# Register study on noise from wind turbines and health

The number and size of wind turbines has increased markedly during the last decades. Although research has found that traffic noise increases the risk for major diseases such as those of the cardiovascular system (1-4) and diabetes (5), potential health effects of wind turbine noise are virtually unexplored.

**The aim** of this project is to use unique Danish registers to investigate the following hypotheses:

- long-term exposure to wind turbine noise is associated with increased risk for diabetes
- long-term exposure to wind turbine noise is associated with increased use of anti-hypertensive medicine
- long-term exposure to wind turbine noise is associated with increased use of anti-depressants
- long-term exposure to wind turbine noise is associated with increased use of sleep medication
- exposure to wind turbine noise during pregnancy is associated with perinatal outcomes, including low birth weight and small for gestational age

## BACKGROUND

Hearing is a permanent process essential for human survival and communication. However, the human organism is not able to shut off noise and therefore noise can have a number of unwanted effects, such as reduction of fidelity of communication, interference with cognitive processes and disturbance of sleep.

Figure 1 shows two pathways through which noise exposure can affect human health: directly (a) and indirectly via sleep disturbance (b + c) (6).

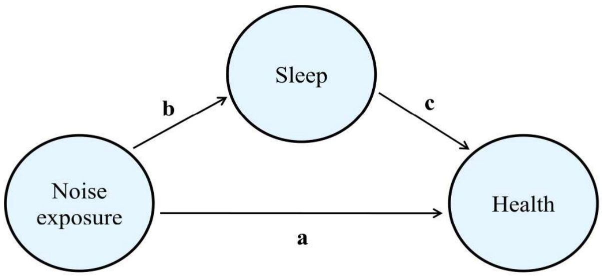


**Figure 1: Assumed relationship between noise exposure, sleep and health (modified from WHO, 2009)**

Noise acts as a stressor and, according to the general stress model, provokes a typical stress response, including hyperactivity of the sympathetic autonomic nervous system and activation of the hypothalamus–pituitary–adrenal axis, resulting in increased blood pressure and heart rate as well as high levels of the stress hormone cortisol (7, 8).

Exposure to noise during night-time is thought to be particularly hazardous (6). Studies have shown that traffic noise at night causes a full range of sleep disturbance from minor unconscious autonomic perturbations, such as sleep stage changes and body movements, to full awakening (9-11). Disturbance of sleep has been associated with various physiological changes, such as effects on metabolic, endocrine, endothelial and immune system function (12-17).

Long-term exposure to traffic noise has consistently been associated with cardiovascular disease (1-4). However, given the proposed mechanism of actions (stress and sleep disturbance), other health outcomes are likely to be associated with exposure to noise, including:

- *Diabetes*. Sympathetic reactivity and sleep disturbances have been associated with reduced insulin sensitivity, increased morning levels of glucose, decreased leptin and elevated ghrelin levels resulting in up regulation of appetite, as well as an increased risk for diabetes in epidemiological studies (18-23). Furthermore, we have recently found that exposure to road traffic noise was associated with an increased risk for diabetes in a prospective cohort of more than 50 000 participants (5).

- *Hypertension.* Noise exposure has been associated with increased risk for hypertension (24). In a large field study of 4 800 persons living close to airports, significant dose-response relationships between both aircraft and road traffic noise and risk of hypertension was found (25). The study also found aircraft noise to be associated with an increased risk of self-reported use of antihypertensive medication in the Dutch and UK part of the study, although this was not seen for four other study centers (26).

- *Depression*. Chronic stress (27) and sleep disturbances (28, 29) are known risk factors for depression. Also, depression is among the symptoms ascribed to wind turbines by nearby residents (30, 31), although there are no scientific studies on this. For other sources of environmental noise, results are inconclusive. Early studies on airport noise reported increased risk of psychiatric admission or diagnose (32, 33). However, these studies had severe methodological limitations. A later study on road traffic noise from 1996, including better control for confounders than the earliest studies, did not find any significant associations with questionnaire based depression scores (34). More recently, associations between noise annoyance and use of anti-depressive medication or physician diagnosed depression have been reported for noise from road traffic and other neighborhood sources (35) and for airport noise (26). All the studies are, however, relatively small and based on self-reported data, which is inherently prone to biases.

- *Sleep.* Sleep disturbance is a common complaint from people residing close to wind turbines (30, 31). Studies on this are, however, inconsistent and have a range of methodological weaknesses, including reliance on self-reported sleep disturbance. Studies with modeled noise levels from other environmental sources, but relying on self-reported use of sleep medication have found some suggestions of an association but not consistently across studies or noise sources (26, 36, 37). Preliminary data from a Norwegian study investigating both objective register-based prescription data and the more bias prone information on self-reported use of sleep medication, found a positive association between modeled road traffic noise and likelihood of redeeming sleep medication, whereas no such association was seen for self-reported medication (38).

- *Perinatal endpoints*. Studies have suggested that maternal prenatal stress and sleep disturbance can result in preterm birth and low birth weight of the offspring (39-41). Also, a recent study found that in a cohort of almost 70 000 singleton births, exposure to road traffic noise during pregnancy was significantly associated with lower birth weight (42).

Wind turbine noise levels are generally low compared to urban traffic noise levels. According to Danish regulations, the level of wind turbine noise at dwellings in open country is not allowed to exceed 44 dB (at wind speeds of 8 m/s), whereas for road traffic noise one third of all Danish dwelling are exposed to more than 58 dB ($L_{den}$). However, as the sound power level from a wind turbine depends on the wind velocity, the immission levels vary irregularly (43), whereas traffic noise usually are more constant and predictable. In a recent study, Janssen et al. found that wind turbine noise induced a higher proportion of annoyed residents than traffic noise does at comparable sound levels (43). Also, annoyance due to wind turbine noise was found at lower noise levels than traffic noise. However, the study also showed that annoyance was lower among residents who received economic benefit from wind turbines (43).

Wind turbine noise has been suggested to be associated with sleep disturbances, stress and general health, although results are inconsistent (30, 44-48). All these studies are cross-sectional and uses self-reported data on sleep, stress and health. Also, they are generally based on a small number of exposed persons. Some of the studies indicate that associations between wind turbine noise and sleep, stress and health are present only among annoyed people whereas there seems to be no relationship between modeled/measured wind turbine noise and sleep disturbances, stress and health among people that report not be annoyed by noise from nearby wind turbines (45, 48).

The hypothesis of potential health effects of wind turbine noise can been investigated using different study designs, primarily questionnaire-based studies, studies based on biological markers and register-based studies. In Denmark we have unique opportunities to conduct register-based studies. Firstly, Denmark has been a pioneer in setting up wind turbines and therefore we can follow the health effects of wind turbines over many years (Figure 2), and secondly Denmark has unique national registers that enables us to trace the addresses of all Danish citizens since 1971 and various health registers, e.g. registers on birth outcomes, prescriptions and hospitalization.

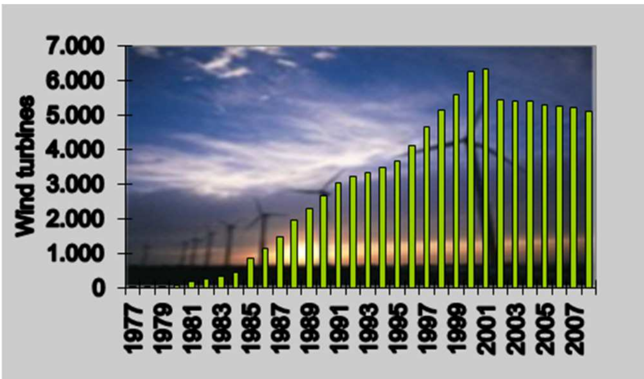


**Figure 2** Growth in number of wind turbines in Denmark (modified from energinet.dk)

Existing studies on wind turbines and health have been small and based on active participation and questionnaire data. In contrast, epidemiological studies based on high quality register data, such as the Danish, are inherently objective with no potential for recall, participation or selection bias. Also, when registers are nationwide and covering long time periods, studies based on these registers generally include large populations with information on exposures and diseases back in time. Therefore, both the statistical power and the ease of interpretation of such studies are generally higher than in other study designs.

## METHODS

### Exposure assessment

The Danish Energy Agency and Energinet.dk have established a register of all Danish wind turbines. This register is updated monthly, and contains information on all wind turbines back to 1980 including the exact location of each wind turbine (geographical coordinate), date of grid connection, cancelation date for decommissioned turbines, manufacture, type, hub height and diameter of rotor blades. The registry contains data for approximately 5,000 wind turbines in operation and 2,500 decommissioned wind turbines.

There is a strong association between wind velocity and the noise emitted from a wind turbine which is characteristic and available for each type of wind turbine (49). We will use these data to develop a model for noise immission from all types of wind turbines at all wind velocities. Based on these modeled noise levels for each turbine we will identify all dwellings within the immission area of wind turbine noise using geographical information system (GIS), and the noise level at each dwelling will then be calculated using the distance between the wind turbine and the dwelling. It will in many cases be necessary to calculate the noise contributions from several wind turbines, which will then be summed for each dwelling.

Nord2000 is a highly accurate method for calculation of noise, verified by measurements of noise from wind turbines and other sources (50). As calculations with Nord2000 are very time consuming and costly, we will use a simplified version of the method described in details in “Vindmøllebekendtgørelsen” from the Danish EPA (51). We consider this method to be well suited for the extensive calculations needed for this project. In addition, we will correct all modeled values for the attenuation that occurs when sound propagates in headwind (appendix 1).

Data on speed and direction of the wind at each wind turbine location in Denmark back to 1980 will be produced based on the mesoscale wind analysis method developed by DTU Wind Energy and used in many studies (52-54). These data will be provided at a spatial resolution of approximately 5 km and downscaled to each required location at a 1-hour or 3-hour resolution and at different heights, including 10 m above ground and hub height of the wind turbines. The wind analysis method makes use of the advanced Weather Research and Forecasting (WRF) model (55) and a dynamic downscaling atmospheric reanalysis technique (56).

**Study population and design**

Based on modeled noise immission from all types of wind turbines (see exposure section) we will identify all residential addresses within the immission area using GIS and the official Danish address database (www.ois.dk). Subsequently, we will identify all persons who have lived at those addresses in the period 1980-2012 by linking the addresses with the Danish civil registration system, thereby retrieving their unique personal identification number (57). We will include all persons at start of exposure (set up of new turbine or moving into a noise immission area), who were exposed to noise from wind turbines in more than one year in the period from 1980 to 2012. We estimate that this will sum up to approximately 10,000–15,000 persons. This estimate is based on the following: 1) 7,500 wind turbines in Denmark (total of turbines in operation and decommissioned), 2) for most single wind turbines there will be one dwelling just below the noise limit value, as this determines the dimensions of the turbine and the required distance to dwellings, 3) for smaller groups of wind turbines (typically 3-5) we estimate that 2-3 dwellings will be exposed just below the noise limit value, 4) for large wind farms with up to 100 turbines we estimate that 3-10 dwellings will be exposed just below the noise limit value, and 5) for both single and multiple wind turbine areas we expect that in many cases there will also be dwellings within the immission area but at lower exposure than the limit value.

Secondly, we will identify a population of 30,000 unexposed persons living just outside the wind turbine noise immission areas. This will be done using GIS and the official Danish address database (OIS) to identify dwellings within an area of approximately three times the distance from the wind turbine (Figure 3), providing a total study population of 40,000-45,000 persons (10-15,000 exposed). We will then identify all persons who have lived in dwellings within the outer geographical circle (Figure 3) in the period between 1980 and 2012 by linking the addresses with the Danish civil registration system, thereby retrieving their unique personal identification number (57). Similarly to the exposed population, we will only include persons who have lived at least one year at these addresses. The selection of the unexposed population from the same geographical region as the exposed, rather than using a random sample of Danes without geographical restrictions, ensures a higher similarity between exposed and unexposed members for potentially relevant unmeasured factors.

We will determine the mobility of both the exposed and the unexposed population and based on this set up a strategy for handling moving out of the geographical areas, e.g. if the mobility is low we will exclude all cohort members who lived less than 80 % of the follow-up time in residences within the included geographical areas.

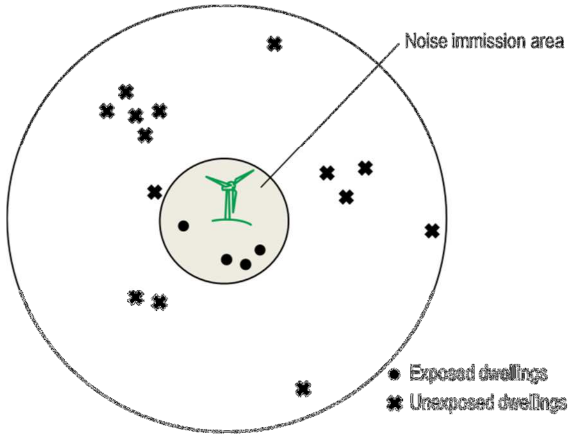

**Figure 3** Identification of the unexposed population.

To be able to adjust all statistical analyses for socioeconomic status we will link the personal identification number of all population members to Statistic Denmark (58) to collect information on level of education, individual and household income, affiliation to the work market and cohabiting status.

Exposure to road traffic noise and/or air pollution could potentially confound the results. We have previously developed a GIS road network with traffic data for the period 1960–2005 (59). We will use this database together with the geocode of all dwellings in the study to derive three variables indicating the amount of traffic near each dwelling: distance to the nearest road with a traffic density > 10,000 vehicle/day (major road), and two variables summarizing the total amount of vehicle kilometers driven each day within 200 m and 500 m, respectively, calculated as the product of street length and traffic density added up for all street lines within a 200/500 m circle around the address.

**Health outcomes**

*Selection of health outcomes*

We initiated the process of designing the present study protocol by evaluating which health outcomes could potentially be associated with exposure to wind turbine noise, given the present level of scientific knowledge, and whether it was possible to investigate the hypotheses using a strictly register-based design. The evaluation was performed in following steps:

1. Evaluation of potential biological mechanisms linking noise (directly or via stress/sleep disturbance) with different possible health effects based on a literature search
2. Evaluation of the epidemiological evidence:
    a. Literature search on effects of stress and sleep disturbance in relation to different possible outcomes
    b. Literature search on effects of noise in relation to different possible outcomes
3. Evaluation of quality of data available from existing registers on the different possible outcomes
4. Evaluation of the statistical power (based on an estimated number of cases for each of the possible outcomes)

Based on this evaluation we concluded that the hypothesis was plausible and a register study achievable for investigating associations between wind turbine noise and diabetes, perinatal outcomes, sleep, depression and hypertension. Some studies have suggested a link between stress/sleep problems and other endpoints such as migraine and dementia, but the register data available would not allow sufficient statistical power or precision in identification of cases. Cancer endpoints were discounted *a priori* as, even if a plausible hypothesis should exist, we concluded that it was unlikely to find associations with wind turbine noise, given the frequencies of the specific cancer types in the Danish population.

*Diabetes*

Information on incident diabetes in the period from 1995 to 2012 for the study population of 40,000-45,000 persons will be found by linking their personal identification number to the National Diabetes Register, which has been nationwide since 1995 (60). We will exclude all participants diagnosed with diabetes before moving into dwellings within the geographical noise exposure circles used in this study. Participants with diabetes before 1995 will be identified through linkage with the Danish National Patient Registry (61) and the National Prescription Registry (nationwide since 1994)(62). We estimate that approximately 2100 persons (700 exposed) will be registered with diabetes during the study period based on information on national diabetes incidence.

*Outcomes identified in the Danish National Prescription Register*

We will use the Danish National Prescription Register (62) to identify incident users of anti-hypertensiva, anti-depressants and sleep medication according to relevant ATC codes (Anatomical Therapeutic Chemical Classification system) (Table 1). For each endpoint we will exclude potentially prevalent cases at study entry i.e. all persons who redeem one or more of the relevant prescriptions (Table 1) in 1995 or before first inhabiting one of the addresses defining our cohort. For anti-hypertensive medication, which may be prescribed for a range of diseases, we will increase specificity towards hypertensive indications by counting people as cases from their second redeemed prescription within a year and by taking into account information on first diagnosis of a cardiovascular disease in the National Patient Register or diabetes in the Danish Diabetes register. In a sub-analysis we will additionally apply criteria of Defined Daily Doses (DDD), a standardized measure of prescribed drug dose recorded in the register, to further increase specificity.

**Table 1** Medication groups for health outcomes to be identified in the Danish National Prescription Register

| Medication group | ATC* CODE | Exclusions |
|---|---|---|
| Anti-hypertensive | C02, C03, C07A-C, C07F, C08, C09AA,C09BA, C09CA, C09DB | |
| Anti-depressive | N06A | N06AX21 |
| Sleep | N05CF og N05CD | N05CD08 |

**Anatomical Therapeutic Chemical Classification System*

For anti-depressive medication we will disregard prescriptions for Yntreve® (in ATC-group N06AX21) which is solely indicated for stress incontinence. For sleep medication we will disregard prescriptions from ATC-group N05CD08 as the indications are epilepsy and preoperative sedation.

We expect 4500 incident users (1100 exposed) of anti-hypertensive medication, 2800 (700 exposed) of sleep medication and 3200 (800 exposed) of anti-depressive medication over the study period.

*Perinatal outcomes*

Information on birth weight and gestational age in the period from 1980 to 2012 for children born within the study population will be found by linking their personal identification number to Danish Medical Birth Register (63). Small for gestational age (SGA) births will be defined as those with birth weights below the 10th percentile of the cohort, stratified by sex, for each week of gestation. From the register we will also obtain information on parity, maternal age, maternal smoking during pregnancy and prenatal maternal BMI. We estimate that during the study period approximately 7500 children (2500 exposed) will be born within the study population based on information on national fertility rates.

## Statistical analyses

*Adult outcomes*

For use of sleep, anti-hypertensive and anti-depressive medication as well as diabetes, statistical analyses will be based on Cox proportional hazards model with age as the underlying time scale, ensuring comparison of individuals of the same age (64). We will use left truncation at age of enrolment into the population on January 1996 (January 1995 for diabetes), first moving into an area close to a wind turbine (Figure 3) or erection of new wind turbine), so that people will be considered at risk from enrolment into the cohort, until end of follow-up at the age at diagnosis (event), death or December 31th 2012, whichever came first. Exposure to wind turbine noise will be modeled as time-weighted averages over the preceding 1-, 5-and 10- years at any given age, and entered as time-dependent variables into the statistical risk model. Time-weighted averages will be calculated based on 1) 24h exposure and 2) only nighttime exposure.

All risk estimates will be calculated crude and adjusted for a priori defined potential confounders: sex, level of education, calendar year, individual and household income, affiliation to the work market and cohabiting status. We will also adjust for distance to major road and traffic load within 200 m and 500 m of the residence as proxies for air pollution and road traffic noise. For each of the adult endpoints proposed we will also analyze for potential interactions with other diseases proposed as endpoints in the present study, as several are comorbid and may be predisposing factors for each other.

*Perinatal outcomes*

We will use multivariate regressions models to test for associations between exposure to wind turbine noise and the outcome variables birth weight and gestational age as continuous variables. Odd ratios (OR) for SGA will be estimated using logistic regression. We will calculate two-sided 95% confidence intervals based on Wald's tests. We will investigate effects of time-weighted averages of wind turbine noise exposure during the 1st, 2nd and 3rd trimester as well as for the entire pregnancy period. These time-weighted averages will be calculated based on 1) 24h exposure and 2) only nighttime exposure. Analyses will be adjusted for maternal age, parity, level of education, calendar year, individual and household income, affiliation to the work market, cohabiting status, distance to major road and traffic load. Furthermore, we will in sensitivity analyses, adjust for maternal smoking during pregnancy (available from 1991 and onwards) and prenatal BMI (available from 2003 and onwards).

**Power**

We have good statistical power to detect even small increases in risk associated with noise exposure from wind turbines. Based on conservative estimates of number of exposed we have a power of 80% to detect a risk increase of 15% or more for hypertension and depression, 17% for sleep disturbances and 19% for diabetes.

## SIGNIFICANCEAND DISSEMINATION

Exposure to wind turbine noise is suspected of affecting health and has caused concern among people living close to wind turbines. However, very limited scientific data exists on associations between noise from wind turbines and health. This study will, therefore, be among the first to investigate if noise from wind turbines affects the risk for major diseases and conditions. The results may be used for guidance on regulations for human habitation close to wind turbines.

Results will be published in international peer-reviewed journals and presented to the general population through national media and popular science articles.

## FEASIBILITY

The Danish Cancer Society research group members have many years of experience in conducting environmental epidemiology research, and have during the last years specialized in investigating health effects of noise. We expect no problems in collecting and generating data and results for this study. Information on all Danish wind turbines is readily available from The Danish Energy Agency and Energinet.dk. We have extensive experience in collecting, managing and analyzing data from the national registers to be used in this study and expect no difficulties in gaining access to these registers or in obtaining permission from the Danish Data Protection Agency. We also have extensive experience in wind speed and traffic modelling and the applicant has already been in contact with two acoustical consultant agencies interested in modelling the wind turbine noise for the project. Many of the research group members have successfully collaborated in several projects.

## TIMELINES

The project runs for 36 months:

Month 1: The Danish Cancer Society and DTU Wind Energy will meet with at least two acoustical consultant agencies to discuss and plan the wind turbine noise modeling. Based on this one consultant will be selected and a contract written and signed.

The Danish Cancer Society will apply the Danish Data Protection Agency and national registers (OIS, Statistic Denmark and 'Statens Serum Institut') for permissions for use of data for the study.

Month 2-3: The consultant agency will generate a model for noise immission from all types of wind turbines to be used for identifying the exposed Danish dwellings.

Month 2-6: DTU Wind Energy will model wind speed and direction time series at each wind turbine location.

Month 4-5: Based on the modeled noise immission data the Danish Cancer Society will use the Danish address database (OIS) to identify addresses of all Danish dwellings exposed to wind turbine noise as well as unexposed dwellings. Subsequently, these addresses will be linked to the Danish civil registration system, followed by linkage to the National Diabetes Register, the Danish National Prescription Registry, the Danish Medical Birth Register and Statistic Denmark.

Month 7-9: Based on wind modeling data and addresses of all exposed Danish dwellings the consultant agency will model wind turbine noise for all exposed dwellings.

Department of Environmental Science, Aarhus University, will generate traffic proxies and obtain information on historical background air pollution and temperature measurements.

Month 10-15: The Danish Cancer Society will conduct the statistical analyses on perinatal outcomes

Month 16-21: The Danish Cancer Society will conduct the statistical analyses on diabetes

Month 22-31: The Danish Cancer Society will conduct the statistical analyses on prescription data

Month 16-36: The Danish Cancer Society will write scientific papers with input from all other research group members

## THE RESEARCH GROUP

The highly interdisciplinary research team will be headed by the applicant Mette Sørensen. The expertise of the team includes noise exposure, wind energy, register-based health research, use of GIS and biostatistics:

**Mette Sørensen**, PhD, senior scientist in the environment and cancer research group at the Danish Cancer Society, has many years of experience in environmental epidemiology. Since 2008 her research has focused on health effects of traffic noise, which among others have resulted in publications that as the first ever showed exposure to road traffic noise to be associated with risk for stroke and diabetes (3, 5). In March 2012 she received a 5-year starting grant from the European Research Council to investigate health consequences of noise exposure from road traffic (QUIET).

**Aslak Harbo Poulsen**, PhD, post doc in the environment and cancer research group at the Danish Cancer Society. Aslak has previously worked on electromagnetic fields from power lines and mobile phones which as noise from wind turbines constitute a diffuse environmental exposure. He has also more than 10 years of scientific experience in analysis and managing of large datasets including prescription data which will also be used in the present study. Aslak will be the daily manager of the project, and responsible for the statistical analyses and scientific reporting.

**Ole Raaschou-Nielsen**, PhD, head of the environment and cancer research group at the Danish Cancer Society, has many years of experience in health effects of traffic pollution, and participates in designing the study, choosing consultant agency, dialog with consultant agency etc.

**Rikke Nordsborg**, post doc in the environment and cancer research group at the Danish Cancer Society. Rikke mastered in geography and has extensive experience in the use of GIS. She will be responsible for identification of dwellings in the vicinity of wind turbines using GIS, and for identifying persons living in the dwellings during the study period and link them to national registry data.

An **epidemiologist** (post doc) will be employed at the Danish Cancer Society for a period of 10 months. He/she will participate in conducting the statistical analyses and scientific reporting. A **data manager** will be employed at the Danish Cancer Society to assist in managing of the large datasets included in the study.

**Alfredo Peña**, PhD, senior scientist at DTU Wind Energy has extensive experience in wind resource assessment, wind power meteorology and meso-scale modeling. He will be responsible for providing the simulated wind speed and direction time series at the wind turbine locations.

Responsible for the modeling of wind turbine noise will be a **consultant agency** with extensive expertise within the area of wind turbine noise. To ensure the best value for money at least two consultant agencies will be approached.

**Matthias Ketzel**, PhD Senior Scientist, Department of Environmental Science, Aarhus University has extensive experience in air pollution modeling and will be responsible for generating traffic proxies and historical background concentrations of air pollution.

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