reported figures from reports and experts on the field, see for instance Etkin (2006). As implied earlier, these emissions are not surprising considering the shape and function of the bearings: A completely sealed bearing would not be able to move and thus not function. Also, the seals may break.

Regarding the gear oil, experts claim that if the oil hose from the bottom of the gearbox breaks, all will leak out and that for a large wind power plant this mean 400-500 liter. In the environmental impact assessment of the wind power park in Ulvatorp, the amount of gearbox oil is stated at about 350 liter (Gothia Vind AB and Airtricity 2009), which is similar to the figures reported by experts.

However, according to the experts such breaks are unusual, whereas the most common leakage occur due to improper change of filters for the gear system. For those cases, an oil level sensor, if there is one, will stop the turbine after about 25 % of the oil has leaked out (i.e. about 100 liter). Depending on the design of the nacelle, the oil may leak out to the bottom of the nacelle and out on the tower outside. This may explain the leakage shown on the pictures in Appendix 1. However, sometimes the leakage is kept within the nacelle and may only reach the bottom of the plant, which will act as a container for the oil (Gothia Vind AB and Airtricity 2009).

Considering the uncertainty and variation in wind power plant construction, a worst case scenario has been considered in this report. A 2 MW wind power plant from which gearbox oil can leak out from the nacelle has been considered. The baseline case scenario is a pulse emission where the bottom of the oil house breaks and all oil (400 liter) together with all grease (25 kg) are emitted at the same time. For the grease, the scenario corresponds to an unlikely case where all seals on the blade and YAW bearings break. It could also correspond to a scenario where a boat collides with the wind power plant, although this was considered unlikely by Etkin (2006). However, if this scenario would imply a risk, it would give a clear signal that the leakages should be prevented. The effect of the emission size has been tested in a sensitivity analysis, where the impact of significantly lower emissions, 1 percent of the total available grease and oil, was investigated. This scenario has been referred to as the "low emission scenario", and roughly corresponds to "tight" seals with no visible leakages.

3.2 Stressors and endpoints

The choice of stressors was based on studies of material safety datasheets showing risk phrases and on available data. Compounds with risk phrases and available data were chosen. Regarding the grease, three different stressors have been considered:

- Mineral oil, which is the main component in lubricant grease (OECD 2004).
- Phosphate isodecyl/phenyl compounds, which are used as antioxidants (US EPA 2001).
- Zinc alkyl dithiophosphate, which is used as antiwear agent and antioxidant (Henry 1998; Krop 2002).

The mineral oil is assumed to only consist of alkanes with the general chemical formula C_nH_{2n+2} rather than of aromatic compounds, since this is the most common scenario (OECD 2004). Indeed, mineral oil and paraffinic liquid can most often be regarded as synonyms (Anderson et al. 2006). Regarding the synthetic oil which is often the main constituent of lubricant oil, it is assumed here to also consist of alkanes, which is not uncommon (OECD 2004). These alkanes can be very similar to mineral oil, and the two are assumed here to be equivalent. These two stressors together have henceforth been denoted "alkanes" only. The CAS number, function, chemical structure and typical concentrations of these compounds can be seen in Table 1. The endpoints considered were aquatic organisms such as fish, *Daphnia magna* and bacteria. It is further assumed that the organisms live in the vicinity of the wind power plant, which it true for several aquatic organisms, including some fish species. The air, soil and sediment compartments were not included.

Table 1. The CAS number, function, chemical structure and typical concentration of the stressors included in the ERA.

Chemical name	**CAS No.**	**Function**	**Chemical structure**	**Typical concentrations**
Grease				
Alkanes	-	Lubricant	C_nH_{2n+2}	70 %
Phosphate isodecyl/phenyl compounds	For instance 25448-25-3 25550-98-5 26544-23-0 101-02-0	Antiwear agent and antioxidant	Exemple: $(C_6H_5O)_2P(OC_{10}H_{21})$	1 %
Zinc alkyl dithiophosphate	68649-42-3	Antiwear agent and antioxidant	See Figure 3	5 %
Gear oil				
Alkanes	-	Lubricant	C_nH_{2n+2}	70 %

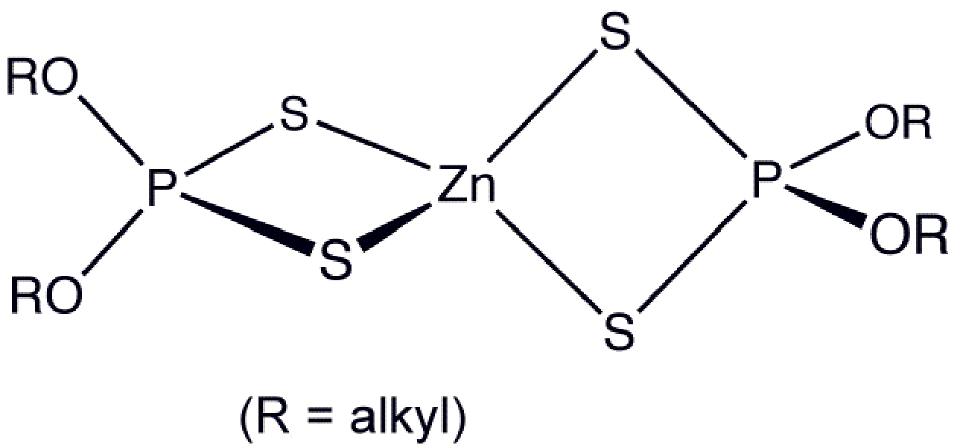

Figure 3. Chemical structure of zinc alkyl dithiophosphate.

4 Exposure assessment

The fate and transport of oil emitted to sea is described in detail in the book *Oil in the Sea* by the National Academy of Sciences (2003). Fate mechanisms which describe the environmental behavior of the oil based on information of the composition of the oil and properties of the water are presented. Among others, the following fate mechanisms are discussed:

Weathering – Physical and chemical breakdown of the oil.

Evaporation – The components of the oil enters gas phase.

Emulsification – The formation of water-oil colloidal mixtures.

Dissolution – Some water soluble components of oil may dissolve in water.

Oxidation – The reaction of oil with oxygen which ultimately creates carbon dioxide and water. This reaction can be mediated by sunlight and microorganisms.

Advection – The transport of oil due to the movement of water.

Langmuir circulation – The formation of different areas in the water due to for example wind currents, see photo in Appendix 2.

Horizontal dispersion

Vertical dispersion

Sinking and Sedimentation

Overwashing – The oil is “floating” just below the sea level.

Considering the many fate mechanisms, it is difficult to calculate a PEC for oil and grease in sea. The spreading of the oil both horizontally (due to e.g. Langmuir circulation, horizontal spreading) and vertically (due to e.g. vertical spreading, sinking, sedimentation, emulsification and dissolution) are depending on location and on uncertain and varying environmental parameters such as wind velocity and sea currents. Even to establish a concentration of oil in water, which is required to determine a PEC in an ERA, is difficult due to the partly heterogeneous nature of oil in water, see the photo in Appendix 2.

Due to these uncertainties and difficulties, a multi scenario approach has been applied. The concentration of stressors will depend on how far they spread horizontally (x), and on how far they spread vertically (y), see Figure 4. These distances x and y has been set to different values ranging from 0.1 m to 1000 m. A high value on x and a low value of y represent the case where almost no oil sinks, dissolves etc., but most oil stay floating on the sea surface. Contrary, a low value on x and a high value of y represents the case with low horizontal spreading. Note that since the density of oil is about 0.8 kg/m^3, compared to about 1 kg/m^3 for water, scenarios with high values of x and lower values of y are probably more realistic. But note also that big waves, surfactant additives etc. may change this common sense picture for some cases, and thus also scenarios with high values of y and low values of x are considered. A non-dynamic model is applied due to the lack of dynamic equations describing the fate of oil and grease in water.

It has been assumed here that the spreading is symmetric around the wind power plant with a radius of x. It is further assumed that there is an instant mixing in the water, leading to no concentration gradient. Instant mixing may seem crude, but is often assumed in chemical risk assessment (van Leeuwen and Vermeire 2007). Weathering and oxidation are omitted, but since biodegradation was suggested the most important route for which lubricants are removed from both soil and water (Lopes et al. 2010) is it included here. Bioavailability is excluded, since a PNEC for aquatic organisms is normally related to the concentration in water, and not the uptake. Evaporation is included and reduces the amount of oil and grease that may sink or spread. This results in the following equation for the none-dynamic pulse emission of alkanes in mineral and synthetic oil:

$$PEC(x,y) = \frac{m_{em} - m_{evap} - m_{bio}}{\pi x^2 y} \tag{1}$$

In equation 1, m_{em} is the emission, m_{evap} is the evaporization and m_{bio} is the biodegradation. All these are measured in kg. The book *Oil in the Sea* states that the evaporation of gasoline is close to 100 percent, about 40 percent for crude oil and about 5 percent for bunker oil (National Academy of Sciences 2003). Diesel oil evaporation does not seem to adopt a constant value, but rather continues to increase with time (National Academy of Sciences 2003). Diesel contains alkanes with 8 to 21 carbon atoms per molecule, and gasoline contains alkanes with 4 to 12 carbon atoms. The higher tendency of gasoline to evaporate is much due to the shorter alkane molecules. Mineral oil contains mainly of alkanes with 15 to 40 carbon atoms, and should thus be even less inclined to evaporate. The exact evaporation percentage of mineral and synthetic oil is difficult to estimate, but a fair estimate based on basic chemistry would be 20 percent, which was applied for the baseline case in this report. This is a typical evaporation percentage for mineral oil (Lansdown and Gupta 1985). The range of 5-50 percent was however tested in a sensitivity analysis. Regarding biodegradation, it is assumed that the amount of mineral oil not evaporated is exposed to biodegradation, and for the baseline case 40 percent biodegradation is assumed, but the range 20-60 percent which was reported in a study (Willing 2001) was tested in a sensitivity analysis. The exact content of synthetic oil varies depending on application, but it is assumed here that is approximates that of mineral oil.

For phosphate isodecyl/phenyl compounds very little information on biodegradation, stability, transport and distribution exist (US EPA 2001). One of the compounds in that group, diisodecylphenyl, was reported not to be biodegradable (US EPA 2001). This indicates that m_{bio} is small for the whole group, and was thus assumed to be zero. No information on evaporation has been found, but since the molecule is quite heavy with a molecular weight of 374 g/mol the evaporation is probably low due to extensive formation of van der Waal bonds and was thus assumed to be zero. Regarding zinc alkyl dithiophosphate, it is not biodegradable (Krop 2002). No evaporation data whatsoever has been found regarding the fate of this compound, although it is known to be surface active and dissolves relatively easily in water. It was thus conservatively assumed that both m_{bio} and m_{evap} are zero. Judging by its heavy molecular weight of about 850 g/mol it is probably not very volatile. Both the phosphate isodecyl/phenyl compounds and the zinc alkyl dithiophosphate were assumed to mix instantly, as was assumed for the alkanes, and equation 1 was used to calculate the PEC according to the conceptual model in Figure 4 for these compounds as well.

We do not present explicit results from the exposure assessment here, but instead compare the PECs to the PNECs in the risk characterization below.

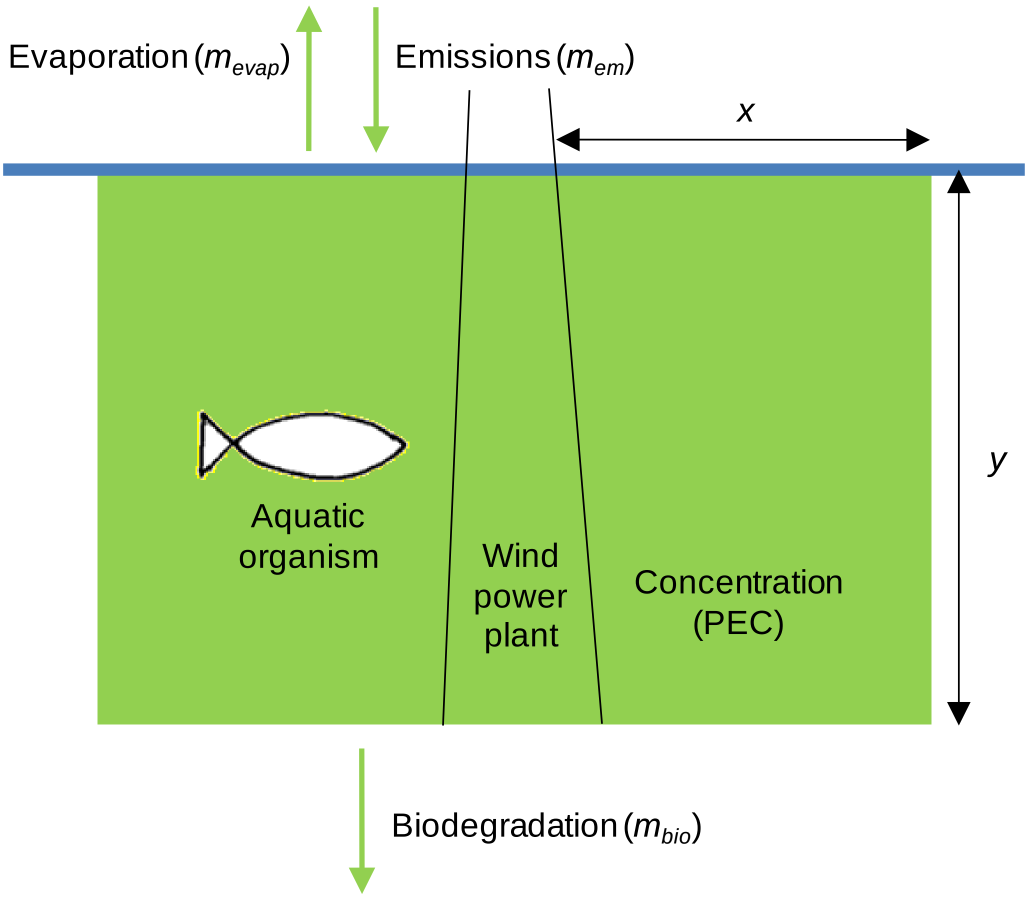

Figure 4. Conceptual model describing the procedure of the exposure assessment in this study, which is applied in the light of the high uncertainties. The parameters *x* and *y* are varied to cover many potential sinking and spreading scenarios.

5 Effect assessment

In the effect assessments, (eco)toxicological data was acquired to estimate at which concentration adverse effects from the stressors can be expected. Often such data is scarce, and must often be extrapolated from data on other organisms than those of interest. There exist several toxicological studies on mineral oil with for instance rat as endpoint, see for instance Henry (1998) or Warne and Halder (1984). However, when interested in the effects on aquatic organisms, these data are of little relevance. Besides, the same problem of establishing a PEC in the light of the heterogeneity of oil in water is present when establishing a PNEC as well. When interested in the effects of a water insoluble substance such as oil or grease on aquatic organisms, the problem of heterogeneity arises again: Since the substance does not spread evenly in water it is difficult to obtain a homogenous concentration. Significant parts of the test substance may be floating on the surface, thus not exposing organisms in other parts of the test system. Organisms that approaches the surface may be trapped in the organic layer, leading to an overestimation of toxicity (Willing 2001). But by applying the concept of water accommodated fractions (WAFs), which includes continuous stirring of the water and removal of the insoluble fractions, these problems can be somewhat managed. Although it is difficult for us to judge if this method of mixing the phases is the most appropriate, these figures have been applied. This seems to be a conservative choice since ecotoxicological results from studies of spent lubrication oil where no mixing took place seem to indicate lower toxicity (Otitoloju 2006), although one could of course argue that a system with no mixing of oil and water may be the more environmentally relevant thing to study. On the other hand, the mixing may be higher in natural systems compared to laboratories due to wind, waves, biodegradation, currents etc.

The lowest ecotoxicological value for mineral oil in Willing (2001) was for fish at 500 mg/l, see Table 2. However, these tests were for acute ecotoxicity. In order to obtain a PNEC which accounts for chronic damages, LC50 values are often divided by an assessment factor, commonly 10 (Burgman 2005). The PNEC applied in this study for alkanes is thus 50 mg/l. This figure is assumed to be valid for synthetic oil as well.

Toxicity data existed for diisodecylphenyl phosphate and isodecyldiphenyl phosphate, which both belong to the group phosphate isodecyl/phenyl compounds. The lowest toxicity value for each organism was chosen, see Table 2. In this case, *Daphnia magna* seems to be the most sensitive organism with an EC50 value of 0.2 mg/l. Since this was for acute toxicity, again the figure is divided with 10 to obtain chronic toxicity values, giving 20 µg/l as PNEC for phosphate isodecyl/phenyl compounds.

Several toxicity values for zinc alkyl dithiophosphate was reported in Skak et al. (2005). The lowest was for *Daphnia magna*, where some acute toxicity values were as low as 0.1 mg/l, see Table 2. Again, by dividing with 10 to obtain a PNEC of 10 µg/l.

The approach in this report is to study three stressors separately. In a memorandum from the United States Environmental Protection Agency (US EPA) toxicity studies using a different approach are presented (Anderson et al. 2006). In that memorandum toxicity values for whole lubricant products are given, rather than focusing on single chemical compounds as in this report. One benefit with that method is that synergetic effects are taken into account, which may give a more realistic idea of the joint toxicity of the product. However, it is not certain that the product stays inert in the environment. Some chemical compounds may degrade or evaporate faster than other, so organisms may not become exposed to the same mixture that was studied for its toxicity. Also, it may be difficult to extrapolate the results to a lubricant oil or fat with different composition. As stated by Anderson et al. (2006), one of the major uncertainties in the studies were "Not knowing the constituents of the products that are applied and their relative proportions." Applying that method it may also be difficult to give advices for risk management. Perhaps the toxicity of the whole product was mainly the cause of one single additive which is easy to substitute? Or perhaps a compound which constitutes more than 90 percent of the product caused most of the toxicity? In the formed case substituting the single additive may be the best way to reduce risk, whereas in the later case a more radical substitution may be needed for risk reduction.

It should however be noted that Anderson et al. (2006) report the EC50 value for the whole products of less than 1 mg/l for *Daphnia magna*. The lowest reported EC50 value for the same organism was 0.02 mg/l. Applying any of these values for all of the fat and oil would result in a significantly higher total risk than the approach in this report.

Table 2. Ecotoxicological data for alkanes (mineral oil), phosphate isodecyl/phenyl compounds and zinc alkyl dithiophosphate.

Stressor	**Indicator**	**Value**	**Reference**
Alkanes (mineral oil)	LC50 for fish [mg/l]	500	Willing (2001)
Alkanes (mineral oil)	EC50 for *Daphnia magna* [mg/l]	>1000	Willing (2001)
Alkanes (mineral oil)	EC0 for bacteria [mg/l]	>1000	Willing (2001)
Phosphate isodecyl/phenyl compounds	LC50 for fish [mg/l]	>16	US EPA (2001)
Phosphate isodecyl/phenyl compounds	EC50 for algae [mg/l]	1.6	US EPA (2001)
Phosphate isodecyl/phenyl compounds	EC50 for *Daphnia magna* [mg/l]	0.2	US EPA (2001)
Zinc alkyl dithiophosphate	LC50 for *Daphnia magna* [mg/l]	0.1	Skak et al. (2005)

6 Risk characterization

Here the PECs for alkanes, phosphate isodecyl/phenyl compounds and zinc alkyl dithiophosphate, which were derived in the exposure assessment chapter, are compared to the PNECs for the same compounds, which were derived in the effect assessment chapter. See Table 3-5 for results. As stated above, a ratio PEC/PNEC above one indicate risk, and has thus been marked red in the tables.

6.1 Alkanes

As can be seen, if the alkanes would spread 0.1 or 1 m horizontally and 1000 m vertically, the concentration of alkanes would be so high that there would be a risk for aquatic organisms. Similarly, if the alkanes would spread 0.1 or 1 m vertically, and 1000 m horizontally, there would also be a risk. Table 3 also reveals that if the alkanes spread approximately the same distance in both directions, there would be a risk for damage to aquatic organisms if they would spread about 10 m in each direction. For high values (>100 m) of both *x* and *y*, the alkanes would be so diluted that they would not constitute a risk.

As stated above, the most probable scenario is that the alkanes will spread the most in the horizontal direction and less in the vertical direction, meaning that the value of *x* will probably be higher than the value of *y*. This is due to the lower density of alkanes compared to water and that alkanes are difficult to dissolve in water (Boyde 2002). A probable scenario for many cases would thus be that the alkanes spread only 0.1-1 m vertically, although for example high waves may change this. But 1000 m is in any case a very unlikely value for *y*. For one thing, many sea waters are not even 1000 m deep, especially those waters where wind power plants are being built. But even if the spreading of alkanes vertically would be as low as 0.1-1 m, Table 3 shows that the alkanes can spread as much as 1 km away from the wind power plant horizontally and still reach concentrations higher than the predicted safe concentration. If the alkanes would stay close to the surface, the concentration in that region many thus be high enough to constitute a risk despite massive horizontal spreading. This indicates that leakage of alkanes from wind power plants constitutes a risk for aquatic organisms and should be prevented.

Note that the scenario where both *x* and *y* are low (0.1-1 m) constitutes quite unlikely scenarios, since it requires that the alkanes spread very little in sea water. That the alkanes would stay within 1 m^3 close to the wind power plant would almost defy the second law of thermodynamics, which in its simplified form is sometimes stated "everything spreads". Thus the very high PEC/PNEC ratio for the low values of both *x* and *y* would probably not be encountered in nature. Note also that the results in Table 3 depend on the emissions of alkanes, which was assumed to be very high in this baseline case scenario. The results also depend on the evaporation and biodegradation which were difficult to estimate for some cases. These three parameters have thus been tested in a sensitivity analysis below.

6.2 Phosphate isodecyl/phenyl compounds

The same pattern as for alkanes can be found for phosphate isodecyl/phenyl compounds, see Table 4. If the phosphate isodecyl/phenyl compounds would spread 0.1 or 1 m horizontally and 1000 m vertically, the concentration of phosphate isodecyl/phenyl compounds would be so high that there would pose a risk to aquatic organisms. Also, if the phosphate isodecyl/phenyl compounds would spread 0.1 or 1 m vertically, and 1000 m horizontally, there would also be a risk. If the phosphate isodecyl/phenyl compounds would spread approximately the same distance in both directions, there would be a risk for damage to aquatic organisms if they would spread about 10 m in each direction. For high values (>100 m) of both *x* and *y*, the phosphate isodecyl/phenyl compounds would be so diluted that they would not constitute a risk.

For the phosphate isodecyl/phenyl compounds it is very difficult to say which values of *y* and *x* that are most likely. Again, that the phosphate isodecyl/phenyl compounds would stay within 1 m^3 of the water close to the wind power plant, thus obtaining PEC/PNEC rations of $>10^4$, seems unlikely. But whether they will spread the most in horizontal or vertical direction is difficult to say due to the scarce data regarding the fate of phosphate isodecyl/phenyl compounds (US EPA 2001). In any case, the results in Table 4 indicate that exposure to phosphate isodecyl/phenyl compound emissions from wind power plants may pose a risk to aquatic organisms.

6.3 Zinc alkyl dithiophosphate

For zinc alkyl dithiophosphate, the risk was slightly higher than for alkanes and the phosphate isodecyl/phenyl compounds, see Table 5. The results are mostly the same: If the zinc alkyl dithiophosphate would spread 0.1 or 1 m horizontally and 1000 m vertically, the concentration of zinc alkyl dithiophosphate would be so high that there would be a risk for aquatic organisms. Also, if the zinc alkyl dithiophosphate would spread 0.1 or 1 m vertically, and 1000 m horizontally, there would also be a risk. If the zinc alkyl dithiophosphate would spread approximately the same distance in both directions, there would be a risk for damage to aquatic organisms if they would spread about 10 m in each direction. For high values (>100 m) of both *x* and *y*, the zinc alkyl dithiophosphate would be so diluted that they would not constitute a risk. However, for the case of 100 m spread in one direction, and 10 m spread in the other, zinc alkyl dithiophosphate show risk, which was not the case for the other two stressors. Again, similar to the phosphate isodecyl/phenyl compounds, it is very difficult to say anything about the likeliness of the values of x and y for the case of zinc alkyl dithiophosphate due to lack of data. The spreading will however again probably go beyond the 1 m^3 closest to the wind power plant.

Table 3. The ratio PEC/PNEC for alkanes is shown for different values on *x* and *y* from Figure 3, for the baseline case. Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^6	10^5	10^4	1000	100
	1	10^5	10^4	100	10	1
	10	10^4	100	1	0.1	0.01
	100	1000	10	0.1	0.001	10^{-4}
	1000	100	1	0.01	10^{-4}	10^{-6}

Table 4. The ratio PEC/PNEC for phosphate isodecyl/phenyl compounds is shown for different values on *x* and *y* from Figure 3, for the baseline case. Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^6	10^5	10^4	1000	100
	1	10^5	10^4	100	10	1
	10	10^4	100	1	0.1	0.01
	100	1000	10	0.1	0.001	10^{-4}
	1000	100	1	0.01	10^{-4}	10^{-6}

Table 5. The ratio PEC/PNEC for zinc alkyl dithiophosphate is shown for different values on *x* and *y* from Figure 3, for the baseline case. Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^7	10^6	10^5	10^4	1000
	1	10^6	10^4	1000	100	10
	10	10^5	1000	10	1	0.1
	100	10^4	100	1	0.01	0.001
	1000	1000	10	0.1	0.001	10^{-5}

7 Limited sensitivity analysis

Apart from x and y, which have already been set to different values above, the results shown in Table 3-5 depend on the emissions of oil and grease (m_{em}), the evaporation (m_{evap}) and the biodegradation (m_{bio}). These parameters have thus been varied within probable ranges below.

7.1 Low emission scenario

The emissions in the baseline case, which was a worst case scenario, were set to 400 l of oil and 25 kg of grease. As stated above, these figures correspond to a total breakdown of the wind power plant, and are applied for conservative reasons due to the high uncertainties. To estimate the sensitivity of these emissions, both the emission of oil and grease were reduced to 1 percent in a so called low emission scenario. This corresponds to oil emissions of 4 l and grease emissions of 0.25 kg. Table 6-8 gives the results for the low emission scenario for the tree stressors studied.

It can be seen that the risk has decreased somewhat. But the main message from the baseline case still remains: At low vertical spreading, which is expected at least for alkanes, the risk of adverse effects on aquatic organisms is significant even if the stressors spread significantly horizontally. An expected low vertical spreading of the stressors will lead to risk of adverse effects on aquatic biota at a horizontal distance of as far away as 10-1000 m from the wind power plant. So even if the emissions are significantly lower than for the baseline case, this sensitivity analysis show that the conclusions from the risk characterizations still hold. Again, zinc alkyl dithiophosphate shows slightly higher risk than the other two stressors, and alkanes and phosphate isodecyl/phenyl compounds show similar risk.

Table 6. The ratio PEC/PNEC for alkanes is shown for different values on *x* and *y* from Figure 3, for the low emission scenario (1 percent of baseline case). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^4	1000	100	10	1
	1	1000	10	1	0.1	0.01
	10	100	1	0.01	0.001	10^{-4}
	100	10	0.1	0.001	10^{-5}	10^{-6}
	1000	1	0.01	10^{-4}	10^{-6}	10^{-8}

Table 7. The ratio PEC/PNEC for phosphate isodecyl/phenyl compounds is shown for different values on *x* and *y* from Figure 3, for the low emission scenario (1 percent of baseline case). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^4	1000	100	10	1
	1	1000	10	1	0.1	0.01
	10	100	1	0.01	0.001	10^{-4}
	100	10	0.1	0.001	10^{-5}	10^{-6}
	1000	1	0.01	10^{-4}	10^{-6}	10^{-8}

Table 8. The ratio PEC/PNEC for zinc alkyl dithiophosphate is shown for different values on *x* and *y* from Figure 3, for the low emission scenario (1 percent of baseline case). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^5	104	1000	100	10
	1	104	100	10	1	0.1
	10	1000	10	0.1	0.01	10^{-3}
	100	100	1	0.01	10^{-4}	10^{-5}
	1000	10	0.1	10^{-3}	10^{-5}	10^{-7}

7.2 Variations in evaporation

In the baseline case, an evaporation of 20 percent was applied for the alkanes. However, this figure was derived much from chemical reasoning and is thus regarded as uncertain. The book *Oil in the Sea* lists how many percentages of different substances that are expected to evaporate (National Academy of Sciences 2003). The lowest evaporation is expected at about 5 percent, with is for bunker oil, which contains carbon compounds with 9 to 70 carbon atoms. Mineral oil normally has 15 to 40 carbon atoms, and it is thus unlikely that the mineral oil would have a lower evaporation. 5 percent is thus a reasonable lowest limit. Regarding highest limit, crude oil evaporates to a degree of 50 percent. Since mineral oil is produced through distillation of crude oil, it seems very unlikely that crude oil could ever be more volatile than mineral oil. 50 percent is thus a reasonable highest limit. This is confirmed by evaporation tests performed by Lansdown and Gupta (1985). Again, the same figures as for alkanes in mineral oil are assumed for the alkanes in synthetic oil.

Results for the case of 5 percent evaporation of alkanes are shown in Table 9. The results show that a lower evaporation gives a very similar result as the baseline case. For the high evaporation scenario, however, the risk became slightly lower for aquatic organisms, see Table 10. It should however be noted that this means that the alkanes enter the air compartment and can thus cause harm to organisms there, for instance sea birds. These are however not included in this ERA.

The other two stressors, zinc alkyl dithiophosphate and the phosphate isodecyl/phenyl compounds, were not included in the sensitivity analysis of the evaporation since no data to provide a basis for such a sensitivity analysis has been found for these compounds.

Table 9. The ratio PEC/PNEC for alkanes is shown for different values on *x* and *y* from Figure 3, for the low evaporation scenario (5 percent evaporation). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^6	10^5	10^4	1000	100
	1	10^5	10^4	100	10	1
	10	10^4	100	1	0.1	0.01
	100	1000	10	0.1	0.001	10^{-4}
	1000	100	1	0.01	10^{-4}	10^{-6}

Table 10. The ratio PEC/PNEC for alkanes is shown for different values on *x* and *y* from Figure 3, for the high evaporation scenario (50 percent evaporation). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^5	104	1000	100	10
	1	104	100	10	1	0.1
	10	1000	10	0.1	0.01	10^{-3}
	100	100	1	0.01	10^{-4}	10^{-5}
	1000	10	0.1	10^{-3}	10^{-5}	10^{-7}

7.4 Variations in biodegradation

In the baseline case, the biodegradation was set to 40 percent. However, there are indications that the biodegradation can vary between 20-60 (Willing 2001). These scenarios were thus tested in this sensitivity analysis. The results shown in Table 11 and 12 reveal that the low biodegradation scenario did not vary significantly compared to the baseline case. However, for the high biodegradation scenario, the risk became slightly lower than for the baseline case.

Again, due to lack of biodegradation data for the phosphate isodecyl/phenyl compounds, and a reference stating clearly zinc alkyl dithiophosphate was not biodegradable (Krop 2002), these were not included in the sensitivity analysis of biodegradation.

Table 11. The ratio PEC/PNEC for alkanes is shown for different values on *x* and *y* from Figure 3, for the low biodegradation scenario (20 percent biodegradation). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^6	10^5	10^4	1000	100
	1	10^5	10^4	100	10	1
	10	10^4	100	1	0.1	0.01
	100	1000	10	0.1	0.001	10^{-4}
	1000	100	1	0.01	10^{-4}	10^{-6}

Table 12. The ratio PEC/PNEC for alkanes is shown for different values on *x* and *y* from Figure 3, for the high biodegradation scenario (60 percent biodegradation). Ratios above one indicate risk and have thus been marked red.

		***x* [m]**				
		0.1	**1**	**10**	**100**	**1000**
***y* [m]**	**0.1**	10^5	104	1000	100	10
	1	104	100	10	1	0.1
	10	1000	10	0.1	0.01	10^{-3}
	100	100	1	0.01	10^{-4}	10^{-5}
	1000	10	0.1	10^{-3}	10^{-5}	10^{-7}

8 Discussion and recommendations

One important suggestion for future studies based on our findings is to reduce the uncertainties in input data outlined in this study. Above all, emissions of oil and grease from wind power plants must be monitored and reliable data must be obtained. Only then can more detailed ERAs be performed. The origin of these emissions and which conditions that is required for emissions to occur should also be determined. Besides information about emissions, further efforts should be put into quantifying the different fate mechanisms outlined in *Oil in the Sea* (National Academy of Sciences 2003). Especially sedimentation and sinking are important to quantify, since the value of those may tell if the sediments below the wind power plant are threatened by oil and grease emissions. In this study, only aquatic organisms were considered endpoints. It may be a possibility to develop a more time dependent model and estimate influence area taking continuous emissions and sink processes into consideration. More detailed data regarding the fate of especially the two additives should be obtained by either more intense data gathering or by experimental tests. For the effects assessment the influence on the surface-microlayer bacterial and algal flora might be interesting to assess. The model calculations performed here would benefit from comparison with measurements of the included stressors from the surrounding of off-shore water power plants.

Also, the importance of scale should be included in future ERAs of chemical emissions from wind power plants. In this report, only one single wind power plant is considered. For a wind power park, the problem would be scaled up. For instance, the newly built wind power park Lillgrund between Sweden and Denmark consist of 48 wind power plants (Jeppsson et al. 2008). These wind power plants will be situated in a more or less spherical group with about 100 m distance between them (Jeppsson et al. 2008). Thus, if leakages would occur, the concentration of oil and grease in that area could be many times higher than estimated in this report for one wind power plant only. Such large wind power plant parks are likely to be built in the future as well. In addition, wind power plants are of course not the only technical device that makes use of fat and grease. Many other applications remain to be studied.

Below some recommendations for improvements are given based on the results of this study for the specific case of wind power.

8.1 Technical risk reduction

One major recommendation is to use oil and grease that are less toxic and more biodegradeble, such as natural triglyceride oil from rapeseed, canola or soybean (Boyde 2002). For instance, lubricant materials such as native and synthetic esters were shown to have a much lower ecotoxicity compared to mineral oil (Willing 2001). In addition, the biodegradation of such biolubricants as described in Boyde (2002) were shown to be significantly higher than for mineral oil and synthetic oil; almost 100 percent. Of course, the technical performance of such oils must also be taken into consideration. But if leakages are to an extent inevitable, biodegradable oil and grease may be a good option. Bearings and seals that reduce oil and greas emissions would also be recommended based on this study. The perhaps most important technical improvement would be better monitoring systems. Oil level sensors that allow 25 percent of the oil to be emitted before it stops the wind turbine, as described by some experts, is obviously a system that could be improved.

8.2 Organizational risk reduction

Besides technical aspects, the way wind power plant owners organize the maintenance may influence the leakage of oil and grease. The impact of organizing on environmental performance was studied by Brunklaus (2008). One example given was the lower energy and water requirements of some houses, which were shown to be due to the different management practices of the housing companies. The one with the lowest energy and water requirements employed personal that felt strongly for the building and did continuous caretaking. The other housing company had a more emergency-driven approach, and seldom performed preventive measures. Whether the same logic applies to wind power is uncertain, since wind power plant management has not yet been studied from an environmental point of view. But surely organizational aspects are of importance. For instance, emissions of oil and grease may occur during maintenance. These could be reduced if, for instance, the personal was provided with suitable equipment. More extensive monitoring by maintenance personal would provide increased safety and reduce the dependence on the technical monitoring. Currently, maintenance of wind power plants is often conducted one time every year, and there are plans to reduce this to one time per two years. Increasing maintenance, rather than reducing it, may help to reduce oil and grease emissions.

9 References

Anderson, Brian, Stephen Carey and Mark Corbin (2006). *Memorandum Describing the Environmental Fate and Effect Division's Ecological Risk Assessment on Aliphatic Oils*. Washington DC: US EPA.

Boyde, S. (2002). Green lubricants. Environmental benefits and impacts of lubrication. *Green Chemistry* 4(4): 293-307.

Brunklaus, B. (2008). Organising matters for the environment - Environmental studies on housing managemant and buildings. Environmental Systems Analysis. Gothenburg, Chalmers University of Technology. PhD.

Burgman, M.A. (2005). *Risks and Decicions for Conservation and Environmental Management*. Cambridge: Cambidge University Press.

EEA and UNEP (1998). *Chemicals in the European Environment: Low Doses, High Stakes?*

Einarsson, Elin (2009). Emissioner från bildäck - Metod och tillämpning av miljöriskbedömning för emissions från varor. Institutionen för Teknik och samhälle. Lund, Lunds Tekniska Högskola. Civilingenjör.

Etkin, D.S. (2006). *Oil Spill Probability Analysis for the Cape Wind Energy Project in Nantucket Sound*. Cortlandt Manor: Environmental Research Consulting.

Gothia Vind AB and Airtricity (2009). *Samrådsunderlag Vindpark Ulvatorp*.

Henry, J.A. (1998). Composition and toxicity of petroleum products and their additives. *Human & Experimental Toxicology* 17: 111-123.

Jacobson, M. Z. (2009). Review of solutions to global warming, air pollution and energy security. *Geochimica Et Cosmochimica Acta* 73(13): A581-A581.

Jacobson, M.Z. and M.A. Delucchi (2009). A Path to Sustainable Energy by 2030. *Scientific American* November: 58-65.

Jeppsson, J., P.E. Larsen and Å. Larsson (2008). *Technical Description Lillgrund Wind Power Plant*: Swedish Energy Agency and Vattenfall.

Krop, H.B. (2002). *Health and environmental hazards of commonly used additives in lubricants*. Amsterdam: European Lubricating Grease Institute.

Lansdown, A.R. and R. Gupta (1985). *The Influence of Evaporation on Grease Life*: NLGI Spokesman.

Lopes, Paulo, Renato Montagnolli, Renata de Fátima Domingues and Ederio Bidoia (2010). Toxicity and Biodegradation in Sandy Soil Contaminated by Lubricant Oils. *Bulletin of Environmental Contamination and Toxicology* 84(4): 454-458.

Lu, Xi, Michael B. McElroy and Juha Kiviluoma (2009). Global potential for wind-generated electricity. *Proceedings of the National Academy of Sciences* 106(27): 10933-10938.

National Academy of Sciences (2003). *Oil in the Sea III*. Washington DC: The National Academies Press.

OECD (2004). *EMISSION SCENARIO DOCUMENT ON LUBRICANTS AND LUBRICANT ADDITIVES*. ENV/JM/MONO(2004)21: OECD Series on Emission Scenario Documents No. 10.

Otitoloju, Adebayo A. (2006). Joint action toxicity of spent lubrication oil and laundry detergent against *Poecilia reticulata* (Telostei: Poeciliidae). *African Journal of Aquatic Science* 31(1): 125-129.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, et al. (2009). A safe operating space for humanity. *Nature* 461(7263): 472-475.

Skak, Christine, Jens Otto Rasmussen, Morten Nilsson, Michael M. Pederson and T. Mathieson (2005). *Mapping and development of alternatives to chlorinated lubricants in the metal industri (KLORPARAFRI)*: Danish Environmental Protection Agency.

Suter, G.W., L.W. Barnthouse, S.M. Bartell, T. Mill and S. Patersson (1993). *Ecological Risk Assessment*. Cambridge: Cambridge University Press.

Swedish Energy Agency (2008). *Energiläget 2008 (Eng. State of energy in 2008)*: Eskilstuna, Sweden.

Swedish Environmental Objectives Council (2009). *Sweden's Environmental Objectives in Brief and a Summary of the Environmental Objectives Council's Progress Report*.

Swedish EPA (2010). *Vindkraftens miljöpåverkan - resultat från forskning 2005-2009 inom Vindval*.

US EPA (1998). *Guidelines for Ecological Risk Assessment*: Washington DC.

US EPA (2001). *U.S. HIGH PRODUCTION VOLUME (HPV) CHEMICAL CHALLENGE PROGRAM JUSTIFICATION, TEST PLAN, AND ROBUST SUMMARIES: PHOSPHITE ISODECYL/PHENYL CHEMICAL CATEGORY*: Washington, D.C.

van Leeuwen, C.J. and T.G. Vermeire (2007). *Risk Assessment of Chemicals*. Dordrecht: Kluwer Academic Publishers.

Warne, T.M. and C.A. Halder (1984). Toxicity of Lubricationg Oils. *Journal of the American Society of Lubrication Engineers* 42(2): 97-103.

Vattenfall (2005). *Life-Cycle Assessment of Vattenfall's Electricity in Sweden*.

Willing, Andreas (2001). Lubricants based on renewable resources - an environmentally compatible alternative to mineral oil products. *Chemosphere* 43(1): 89-98.

10 Appendix 1

Photo of oil leakage from wind power plant. Source:
http://www.iberica2000.org/documents/eolica/photos/contamination/.

Photo of oil leakage from wind power plant. Source:
http://www.iberica2000.org/documents/eolica/photos/contamination/.

Photo of oil leakage from wind power plant. Source:
http://www.iberica2000.org/documents/eolica/photos/contamination/.

Photo of contaminated soil below a wind power plant. Source:
http://www.iberica2000.org/documents/eolica/photos/contamination/.

Photo of washing of a wind power plant. Source:
http://www.iberica2000.org/documents/eolica/photos/contamination/.

Photo of washing of a wind power plant. Source:
http://www.iberica2000.org/documents/eolica/photos/contamination/.

11 Appendix 2

Photo of oil in water, showing the partly heterogeneous mixing of the two liquids, which makes it difficult to establish a PEC of oil in water. Photo taken from national Academy of Sciences (2003).