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Evidence on Wind Farms and Human Health

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WORKING TO BUILD A HEALTHY AUSTRALIA

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Summary of the evidence

Introduction

- This Information Paper provides a summary of evidence from research on wind farms and human health, based on the findings of comprehensive independent reviews commissioned by the National Health and Medical Research Council (NHMRC).
- Internationally, there is little research evidence regarding the health effects of wind farms. Over 4,000 papers were identified in the reviews and, of these papers, only 13 studies were found that considered possible relationships between wind farm emissions and health outcomes (direct evidence). Only one of these studies was conducted in Australia.
- Following comprehensive assessment of the evidence obtained from the independent reviews and additional information provided by expert review and public consultation, the body of direct evidence was found to be small and of poor quality.
- Supporting evidence was also reviewed to gain greater understanding of the characteristics of wind farm emissions (background evidence), their likely effects on the human body (mechanistic evidence) and whether any health effects have been observed from other sources producing similar emissions (parallel evidence).

Statement on the evidence

- Examining whether wind farm emissions may affect human health is complex, as both the character of the emissions and individual perceptions of them are highly variable.
- After careful consideration and deliberation, NHMRC concluded that there is currently no consistent evidence that wind farms cause adverse health effects in humans. This finding reflects the results and limitations of the direct evidence and also takes into account parallel evidence on the health effects of similar emissions from other sources.
- Given the poor quality of current evidence and the concern expressed by some members of the community, there is a need for high quality research into possible health effects of wind farms, particularly within 1,500 metres (m).

Noise

- *Physical and mental health* — There is no direct evidence that exposure to wind farm noise affects physical or mental health. While exposure to environmental noise is associated with health effects, these effects occur at much higher levels of noise than are likely to be perceived by people living in close proximity to wind farms in Australia. The parallel evidence assessed suggests that there are unlikely to be any significant effects on physical or mental health at distances greater than 1,500 m from wind farms.
- *Annoyance* — There is consistent but poor quality direct evidence that wind farm noise is associated with annoyance. Bias of different kinds and confounding factors are possible explanations for the associations observed. While the parallel evidence suggests that prolonged noise-related annoyance may result in stress, which may be a risk factor for cardiovascular disease, annoyance was not consistently defined in the studies and a range of other factors may have contributed to its reported association with wind farm noise.

- *Sleep disturbance* — There is less consistent poor quality direct evidence of an association between sleep disturbance and wind farm noise. However, sleep disturbance was not objectively measured in the studies and bias of different kinds and confounding factors are possible explanations for the associations observed. While chronic sleep disturbance is known to affect health, the parallel evidence suggests that wind farm noise is unlikely to disturb sleep at distances of more than 1,500 m from wind farms.
- *Quality of life* — There is also less consistent poor quality direct evidence of an association between wind farm noise and poorer quality of life. Measurement of quality of life is generally subjective and the studies did not explore whether the reported associations could be explained by bias of different kinds or confounding factors.
- *Infrasound and low-frequency noise* — There is no direct evidence that considered possible effects on health of infrasound or low-frequency noise from wind farms. Exposure to infrasound and low-frequency noise in a laboratory setting has few, if any, effects on body functions. However, this exposure has generally been at much higher levels than occurs in the vicinity of wind farms, has been of short duration and has not replicated all of the characteristics of wind farm noise.
- *Perception of wind farm noise* — Background evidence indicates that wind farm noise is generally in the range of 30–45 A-weighted decibels (dBA) at a distance of 500–1,500 m from a wind farm and below 30–35 dBA beyond 1,500 m. Although individuals may perceive aspects of wind farm noise at greater distances, it is unlikely that it will be disturbing at distances of more than 1,500 m. Noise from wind farms, including its content of low-frequency noise and infrasound, is similar to noise from many other natural and human-made sources. However, there are some unique characteristics of wind farm noise, such as the "whoosh" or "thump" sometimes heard, which might influence the way in which it is perceived.

Shadow flicker

- There is insufficient direct evidence to draw any conclusions on an association between shadow flicker produced by wind farms and health effects.
- Flashing lights can trigger seizures among people with a rare form of epilepsy called photosensitive epilepsy. From the parallel evidence, the risk of shadow flicker from wind farms triggering a seizure among people with this condition is estimated to be extremely low.

Electromagnetic radiation

- There is no direct evidence from which to draw any conclusions on an association between electromagnetic radiation produced by wind farms and health effects.
- Extremely low-frequency electromagnetic radiation is the only potentially important electromagnetic emission from wind farms that might be relevant to health.
- Limited evidence suggests that the level of extremely low-frequency electromagnetic radiation close to wind farms is less than average levels measured inside and outside suburban homes.
- There is no consistent evidence of human health effects from exposure to other sources of extremely low-frequency electromagnetic radiation at much higher levels than are present near wind farms.

Introduction

Purpose of this document

This Information Paper provides Australians with a summary of the evidence on possible health effects of wind farms in humans and explains how NHMRC developed its summary based on the findings of independent reviews of the evidence.[1,2] It is intended for use by any person or group interested in wind farms.

Wind farms in Australia

Wind turbines use rotating blades attached to towers to convert wind energy into electricity. A group of wind turbines is known as a wind farm and may be located on land or offshore. Wind turbine design has evolved over the last 20 years to enable better harnessing of wind energy.[3]

Wind farms have been promoted as a viable and sustainable alternative to traditional, non-renewable forms of energy production. Since the introduction of the *Renewable Energy Act 2000*, the number of wind farms in Australia has grown substantially. At the end of 2013, there were 68 wind farms across the country and more were being constructed or planned.[4]

Why NHMRC is conducting this work

NHMRC is responsible for ensuring that Australians receive the best available, evidence-based advice on matters relating to improving health and to preventing, diagnosing and treating disease. Concern about the effects on health from living near a wind farm has been expressed by some members of the community. Therefore, NHMRC examined the evidence on health effects associated with exposure to specific emissions from wind farms — noise, shadow flicker and electromagnetic radiation.

The current investigation of the potential health effects of wind farms builds upon NHMRC's previous work in this area. In 2010, NHMRC's *Public statement: Wind turbines and health*[5] was published, with supporting evidence from *Wind turbines and health: A rapid review of the evidence*.[6] The 2010 NHMRC Public Statement concluded that there "is currently no published scientific evidence to positively link wind turbines with adverse health effects".[5] Due to the limited amount of published scientific literature, NHMRC committed to carrying out a more extensive search for evidence.

This Information Paper provides an update to NHMRC's previous work in this area. It is based on a comprehensive review of the available scientific evidence following well-established systematic review principles, which provide the most rigorous process for identifying and critically appraising evidence.

In Australia, responsibility for regulating the planning, development and operation of wind farms lies with state, territory and local governments. The outcomes of NHMRC's review may assist these organisations to make decisions about the regulation of wind farms.

NHMRC's review of the evidence will enable well-designed and targeted research to be undertaken in areas that have been identified as gaps in the evidence base (see Chapter 7, page 25).

1. Overview of the process

The development of this Information Paper involved various comprehensive evidence review and quality assurance processes to ensure that the evidence from research on wind farms and human health was appropriately identified, assessed and translated into an evidence-based summary for the Australian community. These processes are outlined below and summarised in Figure 1 (see page 6).

1.1 Independent review

In examining the possible health effects of wind farms in humans, NHMRC commissioned Adelaide Health Technology Assessment to conduct an independent review of the scientific evidence. To ensure that the independent review process was robust and transparent, internationally recognised methods were used to direct the identification, assessment and collation of the evidence.

As this is an emerging area of evidence, the independent review involved:

- a systematic review of scientific research that investigated whether health effects were directly related to distance from or exposure to any emissions from wind farms (direct evidence); and
- a broader review of supporting literature to establish:
  - the likely level of exposure to emissions produced by wind farms at nearby residences (background evidence);
  - whether it is plausible that noise, shadow flicker and electromagnetic radiation (of the type and at the levels produced by wind farms) might affect healthy functioning of the human body (mechanistic evidence); and
  - whether any health effects have been observed from these emissions when they are produced by sources other than wind farms (parallel evidence).

To ensure that this Information Paper was informed by all relevant literature, an independent review was conducted to identify peer-reviewed direct evidence published after the cut-off date for the first review. The second review also included evidence provided through public consultation and expert review of the draft Information Paper (see Section 1.4, page 5). This independent review of additional evidence was conducted by a collaborative team from the Australasian Cochrane Centre and the Monash Centre for Occupational and Environmental Health at Monash University.

1.2 Oversight by the Reference Group

The review of evidence and development of the Information Paper was guided by the Wind Farms and Human Health Reference Group (Reference Group). The Reference Group had expertise in public and environmental health, research methodology, acoustics, psychology and sleep and included a consumer advocate. Information on the membership and terms of reference of the Reference Group is included at Appendix A (see page 28).

The Reference Group:

- assisted the reviewers to develop research questions;
- reviewed and commented on drafts of the reports of the independent reviews;
- provided scientific advice on the interpretation of the evidence;
- reviewed and interpreted the parallel evidence;
- guided the development of the Information Paper;
- considered expert reviews of the draft Information Paper and submissions received through public consultation (see Section 1.4); and
- identified gaps in the evidence base to make recommendations for further research (see Chapter 7, page 25).

NHMRC appointed two observers to attend Reference Group meetings and teleconferences to observe the process. The observers' contributions to Reference Group meetings were limited to offering factual information or providing it at the request of Reference Group members at the discretion of the Chair. The observers did not engage in the scientific discussions or decision-making processes of the Reference Group.

1.3 Quality assurance processes

Rigorous quality assurance processes support the development of all NHMRC health advice, including identifying any conflicts of interest of Reference Group members, involving observers, independent methodological review, public consultation and expert review.

More detail on the processes used to ensure the quality of the review of evidence and development of the Information Paper is included in Appendix B (see page 30).

1.4 Public consultation and expert review

To ensure that all relevant evidence was identified and considered, a draft Information Paper was released for public consultation in February 2014 and submission of evidence invited. To ensure that the evidence had been accurately represented in the Information Paper, six Australian and international expert reviewers were also invited to provide comments on the draft document. The feedback from public consultation and expert review informed the further development of the draft Information Paper.

Many of the 36 public consultation submissions received detailed individual experiences of living near a wind farm and expressed concern about the possible health effects and other social impacts of wind farm developments on the surrounding community, including conflict among neighbours. While the Reference Group considered that the broader social impact of wind farms was beyond the scope of the review, it acknowledged the high level of concern that some members of the community expressed and noted the importance of considering the best available evidence to provide Australians with reliable advice on this issue.

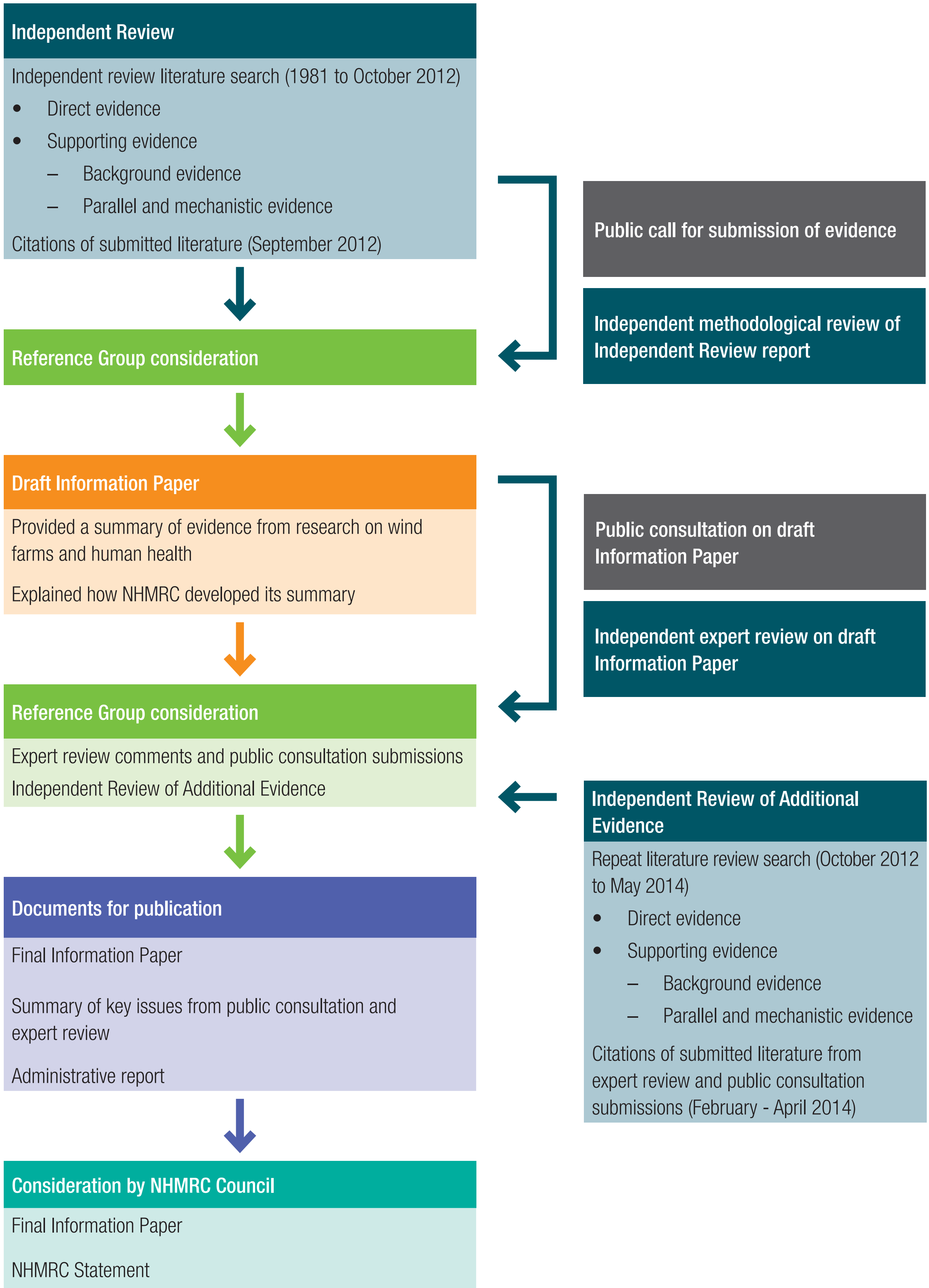


Figure 1: Overview of the comprehensive evidence review and quality assurance processes in the development of the NHMRC Information Paper: Evidence on Wind Farms and Human Health

2. Examination of the direct evidence

2.1 Identification of the direct evidence

The independent reviews searched for all of the scientific evidence on possible health effects specifically related to exposure to any emissions from wind farms. This is referred to as the *direct* evidence.

The reviewers undertook a comprehensive search of the literature in accordance with a pre-approved review protocol and search strategy for the independent reviews. While noise, shadow flicker and electromagnetic radiation were considered to be the likely emissions of interest from wind farms, the search strategy was kept broad to make sure that relevant evidence was captured. The potential effects on human health from wind farm manufacturing and monitoring (such as occupational health and safety issues), health effects due to ice throw under certain weather conditions and accidents due to mechanical failure were all considered beyond the scope of this review.

Literature for possible inclusion in the direct evidence component of the review was identified by:

- searching publication databases for peer-reviewed health literature;
- searching for relevant non peer-reviewed literature (commonly referred to as grey literature) in Google Scholar, databases of conference proceedings, selected government and scientific association websites and other grey literature sources; and
- checking the reference lists of relevant reviews and reports.

NHMRC also called for public submissions of relevant literature for inclusion in the independent review in September 2012 to help ensure that new and emerging direct evidence was considered.

The first independent review encompassed evidence published between 1981 and October 2012 and identified 2,848 references. In addition, references to 506 publicly available documents were received by NHMRC during the call for public submissions and considered in the independent review.

The independent review of additional evidence, which covered peer-reviewed literature published between October 2012 and May 2014, identified 1,912 references. During public consultation in February 2014, NHMRC again called for submissions of evidence and the 249 references received were considered in the independent review of additional evidence.

2.2 Selection of the direct evidence

For information to be considered as direct evidence it had to:

- be publicly available;
- look at exposure to wind farm emissions;
- *not* choose *only* participants who had reported health effects they attributed to wind farm emissions;
- compare two or more groups with different levels of exposure to wind farms (e.g. a “near” group and a “far” group);

- explain how the data were collected;
- assess health outcomes in the groups studied; and
- analyse the results.

While the Reference Group's Terms of Reference specified that new peer-reviewed literature be identified, the Reference Group considered it appropriate to also include non-peer-reviewed direct and background evidence in the review. This is an emerging area of research and it was deemed important to capture and consider all relevant evidence.

Personal stories, opinions and medical records submitted by individuals were not considered in the independent reviews. While individual experiences can raise the possibility of health effects from wind farms, only systematic research provides the necessary evidence to determine whether reported health effects result from exposure to wind farms.

Animal studies were also excluded, as the focus of the reviews was possible health effects in humans. The emissions investigated through animal studies differ from wind farm emissions in level and duration and the applicability of these studies to human health is uncertain. However, it is recognised that animal studies might suggest mechanisms to explain how human health effects could be caused by wind farm emissions.

In the first review, titles and abstracts of all 2,848 identified papers and the additional 506 submitted references were reviewed for relevance and 161 papers were then read in detail. Seven studies (described in eleven papers)[7-17] met the inclusion criteria for direct evidence listed above.

In the independent review of additional evidence, titles and abstracts of the 1,912 identified papers and the 249 references submitted through the public consultation process were reviewed for relevance and 94 papers were then read in detail. Six studies (described in seven papers)[18-24] were identified as providing direct evidence. One additional direct evidence paper contained further analysis of data from three studies included in the first independent review.[25]

Appendix C (see page 31) provides more detail on the process of selecting the studies.

2.3 Studies included as direct evidence

The studies included as direct evidence in the independent reviews examined wind farm noise, shadow flicker or other visual stimuli and changes to one or a combination of physical health, mental health, annoyance, sleep and quality of life.

- Seven studies (reported in nine papers) assessed self-reported **physical health** and estimated level of wind farm noise[7,10-13,18] or proximity to wind farms.[14,15,21]
- Five studies (reported in seven papers) assessed aspects of self-reported **mental health** (stress, irritability, psychological distress, anxiety and depression) and estimated level of wind farm noise[7,9,11,13] or proximity to a wind farm.[14,16]
- Six studies (reported in twelve papers) assessed **annoyance** and estimated level of wind farm noise[7,9-13,17,19,20,25] or proximity to a wind farm,[8,15] one of which also assessed annoyance and shadow flicker from wind farms.[8] One study[22] assessed annoyance associated with aircraft warning lights on wind turbines.
- Nine studies (reported in eleven papers) assessed self-reported **sleep quality** and estimated level of wind farm noise[7,9-11,13,19] or proximity to a wind farm.[8,14-16,21]
- Four studies (reported in five papers) assessed **quality of life** and proximity to wind farms.[14-16,23,24]

Of the included studies, only one was conducted in Australia. The remaining studies were conducted in Canada, Germany, Japan, the Netherlands, New Zealand, Poland, Sweden and the United States of America.

In all of these studies the participants **self-reported** their health outcomes — none of the outcomes was objectively measured (e.g. by using a test performed by a doctor or scientist).

No studies were identified that specifically looked at possible effects on human health of **infrasound** (sound at a frequency lower than 20 Hertz), **low-frequency noise** or **electromagnetic radiation** from wind farms.

2.4 Critical appraisal of the direct evidence

Critical appraisal is a systematic process used to identify the strengths and weaknesses of published research in order to assess the validity of the findings and their usefulness.

The most important components of critical appraisal of individual studies are an evaluation of the appropriateness of the study's design for the research question and a careful assessment of the key methodological features of this design.[26] Specific factors that should be considered when critically appraising epidemiological research on the association between environmental exposures and health effects include the way in which participants were selected, how information about their exposures and health outcomes was collected, whether the study adequately considered all plausible explanations for any association between an exposure and a health outcome, the suitability of the statistical methods used, and the interpretation of the findings.

The number of people included in a study is also important. When the number of participants is large, possible confounding effects can be more readily examined in the analysis and chance can be more confidently excluded as a cause for an observed association between an exposure and a health effect, or the lack of such an association. The authors' conflicts of interest should also be considered.

Considering all studies relevant to a particular research question, the evidence for an association between an exposure and an effect is stronger if there are multiple "well-conducted" studies that are consistent in their findings with respect to the association.

To support critical appraisal, the key features of the direct evidence studies reviewed were summarised in tables in the report of the initial independent review[1] (see Table 7, page 46 of the initial review) and the independent review of additional evidence[2] (see Table 1, page 13 of the additional review). An overview of the Reference Group's consideration of this evidence is provided below.

Study design and sample sizes

All of the studies that met the inclusion criteria for direct evidence used a cross-sectional design. Cross-sectional studies examine the relationship between an exposure (in this case wind farm emissions) and specific health outcomes in a defined population at a single point in time. Environmental noise studies are almost always cross-sectional studies. Longitudinal studies (studies that measure health effects after a period of exposure to their suggested cause) sufficiently large to address a range of potential health effects, including for example heart disease, are very expensive and require strong justification.

Because the exposure and health outcomes were assessed at a single point in time, none of the included studies was able to provide any indication of the order of events — that is, whether a health outcome first occurred before or after the exposure began. This might mean that a person's self-reported health outcomes were present *before* the person's exposure to wind farms. However, the sequence of events is not as important in environmental noise studies as in some other epidemiological studies because conclusions can often be made based on what is known historically of exposure and the time of onset of changes in exposed people's health status.

The number of participants in most of the studies was modest. Larger numbers provide greater certainty as to whether any observed association between an exposure and an outcome can be explained by chance. Larger numbers are particularly important if an exposure is likely to have only a small effect on the outcome and when an exposure or health outcome is rare in the study population.

Bias

In scientific studies, the term *bias* is used to describe the effect of an error in the design of a study or an error or problem in the collection, analysis, reporting, publication or review of study data that leads to untrue results.

All studies included as direct evidence had low participation rates, which means that many people who were approached to be part of the study did not participate. There is a high risk of selection bias in a study with a low participation rate, as those who chose to participate in the study may have different exposure and health outcomes to those who did not. For example, people who are unwell may be less likely to participate in studies in general but may be more willing to participate if they live closer to a wind farm, particularly if they knew that the study was about health effects of wind farms.

One study[9] conducted a non-response analysis to determine whether the responses that study participants gave to the questions they were asked differed from the responses given by those who chose not to participate when asked to answer just a few questions. There were no significant differences in exposure to wind farm noise, exposure to background noise or self-reported annoyance depending on participation. However, differences in responses to physical and mental health questions were not assessed.

In many of the studies, the purpose of the research was not masked (i.e. hidden) from participants. Where the studies did attempt to hide the intent of the study from participants, this may not have been effective as participants would probably be aware of the presence of a wind farm in their environment. A lack of successful masking of a study's purpose in this context can contribute to selection bias by making it more likely that a person concerned about wind farms will participate than a person who is not concerned about wind farms. However, effective masking of study intent is difficult in environmental noise studies as they are by necessity conducted in the vicinity of a noise source and often in a climate of controversy about the noise it produces.

All of the health outcomes recorded in the included studies were self-reported. Studies have shown that people often have difficulty in accurately recalling their health details and the timing of onset of their symptoms.[27,28] If this inaccuracy is not random, a false association may be observed. For example, knowledge of a wind farm study's purpose may make people who lived near a wind farm try harder to recall their health details than people who lived further away. This could make people who lived further away from the wind farm appear less sick than those who lived closer, when there is actually no difference.

Confounding factors

When there seems to be an association between an exposure and an outcome, it is important to consider whether this might be due to another factor that is associated with both the exposure and the outcome — such a factor is known as a *confounding factor*. For example, most common physical health conditions (e.g. high blood pressure, diabetes, heart disease) are more common in older than younger people. If people in a study who lived nearer to wind farms were, on average, older than people who lived further away, physical health conditions would be more common in those who lived close to the wind farm. This association between proximity to wind farms and health might only be due to the age difference and have nothing to do with wind farms. In this example, age is a confounding factor and failure to control for it could lead to an incorrect conclusion that wind farms affect health. We could also be misled, but in the opposite direction, if people who lived nearer to wind farms were instead *younger* and therefore likely to be healthier than people who lived further away.

There are a number of confounding factors that might provide an alternative explanation for any observed association between wind farms and health (such as: socioeconomic status; pre-existing chronic diseases; attitude to, visibility of or economic benefit from wind farms; and negative or positive expectations about the potential effects of wind farms). These factors were not consistently measured in the available studies. When they were, their possible effects on associations between wind farms and health effects were not always taken into account when analysing the results.

In addition, it is possible that variables thought to be confounding factors might instead be effect modifiers, which influence the magnitude of, rather than explain, any true association between wind farms and health. Effect modification can be difficult to uncover, especially in studies with small sample sizes.

Consistency

It is rarely possible to be confident that there is a cause-and-effect relationship based on one study because the results may be affected by chance, bias, or confounding. However, if an observed association in one study is consistently found in other studies (that ideally have been conducted in different ways and by different investigators), this consistency strengthens the case for a cause-and-effect relationship. Similarly, when study results are not consistent, it is more likely that the association is due to chance, bias, or confounding — that is, the association does not indicate a cause-and-effect relationship.

Among the studies reviewed, there was no consistency in finding an association between wind farm exposure and self-reported physical or mental health outcomes. However, there was consistency in showing an association between wind farm exposure and annoyance and disturbed sleep, though the evidence on the latter was less consistent. There was also less consistency in showing an association with poorer quality of life.

Quality of the overall body of evidence

In order to determine the overall quality of the body of evidence on the possible health effects of noise, shadow flicker and electromagnetic radiation, the Reference Group examined each of the individual studies in terms of the factors discussed above (including each study's design, risk of bias and possible confounding factors, as well as the consistency of results between the studies). Based on these factors, all of the individual studies included as direct evidence were considered to be poor quality.

The Reference Group considered the overall body of direct evidence on wind farm emissions and health effects to be weak, as chance, bias and confounding cannot be excluded as possible explanations for any associations observed. Given the limitations of the direct evidence, the Reference Group considered mechanistic and parallel evidence on the health effects of similar emissions from other sources to inform its consideration of the direct evidence and in forming its overall conclusions.

3. Review and assessment of the supporting evidence

3.1 Identification of the supporting evidence

As outlined in Section 1.1 (page 4), supporting evidence was reviewed to gain greater understanding of the characteristics of wind farm emissions, the likely level of exposure to those emissions among people living nearby and whether and how these emissions may affect human health.

The first independent review included specific questions to identify supporting evidence. The independent review of additional evidence did not specifically seek to identify supporting evidence but considered a number of studies identified through the repeat literature search or provided through public consultation submissions or expert review.

Background evidence

The first independent review did not systematically search and select background studies due to the breadth of the topics covered. Rather, key publications in the peer-reviewed literature were identified, particularly those providing up-to-date reviews of relevant evidence, as well as technical reports and analyses prepared by expert panels and environmental health agencies.

A number of studies submitted through the public consultation process or identified by expert reviewers were considered as background evidence in the independent review of additional evidence. These were mostly environmental noise surveys.

Reference Group members also identified additional relevant background evidence for consideration by the Group in developing the Information Paper, based on their knowledge and expertise in the relevant subject matters (including public and environmental health, research methodology, acoustics, sleep and psychology).

Mechanistic and parallel evidence

The review of mechanistic and parallel evidence followed a more structured approach than that of the background evidence in the first independent review. To facilitate the identification of high-level evidence, only peer-reviewed studies were included. Publication databases of peer-reviewed health literature were searched using pre-specified key words and search terms.

Some studies identified through the public consultation, expert review and repeat literature search processes were considered as mechanistic or parallel evidence in the independent review of additional evidence.

3.2 Studies included as supporting evidence

Background evidence included a United States report on the impact of wind farms,[3] discussion of outdoor sound propagation in the vicinity of wind farms,[29] studies of noise and infrasound levels near wind farms and other environments,[30-35] studies of shadow flicker near wind farms[36,37] and World Health Organization (WHO) reports on electromagnetic radiation emissions from household appliances and the environment.[38,39]

Parallel evidence included WHO reports on health effects associated with environmental noise,[40,41] recent studies on cardiovascular outcomes associated with environmental noise[42-44] and with chronic sleep disturbance[45] and epidemiological studies on exposure to electromagnetic radiation.[46]

Mechanistic evidence included laboratory studies on changes in functioning of the human body due to exposure to infrasound or low-frequency noise[47-49] and exposure to shadow flicker.[50]

3.3 Assessment of the supporting evidence

Given the exploratory nature of this component of the independent review and the diverse nature of the publications considered (including technical reports, environmental noise surveys and laboratory studies), no formal quality appraisal of these studies was conducted. However, in formulating the overall conclusions and developing the Information Paper, the Reference Group carefully considered the overall methodological quality of each article or study and the strength of the evidence it provided.

4. Deciding whether wind farms cause health effects

Studies investigating whether living near wind farms might have adverse health effects (direct evidence) can only establish whether there is an *association* between living near wind farms and experiencing a particular health outcome. Generally, an association is "established" if it has been directly observed in several different studies and is judged unlikely to be simply a chance finding. Deciding whether an association between wind farm exposure and a particular health outcome is causal — that is, wind farm exposure *causes* the health outcome — requires more evidence.

- First, it must be clear that the exposure (to wind farms) preceded the outcome (the health effect).
- Second, it must be possible to rule out alternative explanations for the association, including both:
  - bias resulting from the design of the study or the way the study was conducted; and
  - causation by one or more confounding factors associated with wind farm exposure.

Evidence in respect to these points is provided by the *direct* evidence.

- Third, it should be shown:
  - that the association is consistent with other evidence on the effects of the exposure (e.g. noise from some other source); and, ideally,
  - that there is a biological mechanism by which the exposure could cause the health outcome with which it is associated, which is usually established by finding one or more plausible mechanisms in animal studies and then showing that at least one corresponding mechanism is activated by the exposure in humans.

Evidence in these respects is provided by the *supporting* evidence. While causation is sometimes established without supporting evidence of these kinds, it would usually only be if there was very strong direct evidence.

5. Emissions from wind farms

5.1 Noise

Noise is considered an important wind farm emission and is the most studied of the emissions.

Sound and noise perception

Sound travels from a source as a wave (pressure variation) through a medium (e.g. air, water) to a receiver (e.g. the human ear). The number of complete waves passing a given point in one second is the frequency of the wave, expressed in terms of the number of cycles (waves) per second. The unit of frequency is the Hertz (Hz) — 1 Hz is one cycle per second. People sense the frequency of a sound by what they describe as its pitch — e.g. high pitch is used to describe a high-frequency sound and low pitch is used to describe a low-frequency sound. However, what is sensed as pitch is affected by both the level ("loudness") of the sound and its frequency.

Sounds in the frequency range 20–20,000 Hz can normally be heard by humans at sound levels that commonly occur (the upper limit decreases with age).[51] Sound at a frequency lower than 20 Hz is generally termed "infrasound". Human hearing becomes gradually less sensitive as frequency decreases, so a low-frequency sound (lower than 100 Hz) needs to be at a higher level (more physical sound, more "volume") to be heard as loudly as a mid-range frequency (e.g. 1,000 Hz). High-frequency sound reduces in level (becomes quieter) more quickly with increase in distance from its source than low-frequency sound and is attenuated more by walls, doors and windows (i.e. does not pass through as easily). Lower frequency sounds can travel further through most media than higher frequency sounds.[52]

Sound level is measured in a unit called a decibel (dB). Because the ability of humans to hear sound varies with frequency, measurements of noise (which is usually made up of sound of many frequencies) often take this variation into account by giving more weight to frequencies that are more easily heard and less weight to frequencies that are harder to hear at the sound levels at which these frequencies normally occur. This "filtering" is called A-weighting and the sounds measured in this way are expressed in terms of dBA. A-weighted measurements include all frequencies but give less weight in the total measured noise level to low frequencies and infrasound. The G-weighting function, expressed in terms of dBG, gives higher weight to lower frequency sounds and is used when quantifying sound that has a significant portion of its energy in the infrasonic range (below 20 Hz).[30]

A sound or a combination of sounds is usually referred to as noise when it is unwanted. The human perception of sound is only partly related to the acoustic stimulus — that is, to the mix of frequencies in the sound, its level and its other physical characteristics (e.g. variation over time or tonality*). Many other factors are important in determining the perception and reaction to a given sound. These include a person's physical health and psychological state, their attitude towards the perceived source of the sound, their perceived control of the sound, individual variation in how the brain processes sounds when awake and during sleep, and timing (e.g. sounds considered acceptable during the day may be perceived as noise during the night).[54] In NHMRC's review of wind farms and human health, all sound from wind farms is referred to as "noise".

* Noise containing a prominent frequency and characterised by a definite pitch.[53]

Characteristics of wind farm noise

The main noise from modern turbines is "aerodynamic noise" — the "swishing" noise generated by the interaction of flow turbulence with the surfaces of the rotor blades.[11,13,55] This noise is generally in the range of 200–1,000 Hz.[56,57] Wind turbines also produce mechanical noise at a frequency of 20–30 Hz (for a 1,500 kilowatt turbine).[3]

Wind farm noise is said to be amplitude modulated when its level (loudness) exhibits periodic fluctuations at a rate corresponding to the frequency at which a rotor blade passes a fixed point. For a modern Multi-megawatt three-bladed wind turbine, the typical blade-passing frequency would be 0.8 Hz (slightly less than once a second). In some wind farm sites, the resultant variation in the overall A-weighted sound pressure level exceeds 6 dB. This noise has been described as being more impulsive in character and better described as a "whoosh" or "thump" than as a "swish", with a shift in the dominant frequency range to around 400 Hz.[58]

The occurrence of amplitude modulation depends on a complex range of factors, including local atmospheric conditions, topography, turbine blade design and the way in which they are controlled. A particular turbine type may exhibit the effect in one site but not in another. The effect varies greatly with distance, wind direction and over time, including whether it is day or night time (it may be more common in the evening or night).[58]

When multiple wind turbines are producing sound, the total sound pressure level at a particular location is affected by the sequence of the arrival of the sound (referred to as coherence). For example, if each of the turbines' blades are turning at the same time and are the same distance from the location, the sound from all the turbines would arrive at the same time, increasing the "loudness" of the sound. Amplitude modulation may be enhanced when this coherence effect occurs.[59] However, if some turbines are further away or located at 180 degrees, there will be "cancellation" of some of the sound. These effects also vary depending on meteorological conditions, distance and location.

Wind farm noise is complex and highly variable in character (e.g. tonality, frequency content and impulsivity). These characteristics and the duration of exposure influence the way in which wind farm noise is perceived. Perception is also influenced by characteristics of the person perceiving the noise — people who detect and recognise wind farm noise more easily may find it more annoying[60] and people living in quiet environments may be more sensitive to low-frequency noise.[35]

In wind farm noise studies, the predicted or estimated noise level from a wind farm based on a mathematical model can only consider the sound level of the noise source, distance of the receiver, siting of each source relative to each other, topographical features and meteorological conditions. It is not yet possible to predict the complex and highly variable characteristics of wind farm noise (e.g. amplitude modulation). However, when actually measuring noise from a wind farm, the total noise is assessed rather than the noise from each individual turbine. Therefore amplitude modulation and other unique characteristics of wind farm noise would be included in the measurements.

While wind farm noise is difficult to measure in the presence of background noise, its level is generally in the range of 30–45 dBA at a distance of 500–1,500 m from the wind farm.[29] Under occasional and distinct circumstances (depending on the size and output of individual turbines, wind farm size and layout, terrain and meteorological and atmospheric conditions, including wind speed and wind direction), noise levels may be considered disturbing at 500–1,500 m from wind farms. Although individuals may perceive aspects of wind farm noise at greater distances, it is unlikely that wind farm noise would be considered disturbing at distances of more than 1,500 m. At this distance, wind farm noise is usually below 30–35 dBA, below the noise levels of household devices and similar to a quiet residential area (see Figure 2, page 17). [29,41,54]

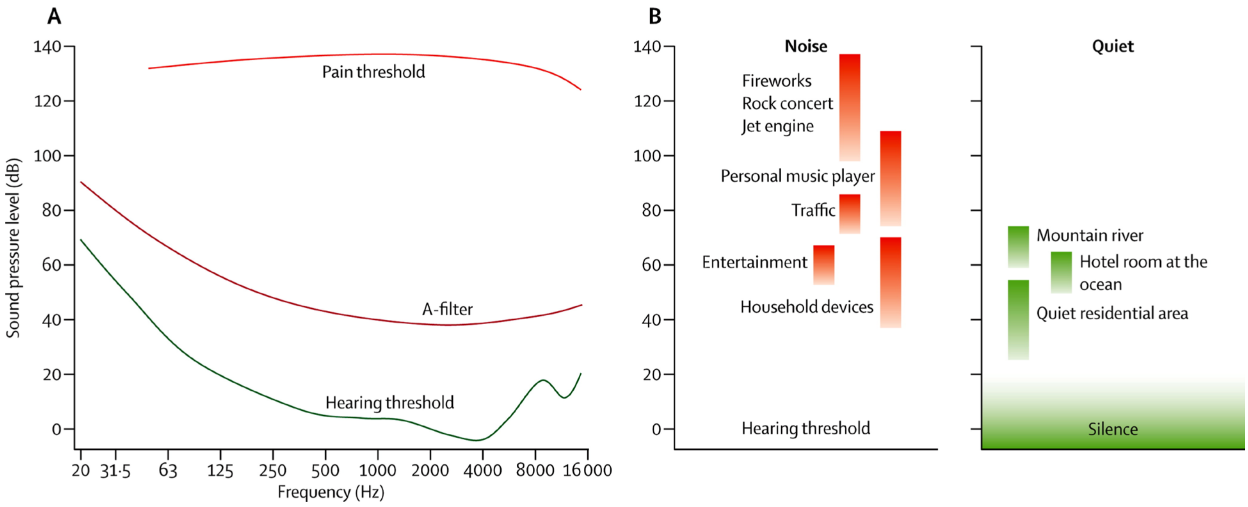


Figure 2: Typical sound pressure levels for common environmental noise sources. (A) The sensitivity of the auditory system depends on sound frequency and sensitivity is highest between 2000 Hz and 5000 Hz (green line). The A-filter (dark red line) is a frequency-weighting of sound pressure levels that mimics the sensitivity of the auditory system (e.g. low-frequency sounds contribute little to the A-weighted dB level). (B) A-weighted sound pressure levels for several environmental sounds, emphasising that whether or not a sound is perceived as noise depends largely on the context and the individual, and is only partly determined by its sound pressure levels.

Source: Reprinted from The Lancet, Volume no. 383(9925), Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S et al, Auditory and non-auditory effects of noise on health (Figure 1),[54] page no. 1,325–32, Copyright (2014), with permission from Elsevier.

Evidence suggests that the component of wind farm noise that is low frequency noise may increase with the power-generating capacity of turbines[34] and under certain wind farm operating and weather conditions.[35] Infrasound measured in the vicinity of wind farms (at distances of 85–7,600 m) has been reported at levels significantly below the accepted audibility threshold of infrasound frequencies (i.e. greater than 85 dBG)[32] both outside[30,31,33,34] and inside residences[30,32-35] and levels are similar to those at other locations (e.g. at the beach, in the vicinity of a coastal cliff, near a gas-fired power station and in a city centre away from major roads).[31] In some circumstances low-frequency noise may result in vibration in some residences in the form of rattling of windows or objects on shelves.[61]

5.2 Shadow flicker and other visual stimuli

Shadow flicker, as it relates to wind farms, is defined as the flickering effect caused when rotating wind turbine blades intermittently cast moving shadows on the ground, resulting in alternating changes in light intensity.

Exposure to flicker from a wind turbine depends on its hub height and blade diameter, the wind direction, geographical location and the direction and height of the sun (which is affected by the time of day and time of year).[36,37] Shadow flicker is generally present only at distances of less than 1.4 km from wind farms.[3]

Warning lights are required on some wind turbines in Australia for aviation safety. These are generally a pair of red lights that flash simultaneously[62] and could be perceived as annoying.

5.3 Electromagnetic radiation

Electromagnetic radiation broadly refers to combinations of electric and magnetic waves. Electromagnetic radiation is emitted by a range of common domestic appliances (e.g. vacuum cleaners, microwave ovens, colour televisions and mobile phones).

Extremely low-frequency electromagnetic radiation is the only potentially important electromagnetic emission from wind farms that is relevant to health.[63] The available information suggests that the level of extremely low-frequency electromagnetic radiation close to wind farms is lower than that found close to common household appliances when in use[38,64] and much lower than the average level measured inside and outside suburban homes.[38] However, levels are high near high-voltage power lines transmitting the electricity that wind farms generate, as they are near any power lines of equivalent voltage.[64]

6. Findings of the review

6.1 Noise

6.1.1 Direct evidence

This section describes associations for which there is direct evidence in the reviewed literature. It is important to note that all the individual studies that provided direct evidence were considered to be of poor quality and no detailed critical appraisal of each mentioned paper is included in this descriptive section. Overall, wind farm noise was not directly measured at participants' homes in any of the studies included as direct evidence. Rather, people's exposure to wind farm noise was estimated based on how far they lived from the wind farm (proximity) or by using mathematical models to estimate the level of sound where they lived. The mathematical models take into account a range of factors including sound output from the turbines and distance to the house. In addition, even where consistent associations were found between estimated wind farm noise and effects such as annoyance, it was not possible to tell whether the noise was driving the association or whether the association could be explained by one or more other factors that are more common among people living close to wind farms (such as attitude to, visibility of or economic benefit from wind farms).

The overall conclusions of the Reference Group about wind farm emissions and the effects examined in these studies are presented in Section 6.4 (see page 23).

Physical health

Seven studies assessed self-reported physical health and estimated level of wind farm noise[7,10-13,18] or proximity to wind farms.[14,15,21] Collectively these studies reported on chronic diseases, cardiovascular disease, ratings of general health, blood pressure, headaches, tinnitus, vertigo, hearing loss and whether participants had sought help from a doctor.

The results of one study suggested a link between estimated wind farm noise and tinnitus[10,13] and another study suggested a link between wind farm noise and increased prevalence of diabetes.[10,11] However, other studies that looked at tinnitus[7,10,11,14,21] or diabetes[7,10] did not find a significant association. One study found an association between proximity to wind farms and self-reported vertigo.[21] No links were found between estimated wind farm noise or distance from wind farms and any of the other physical health outcomes.[7,10,11,13-15] A small survey with a very low response rate suggested that reporting of physical symptoms was more closely related to the perception of noise than to actual noise exposure.[18]

Mental health

Five studies assessed aspects of self-reported mental health (stress, irritability, psychological distress, anxiety and depression) and estimated level of wind farm noise[7,9-11,13] or proximity to a wind farm.[14,16] Four studies found no significant differences in the mental health of participants depending on noise level or distance.[7,9-11,13,14] Three of these studies masked the study's purpose.[9,11,13] One study reported that individuals who lived closer to wind farms had lower mental health scores on a self-completed health questionnaire. However, the purpose of that study (being to investigate the health effects of wind farms) was explained to participants.[16]

One study found that psychological distress was significantly related to annoyance and not sound level.[9]

Annoyance

Annoyance is a negative response that does not necessarily affect health status but may result in stress, which over the longer term may affect physical and mental health.[54,65]

Six studies assessed the association of annoyance with exposure to estimated wind farm noise[7,9-13,17,19,20] or proximity to a wind farm.[8,15] The studies all reported an association between annoyance and higher estimated levels of wind farm noise[7,9-13,17,19,20] or living closer to a wind farm.[8,15] Rates of annoyance differed greatly between studies depending on the estimated noise exposure, definition of annoyance and whether the purpose of the study was masked from participants.

Further analysis of three studies[7,10-13,17] found that, in comparison to other sources of environmental noise, annoyance due to wind farm noise occurred at relatively low noise exposure levels.[25] Reported annoyance was higher when wind turbines were visible from the dwelling and lower when participants received economic benefit from the wind farm.[25] Annoyance reported by participants may also have been influenced by factors other than the noise produced by wind farms, such as the participants' demographic, psychological and biological factors, their attitudes and perceived degree of control, and situational factors (including day and time, activity disturbance, terrain and features of the dwelling).[66]

Sleep

Noise at night can disturb sleep[41] and objectively measured[67] chronic sleep disturbance is known to have an effect on health.[54]

The association of wind farm noise with self-reported sleep quality was assessed in nine studies.[7-11,13-16,19,21] Eight studies reported poorer sleep (mostly disturbed sleep and poor sleep quality) among people exposed to higher estimated levels of wind farm noise[7,9,10,13,19] or living closer to wind farms.[8,14-16,21] One of these studies asked participants whether they slept better when they were away from wind farms and most participants said they did sleep better.[16]

However, sleep disturbance in the studies was not objectively measured and therefore it was not clear whether it would be sufficient to affect health.

The reported associations of wind farm noise with sleep quality were generally weak. In some of the studies the association between estimated wind farm *noise* and sleep quality was weaker than the association between wind farm noise *annoyance* and sleep quality.[9-11,13]

Only some of the studies considered possible confounding factors in their analysis. In one study that did consider possible confounding factors participants who did *not* benefit economically from wind farms reported more sleep interruption than others.[7] This was reported regardless of how close they were to the wind farm. Therefore it is possible that factors other than noise (such as economic benefit) could explain or modify the apparent association between wind farm proximity and sleep disruption.

Quality of life

Quality of life is a broad and holistic construct that measures health and wellbeing across multiple domains, including those that are physical, mental and social. It refers to a person's view of their position in life in the context of the culture and value systems in which they live, and in relation to their goals, expectations, standards and concerns.[68] Quality of life may be affected by physical health, psychological state, level of independence, social relationships and features of the environment.[68] Measurement of quality of life is generally subjective. Poor quality of life may be an indicator of poor health.

Four studies assessed quality of life and proximity to wind farms.[14-16,23,24] Only one study attempted to mask the purpose of the study from participants and used a formally validated questionnaire.[15] This study found an association between proximity to wind farms and poorer overall quality of life. A second study conducted in this community 2 years later (using the same study design but a different sample of the population) made the same observation.[23]

Two other studies used author-formulated questions and did not mask the purpose of the study. In one of these studies the majority of people reported that their quality of life had altered since living near a wind farm, regardless of how close they lived to the wind farm.[14] The other study reported that more residents living close to a wind farm wanted to move away than residents living further from a wind farm.[16] The studies did not explore whether these associations could be explained by other factors (e.g. annoyance at the wind farm, visibility of the wind farm or economic benefit from the wind farm).

One study using a validated questionnaire found that quality of life was higher for participants whose residences were closer to a wind farm.[24] Masking was not mentioned in this study and the participation rate was not reported. Adjustment for socioeconomic status and health variables did not explain the inverse relationship. Information on whether participants benefitted economically from the wind farm was not collected.

6.1.2 Parallel and mechanistic evidence

Noise in other environments

Most of the studies into the health effects of environmental noise have been about exposure to noise from road traffic, aircraft or rail[3] and generally examine exposure to noise at levels in the order of, or higher than, that expected from wind farms at 500 m.

High levels of noise from sources other than wind farms have been consistently associated with hearing loss, disturbed sleep and annoyance.[40,54] Prolonged exposure to high levels of environmental noise (greater than 55 dBA) may also contribute to the prevalence of high blood pressure and heart disease.[40,42-44] A poorly understood condition referred to as “vibroacoustic disease” has also been reported in people exposed, mainly occupationally, to high levels of low-frequency sound and infrasound. The condition is described as being “characterised by the abnormal proliferation of collagen and elastin, in the absence of an inflammatory process”.[69] Its relationship to low-frequency sound and infrasound has been inconsistently corroborated by independent research.[70,71]

The WHO reported a number of effects on sleep when night noise was in the range of 30–40 dBA (measured outside).[41] These include body movements, awakening, self-reported sleep disturbance and arousals. The intensity of the effect varies with the nature of the source of the noise and the number of noise events. Vulnerable groups (e.g. children, people who are chronically ill and elderly people) are more susceptible to effects on sleep. However, even in the worst cases, the effects seem modest.[41] A recent meta-analysis concluded that people consistently reporting 5–6 hours or less sleep a night have a higher risk of heart disease and stroke.[45]

Prolonged noise-related annoyance may also cause health effects,[54] as evidence suggests that stress pathways may be active in annoyed individuals[66] and psychological stress may be a risk factor for cardiovascular disease.[65]

There is no evidence to suggest that the health effects from wind farm noise would differ from health effects of other noise sources at similar levels. Based on the studies referred to above, wind farms would be unlikely to cause health effects at distances of more than 500 m, where noise levels are generally less than 45 dBA. At this distance, effects on sleep are likely to be modest at the population level. At distances of more than 1,500 m from wind farms, where the wind farm noise level may be in the order of 30–35 dBA, sleep disturbance is unlikely. There is insufficient evidence to establish whether self-reported sleep disturbance associated with wind farm noise is of the duration and intensity known to cause health effects.

The table below shows a comparison of wind farm noise with other typical environmental noise sources.

Wind farm noise and other typical sources of environmental noise	Approximate noise levels (dBA)
Traffic	70 – 85
Household devices	35 – 70
Wind farm at 500 m to 1,500 m	**30 – 45**
Wind farm beyond 1,500 m	**30 – 35**
Quiet residential area	25 – 55

Table 1: Approximate levels from wind farm noise and other typical environmental noise sources

Source: Data adapted from Basner M, Babisch W, Davis A, Brink M, Clark C, Janssen S et al., 2014 [54] and Bullmore A & Peplow A, 2012[29].

Studies have shown that infrasound from other environmental noise sources is at similar levels to that from wind farms.[30,31] As infrasound is a component of noise, the evidence summarised above applies as much to infrasound as it does to other sound frequencies from wind farms.

Human laboratory studies

Laboratory studies have investigated changes in functioning of the human body when people are exposed to infrasound or low-frequency noise. One study suggested that high levels of low-frequency noise and infrasound may lead to small and inconsistent changes in blood pressure, pulse or heart rate.[47] High levels of low-frequency noise may also cause temporary hearing loss.[48,49] These studies involved higher levels of noise (greater than 90 dB) and shorter exposures than those experienced in the proximity of wind farms and the characteristics of wind farm noise were not fully replicated.

Other laboratory studies have suggested that both negative and positive expectations of the effect of infrasound may influence its perception.[72,73]

6.2 Shadow flicker and other visual stimuli

6.2.1 Direct evidence

No studies were identified that assessed the health effects of shadow flicker or other visual stimuli from wind farms. One small study with a high risk of bias reported that people who lived within 5 kilometres (km) of a wind farm were more likely to notice and be annoyed by shadow flicker than those who lived 5–10 km away.[8]

Although of no specific relevance to shadow flicker, a small study[22] examined the association of annoyance with illuminated aircraft warning markers on wind turbines and found that the markers contributed less to annoyance than other characteristics of wind farms, such as noise.

6.2.2 Parallel and mechanistic evidence

It is known that flashing lights can trigger seizures among people with a rare form of epilepsy called photosensitive epilepsy. The risk of shadow flicker from wind farms causing an epileptic seizure is estimated to be less than 1 in 10 million in the general population[74] and 17 in 1 million among people at risk of photosensitive epilepsy.[36]

People exposed for short periods to simulated wind turbine shadow flicker in a laboratory have shown some evidence of impaired cognition and a physiological stress response.[50]

6.3 Electromagnetic radiation

6.3.1 Direct evidence

No studies were identified that specifically assessed the health effects of electromagnetic radiation from wind farms.

6.3.2 Parallel and mechanistic evidence

Concerns regarding the safety of exposure to electromagnetic radiation were raised with the publication of a study reporting a link between childhood leukaemia and extremely low-frequency electromagnetic radiation exposure from electricity transmission lines.[46] Subsequent research has looked for possible links between occupational exposure to extremely low-frequency electromagnetic radiation and cancer and cardiovascular, neurological, psychological or reproductive conditions in adults. The results of these studies have been inconsistent and no conclusions can be drawn about a cause-and-effect relationship between extremely low-frequency electromagnetic radiation exposure and human health effects.[75] The exposures in these studies were considerably higher than electromagnetic emissions from wind farms.

Exposure to extremely low-frequency electromagnetic radiation can induce electrical currents in human tissue — the significance of these currents to human health is not known.[39]

The level of extremely low-frequency electromagnetic radiation close to wind farms is lower than the average level measured inside and outside suburban homes (see Section 5.3, page 18).

6.4 Conclusions

After careful consideration and deliberation, NHMRC concluded that there is no consistent evidence that wind farms cause adverse health effects in humans. This finding reflects the results and limitations of the direct evidence and also takes into account the relevant available parallel evidence on whether or not similar noise exposure from sources other than wind farms causes health effects.

NHMRC found no direct evidence that exposure to wind farm noise affects physical or mental health. The few associations reported by individual studies may have been due to chance. The parallel evidence indicates that there is unlikely to be any significant effects on physical or mental health at distances greater than 1,500 m from wind farms.

NHMRC found consistent but poor quality direct evidence that wind farm noise is associated with annoyance. While the parallel evidence suggests that prolonged noise-related annoyance may result in stress, which may be a risk factor for cardiovascular disease, annoyance was not consistently defined in the studies and a range of other factors may have contributed to its reported association with wind farm noise.

The direct evidence of an association between wind farms and sleep disturbance is less consistent and also of poor quality. While chronic sleep disturbance is known to affect health, it was not objectively measured in the wind farm studies and may not have been sufficient to affect health. Parallel evidence suggests that sleep disturbance is unlikely at distances of more than 1,500 m from wind farms.

The direct evidence on an association between proximity to wind farms and poorer quality of life is also less consistent and of poor quality. Measurement of quality of life is generally subjective and the studies did not explore whether the reported associations could be explained by other factors.

Observation of associations between wind farms and these effects does not necessarily mean that wind farms caused them. Given the poor quality of the evidence, bias of different kinds and confounding factors are possible explanations for the associations observed.

When building a body of scientific evidence, it is difficult to establish absence of an outcome (i.e. a negative conclusion, such as that an exposure does not cause health effects). Thus lack of consistent evidence that wind farms affect human health may not mean that wind farms have no health effects. While parallel evidence indicates that significant health effects are unlikely at distances greater than 1,500 m, it might simply be that the research done has been of insufficient quality or statistical power to show an effect, particularly where the study has a small number of participants.

7. Areas for further research

Further evidence is needed to explore the relationships between noise at varying distances from wind farms and effects such as annoyance, sleep and quality of life. Research is also required to investigate the broader social and environmental circumstances that may influence the reporting of health effects in people living near wind farms.

7.1 Engagement with the community

Gathering sufficient quality evidence in these areas may assist governments and planning authorities to make evidence-based decisions regarding wind farm policy, planning and development. Wider engagement and participation, including by the community, in the various stages of research would be beneficial in ensuring that research is appropriately targeted to the community's areas of concern. This could include community members being involved in deciding what to research, deciding how to conduct the research, overseeing conduct of the research, disseminating the findings and deciding what to research next.[76] Researchers are encouraged to demonstrate community engagement and participation in the development of their research proposals, particularly to identify the specific concerns of individuals and communities living in proximity to wind farms.

7.2 Themes for further research

The Reference Group has identified a number of themes for further research. It is important that research measuring and characterising wind farm noise exposure is completed prior to undertaking research into health effects and possible interventions. Three main themes have been identified to provide high-level guidance on the areas for research to address current gaps in the evidence. These areas are not exclusive and research should also allow for innovative proposals that are broadly relevant to these themes.

The three themes for further research are discussed below.

7.2.1 Improve the measurement of noise

The studies identified in the independent reviews did not directly measure wind farm noise at participants' homes. People's exposure to wind farm noise was estimated based on how far they lived from the nearest wind farm (proximity) or by using mathematical models to estimate the level of sound where they lived. However, it is difficult to estimate the level of noise from wind farms in the presence of background noise.

Where consistent associations were found between estimated wind farm noise and an effect, such as annoyance, it was not possible to tell whether *noise* was driving the association or whether the association could be explained by one or more other factors that are more common among people living in close proximity to wind farms (such as attitude to, visibility of or economic benefit from wind farms).

The Reference Group considers that further research is required to characterise wind farm noise (audible, low-frequency and infrasound) at distances ranging from 500 m to 3 km and beyond, in different terrains and under varying weather conditions. These outcomes may inform whether a "wind farm signature" can be developed and validated as a specific indicator of wind farm noise.

Infrasound is considered by some to be an important component of the noise from wind farms. The Reference Group considers that there is a need to develop standardised methods to measure infrasound indoors and outdoors and at various distances from a wind farm (ranging from 500 m to 3 km and beyond). This would ensure there is consistency in the measurement of infrasound from wind farms and aid interpretation of the body of evidence on the effects of wind farm noise. Indoor measurement of vibration associated with low-frequency noise may also contribute to understanding of the effects of wind farm noise.

Field studies to establish the characteristics of noise that are exclusive to wind farms (if any) and to consider how wind farm noise varies over the course of the day, in different terrains, under different weather conditions and with further increases in distance would be useful approaches to address this issue. Further, an assessment of the subjectively measured human perception of wind farm noise (including audible noise, low-frequency noise and infrasound) may improve understanding of whether wind farm noise is perceived differently from other similar noise sources.

7.2.2 Examine the relationship between wind farm noise and health effects

All the studies identified as direct evidence in the independent reviews used self-reported measures of health outcomes to determine whether there was any association between these outcomes and exposure to wind farm emissions. Given the lack of objective health measurements in these studies, bias cannot be excluded as an explanation for any apparent association. In addition, the measurement of annoyance, sleep disturbance and mental health in relation to wind farm proximity lacked the consistent use of validated questionnaires.

Field studies that include objectively measured physiological and biochemical characteristics (including sleep) along with an individual's self-reported physical and psychological status (including annoyance and stress) and consistently use validated self-reporting instruments are required to address methodological shortcomings in the existing evidence. Measurements of these variables should be made in relation to objectively recorded noise from wind farms (measured inside and outside residences) and exposure in the field to simulated wind farm noise generated by a loudspeaker. Another possibility would be measurement of physiological and biochemical characteristics and assessment of self-reported physical and psychological status before and after a period of removal from the wind farm environment.

Laboratory studies would also be useful to examine the effects of validated wind farm noise on objectively measured physiological and biochemical characteristics. These findings could then be considered alongside comparable field studies.

7.2.3 Investigate the social and environmental circumstances

The Reference Group recommends further investigation of the broader social and environmental circumstances that influence annoyance, sleep disturbance, quality of life and health effects that are reported by residents living in proximity to wind farms.

Factors that influence changes to health effects may include people's expectations of their environment, perceived loss of control, aesthetics and impacts on visual landscape, impacts on land values, uneven distribution of financial benefits, local community relationships and exposure to other noise sources (e.g. road traffic and wind noise).

Further research would improve the understanding of the potential confounding or modifying effects of these factors on the relationship between objectively recorded exposure to validated wind farm noise and:

- an individual's self-reported physical and psychological status (including annoyance); and
- an individual's objectively measured physiological and biochemical characteristics.

This could be achieved through a program of psychosocial research to investigate, develop and test interventions that might reduce the impacts of wind farm developments on nearby residents. This research may assist in developing possible policy or consultative interventions that may address the above-mentioned broader factors and thereby reduce the reported health effects of wind farms.

7.3 Other research-related issues

In addition to further research, expert assessment of some existing research on human physiological responses to noise is needed. Community concern and some research on possible health effects of wind farms have tended to focus on low-frequency sound and infrasound as likely causes of harm. Some physiological or pathological mechanisms have been suggested to explain how these sound frequencies in wind farm noise might lead to human health effects, such as through unique effects on the cochlea[77] or the more systemic "vibroacoustic disease".[69] Closer examination of these hypotheses was outside the scope of work of the Reference Group. Expert analysis of the body of evidence exploring human physiological and suggested pathological responses to noise may assist in determining the plausibility of the mechanisms that have been proposed and their relevance to the wind farm context. This work may include further assessment of existing animal studies investigating possible mechanisms whereby wind farm emissions could cause human health effects, which was also beyond the scope of the Reference Group's work. This will inform whether further research on these possible physiological and pathological mechanisms is warranted to improve understanding of the effects of infrasound and low-frequency sound from wind farms.

Appendices

A Membership and terms of reference of the Reference Group

Membership

Members	Area(s) of expertise	Affiliation
Professor Bruce Armstrong (Chair)	Environmental epidemiologist	Emeritus Professor School of Public Health The University of Sydney
Professor Michael Abramson	Environmental epidemiologist and respiratory physician	Professor of Clinical Epidemiology Epidemiology and Preventive Medicine School of Public Health and Preventive Medicine Monash University
Professor Ronald Grunstein	Specialist physician in sleep medicine	Professor of Sleep Medicine Woolcock Institute of Medical Research Central Clinical School The University of Sydney and Royal Prince Alfred Hospital
Professor Debra Rickwood	Health and community psychology	Professor of Psychology Faculty of Health, University of Canberra Chief Scientific Advisor headspace National Youth Mental Health Foundation
Professor Wayne Smith	Environmental epidemiologist	Director Environmental Health Branch, NSW Health Conjoint Professor of Epidemiology University of Newcastle Honorary Professor of Public Health The University of Sydney
Dr Norm Broner	Acoustic consultant	Principal, Broner Consulting (Previously Practice Leader Acoustics, Noise and Vibration Jacobs)
Dr Elizabeth Hanna	Epidemiologist	Fellow National Centre for Epidemiology and Population Health ANU College of Medicine, Biology and Environment
Anne McKenzie	Consumer Advocate	Consumer Advocate The University of Western Australia's School of Population Health and the Telethon Kids Institute
Observers		
Peter Mitchell		Honorary Chairman Waubra Foundation Member of Board of Governors Florey Neuroscience Institute Patron, Children First Foundation
Russell Marsh		Policy Director Clean Energy Council

Terms of reference

1. The Wind Farms and Human Health Reference Group will guide the development of a systematic review to determine if new evidence exists in the peer reviewed scientific literature on possible health effects of wind farms, by providing advice to the Office of NHMRC on the:
   a. scope and questions the systematic review will address;
   b. methods to identify relevant published guidelines and systematic reviews; and
   c. methods to evaluate relevant published guidelines and systematic reviews.
2. The Wind Farms and Human Health Reference Group will consider the outcomes of the review and use these finding to:
   a. inform updating NHMRC's Public statement: wind turbines and human health; and
   b. identify critical gaps in the current evidence base.
3. The Wind Farms and Human Health Reference Group will provide NHMRC's Prevention and Community Health Care Committee with a report on wind farms and human health, which is to include advice on the systematic review outcomes, updating the Public Statement and possible need for further research, for consideration before recommendation to Council.

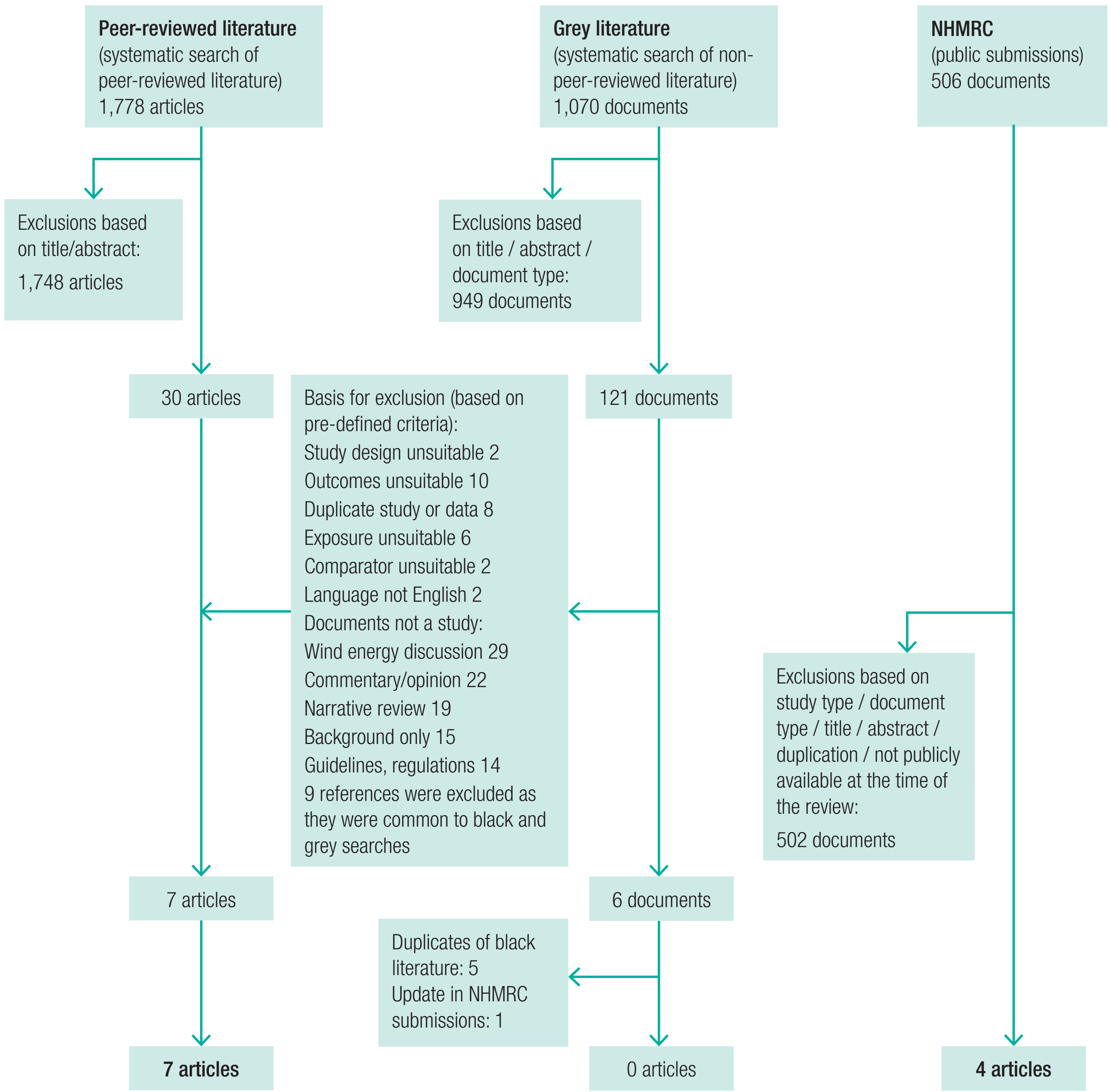
B Quality assurance processes

Rigorous quality assurance processes support the development of all NHMRC health advice. The quality assurance processes used to support the quality of the independent reviews of the evidence and the Information Paper are outlined below.

- *Reference Group observers* — Two observers were appointed to the Reference Group to observe process. The observers did not contribute to the scientific discussions or decision-making processes of the Reference Group. While bound by a deed of confidentiality with respect to the details of the Reference Group's deliberations, the observers are free to comment in general terms on the process they observed following publication of this Information Paper.
- *Reference Group declaration of interests* — As part of their formal appointment to the Reference Group, each member and observer was required to disclose any factors that may cause or be perceived to cause a conflict of interest with their duties as members of the Reference Group. The declared interests of all Reference Group members and observers have been published on NHMRC's website. The Reference Group Chair reviewed each member's declared interests and no unmanageable conflicts were identified. While some members of the Reference Group had relevant interests, most members did not. All discussions of the group were robust and open and decision-making was consensus-based.
- *Methodological review* — Independent reviewers from the National Collaborating Centre for Environmental Health in Canada examined the methodological quality of the report of the first independent review to ensure that the review followed the systematic and rigorous approach documented in the review protocol. The methodological reviewers were appropriately qualified in systematic review processes and had previous experience in reviewing the scientific evidence on possible health effects of wind farms. The methodological review team completed a declaration of interest process before being appointed by NHMRC and no conflicts of interest were identified. The independent reviewers assessed the methodological quality of the review as high.
- *Public consultation* — The draft Information Paper was released for public consultation, accompanied by the supporting independent review report. The public consultation process allowed members of the public to make submissions about the document, comment on the evidence-based approach that was undertaken and provide any relevant additional evidence for consideration. The draft Information Paper was revised in light of the submissions that were received during public consultation.
- *Expert review* — In parallel with public consultation, the draft Information Paper underwent expert review to ensure that the evidence was appropriately interpreted and synthesised. The expert reviewers were asked to evaluate the appropriateness of the conclusions based on the existing body of evidence. In addition, the expert reviewers were asked to consider whether:
  - the rationale applied in examining the evidence was clearly explained;
  - the evidence was accurately translated into the draft Information Paper; and
  - the conclusions in the document aligned with their understanding of the latest evidence in their specific area of expertise.
- NHMRC selected a number of Australian and international experts in the fields of acoustics, aerospace engineering, mental health, sleep, epidemiology and environmental health to conduct the expert review. Before being appointed, potential expert reviewers were required to declare any interests that may be perceived to cause a conflict with their role as an expert reviewer.
- *Consideration by the Council of NHMRC* — The consultation draft and final Information Paper were considered by the Council of NHMRC for its recommendation to the Chief Executive Officer that the documents be released. The Council has a broad range of experience and expertise in health and medical research. Council's final approval of NHMRC health advice documents ensures that the checks and balances at all stages of the process have been met and that any material issued by NHMRC is evidence-based, robust and meets international standards.

C Process of selecting literature for inclusion

Systematic literature search in first independent review (material published 1981 – October 2012)



Study design unsuitable — qualitative study design or case reports

Outcomes unsuitable — sound or noise level measures, sound directivity, attitude or other non-health-related outcomes

Duplicate study or data — the study duplicates the work or data reported in a previously identified and included study

Exposure unsuitable — exposure is noise from sources other than wind farms

Comparator unsuitable — comparisons between groups exposed to different noise sources

Figure 3: Process of selecting literature for inclusion in the first independent review

Source: Adapted from the report of the independent review,[1] Figure 1, page 43.

Repeat systematic literature search in independent review of additional evidence (material published October 2012 – May 2014)

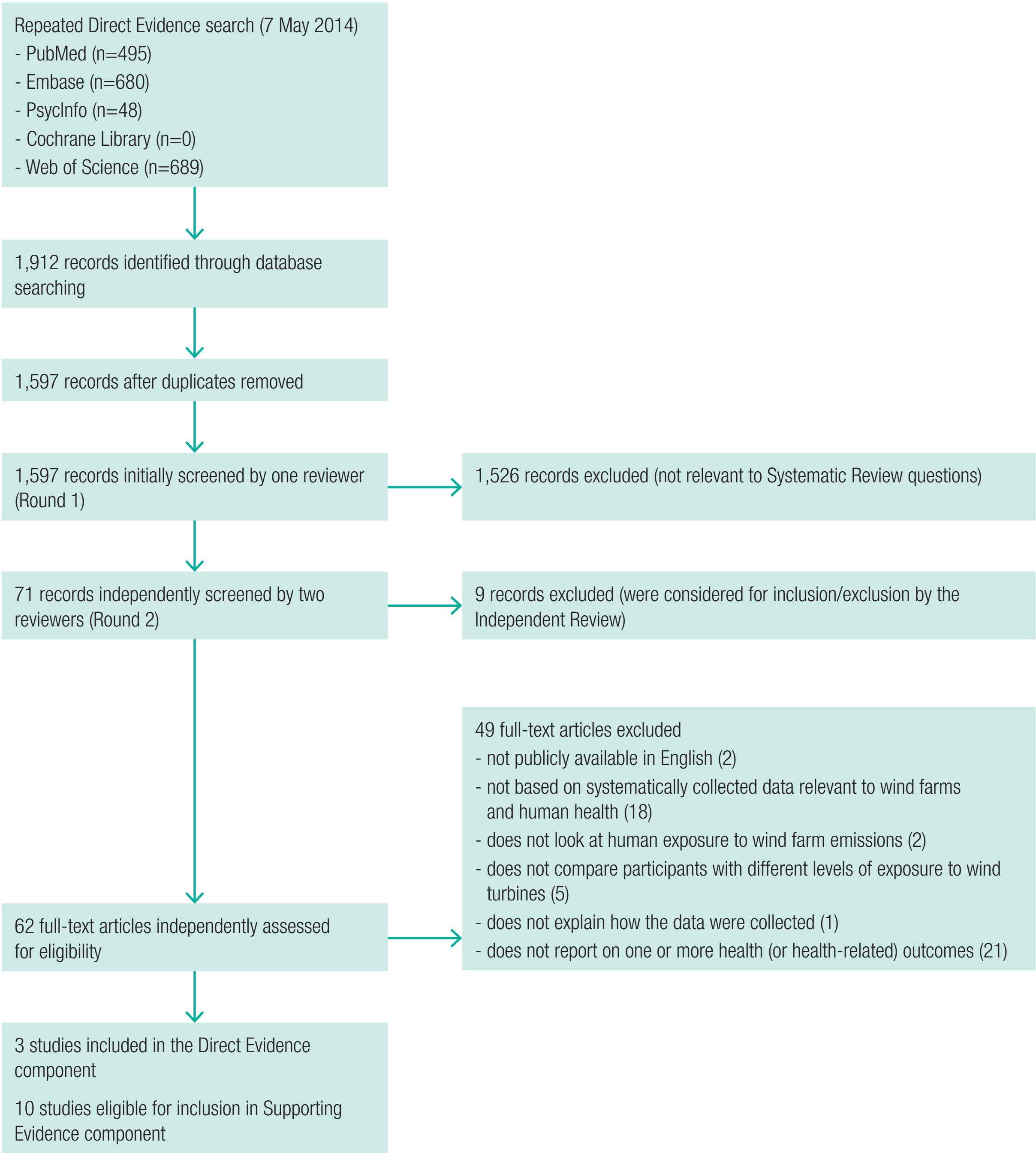


Figure 4: Process of selecting material from repeat systematic literature search for inclusion in the independent review of additional evidence

Source: Adapted from the report of the independent review of additional evidence,[2] Figure 1, page 7.

Assessment of submitted literature in independent review of additional evidence

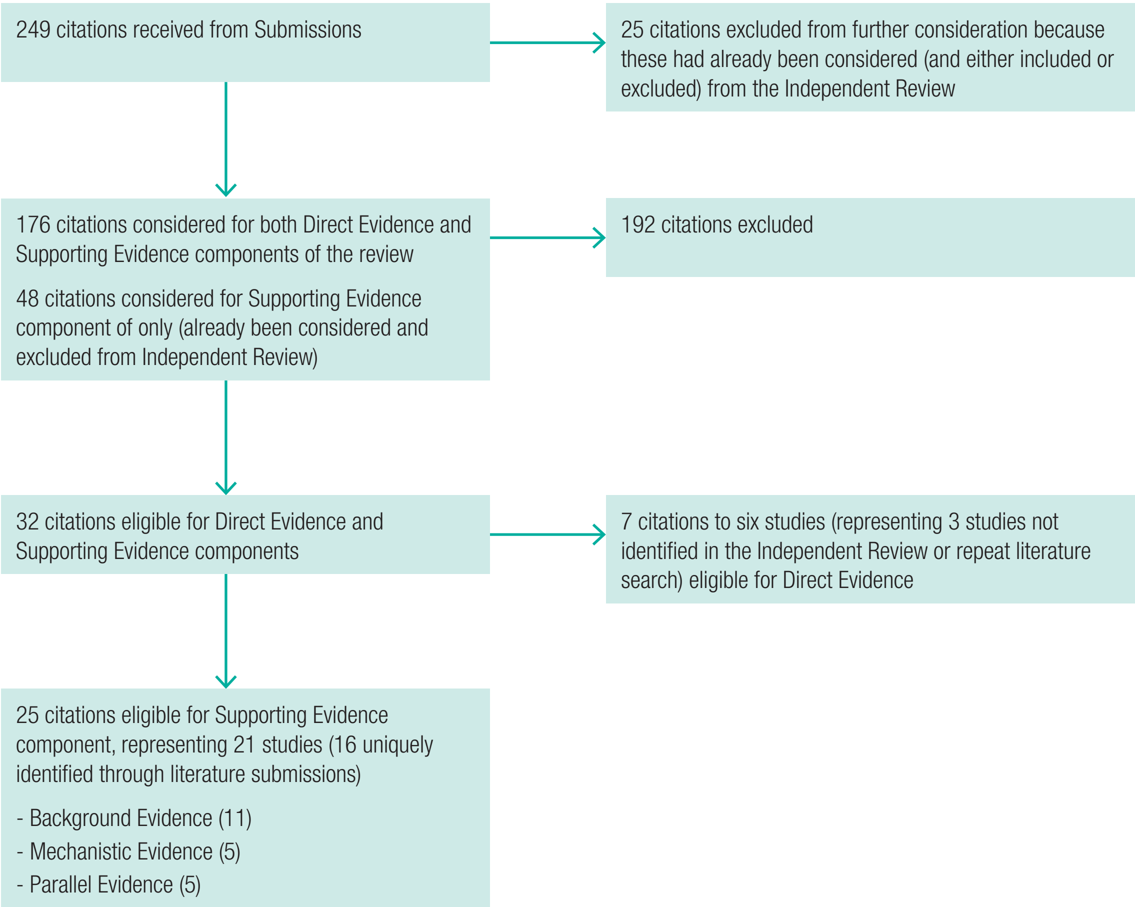


Figure 5: Process of selecting submitted literature from public consultation and expert review for inclusion in the independent review of additional evidence

Source: Adapted from the report of the independent review of additional evidence,[2] Figure 2, page 9.

Glossary

A-weighted decibels: Noise levels adjusted to represent the response of the human ear (expressed as dBA).

Acoustics: The science that deals with the study of the generation, transmission and reception of sound, ultrasound and infrasound.

Aerodynamic sound: For wind turbines, the sound generated by the interaction of the blade trailing edge, tip or surface with turbulent air flow.

Annoyance: An unpleasant mental state characterised by effects such as irritation and distraction from one's conscious thinking.

Association:* Statistical dependence between two or more events, characteristics or other variables.

Bias:* The effect of an error in the design of a study or an error or problem in the collection, analysis, reporting, publication or review of study data that leads to untrue results.

Chance:* The probability that an event will happen# or, in a phrase such as "happened by chance", the occurrence of events in the absence of any obvious intention or cause.

Confounding:* The distortion of a measure of the effect of an exposure on an outcome due to the association of the exposure with other factors (confounders) that influence the occurrence of the outcome.

Cross-sectional study:* A study that examines the relationship between diseases (or other health-related characteristics) and other variables as they exist in a defined population at one particular time.

Decibel: A unit of measure used to express sound pressure amplitude associated with a sound, calculated as the logarithmic ratio of sound pressure level against a reference pressure, multiplied by 20 (expressed as dB).

Direct evidence: Evidence directly linking an exposure with a health outcome of interest.

Economic benefit: A benefit to a person, business or society that can be expressed numerically as an amount of money that will be saved or generated as the result of an action.

Effect modifier:* A factor that, when it varies, modifies the effect of another factor on an outcome with which it is causally associated.

Electromagnetic radiation: Radiation that is a combination of electric and magnetic waves (such as x-rays, ultraviolet rays, infrared rays, visible light and radio waves) transmitted in a wave-like pattern as part of a continuous spectrum.

Emission: For wind farms, recognised emissions include noise (including infrasound and low-frequency sound), shadow flicker and electromagnetic radiation.

Epidemiology: The study of the patterns, causes and effects of health and disease conditions in human populations.

* Adapted from the International Epidemiological Association *Dictionary of epidemiology*.[78]

The International Epidemiological Association definition[78] states "possibility" rather than "probability". However, for the purposes of the systematic review "probability" was preferred.

Epilepsy: A neurological condition marked by sudden recurrent episodes of sensory disturbance, loss of consciousness or convulsions, associated with abnormal electrical activity in the brain.

Exposure: For this review, exposure relates to being in the vicinity of wind farm emissions.

Frequency: The number of sound waves or cycles passing a given point per second (measured in cycles per second and expressed as Hz).

G-weighted decibels: Noise levels adjusted so as to give greater weight to low-frequency sounds than A-weighted decibels do and used to quantify sound with a significant portion of energy in the infrasonic range below 20 Hz (expressed as dBG).

Grey literature: Multiple document types and literature produced by government, academia, business and other organisations in electronic or print format. Grey literature is not always peer-reviewed and is not controlled by commercial publishing.

Health outcome: A defined disease, state of health or health-related event that has been measured in a study.

Hertz: A measure of frequency (one cycle per second = 1 Hz).

Infrasound: A term used to describe sound in the frequency range lower than 20 Hz.

Low-frequency sound: Sound that falls within the frequency range of 20 Hz to 200–250 Hz.

Masking:* Procedures intended to keep participants in a study from knowing some facts or observations that might bias or influence their actions or decisions regarding the study (also called "blinding").

Mechanical sound: For wind turbines, the sound produced by the interaction of electrical and rotational parts such as the gearbox and generator.

Narrative review: A literature review that is conducted without a predefined protocol or method.

Noise: Unwanted sound or combination of sounds.

Participants: People who have taken part in a trial or study or have responded to a survey questionnaire or interview.

Peer-reviewed literature: Published literature that before it was published, was reviewed critically by other people in the same field of research and revised in response to the critical review as a condition of publication.

Prevalence:* A measure of occurrence or disease frequency that refers to the proportion of individuals in a population who have a disease or condition.

Psychology: The scientific study of mental functions and behaviour.

Quality of life: A person's perception of their position in life in the context of the culture and value systems in which they live, and in relation to their goals, expectations, standards and concerns.

Selection bias:* Distortions in outcomes that result from the procedures used to select participants and from factors that influence participation in a study.

Self-report: Information on a person's history or personal characteristic that a person themself provides, generally from memory.

Shadow flicker: The flickering effect caused when rotating wind turbine blades intermittently cast shadows over neighbouring objects and terrain as they turn.

* Adapted from the International Epidemiological Association *Dictionary of epidemiology*.[78]

Socioeconomic status:* A descriptive term for a person's position in society, which may be expressed on an ordinal scale using such criteria as income, level of education attained, occupation, value of dwelling place etc.

Sound pressure: The local pressure deviation from the ambient (average or equilibrium) atmospheric pressure caused by a sound wave. Sound pressure can be measured in air using a microphone and in water using a hydrophone. The International System unit for sound pressure is the pascal (expressed as Pa).

Sound pressure level (or sound level): A logarithmic measure of the sound pressure of a sound relative to a reference value. It is measured in dB above a standard reference level. The standard reference sound pressure in air or other gases is 20 micropascals, which is usually considered the threshold of human hearing (at 1 kHz).

Sound: An energy form that travels from a source in the form of waves or pressure fluctuations, transmitted through a medium (e.g. air, water) and may be received by a receiver (e.g. human ear).

Supporting evidence: Includes evidence obtained from related fields that support the association between an exposure of interest and an adverse health effect (parallel evidence) and evidence for a mechanism by which an exposure of interest may cause a particular health outcome of interest (mechanistic evidence) — the mechanism may be biological, chemical or mechanical.

Systematic literature review: A process that provides a transparent and reproducible means for gathering, synthesising and appraising the findings of studies on a particular topic or question. The aim is to minimise the bias associated with the findings of single studies or non-systematic reviews.

Tinnitus: The perception of sound within the human ear (ringing in the ears) when no actual sound is present.

Tonality: # Noise containing a prominent frequency and characterised by a definite pitch.

Wind farm: A collection of wind turbines.

Wind turbine: A device that uses kinetic energy from the wind to produce electricity.

* Adapted from the International Epidemiological Association *Dictionary of epidemiology*.[78]

Definition from NSW industrial noise policy.[53]

List of acronyms and abbreviations

dB	decibels
dBA	A-weighted decibels
dBG	G-weighted decibels
Hz	Hertz
km	Kilometre
m	Metre
NHMRC	National Health and Medical Research Council
WHOQOL	World Health Organization Quality of Life scale
WHO	World Health Organization

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