ZEPHYR

Towards a more efficient exploitation of on-shore and urban wind energy resources

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D3.7: Atmospheric Propagation Towards Communities and Human Factors: Final Public Report (WP3)

Executive summary
The focus of this public report is the sound emitted by wind turbines and the way it is perceived by humans. The literature on social acceptance of wind energy has demonstrated that noise is one of the most frequent factors for opposing wind-energy projects. The research on noise matters has been one of the priorities of the zEPHYR project. Therefore, this report summarizes the research and educational activities on the topic of wind-turbine noise conducted in the framework of the project.

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Change log

Date	Version number	Author/Editor	Summary of changes made

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List of abbreviations

ESR Early Stage Researcher
WHO World Health Organisation

1 Introduction

Wind energy is a source of green power that does not pollute water and air and does not produce waste by-products. While providing lots of benefits to society, wind-energy projects are often opposed by communities living in proximity to planned or actual wind parks (Devine-Wright, 2014). A growing body of research has demonstrated that there are multiple factors for public opposition towards wind energy projects, including the negative impact of wind energy on landscapes (Walker, Devine-Wright, Barnett, et al., 2014), possible noise annoyance, negative health effects, and safety issues.

The focus of this public report is on the sound emitted by wind turbines and the way it is perceived by humans. Sound is the propagation of low-amplitude pressure waves created by a vibrating object and travels with the speed of sound and is considered as noise when it is not desired (Szasz & Fuchs, 2010). The literature on social acceptance of wind energy has demonstrated that noise is one of the most frequent factors for opposing wind energy projects. Scholars working on this topic have demonstrated that people often associate the noise produced by wind turbines with potential negative health effects, including irritation, anxiety, disturbance in sleep, and hearing loss. Further, the noise from wind turbines can have negative effects on natural habitats as it might disturb birds, which, in turn, affects their breeding and feeding behavior (Dai, Bergot, Liang, Xiang, & Huang, 2015). National and local governments often cope with this problem by establishing acceptable levels of noise pollution in particular areas (Dällenbach & Wüstenhagen, 2022). While this allows the setting up of legal limits to noise exposure, these measures are not always sufficient to make people accept wind energy projects.

The literature on public acceptance of wind energy demonstrates that wind turbine noise is a complex issue as noise perception may vary per person and depend on multiple factors, including sensory acuity and sensitivity, as well as personal attitudes and beliefs (Alamir, Hansen, Zajamsek, & Catcheside, 2019; Radun, Hongisto, & Suokas, 2019). On top of that, the level of noise pollution is also dependent on external factors such as weather conditions, landscape characteristics, and other variables. All this demonstrates that noise is a complex issue and is “a subject of controversy, linked to disagreements within society around what and whose definitions, concerns, and knowledge should be recognized” (Solman, Kirkegaard, & Kloppenburg, 2023, p. 1).

The research on noise matters has been one of the priorities of the zEPHYR project. The project has strived to combine the literature review on noise as the key factor influencing social acceptance of wind energy projects with psychoacoustic studies. Further, the different factors affecting noise perception were highlighted in the framework of the workshop titled ‘Human response to sound vibration’. The workshop was conducted in November 2022 and served as a tool to acquaint engineers with societal aspects of noise perception.

This report aims to summarize the research and educational activities conducted in the framework of the zEPHYR project. The remainder of the report is structured as follows. First, the report presents the discussion about noise perception in the social science literature. Second, it briefly discusses psychoacoustic indicators for predicting wind turbine noise. Further, we focus on the workshop ‘Human response to sound vibration’ and suggest how it can be used as an instrument for educating engineers about public concerns about prospective wind turbine noise. We conclude by discussing the implications of research activities undertaken in the framework of the zEPHYR project for policy-making.

2 Public perception of wind turbine noise

There are different sources of sound at wind farms. Therefore, it might be difficult to identify a single cause of noise annoyance. In deliverable 3.5, we discussed two types of noise – mechanical and aerodynamic. Mechanical noise originates from the motion of mechanical components of a wind turbine, namely a wind turbine power generator and a gearbox (Raman, Ramachandran, & Aldeman, 2016). The second type of noise is aerodynamic noise, and it originates from the interaction between the blades and the air (Raman et al., 2016). Both types of noise might be perceived as annoying to a certain degree depending on multiple factors, including weather conditions (temperature of air, humidity), landscape characteristics, and the presence of obstacles at a specific locale.

The studies have shown that, in fact, the noise produced by a modern typical wind turbine located in rural areas is not significantly high compared to regular noise that people are used to, such as electronic domestic appliances or traffic noise. At the same time, Pedersen has found that wind turbine noise has a higher level of annoyance than noise caused by air traffic, road traffic, and railways at the same sound power level (Pedersen & Persson Waye, 2004). This might be attributed to three specific characteristics of wind turbine noise that make it recognizable and more annoying, i.e., amplitude modulation, tonality, and low-frequency noise (Hansen, Doolan, & Hansen, 2017). The amplitude modulation is a periodic variation in the amplitude of a noise or vibration signal and gives the sensation of pulsating noise. There are two types of amplitude modulation, i.e., amplitude modulation, which is inherent to wind turbine operation, and enhanced amplitude modulation, which is generated by different mechanisms. Amplitude modulation is caused by changes in the direction of trailing edge noise relative to a stationary receiver. The tons are defined as higher sound pressure levels at a specific frequency or small frequency range compared with neighboring frequencies. A noise with tonal components causes more annoyance than an equally loud noise without tones (Landström, Åkerlund, Kjellberg, & Tesarz, 1995). Wind turbine tones are mainly associated with the gearbox, generator, and wind turbine power electronics. Tonal noise has specific regulations and standards (Vanhollebeke, 2015). The low-frequency noise is more annoying than high-frequency noise since it is perceived at a long distance. It is estimated that a wind turbine could be heard at a distance of 3 km, depending on wind characteristics and operating conditions. Low-frequency noise is insignificantly attenuated on reflection from the ground or due to air absorption, whereas high-frequency noise is usually absorbed by the environment or solid surface.

The identification of noise characteristics allows us to address the problem of noise annoyance at a technical level. For instance, mechanical noise can be reduced by acoustic treatment in the nacelle and by using specific mechanical components and couplings. Furthermore, international organizations and national governments address the problem by developing regulations and guidelines that specify allowed levels of noise exposure or suggesting a minimum distance between a wind turbine and residential areas. For instance, The World Health Organisation (WHO) sets a conditional recommendation that noise levels of wind turbines in residential areas not exceed 45 dB(A) in the European Region (World Health Organization, 2018). National governments might also establish their own noise regulations that take into account various parameters of wind turbine noise. For instance, The Danish statutory order on wind turbine noise was amended in 2012 to establish new rules for low-frequency noise (Jakobsen, 2012). The revised 'which is 20 dB A-weighted level of the calculated indoor sound level in the 1/3–octave bands 10 – 160 Hz' (Jakobsen, 2012). By amending the regulation, the Danish authorities aimed to ensure that people living in the vicinity of wind turbines are disturbed neither by the usual noise nor the low-frequency noise.

While the noise regulations might increase the acceptance of wind energy projects, social research on wind turbine noise has demonstrated that people's response to wind turbine noise is shaped not only by the sound level itself but by the multiplicity of other accompanying factors such as visual annoyance and safety associated with wind turbines (Voicescu et al., 2016). Furthermore, the level of annoyance might be related to the perceived cost-benefit distribution within a particular wind energy project and the concept of fairness. Studies demonstrate that residents who receive economic benefits from wind turbines have a higher level of acceptance of wind energy in general and, thus, are less likely to be annoyed by wind turbine noise (Breukers & Wolsink, 2007; Devine-Wright, 2014). In addition, Hirsh and Sovacool (Hirsh & Sovacool, 2013) have demonstrated that the sense of unfairness might cause higher degrees of annoyance with wind energy projects. The authors argue that people living in rural areas might be dissatisfied with wind energy projects related to their 'sense of nature and antipathy toward urban business people who seek to exploit resources at the expense of rural residents' (Hirsh & Sovacool, 2013, p.723). We aimed to demonstrate how these accompanying factors contribute to the annoyance with wind turbine noise in the framework of the workshop 'Human response to sound vibration', which we discuss in more detail in section 5.

The complexity of factors contributing to the annoyance with wind turbine noise requires more complex approaches to managing noise. The literature suggests that one way to tackle the problem is to use participatory tools that allow wind turbine developers to better communicate various issues with local communities and enable their active participation in wind energy projects (Gawlikowska, Marini, Chokani, & Abhari, 2018). In line with this quest, Solman et al.(Solman et al., 2023) have studied one of those tools – a mobile application that was developed by a wind park developer so that residents can report their level of annoyance from a nearby wind park. This study revealed that while the digital app allowed residents to report their experience of wind turbine noise, it excluded certain groups of people from this process. For instance, people living further than 2 km area around the wind farm were not able to use the application (Solman et al., 2023). Further, the authors demonstrated that while the app allowed to provide feedback on the noise level, it did not allow the local community to be actively engaged in the decision-making process and propose concrete solutions to the problem. The authors conclude that the lack of meaningful engagement in the project had led to even more opposition towards a wind farm project (Solman et al., 2023).

The discussion in this section demonstrates that the perception of wind turbine noise is a complex phenomenon. The noise perception is related not only to the sound level itself but to other variables such as visual effects or safety issues. In addition, this section shows that the reasons for annoyance from wind turbine noise may often be rooted in the sense of un/fairness and the perception of cost-benefit distribution in each concrete wind energy project. When understood from this perspective, the noise annoyance issue calls for complex solutions that address both technical and social aspects of the problem.

3 Psychoacoustic indicators for predicting wind turbine noise

While it is important to understand social factors contributing to noise annoyance, the subjective factors should not be ignored as well. As a number of studies show, noise-related annoyance is a subjective psychological state that may result in dissatisfaction, unhappiness, cancellation, melancholy, anxiety, distraction, provocation, or depletion (McCunney, Morfeld, Colby, & Mundt, 2015). A calming and relaxing rhythmic rustling sound for one person may disturb another. Thus, there is no completely satisfactory and unbiased way to measure how disturbing noise can be for any person.

Nowadays, there are several numerical and analytical models that can be used to predict the power spectral density of wind turbine noise, as was demonstrated in deliverables 3.5 and 3.6. However, it is not always easy to evaluate the annoyance of an acoustic signal from the power spectrum. Auralization techniques allow the generation of an audible signal from the power spectral density and, so, perform listening tests in which a group of people can be asked to compare the annoyance of different noise signals. Several psychoacoustic models have been developed to relate the noise spectrum to the annoyance perceived by the listener.

Amplitude modulation has been recognized as one of the most annoying characteristics of wind turbine noise. Fluctuation strength (Fastl & Zwicker, 2007) quantifies the perception of a periodically fluctuating sound, and it is valid for modulation frequencies up to 20 Hz. The unit is vacil, and 1 vacil corresponds to a subjective perception of a 1 kHz pure tone at 60 dB 100% amplitude modulated at 4 Hz. For broadband noise, the fluctuation strength F is calculated as

$$F = \frac{5.8(1.25\mu - 0.25)(0.05L - 1)}{(f_m/5)^2 + (4/f_m) + 1.5} \tag{1}$$

where f_m is the modulation frequency in Hz, L is the broadband noise level in dB and μ is the modulation factor. The modulation factor μ can be computed from the depth of modulation R_{mm}:

$$R_{mm} = 20\log_{10}\left(\frac{1+\mu}{1-\mu}\right). \tag{2}$$

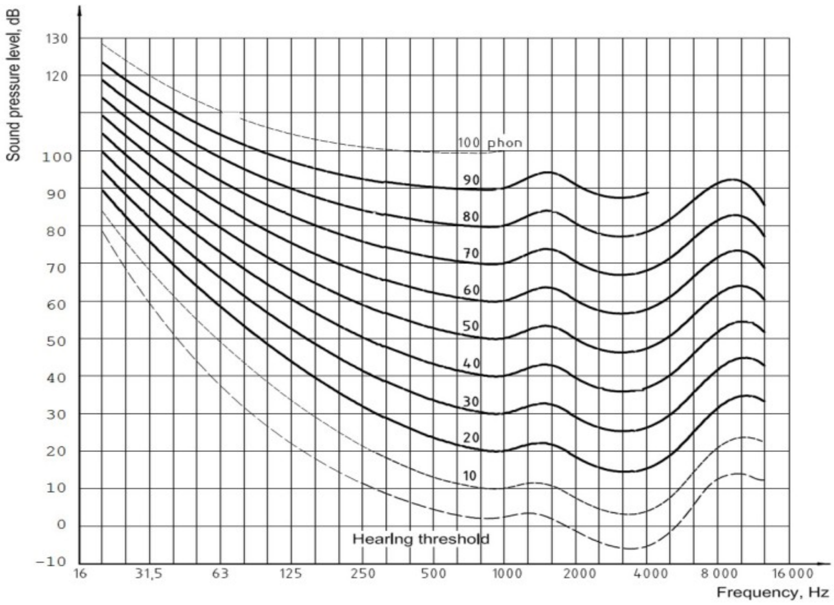

Figure 1: Equal loudness curves from https://acousticsfirst.info/2014/02/19/phones-and-scones-i-mean-phons-and-sones/

Loudness is an indicator particularly important for several applications, including wind turbines ("Measurement", 2017). It is a subjective scale measured in sones or phones (40 phones = 1 sone), which depends on the noise level and frequency for a sound not modulated in amplitude. Equal loudness curves can be established, asking listeners to evaluate on a scale from quiet to loud sounds at different frequencies and different intensities. The result of this listening test is shown in Figure 1. The computation of loudness has been standardized in ANSI/ASA S.3.4 (2007) following the model of Moore and Glasberg and providing a computer program for loudness calculation. Other standards are also used, such as the ISO1996-1 (1975) and the DIN 45631/A1 (2010), and they are based on the model of Zwicker.

Rhythm has been identified as a relevant psychoacoustic indicator for wind turbine noise (Large & Stigwood, 2014). A model for rhythm has been developed by (Fastl & Zwicker, 2007), and it is based on the temporal variation of loudness.

A measure of the annoyance of wind turbine sound that takes into account fluctuation strength and loudness can be derived from the model for *psychoacoustic annoyance*, PA, described in (Fastl & Zwicker, 2007). As suggested in ("Measurement", 2017), the parameters for sharpness S and roughness R can be set to zero. Hence, the psychoacoustic annoyance of wind turbines PA_{WT} can be defined as

$$PA_{WT} = N_5(1 + w_r) \tag{3}$$

where

$$w_r = \frac{2.18}{N_5^{0.4}}(0.4F) \tag{4}$$

and N_5 is the loudness value exceeded for 5% of the sampling time.

4 Educating engineers about public perception of wind turbine noise

While social factors contribute to the way people respond to wind turbine noise, they often tend to be ignored in university curricula for engineers. To address this problem and acquaint ESRs involved in the zEPHYR projects with the societal aspects of public perception of wind turbine noise, we organized the workshop ‘Human response to sound vibration’ in November 2022. This chapter summarizes the workshop and briefly discusses its results.

4.1 Serious games as a tool for discussing complex problems around wind energy

The workshop drew on the serious game approach. A serious game can be defined as an "imitation of the key characteristics, behaviors, and functions of the selected physical or abstract system or process” (Solinska-Nowak et al., 2018, p.1014). Serious gaming has recently become a popular educational tool that allows to teach the audience about complex matters such as wind turbine noise. In serious games, complex phenomena are intertwined with gaming elements such as rules, roles, and rewards. Due to this, serious gaming allows us to teach not mere facts but principles and mechanisms behind a particular process. Further, this approach helps to engage multiple stakeholders in problem identification, development, and experience.

For the workshop, we have developed the ‘Beyond NIMBY’ game that aimed to demonstrate multiple challenges that emerge in the decision-making process about locating wind farms. The developed game served as a tool that allowed the zEPHYR ESRs to experience how different stakeholders feel in the process of deciding on where to locate a wind park. This experience, in turn, enabled ESRs to discuss concerns, including noise concerns, of various stakeholders that are involved or affected by onshore wind energy projects. In the proceeding of this section, we describe the design of the game and its results.

4.2 Serious game design

Context for the game

The ’Beyond NIMBY’ game is based on the real case of a wind energy project in the Netherlands. The project was characterized by numerous conflicts between the local community and the wind park developer during the planning and implementation phase. When the project entered its operational phase, the conflict endured as many residents complained about wind turbine noise. Thus, the above-mentioned wind farm in the Netherlands provided a context for the serious game.

An important element of this context is the vision and policy of the Dutch Government on the further realization of wind energy in the country. This includes the plans of the Dutch Government to expand its onshore and offshore wind farms to produce 15 GW on land and 75 GW at sea. The achievement of these goals presupposes fast-track procedures for installing new wind farms. While the Government plans to develop onshore wind energy projects, there is limited land availability for installing wind turbines in the country. This, in turn, may leave wind energy developers with no choice but to install wind turbines in the vicinity of villages and cities since there is no legal minimal distance between turbines and built-up areas. At the same time, the legal norm for the noise level in the Netherlands is 47 dB Lden and 41 dB Lnight.

Game setting

Since the game is based on the real case, we used the real setting to create a board for the game. We located the towns and villages on the board in the same way as they were located in real life. Since in the actual setting, there was a road dividing the area. We also added the road to the board. As a result, the board for the game looked as follows (See Figure 2):

The board represented an area that the provincial government designated for the potential wind farm. The potential wind farm, according to the game legend, was commissioned by the central government and the provincial government. The planned wind energy project would consist of 40 wind turbines with

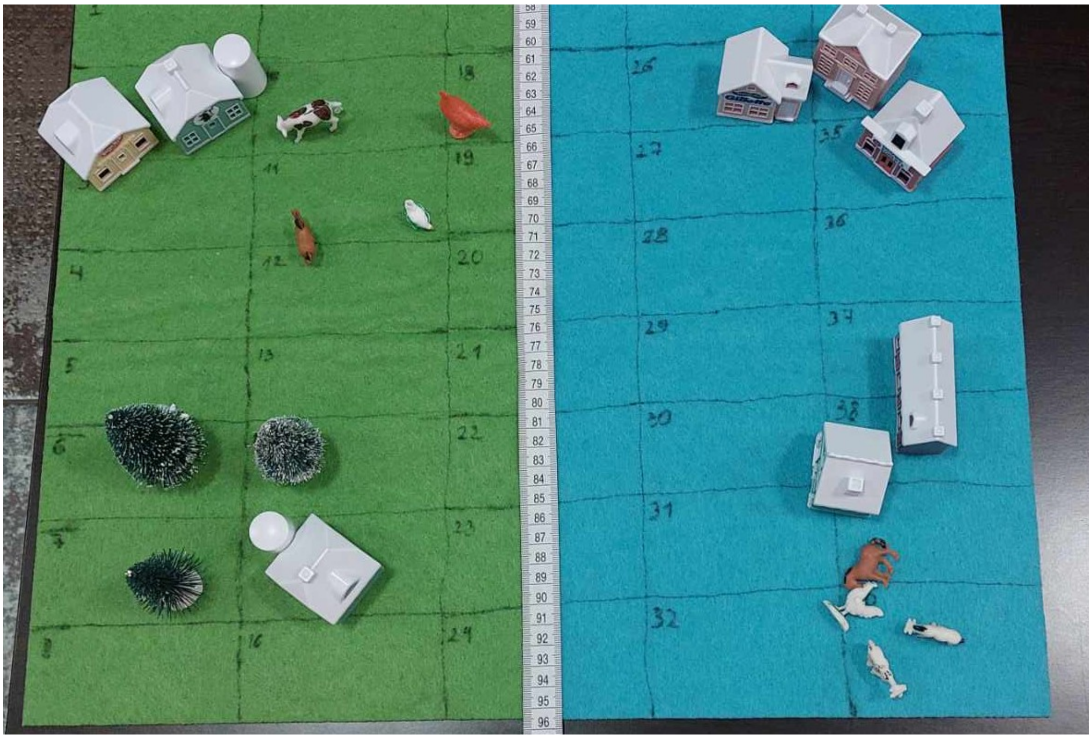

Figure 2: The board that was developed for the 'Beyond NIMBY' game

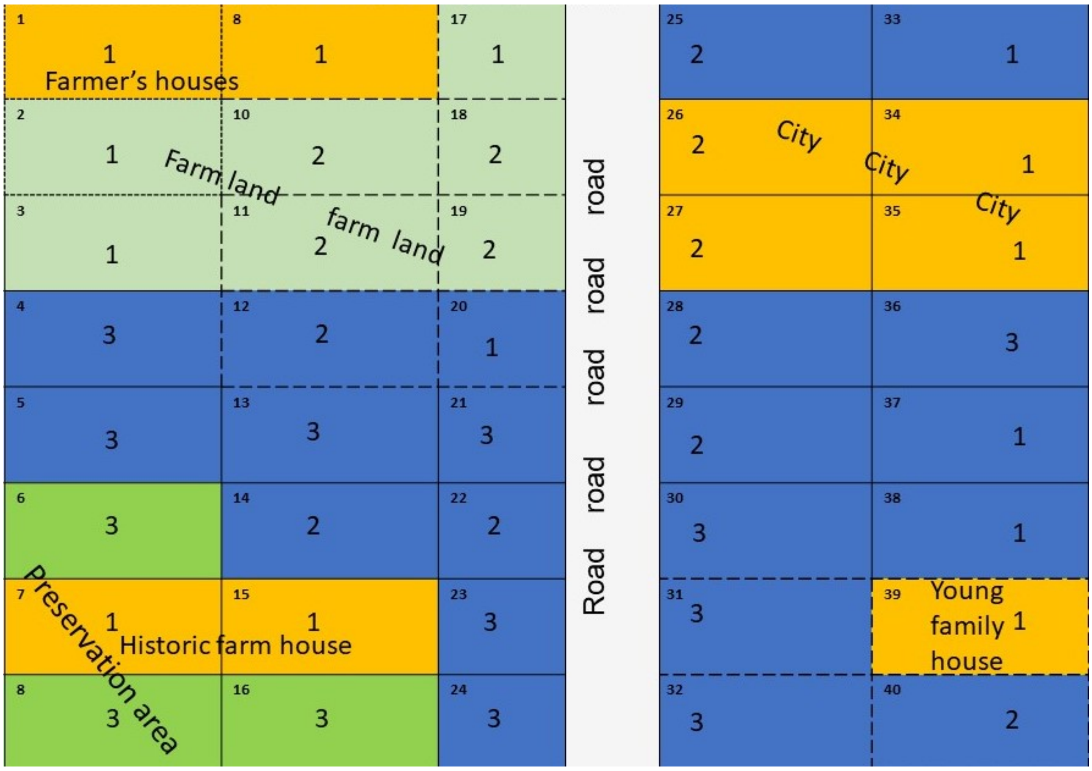

Figure 3: A map accompanying the board game. Numbers 1 -3 – wind intensity, where 3 is the strongest wind

a total installed capacity of 160 MW. The participants had to identify the precise location (exact squares on the board) where the planned wind turbines would be installed. According to the legend, the players were not allowed to install wind turbines in the squares representing a preservation area as well as in the squares where houses are located.

To increase the complexity of the game, the participants were provided with a map that depicted the wind speed in each square on the board (see Figure 3)

Roles within the game

To demonstrate how different stakeholders are affecting and affected by wind energy projects, we divided all the participants into seven groups. Each group represented one of the following stakeholders who had their own objective in the game:

Wind park developer 'zEPHYR Power Inc. aimed to install wind turbines at the most suitable location and maximize the profit from the wind park while keeping public opposition to a minimum

Dutch Ministry of Economic Affairs and Climate Policy had to meet sustainability targets and accelerate renewable energy transition in the Netherlands

Local authorities aimed to meet sustainability targets set by the Ministry of Economic Affairs and Climate Policy and make local residents happy

Expert on wind turbine noise aimed to provide objective information about wind turbine noise to all the stakeholders that request it

Local residents of a senior age aimed to preserve the area as it always has been and avoid any disturbances (including noise that might affect their lifestyle)

Young family with a kid aimed to make sure that your health and the health of your kid are not affected by the noise of wind turbines

Local farmers had to maximize profit from your land

Sometimes, the objectives of stakeholders contradict each other. This was done on purpose to emphasize the complexity of making decisions about wind energy.

4.3 Serious game process

There were two rounds of the game. Before each round, the ESRs had to randomly pick their role. After that, the participants had to find players with the same role and form groups. Once the groups were formed, we distributed role descriptions and gave participants a couple of minutes to read the detailed information about the role they were to play. Later, the groups had to introduce their roles to each other. As soon as the groups got acquainted with their own roles and the roles of others, the game started.

The main goal of the game was to choose a suitable location for a planned wind park on the board while meeting the personal objectives of each group.

Round 1. The aim of the first round was to demonstrate to ESRs how public concerns around wind energy projects develop when the public is excluded from the decision-making process. Therefore, we divided the stakeholders into two larger groups - the authorities and the local community. One group consisted of the wind park developer, the Dutch Ministry of Economic Affairs and Climate Policy, and local authorities. This group had to stay in the main room with the game board and make the decision on where to install the windpark. This group also had to prepare for an information meeting in which it had to announce its decision to the second group.

The group was made up of residents of senior age, a young family with a kid, and farmers who were asked to move to another room and wait there while the first group made a decision. This group had an opportunity to prepare questions for the local authorities and the wind park developer and was allowed to ask those questions only during the information meeting.

After group 1 had decided in which squares they would situate a wind park, both groups were invited to come together and discuss the decision at the information meeting.

All the stakeholders were allowed to consult an expert on wind turbine noise at any time of the game.

Round 2. The second round aimed to show how people's concerns over wind energy projects, including concerns over wind turbine noise, are developed when they participate in the decision-making process. Therefore, in this round, all the stakeholders stayed in the same room throughout the whole game and had to make the decision on where to put wind turbines altogether.

Debriefing session After playing two rounds of the game, the players had a short break that was followed by the reflection session. During the reflection session, ESRs had a chance to discuss what they experienced during the game, the main problems that they were able to identify in the gaming process, the way the events in the game connect to reality, and the way certain outcomes could have been prevented.

4.4 Serious game results

The game has allowed us to demonstrate the multiplicity of issues and concerns that have to be taken into account when choosing the location of a wind energy park. It has also shown that it is almost impossible to fully meet the objectives of all the stakeholders in this process. At the same time, the serious game provided evidence that better decisions can be taken when all the stakeholders are involved in the decision-making process from the very beginning.

In the first round, the level of dissatisfaction with the decision about the wind park location was significantly higher compared to the second round. After round 1, one of the participants who played a local resident of a senior age acknowledged that he was very frustrated with the final decision. He also said that before the game, he thought that people who object to wind energy projects were irrational, but after the game, he realized that 'they are just misheard and misunderstood'. Although in the second round, the players did not manage to make a decision that would be acceptable to everyone, the local community expressed fewer concerns with the final decision than in the first round. This may be related to the fact that, in round 2, residents were able not only to ask questions about the planned wind park but actively negotiate decisions and suggest solutions. According to one of the players, 'the second round was a mess' as lots of people were talking at the same time, and there were a lot of things to discuss and consider. At the same time, this 'messy' process allowed the players to achieve consensus.

Overall, the game allowed ESRs to discuss the concerns of various stakeholders that are involved or affected by onshore wind energy projects. Some ESRs acknowledged that the serious game provided them with a new perspective on the public perception of wind energy projects in general and wind turbine noise issues in particular. Therefore, we conclude that serious games are an effective instrument for introducing engineers to societal aspects of wind energy projects.

We also argue that serious games are a suitable instrument for educating multidisciplinary teams such as the zEPHYR team. In multidisciplinary teams, researchers come from different backgrounds, and therefore, they often encounter lots of unfamiliar information and have to learn about complex issues in a short period of time. Serious games allow to approach a certain problem from multiple angles and, therefore, help students to engage with it in a way that is 'that is as educational as it is entertaining' (Dornhelm, Seyr, & Muskulus, 2019).

5 Conclusion

This report has demonstrated that public perception of wind turbine noise depends on a variety of technical, societal, and psychological factors. We have shown that, on the one hand, the degree of annoyance with wind turbine noise depends on the characteristics of the noise itself. On the other hand, we argued that noise perception is affected by a multiplicity of other factors, including visual impact, safety aspects, as well as the perceived cost-benefit distribution within a certain wind energy project. Therefore, we conclude that such a complex issue as the perception of wind turbine noise also calls for complex solutions that address both technical and societal aspects of the problem.

We have identified a number of tools that can be used to decrease the annoyance of wind turbine noise and increase public acceptance of wind energy projects. First, numerical and analytical models can be used to predict the parameters of wind turbine noise and, thus, to optimize wind turbines in a way that they produce less noise. Second, the problem can be addressed at a policy level by developing regulations that specify allowed levels of noise exposure or suggesting a minimum distance between a wind turbine and residential areas. However, we argue that these tools might not be efficient in decreasing the annoyance from wind turbine noise if wind park developers and authorities do not take into account the broader context and multiple concerns that people have regarding a certain wind energy project. It means that societal factors should be taken into account, and the public should be actively engaged in the decision-making process.

Finally, we argued that innovative and alternative educational tools are necessary to teach engineers about such a complex issue as wind turbine noise. In this report, we have suggested that serious games are a suitable instrument to inform researchers working in multidisciplinary teams about societal aspects related to wind turbine noise.

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