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*A cross-country comparison of impact factors*

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# **Annoyance of residents induced by wind turbine obstruction lights: A cross-country comparison of impact factors**

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**Highlights:**

Stress effects from obstruction lights at wind turbines are assessed.

Obstruction lights can induce strong stress effects under certain conditions.

Perceived fairness and stress during planning process are significant predictors.

Distance to wind turbines is not correlated with obstruction light annoyance stress.

# 1 Annoyance of residents induced by wind turbine obstruction lights: A cross- 2 3 4 country comparison of impact factors 5 6 7 8 9 10

## 11 **Abstract**

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14 Larger wind turbines are developed to harvest greater amounts of wind energy. This development increases  
15  
16 the dilemma between ensuring aviation safety through obstruction lights and reducing citizen annoyance  
17  
18 and possible stress effects caused by obstruction lights. In this study, a unique Danish sample is contrasted  
19  
20 with a combined German-Swiss sample. Stronger stress effects due to the lights for the Danish sample  
21  
22 compared to the German-Swiss study were found, an issue that could be related to the specific technical and  
23  
24 site conditions. The prevalence of strongly annoyed residents was low. Significant factors for predicting  
25  
26 obstruction light annoyance stress were identified, including: perceived fairness, consideration of the  
27  
28 interests of the community, landscape change annoyance stress, number of visible wind turbines and age. It  
29  
30 is recommended to enhance the planning process to reduce the stress among citizens, e.g. through improved  
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32 communication, and to enhance the participation of residents in a way that allows for a meaningful  
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34 consideration of people's concerns.  
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## 1 Introduction

As part of the green transition of the energy sector, many countries have high ambitions of increasing the amount of land-based or nearshore wind energy. For example, the share of wind energy accounted for 14.0% of EU's electricity demand in 2018 (Wind Europe, 2019), and is estimated to increase to a share between 21.6% and 37.6% by 2030 (Wind Europe, 2017). The increase in wind energy capacity is promoted by technology development that provide taller and more efficient wind turbines (WTs), which result in reductions in the levelised cost of energy (LCoE), higher output, and increased value of wind energy in electricity markets through steadier output (Duffy et al., 2020; Kirkegaard et al., 2021; Wiser et al., 2016). Current 6 MW and 7 MW turbines are expected to be replaced by next generation turbines of 12 and 15 MW (Wood Mackenzie, 2019), and especially for offshore wind, this development is predicted to continue to even larger WTs beyond 250 meters of height.

While the increasing height of WTs has economic benefits in terms of cost efficiency (reducing LCoE), it also imposes societal challenges. The physical and visual presence of tall WTs in general and the height of turbines in particular have been discussed as central issues within spatial planning (Harper et al., 2019; Ohl & Eichhorn, 2010; SNH, 2017; van Rendsburg et al., 2015), particularly related to community acceptance (Borch, 2018; D'Souza & Yiridoe, 2014; Hoen et al., 2019; Jones & Eiser, 2010; Landeta-Manzano et al., 2018; Lombard & Ferreira, 2014; Walter, 2014). Yet, particular dimensions of visual impacts (Batel & Devine-Wright, forthcoming) or visual implications of particular elements of wind turbines have rarely been explored.

A particular challenge of spatial planning and community acceptance comprises obstruction lights mounted on wind turbines. Obstruction lights serve to increase the visibility of WTs for pilots of civil, military as well as ambulance aircrafts and to ensure a low risk of collisions under all circumstances. However, they can also cause visual annoyance for local communities. Research on annoyance of obstruction lights on wind turbines has documented that acceptance of wind projects is related to perceived annoyance of the lights (Pohl et al., 2012; Rudolph et al., 2017). Obstruction lights thus become one of the parameters that energy policy and

1 policy implementation have to consider. However, while previous studies have examined people's perceived  
2  
3 annoyance by obstruction lights, there is still a lack of knowledge of what factors contribute to the annoyance  
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5 caused by obstruction lights.  
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9 Currently, there is no guidance on how to work with obstruction lights in terms of mitigating citizen  
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11 annoyance and increasing acceptance. This is problematic for several reasons. First, since visual externalities  
12  
13 and hub heights of wind turbines have been identified, not only as a trigger of local resistance, but also as a  
14  
15 key reason for rejecting planning approval (van Rendsburg et al., 2015), the development of taller wind  
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17 turbines may encounter further barriers when seeking planning approval, especially in light of repowering  
18  
19 projects. Second, in absence of any guidance, project developers and authorities may end up ignoring or  
20  
21 underestimating the importance of obstruction lights, or they risk deciding on mitigation initiatives without  
22  
23 any effect on citizen annoyance. An increased understanding of what factors contribute to the annoyance  
24  
25 caused by obstruction lights is key to inform guidance.  
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31 The article is intended as a contribution to the discussion about the impacts and the management of  
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33 obstructions lights. This paper will compare citizen self-reported annoyance and possible stress effects from  
34  
35 obstruction lights based on investigations in the three countries Denmark, Germany and Switzerland. The  
36  
37 comparison will be used as a point of departure for synthesizing scientific evidence in research literature to  
38  
39 provide the basis for policy initiatives. The study is methodologically inspired by previous comparative studies  
40  
41 (Hübner et al., 2019; Pohl et al., 2012). Analytically, it is based on well-proven stress concepts (Lazarus &  
42  
43 Cohen, 1977), that are used as a framework for studying impacts of obstruction lights on the experiences and  
44  
45 behaviour of nearby residents. The concepts are furthermore used for deriving reliable indicators for ambient  
46  
47 stressors (Baum et al., 1984; Bell et al., 1990). According to this concept the process of developing stress  
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49 starts with the perception of possible stressors (e.g., obstruction lights), followed by the evaluation of those  
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51 stressors (e.g., they annoy), then psychological and physical reactions to or symptoms due to those stressors,  
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1 and finally emotional, cognitive and behavioural coping strategies to mitigate those stressors (e.g., changing  
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3 location of activities).  
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6 The comparison is designed by a rare consideration of contrasting and deviant cases. This allows for the  
7  
8 identification of significant differences between the current development of regular wind turbine projects  
9  
10 (represented by the German-Swiss sample) and what can be seen as a technologically special case that may  
11  
12 be seen to represent the future development with larger wind turbines (the Danish case). This will allow  
13  
14 insights into how annoyance and acceptance is affected by WT size and further factors contributing to stress  
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16 effects.  
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21 The following section 2 will outline the current state-of-the-art on knowledge about obstruction lights and  
22  
23 stress effects. Section 3 will describe the countries and cases before the methods will be explained in more  
24  
25 detail in section 4. Section 5 will describe the results and section 6 will discuss and contextualise the findings.  
26  
27 Finally, section 7 will draw general conclusions and sketch out policy implications.  
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## 32 **2 Obstruction lights of wind turbines and stress effects: State-of-the-Art**

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36 Among other factors, the acceptance of wind farms has been identified to be influenced by the annoyance  
37  
38 of WT emissions. Several studies found moderate negative correlations between annoyance and acceptance.  
39  
40 That means that the more residents felt annoyed by noise, landscape change or obstruction marking, the less  
41  
42 they accepted the wind farm (e.g., Hübner & Löffler, 2013; Hübner & Pohl, 2015; Hübner et al., 2019;  
43  
44 Pawlaczyk-Łuszczynska et al., 2018; Pedersen et al., 2009; Pohl et al., 1999, 2012, 2018, 2020). The way the  
45  
46 planning process is experienced is also related to annoyance and acceptance of the wind farm. Some studies  
47  
48 found moderately strong correlations between e.g. stress during the planning and installation process with  
49  
50 acceptance of the wind farm ( $r = -.58$ ,  $r = -.61$ ) or planning process fairness with acceptance of the wind farm  
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1 (r = .64, r = .57, r = .67; Hoen et al., 2019; Hübner & Löffler, 2013; Pohl et al., 2018) or planning process  
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3 annoyance and planning process fairness with noise annoyance stress (r = .49, r = -.40; Hübner et al., 2019).  
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8 In particular, visual impacts have been widely considered as a central matter of contestation when wind  
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10 farms are proposed. Nevertheless, while doing so, visual impacts have often been employed as a shorthand  
11  
12 for any relation between wind turbines and space (Batel & Devine-Wright, forthcoming), obscuring the  
13  
14 complexity of the visual-spatial dimension. As Wolsink (2018) argues, such a simplified and narrow  
15  
16 understanding of the visual impact does not only easily connote and charge wind turbines with negative  
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18 attitudes, which spurred numerous studies applying economic valuation approaches, such as choice  
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20 experiments and willingness-to-pay studies (e.g., Ladenburg & Dubgaard, 2007). It also reduces the visual  
21  
22 impact to pure visibility of wind turbines and likewise construes the visual impact as the mere physical-  
23  
24 material presence of turbines in a certain environment grounded on certain features, such as height and  
25  
26 shape.  
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32 In consequence, research has so far mostly considered the significance of visual impacts with regard to  
33  
34 individual perceptions of wind turbines or quantitatively measured and evaluated the visibility in terms of  
35  
36 the physical appearance of wind turbines in a landscape (e.g., Lothian, 2020; Meyerhoff et al., 2010), often  
37  
38 highlighting geographical distance as a proxy for annoyance and acceptance. In particular, the latter approach  
39  
40 has been utilised and advanced in numerous studies (e.g., Tsoutsos et al., 2009; Mirasgedis et al., 2014). Yet,  
41  
42 particular dimensions of visual impacts or visual effects of particular elements of wind turbines have rarely  
43  
44 been specified and dissected, which has also resulted in a lack of a nuanced qualification of what may cause  
45  
46 annoyance by visual impacts.  
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51  
52 There are several factors influencing WTs visibility, e.g., distance, perceived size, rotating vs. stationary  
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54 blades, height, number of WTs, landscape features, contrast to the surrounding (for an overview see  
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56 Molnarova et al., 2012). Yet, there seems to be no clear causality between visibility and acceptance of a wind  
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1 farm. Although Jalalil et al. (2016) found a moderate negative correlation in a small sample ( $r = -.61$ ,  $N = 31$ ),  
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3 Hübner and Löffler (2013) and Pohl et al. (2018) reported small negative correlations ( $r = -.34$ ,  $N = 467$ ;  $r = -$   
4  
5  $.35$ ,  $N = 212$ ), while in a representative U.S. sample the association was negligible ( $r = -.11$ ,  $N = 1705$ , Hoen  
6  
7 et al., 2019). Of greater relevance seems to be the variable landscape fit which correlated moderately positive  
8  
9 with attitude ( $r = .57$ , Hoen et al., 2019). For a review of effects of visibility and visual features of WTs on  
10  
11 annoyance and health indicators see Freiberg et al. (2019) and on acceptance see Rand and Hoen (2017).  
12  
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16 By considering the visual annoyance associated with wind turbines beyond a constringed representation of  
17  
18 the visual impact, only few studies have started to focus on obstruction markings and lights as specific  
19  
20 constituents of the visual impact (Pohl et al., 2012; Rudolph et al., 2017). Thus, knowledge about the role of  
21  
22 annoyance from obstruction lights at wind farms for citizens' acceptance of wind energy is, however, still  
23  
24 limited. The first studies with a specific focus on obstruction lights (Pohl et al., 2012; Rudolph et al., 2017)  
25  
26 document a notable annoyance of obstruction lights that is related to citizens' acceptance in the countries  
27  
28 studied. Pohl et al. (2012) termed this annoyance "an emerging acceptance problem" (p. 592), however, with  
29  
30 only a few studies available it is still unclear, which factors contribute to annoyance caused by obstruction  
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32 lights.  
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38 In the study by Pohl et al. (2012), 15.4 % of the respondents reported to be rather or very annoyed by day  
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40 marking and 25.5 % by night marking, but very seldom report symptoms associated with obstruction marking  
41  
42 ( $< 2.0$  %). In the study by Rudolph et al. (2017) the percentages of annoyed residents were 11.2 % (during  
43  
44 daylight) and 51.8 % (in the evening darkness). There are other studies not exclusively focusing on obstruction  
45  
46 markings: e.g., Michaud et al. (2016) found 9.9 % very or extremely annoyed participants by obstruction  
47  
48 markings and Motosu and Maruyama (2016) found 12 % very annoyed respondents by obstruction markings.  
49  
50 Strong annoyance with stress symptoms induced by landscape change has so far only been observed from a  
51  
52 few residents. Hübner et al. (2019) found 1.5 % in an U. S. sample and 0.0 % in an European sample. On the  
53  
54 other hand, laboratory studies with visual stimuli have shown that WTs in the landscape can trigger emotional  
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1 reactions and physiological arousal and influence preferences of different renewable energy systems (Maehr  
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3 et al., 2015; Spielhofer et al., 2021).  
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6 While annoyance and stress effects related to WTs have mainly been considered with regard to noise and  
7  
8 landscape change, stress effects from obstruction markings have not gained attention yet. Considering the  
9  
10 largely neglected role of obstruction lights in wind farm planning and unknown predictors of stress effect  
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12 from obstruction lights, this study seeks to explore two research questions.  
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- 16 1) How do stress effects induced by obstructions lights differ between a technologically special case in  
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18 contrast to regular wind farms?  
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- 21 2) What factors contribute to stress effects from obstruction lights?  
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### 28 **3 Contextualisation of countries and contrasting cases** 29 30

31 The case study of Denmark – representing the technologically special case - concerns what is said to be the  
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33 world’s biggest test site for large WTs (State of Green 2017). It is located near the village of Østerild in the  
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35 north-west of Denmark (see figure 1). The data draws from a study from 2015 with the aim to explore the  
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37 perception of, annoyance and possible stress effects induced by the aircraft obstruction lights. The test centre  
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39 was established in October 2012, after a political decision in the Danish Parliament, followed by a top-down  
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41 planning process that did not provide much leeway for the consideration of public concerns (Larsen et al.,  
42  
43 2015; Rudolph et al., 2017). By the time of the study, the test site consisted of seven turbines with a height  
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45 of up to 222 m that are spatially arranged in a straight line. Given the particular purpose of testing prototypes  
46  
47 and the resultant regular replacement of turbines, the row of turbines is marked with a light mast at each  
48  
49 end. The two 250 m tall towers do not reflect general legislation for wind farms (see table 1), but instead  
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51 constitute a special requirement to account for the particular purpose of the site. Each mast carries high-  
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53 intensity flashing white LED lights mounted at three different levels, instead of having individual markings  
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1 mounted on each WT as per usual legislation for commercial wind farms in Denmark. The synchronized lights  
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3 have three intensity levels that are automatically adjusted according to the time of the day and weather  
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5 conditions. After the study, the test centre has been expanded, however, this has not affected the data. More  
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7 detail about the particularities of the test centre and location can be found in Rudolph et al. (2017). The  
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9 Danish case thus represents a special case insofar as it comprises a unique technical solution as well as a  
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11 centralised and restricted planning process. The juxtaposition of a special case with more regular cases allows  
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13 for the identification of significant differences in and upper limits of potential stress effects and other factors  
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15 influencing stress as well as potentially relevant coping strategies.  
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21 **[insert figure 1 here]**  
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27 In contrast, the German-Swiss (G-S) sample comprises several cases studies. Although the two countries of  
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29 Germany and Switzerland vary in history and capacity in wind energy, they are grouped to strengthen the  
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31 dataset in this comparative study with Denmark. As mentioned above, the German-Swiss data represents  
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33 normal commercial land based wind farms adhering to the legislative schemes (see table 1), while the Danish  
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35 case can be seen as a special case as a test site for tall turbines of up to 330 meters of height. The data from  
36  
37 Germany is based on two studies<sup>1</sup>. One study with the focus on obstruction markings included 13 wind farms  
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39 across seven German federal countries and focused on residents living in the view shed of the wind farms  
40  
41 (Pohl et al., 2012). The aim of this study was a comparison of people's perception of, and annoyance and  
42  
43 possible stress effects induced by different types of aircraft obstruction markings across different terrains. In  
44  
45 the other German study, the focus was on the noise effects of a wind farm, but the effects of obstruction  
46  
47 lights were also investigated (Pohl et al., 2018). The Swiss study included seven wind farms with a minimum  
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49 capacity of 0.6 MW per WT<sup>2</sup>. In addition, in this Swiss study, annoyance through visual impacts of obstruction  
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57 <sup>1</sup> For more information about the 14 German wind farms see Pohl et al. (2012, 2018).

58 <sup>2</sup> For more information about the 7 Swiss wind farms see Hübner & Löffler (2013) and a map with Swiss WTs from  
59 2015 (<https://www.energieschweiz.ch/tools/windenergieanlagen/>)  
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1 markings were comparatively examined along with other perceived impacts on people’s well-being and  
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3 livelihood (Hübner & Löffler, 2012).  
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7 **[Insert table 1 here]**  
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## 10 11 12 **4 Methods**

### 13 14 *4.1 Survey designs and samples* 15

16  
17 Despite the differences in purpose and context, the surveys in the three countries were based on the same  
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19 structure and with largely similar content. The surveys covered four aspects: A) attitudes, perceptions of the  
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21 obstruction lights, and potential feelings of being negatively affected, B) questions on psychological aspects,  
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23 including physical and psychological well-being, C) the efficiency of individually adopted coping strategies,  
24  
25 and D) questions related to respondents’ background (age, profession, etc.) and contact information. The  
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27 assessment of annoyance was based on a single annoyance item and on the “Annoyance Stress-Scale” (AS-  
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29 Scale; Hübner et al., 2019; Pohl et al., 2018).  
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37 Some questions were asked in all three German-Swiss studies, others only in one or two studies depending  
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39 on the focus of the study. Therefore, there are different sample sizes in the combined German-Swiss sample  
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41 (see the information in the results tables). Some Danish items were recoded to get comparable scale levels /  
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43 values with the German-Swiss studies.  
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46  
47 Table 2 illustrates different features of the data collection and the included wind farms. All data were  
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49 collected between 2009 and 2016.  
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56 **[Insert table 2 here]**  
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#### 4.2 Recruitment of survey participants

In the German-Swiss sample, the recruitment of participants in the two studies was based on several steps: 1) randomly selected addresses from public telephone directories, 2) personal letters and telephone calls to these households, 3) at a community meeting and 4) via local contacts. The overall response rate was 28.0% (Hübner & Löffler, 2013; Pohl et al., 2018). In the other study, questionnaires were randomly distributed to households. The overall response rate was 25.0% (Pohl et al., 2012). Incentives were offered in two studies: 15 EUR or participation in a lottery for a 25 EUR Amazon voucher (Pohl et al., 2012), and two balloon rides (Hübner & Löffler, 2013).

In the Danish sample, the participants for the survey were recruited randomly by means of leaflets disseminated face-to-face, a public meeting, a Facebook site, posters in local shops, and newspaper articles (see Rudolph et al., 2017). As incentives, participants took part in a lottery for wine and chocolate.

#### 4.3 Sample comparison and characteristics

To justify sample pooling of the German and the Swiss cases, we checked the samples' comparability for demographic and central variables, such as attitudes toward the local wind farm, emotions, impact on quality of life and place attachment (see Hübner & Pohl, 2015). We also checked correlations between attitude toward the local wind farm and a set of variables including visibility, strain during the planning process, setback distance and impact on landscape. All results showed comparable patterns. Furthermore, in one German study (Pohl et al., 2018) and the Swiss study (Hübner & Löffler, 2013), we could conduct non-response analyses based on four questions. In both samples we did not find relevant differences between responders and non-responders concerning a) attitude toward the local wind farm, b) age, or c) visual impact.

The Danish and the pooled German-Swiss samples are similar on most demographic factors, only showing non-significant differences (Table 3). Significant differences can be found in the factors; marital status, job

1 situation, duration of residency and financial participation in wind project, in which case effect sizes are small.

2  
3 The demographic distribution is thus similar in the two samples.  
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7 **[Insert table 3 here]**  
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13 When it comes to attitudes and actions taken in the planning phase of the wind project, the Danish case,  
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15 however, differs somewhat from the Swiss and German cases. When looking at both attitudes towards the  
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17 wind farm as well as whether they have been active in the planning process, it is evident that the Danish  
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19 sample contains a significantly larger proportion of active citizens, who are opposed to the project (31.0%)  
20  
21 compared to the German-Swiss sample (only 11.3%). Reversely, the Danish sample only holds 29.7% passive  
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23 citizens, who were in favour of the wind project, compared to 68.3% in the German-Swiss sample ( $p < .0001$ ,  
24  
25  $w = 0.327$ , medium effect size). Hence, in relation to attitudes and actions, it is two rather different cases we  
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27 are comparing, as represented by the unique test centre and commercial wind farms.  
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#### 32 33 34 35 36 *4.4 Stress indicators and moderators* 37

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39 Stress indicators and moderators assessed in the Danish and German-Swiss studies are presented in this  
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41 section.  
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##### 44 45 *4.4.1 Indicators* 46

47  
48 A single annoyance item was used to assess annoyance related to specific WT impacts (obstruction lights,  
49  
50 shadow-casting, landscape change, noise). From a psychological perspective a single item annoyance scale  
51  
52 assesses a general evaluation of immissions in the sense of liking or disliking. The participants were asked  
53  
54 to rate their experiences on a 5-point annoyance scale for each impact: 0 ("not at all"), 1 ("slightly"), 2  
55  
56 ("somewhat"), 3 ("moderately") and 4 ("very"). Annoyance due to other sources, such as noise from  
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1 agricultural machinery, was also assessed using the same scale. This annoyance scale was used in several  
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3 earlier studies of the Hübner and Pohl research group (e.g., Hübner & Löffler, 2013; Hübner & Pohl, 2015;  
4  
5 Hübner et al., 2019; Pohl et al., 2012, 2018, 2020). In a longitudinal study the retest reliability for noise  
6  
7 annoyance was  $r = .85$  (Pohl et al., 2018). The correlation between noise annoyance and the ICBEN Q. V.  
8  
9 Scale (Fields et al., 2001) was  $r = .88$  (Hübner et al., 2019).  
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12  
13 The participants were also asked under what time of day and weather conditions the obstruction lights were  
14  
15 perceived as annoying.  
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19 The frequency of symptoms linked to WT impacts was assessed, ranging from 0 ("never") to 4 ("about every  
20  
21 day"). The Danish respondents reported the symptoms in a free format and the German-Swiss respondents  
22  
23 used a list of psychological and somatic symptoms belonging to different domains, e.g., general performance,  
24  
25 emotions and mood, somatic complaints and sleep.  
26

27  
28  
29 Negative impact on daily activities induced by obstruction lights was assessed using a unipolar rating scale,  
30  
31 from 0 ("not at all") to 2 ("to a large degree").  
32

33  
34  
35 Cognitive and behavioural coping responses were also assessed. Here, participants reported if and which  
36  
37 behavioural strategies they applied to reduce the obstruction lights annoyance (e.g., using blinds or curtains)  
38  
39 and to what extent the measures were effective in reducing obstruction lights annoyance (3-point scale from  
40  
41 0 ("no effect") to 4 ("strong reduction")).  
42

43  
44  
45 The single annoyance item might be interpreted as an indicator of attitude. To get a reliable stress indicator  
46  
47 we combined the ratings from the annoyance and symptom scales in the 5-point AS-Scale (Hübner & Löffler,  
48  
49 2013; Hübner et al., 2019; Pohl et al., 2018). If a resident did not perceive any WT light emission, level 0 was  
50  
51 assigned. Level 1 was given if a respondent perceived a WT emission without annoyance. If "slightly annoyed"  
52  
53 was reported on the single annoyance item level 2 was assigned. If someone was at least "somewhat  
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55 annoyed", but reported no symptoms level 3 was given. To be considered as "strongly annoyed" (level 4), a  
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1 resident must be at least somewhat annoyed and experienced at least one physical or psychological symptom  
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3 per month induced by WT. Additionally, for each WT emission an AS-Scale was constructed, e.g., the  
4  
5 Obstruction Lights Annoyance Stress Scale (OLAS-Scale), which has the same levels as the AS-Scale, but is  
6  
7 related only to aircraft obstruction lights.  
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#### 10 11 12 13 14 *4.4.2 Moderators* 15

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17  
18 The influence of several possible moderators of OLAS-Scale levels were analysed. These moderators have  
19  
20 also been used in various studies on the acceptance of wind energy (e.g., Firestone & Kirk, 2019; Hoen et  
21  
22 al., 2019; Hübner et al., 2019; Pohl et al., 2018; Russell & Firestone, 2021).  
23  
24

- 25  
26 • Attitude: The attitude towards the local wind farm and the attitude towards WTs in general were  
27  
28 evaluated by a semantic differential with three pairs of bipolar adjectives in the Danish questionnaire  
29  
30 and with six pairs of bipolar adjectives (for example “unnecessary – desirable”) in the German-Swiss  
31  
32 version. The mean value over these items was used as an indicator for attitude, ranging from –3  
33  
34 (“very negative”) to +3 (“very positive”). The participants were also asked whether they had  
35  
36 undertaken actions to promote their attitude.  
37  
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- 39  
40 • General stress indicators, light and noise sensitivity: Acute stress (during the past 4 weeks for a short  
41  
42 time) and chronic stress (lasting at least one year) were assessed independently of any relationship  
43  
44 to the local wind farm, and light and noise sensitivity were rated on four unipolar scales each with a  
45  
46 range from 0 (“not at all”) to 4 (“very”).  
47  
48
- 49  
50 • Evaluation of the planning process: Perceived fairness and stress during the wind farm planning  
51  
52 process were assessed on three unipolar rating scales each ranging from 0 (“not at all”) to 4 (“very”).  
53  
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- 55  
56 • Physical features: The residents reported the number of WTs visible from their property. The distance  
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58 from the nearest WT was measured from using maps of the area.  
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#### 4.5 Statistical analyses

To analyse group differences for interval-scaled variables, descriptive statistical values, such as the arithmetical mean and standard error of the mean (SEM) were used. For nominal-scaled variables, absolute and relative frequencies (%-values) are reported. Pearson-correlations to identify moderator variables were calculated. We consider only coefficients of 0.30 or higher (a medium effect size according to Cohen, 1988) as relevant. A multiple regression analysis was run for each sample by several variables to predict the OLAS-Scale. We understood Beta weights as effect sizes (Nieminen et al., 2013), and a cut-off of  $> |0.15|$  was used to indicate an influential predictor. Chi<sup>2</sup>-tests for inferential analysis of frequency distributions were used. Mean values of two groups were compared via t-tests. In the case of unequal variances, Welch's t-tests were chosen.

The data analysis and description is based on the principles of Abt's (1987) "Descriptive Data Analysis." Therefore, reported p-values of the two-tailed significance tests serve a descriptive purpose to characterize the extent of group differences. Since the analysis is not a confirmatory data analysis, no alpha-adjustment was made, despite multiple significance tests. We consider p-values of .05 or less as statistically significant. Furthermore, the effect size parameters *d* and *w* were calculated to report practical significance (Cohen, 1988). The effect size categories (small, medium, large) mentioned in the results section are related to statistically significant group differences.

## 5 Results

Inspired by Hübner et al. (2019) and Pohl et al. (2012, 2018), the presentation of the results follows the steps of a stress process. We start with the residents' perception of impacts, their evaluation measured by annoyance, followed by the physical and psychological reactions to the impact and finally the coping strategies they employ in order to mitigate the impacts (first research question). The analysis furthermore adds to the understanding of impacts from obstruction lights by putting them into context of other possible

1 negative impacts from WTs, such as shadow flicker, landscape changes and noise. In the second main part of  
2  
3 the results chapter, the analysis considers the factors (moderators) contributing to stress effects, like  
4  
5 attitude, general stress indicators, evaluation of the planning process, and physical features (second research  
6  
7 question).  
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### 10 11 12 13 *5.1 Perception and annoyance* 14 15

16  
17 A considerably higher percentage of Danish residents than German-Swiss residents perceived obstruction  
18  
19 lights inside the house and outside the house (Table 4). In the Danish sample, a smaller percentage of the  
20  
21 people had shadow perceptions outside the house compared to the respondents of the German-Swiss  
22  
23 sample. Furthermore, in the Danish sample, a smaller percentage perceived noise outside the house  
24  
25 compared to the German-Swiss sample. The same effect with regard to noise perceptions was found inside  
26  
27 the house.  
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31 **[Insert table 4 here]**  
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38 The average annoyance induced by WT impacts and other local sources ranges between low and moderate  
39  
40 (Table 5). Concerning day obstruction markings, there was no difference of annoyance level between the two  
41  
42 samples regardless of the type of markings (LED, Xenon, white or coloured stripes), but the Danish residents  
43  
44 reported a slightly higher mean value for the night marking. Very few Danish residents were annoyed by  
45  
46 shadow casting (n = 3). The Danish sample showed a slightly higher average annoyance by landscape change  
47  
48 and a much higher average annoyance by WT noise than the German-Swiss sample. Hence, even though  
49  
50 fewer Danish residents noticed the noise impacts from the WTs, the ones that did were far stronger annoyed  
51  
52 by it, compared to the Germany-Swiss residents. The Danish residents thus seem to be more annoyed by  
53  
54 noise than the German-Swiss residents, given the unique Danish case. A result that is underlined by the  
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56 comparison of annoyance is caused by general agricultural machinery noise by which the Danish residents  
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1 are also slightly stronger annoyed than the German-Swiss residents. Finally, comparing the means for  
2  
3 annoyance caused by obstruction lights to annoyance caused by noise and landscape changes, it is also  
4  
5 evident that obstruction lights are not the most important impact to consider when trying to understand  
6  
7 what causes stress amongst residents.  
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10  
11 **[Insert table 5 here]**  
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17 When investigating the impacts from obstruction lights more thoroughly, it is evident, that a much higher  
18  
19 percentage of Danish residents than German-Swiss residents were annoyed by obstruction lights, not only  
20  
21 during night, but also during all assessed times of the day and weather conditions (Table 6). Most noticeable  
22  
23 is the strong annoyance during night in both samples, but also under condition with clear sky and in cloudy  
24  
25 conditions in the Danish sample. Annoyance data for specific times of day and weather conditions are based  
26  
27 on items with yes-no answers.  
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31  
32 **[Insert table 6 here]**  
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37 Generally, the Danish residents evaluate the impacts from WTs more negatively than the German-Swiss  
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39 residents. This is especially evident in the case of impacts from obstruction lights, to which they are also more  
40  
41 attentive compared to the German-Swiss residents. This pattern is also evident when investigating the impact  
42  
43 on different daily activities. On average, the negative impact was relatively small (Table 7), but the Danish  
44  
45 residents reported a marginally stronger negative impact than the German-Swiss residents on activities in  
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47 the house, while taking a walk, while doing sports, while relaxing, while driving a car, during conversations  
48  
49 and while hosting guests. Thus, supporting the pattern of respondents in the Danish case being more  
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51 annoyed by obstruction light than residents in the German-Swiss case. The activities where residents, Danish,  
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53 German and Swiss alike, are most disturbed by obstruction lights are generally outside activities, such as  
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1 gardening, walking and driving. This could be related to the local features of the Danish site, which are  
2  
3 characterized by flat landscape, remoteness and associated darkness.  
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8  
9 **[Insert table 7 here]**  
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## 11 *5.2 Physical and psychological stress reactions to impacts and coping responses*

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15 To evaluate the residents' stress level caused by WT impacts, an AS-scale was constructed for each emission.  
16  
17 On average, the annoyance-stress induced by WT emissions was low to medium in both samples (Table 8).  
18  
19 At an overall level, however, shadow casting and noise annoyance stress was slightly higher in the German-  
20  
21 Swiss sample whereas landscape change annoyance stress was markedly higher among the Danish residents.  
22  
23 The obstruction lights annoyance stress-level was much higher in the Danish case, indicating that the Danish  
24  
25 residents' stress reactions to annoyance were stronger than the German-Swiss residents'. Finally, the analysis  
26  
27 of the AS-level supports earlier results that negative impacts from obstruction lights might not be the most  
28  
29 important negative impact from WTs, but it is evidently a contributing factor to creating stress among  
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31 residents.  
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42 **[Insert table 8 here]**  
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49 The percentages of strongly annoyed residents for each of the WT emissions was relatively low (Table 9), but  
50  
51 there was a small percentage of residents which reported at least somewhat moderate annoyance and  
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53 symptoms associated to obstruction lights in the Danish sample and to noise in the German-Swiss sample.  
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59 **[Insert table 9 here]**  
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The German-Swiss residents employed different coping mechanisms compared to the Danish residents when trying to deal with the negative impacts from obstruction lights. E.g., a higher percentage of German-Swiss residents than Danish residents changed location of outdoor activities due to obstruction lights and had thoughts about moving away due to the wind farm (Table 10). Generally, the German-Swiss residents were more inclined to introduce coping initiatives compared to the Danish residents.

**[Insert table 10 here]**

Concerning the ones employing coping mechanisms, the effectiveness of the measures taken were rather similar. To reduce lightning annoyance, installing and using blinds or curtains were the relatively strongest measures (DK: M = 1.38, SEM = 0.09; G-S: M = 1.50, SEM = 0.06, scale 0 to 2, no significant group differences). Other strategies had negligible effects, e.g., talking to others, drinking, smoking, taking sedatives.

### *5.3 Moderators of obstruction lights annoyance-stress*

Following the holistic approach to WT induced stress (Hübner et al., 2019; Pohl et al., 2012, 2018), it is not appropriate to only consider the direct impacts and emissions from WTs on residents' stress, but also to investigate factors which have a moderating effect on stress reactions.

Commonly used moderators are citizens' attitudes towards WTs in general and locally and citizens' evaluation of the planning process. In both samples, the mean values of attitudes toward the local wind farm and WT in general were positive and of comparable strength (Table 11). With regard to feelings of being heard in the planning process, the community interests have been given slightly less consideration in

1 Denmark than in Germany / Switzerland according to the residents. The Danes felt slightly more stressed  
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3 during the planning and construction process.  
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7 **[Insert table 11 here]**  
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11 Further moderating factors, that are commonly used to evaluate stress, include pre-existing sensitivity  
12 towards negative impacts, such as light sensitivity (Pedersen & Waye, 2004; Pohl et al., 2012), noise  
13 sensitivity (Carlile et al., 2018; Hübner et al. 2019) and pre-existing conditions of stress (Pohl et al., 2018). On  
14 average, the Danish residents reported a markedly higher light sensitivity than the German-Swiss ones. There  
15 was no significant difference in noise sensitivity (Table 12) and the Danish respondents perceived slightly  
16 weaker acute and chronic stress than those of the German-Swiss sample.  
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29 **[Insert table 12 here]**  
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35 Besides these possible moderating factors, the analyses also investigated the influence of socio-demographic  
36 factors (age, gender, education and length of residency) and factors related to the visibility of the obstruction  
37 lights (distance to nearest WT/light mast and number of WTs visible from home).  
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43 The analysis of moderating factors of obstruction lights annoyance stress started with Pearson correlations  
44 of the factors mentioned in Table 13 with the OLAS-Scale. In both samples we found five relevant correlations  
45 (criterion:  $r \geq |0.30|$  at least a medium effect size) with the same variables: The more residents were stressed  
46 by landscape change or during planning process, the more they were stressed by obstruction lights (DK:  $r =$   
47  $.59$ ,  $r = .46$ ; G-S:  $r = .43$ ,  $r = .51$ ). The less the attitude toward local wind farms, personal or community  
48 interests were considered, the more they were stressed by obstruction lights (DK:  $r = -.49$ ,  $r = -.53$ ,  $r = -.58$ ;  
49 G-S:  $r = -.65$ ,  $r = -.34$ ,  $r = -.39$ ). Four further relevant correlations could be found in the German-Swiss sample:  
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1 The less the attitude toward WTs in general ( $r = -.51$ ), the more they were stressed by obstruction lights. The  
2  
3 more respondents were stressed by shadow casting or WT noise or the more WTs they saw from the  
4  
5 residents, the more they were stressed by obstruction lights ( $r = .61$ ,  $r = .63$ ,  $r = .44$ ).  
6

7  
8 The correlation coefficients concerning distance to the nearest WT, sensitivities, personal stress and  
9  
10 sociodemographic variables are negligibly small (all  $|r|$  between .02 and .27).  
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15 In order to understand which combined factors precisely had influence on the stress related to obstruction  
16  
17 lights, we performed a multiple regression analysis for each sample in order to predict the OLAS-Scale. Our  
18  
19 model explained a large part of citizens' annoyance with an  $R^2$  adjusted on 0.661 for the Danish sample and  
20  
21 0.555 for the German sample.  
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24

25 We found five relevant predictor variables in the Danish sample and two in the German-Swiss sample (Table  
26  
27 13). Here, relevance is based on beta weights and p-values; a beta weight  $> |0.15|$  is considered relevant for  
28  
29 any coefficient with  $p \leq .05$ . In the Danish sample "my personal interests have been heard to a sufficient  
30  
31 degree", "the community interest had been heard" and "landscape change annoyance stress" showed the  
32  
33 strongest relations. The other relevant factors in the Danish sample were "age" and "stressed during planning  
34  
35 and construction process". In the German-Swiss sample "number of WTs visible from home" and "stressed  
36  
37 during planning and construction process" were relevant predictors. The latter factor was the only factor the  
38  
39 both samples had in common.  
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45 The other factors were negligible, including "Attitudes toward local windfarm" and "Attitudes toward WTs in  
46  
47 general". It indicates that one or more of the included factors in the full regression model suppresses the  
48  
49 effects from the residents' attitudes.  
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54 **[Insert table 13 here]**  
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## 6 Discussion

Increased contestations due to visual and noise impacts of WT's have resulted in reactive responses of policy-makers in Denmark who urge a reduction of the number of onshore WT's through repowering (Danish Energy Agreement, 2018), while the numbers of newly installed capacities in Germany have radically dwindled due to lengthy planning processes, changing support systems and local opposition. The issue of citizen annoyance due to obstruction lights has therefore also received political attention. For example, the political agreement for the Danish National Test Centre for large WT's included a demand for adopting best available mitigation technology for the obstruction lights (The Danish Government, 2017).

In this study, we have explored possible stress effects caused by obstruction light markings of WT's, which reflects an increasingly significant safety requirement as wind turbines grow in size. In doing so, we identified and analysed factors influencing stress effects and compared them between a special case and regular cases.

The main finding from the comparison of stress effects from obstruction markings in the contrasting cases of Denmark and Germany-Switzerland is that the results show stronger stress effects due to the lights for the Danish sample (DK:  $M = 2.16$  vs. G-S:  $M = 1.27$ ,  $p < .0001$ , medium effect size). Following the outlined stress concept, more Danish residents notice obstruction markings (indoors: DK 73.1% vs. G-S 30%; outdoors: DK 89.2% vs. G-S 37.7%), therefore, we have more Danish respondents perceiving direct emissions. They were slightly stronger annoyed at night, but not during daylight, independent of weather conditions. Daily activities were more disturbed. The annoyance stress level was considerably higher (OLAS-Scale) but only few (6.1%) of the residents were strongly annoyed, reporting symptoms related to obstruction lights. Fewer residents in the Danish case got used to it (cognitive coping) and changed the location of outdoor activities (behavioural coping). They reported greater light sensitivity. The stress process in the Danish case seemed to have started during the planning and construction process, because the centralised process was perceived as more stressful. Not only obstruction lights, but also the perceived landscape change led to annoyance stress. The stress effects due to obstruction lights seem to be specific because the Danish residents reported only



1 marginally acute and chronic stress related to personal factors. The Danish case demonstrated that under  
2  
3 special local conditions obstruction markings could lead to stress.  
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6 These findings are interesting taking the contrasting cases into account; the Danish case is a national test  
7  
8 centre for very tall WTs located in a remote area with a distinct system of obstruction lights applied (white  
9  
10 high-intensity blinking lights in Denmark compared to red medium intensity lights at night in the German-  
11  
12 Swiss sample). Due to the special technical features of obstruction markings and due to the top-down  
13  
14 planning process, the results concerning the Danish site cannot be generalized. However, this was not  
15  
16 intended. The methodological approach was to compare a special site with more regular sites (21 German-  
17  
18 Swiss wind farms) to obtain an upper estimate of stress effects. Moreover, the comparison of the Danish  
19  
20 and German-Swiss samples only refers to items that were formulated in a comparable way and where the  
21  
22 scales were the same or where they could be adjusted. As a result, not all of the available information could  
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24 be evaluated. Furthermore, the results need to be viewed in light of the contemporary regulatory context  
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26 in both countries, which changes over time.  
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33 Overall, the regression analysis showed six significant predictors of obstruction light annoyance in both  
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35 samples but varying between the countries. The differences will be discussed towards other studies in the  
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37 following.  
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41 *First*, landscape change is an important and significant predictor of obstruction light annoyance stress in the  
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43 special case of Denmark, but not in the regular cases of Germany/Switzerland. For citizens in the Danish  
44  
45 sample their concern about changes in landscape is highly related to their annoyance by obstruction lights.  
46  
47 The importance of landscape change for annoyance related to WTs tends to be in line with the common  
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49 nature-technology dualism often described in place attachment literature, where perceived disruptions to  
50  
51 emotional, productive, memorable and historical bonds with a place are regarded as a trigger of resistance  
52  
53 (e.g., Devine-Wright, 2009; Kim & Chung, 2019) to place-related changes and where oppositional activities  
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55 are then usefully discussed as place-protective action (Devine-Wright & Howes, 2010). This study contributes  
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1 to the existing knowledge by highlighting how landscape changes may be of particular importance for  
2  
3 understanding citizen annoyance in more special cases.  
4

5  
6 *Second*, people’s perception of the extent to which their personal interests were heard in the planning  
7  
8 process has been identified as a significant predictor of obstruction light annoyance stress in Denmark, but  
9  
10 not in Germany and Switzerland. This difference may be related to the top-down deployment process for the  
11  
12 Østerild wind farm test centre in Denmark (Rudolph et al., 2017), through which the location was decided by  
13  
14 the government without consulting the local population (Lyhne, 2011), while the issue of light pollution has  
15  
16 emerged as a key concern during the planning process (Borch, 2018). In turn, even though this was not  
17  
18 identified as a significant predictor of obstruction light annoyance in the German-Swiss study, it cannot  
19  
20 simply be assumed that people perceive the role of the planning process in these countries as less  
21  
22 meaningful. For example, the planning process fairness has a significant impact on noise annoyance and  
23  
24 acceptance of the wind farm (e.g., Hoen et al., 2019; Hübner & Löffler, 2013; Hübner et al., 2019; Pohl et al.,  
25  
26 2018). Furthermore, numerous quantitative and qualitative studies emphasized the significance of the  
27  
28 planning process in shaping local community responses, in particular the perception of procedural fairness  
29  
30 as part of the participatory process (Ellis & Ferraro, 2016; Firestone et al., 2018; Firestone et al., 2020; Gross,  
31  
32 2007; Liebe et al., 2017). In particular, the possibility of having a say in the process and influencing the  
33  
34 outcome has been identified as a significant predictor of procedural fairness (Firestone et al., 2018). In the  
35  
36 same vein, our findings from Denmark do not only reiterate the importance of a fair and transparent planning  
37  
38 process in informing people’s acceptance, but corroborate the finding that early shortcomings can  
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40 perpetuate over time and permeate people’s annoyance later on (e.g., Hübner et al., 2019; Pohl et al., 2018).  
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49 *Third*, the top-down process described above could explain why the predictor “community interests have  
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51 been heard to a sufficient degree” was positively related to obstruction lights annoyance stress. The more  
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53 community interests are evaluated to have been taken into account, the stronger was the annoyance stress.  
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55 The results reflect the discrepancy between personal and community interests concerning the planning  
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1 process. Likewise, procedural fairness and trust in authorities, in terms of how people perceive the  
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3 consideration of their interests, have been identified as crucial factors determining support or opposition to  
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5 a proposed project in general as well as stress effects in particular (Firestone et al., 2020; Hoen et al., 2019;  
6  
7 Pohl et al., 2018). Other studies have shown that among the motivations of the most engaged citizens in  
8  
9 planning processes community concerns are more prominent than direct personal interests (Lyhne et al.,  
10  
11 2018).  
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14  
15 This is also directly related to a *fourth* predictor. Citizens' perception of stress during the planning process is  
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17 a significant predictor in both countries. This is slightly more important in Germany/Switzerland than in  
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19 Denmark. The Danish test centre was met with local opposition (Borch, 2018), and the significance is  
20  
21 therefore not surprising. According to some of the interviewees, the obstruction lights were a daily reminder  
22  
23 of their stress during the planning process (see Rudolph et al., 2017). Stress during the planning and  
24  
25 construction process may not only refer to the perceived fairness of the process, but can also hint at the  
26  
27 significance of communication (Friedl & Reichl, 2016) and the perception of physical impacts during the  
28  
29 construction. Lack of information provision and communication both from developers about ongoing  
30  
31 activities and for local residents to convey complaints can result in uncertainty and stress. Limited  
32  
33 communication at the development stage can exacerbate preconceived fears and permeate annoyance later  
34  
35 on. Transparent and continuous communication is again particularly relevant for the Danish case which does  
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37 not exhibit a stable and complete wind farm, but a test centre whose WTs are regularly being changed and  
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39 replaced.  
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48 *Fifth*, the number of WTs visible from home is a significant predictor in the German-Swiss sample, but not in  
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50 the Danish one. This indicates a cumulative effect in which citizens may get increasingly annoyed by visual  
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52 impact of turbines. The importance of the number of turbines visible is in part supported by previous studies.  
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54 Ironically some previous Danish studies (Ladenburg, 2006; Ladenburg et al., 2013; Möller, 2006; also  
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56 Molnarova et al., 2012 for Czech Republic) support the importance of the number of turbines in the view  
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1 shed, whereas other Danish studies (Ladenburg, 2015) only found a weak relationship between cumulative  
2 effects based on the number of onshore turbines seen daily. Likewise, a study including the German samples  
3 and an U.S. sample did not find this variable significant (Hübner et al., 2019). Ladenburg (2006) finds that  
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shed, whereas other Danish studies (Ladenburg, 2015) only found a weak relationship between cumulative effects based on the number of onshore turbines seen daily. Likewise, a study including the German samples and an U.S. sample did not find this variable significant (Hübner et al., 2019). Ladenburg (2006) finds that “everything else equal, the attitude towards existing and more turbines becomes more negative the higher the number of turbines installed” (p. 38). The varying results seem to indicate that the effect of number of turbines on obstruction lights annoyance is also related to other variables, such as noise and shadow casting. In general, this may also hint at a threshold where people consider themselves as being overburdened with WTs and their impacts, and also challenges the notion that familiarization can lead to appeasement.

*Sixth*, age is a significant predictor of obstruction light annoyance stress in Denmark, but not in the German-Swiss sample. This may have multiple explanations, hereunder older people may be more sensitive to the impact of emissions, and retired people having more time to engage with their surroundings and thus to become annoyed. The role of age may also appear stronger because the Danish study is based on a single case, whereas the German and Swiss cases were pooled together. It is worth noticing that besides age, demographic characteristics do not predict annoyance or relate to stress symptoms. The importance of age is in part supported by previous studies. It is supported by previous research on attitudes in Denmark (Hevia-Koch et al., 2018), but it was not a significant predictor for WTs noise annoyance in the comparative study between U.S. and European samples (Hübner et al., 2019) and a German study (Pohl et al., 2018).

Among the parameters that other literature identified as significant predictors related to WTs but not this study, are attitudes towards WTs in general and the local wind farm. This is surprising since Hübner et al. (2019) found this kind of attitudes were significant predictors for WT noise annoyance. Similarly, attitudes towards WTs in general is not found to be significant predictor. This is aligned with international literature (Bell et al., 2005, 2013; Wolsink, 2000). One reason why these attitudes are no significant predictors in our study may be suppression effects, which can occur in multiple regression analyses when predictors are highly

1 correlated. In our study, the bivariate correlations of attitudes with the OLAS-Scale are in a small to medium  
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3 range.  
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6 Another often debated parameter that is not found significant in this study is distance or proximity to the  
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8 WTs. This parameter is particularly reflected in accusations of Not-in-my-backyard attitudes (NIMBY), which  
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10 claim that local people selfishly oppose WTs because of the proximity to where they live. However, such  
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12 claims do not consider any rationales as to why people may be annoyed by or opposed to wind farms. Yet, in  
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14 practice, spatial regulation is often based on distances in the understanding that annoyance is reduced by  
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16 distance, which reflects that “planning authorities and energy developers are still led by the presumption  
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18 that the population local to a proposed project will exhibit NIMBY concerns” (Petrova, 2013, p. 586). As an  
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20 example, the Danish spatial regulation involves distances in terms of noise and compensation (Danish  
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22 Ministry of Environment, 2015). The finding that distance or proximity do not give any indication of  
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24 annoyance is in line with Devine-Wright (2009), Hübner et al. (2019), Hübner and Pohl (2015), Rudolph et al.  
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26 (2017) and Warren et al. (2005), who tend to refute NIMBY rationales (Jones & Eiser, 2010) and Willingness-  
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28 to-Pay approaches (e.g., Ladenburg & Dubgaard, 2007). Others (Groth & Vogt, 2014; Hoen et al., 2019) found  
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30 that proximity might even lead to more positive attitudes in general. However, it remains ambiguous again  
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32 whether familiarization leads to contentment or indifference over time.  
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41 The regression analysis does not include technological differences, however, both population samples were  
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43 asked about their preferences in terms of demand-oriented obstruction lights (lights switched on only when  
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45 aircrafts approach). This showed a majority of citizens preferred demand-oriented lights in Denmark (56.3%,  
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47 n = 197) and in Germany-Switzerland (58.6%, n = 413).  
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## 7 Conclusions and policy implications

With limited research on citizen annoyance of obstruction lights, policy-makers currently base their decisions on limited evidence for what causes annoyance.

This paper therefore aims to advance the scientific knowledge about citizen annoyance of obstruction lights by providing insights into how stress effects induced by obstructions lights differ between a technologically special case in contrast to regular wind farms, as well as insights into what factors influence stress effects from obstruction lights. By juxtaposing these new findings with broader literature on citizen annoyance of wind turbines, the paper suggests the following five main conclusions in regards to wind energy policies, especially in a European context:

1) Annoyance of obstruction lights is an issue to consider in wind energy policy. Although annoyance due to obstruction lights and related stress effects are not a widespread issue and annoyance levels are generally low, e.g., compared with WT noise impact, they can have significant effects for a certain number of people. Considering the advanced research on annoyance caused by WT noise, it is striking that the annoyance caused by obstruction lights on average is higher than the annoyance caused by noise in both samples. This is, however, not reflected in the percentage of strongly annoyed residents, where annoyance from noise is equal or more widespread than annoyance from obstruction lights. This points to a need for attention to the cumulative aspects of obstruction lights and the implications of a negative effect on residents that is geographically more widespread than e.g., noise.

2) Annoyance of obstruction lights is influenced by citizens' stress during planning process. A clear finding from this comparative study is that both stress during the planning process and people's perception of being heard during the planning process are significant predictors of obstruction lights annoyance stress. Since this is in line with previous research, it sheds again critical light on the meaning of the planning process and procedural fairness as crucial elements in shaping people's reactions and perception, also after the completion of a project. Experiences of the planning process do not just pervade people's experiences of the

1 outcome, but also co-shape their everyday relations with wind farms. This has two important implications  
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3 for policy-makers: a) to enhance the planning process to reduce the stress among citizens, e.g., through  
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5 improved communication, and b) to enhance the participation of residents in a way that allows for a  
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7 meaningful consideration of people's concerns that goes beyond mere information provision and one-sided  
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9 consultation procedures.  
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13 3) Landscape change related to taller turbines may amplify annoyance of obstruction lights. The comparison  
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15 of the technological special case and the regular cases indicates that some factors influencing annoyance are  
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17 more important with taller turbines. This is true for perceived landscape change and refers to the location of  
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19 the WTs and their fit with the surrounding landscape. Hence, the selection of sites as a first step in the  
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21 deployment of WTs becomes particularly important with taller turbines.  
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26 The perceived impacts of obstruction lights points to the need for demand-side mitigatory solutions, such as  
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28 on demand radar-controlled lights at night, that can help to reduce the emission and physical impacts in the  
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30 first place, but also for when a larger number of WTs are deployed locally.  
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34 4) Annoyance of obstruction lights cannot easily be solved with distance. In line with previous studies, our  
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36 findings demonstrate that spatial distance or proximity are not a significant predictor for annoyance, which  
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38 at least questions the effect of proximity-based monetary measures, such as benefits, payments and  
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40 compensations for only nearest neighbours, as recently proposed both in Denmark and Germany.  
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45 5) Although attitudes towards wind energy in general and towards the local wind farms in particular did not  
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47 prove to be significant predictors in the multiple regression analysis, it can be expected, based on the  
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49 moderately strong correlations, that measures for reducing obstruction light annoyance can also increase  
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51 acceptance.  
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55 Although this paper has provided relevant insights in factors influencing annoyance of obstruction light, more  
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57 studies are required, especially exploring the importance of cultural context for perceived annoyance. This  
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1 will allow a solid platform for developing meaningful guidance for how to deal with obstruction lights in  
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3 future wind energy policies.  
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Figure 1: Test Centre Østerild including southern light mast, facing south; and map of location of Østerild in Northern Denmark (photo: Poul Falk Nielsen)

Table 1: Comparison of requirements to aviation marking of WT's on land in Denmark, Germany and Switzerland. For simplicity, the table includes the two most commonly used schemes for Germany more than 5 km from airports. NOTE: L.I. = low intensity; M.I. = medium intensity; H.I. = high intensity

Aviation markings for land-based WT's				
	Denmark	Germany		Switzerland <sup>1</sup>
Reference and version	BL 3-11 – 2018	1-950-17 – 2017 (two options)		AD I-006 D – 2019
Height* < 100 m	No requirements	Blades: red tips	Blades: red tips	2 L.I. red lights at nacelle
150 m > height > 100 m	2 L.I. red lights at nacelle	DAY: 2 M.I. blinking white lights; blades: red tips NIGHT: 2 M.I. blinking red lights	DAY: blades: red tips and one 6 m red marking NIGHT: 2 L.I. blinking red lights	2 M.I. blinking red lights at nacelle Tower: 4 M.I. blinking red lights
Height > 150 m	DAY: 2 M.I. white blinking lights; NIGHT: 2 M.I. red blinking lights. Tower 3 L.I. red fixed lights	DAY: 2 M.I. blinking white lights; blades: red tips; NIGHT: 2 M.I. blinking red lights Tower: 4 L.I. fixed red lights; 3m red band	DAY: Nacelle red marking, blades: red tips and one 6 m red marking; NIGHT: 2 L.I. blinking red lights Tower: 4 L.I. fixed red lights; 3m red band	One H.I. white blinking light; 2 M.I. blinking red lights at nacelle Tower: 4 L.I. fixed red lights at two heights
Blade painting	No	Yes	Yes	Red tips
Alt. marking, e.g. radar	Yes for turbines > 150 m	Yes during night	Yes during night	No

\*Total height to tip. <sup>1</sup>Red lights are inclusive infrared.

Table 2: Summary of studies, samples and wind farms

	<b>DK Dataset</b>	<b>Combined Dataset (G-S)</b>	<b>Pohl et al. (2012)</b>	<b>Pohl et al. (2018)</b>	<b>Hübner &amp; Löffler (2013)</b>
<b>Country</b>	Denmark	Germany, Switzerland	Germany	Germany	Switzerland
<b>Data collection year</b>	2016	2009–2013	2009	2012	2012–2013
<b>Sample size (N)</b>	197	1099	420	212	467
<b>Number of wind farms</b>	1	21	13	1	7
<b>WTs per wind farm</b>	7	1–18	5–18	9	1–16
<b>WT total height (m)</b> <b>Light mast height (m)</b>	150–222 250	72–150 no mast	118–150 no mast	150 no mast	72–148 no mast
<b>WT capacity (MW)</b>	2.0–8.0	0.6–2.3	0.8–2.3	2.0	0.6–2.0
<b>Distance range to home (km)</b>	0.92–17.80	0.23–16.25	0.44–16.25	1.25–2.89	0.23–5.00
<b>Average distance to home (km)</b>	5.85	1.79	1.49	1.90	1.99

Table 3: Sample demographic statistics

	DK	G-S	Effect size (d, w) p-value (t-test, Chi <sup>2</sup> -test)
<b>Age</b> (mean, SEM, range)	52.46 (1.05) 20–80 n = 152	52.28 (0.45) 17–93 n = 1085	p = .888
<b>Gender</b> Male Female	45.1% 54.9% n = 153	52.0% 48.0% n = 1089	p = .111
<b>Marital status</b> Married/with partner Single	83.0% 17.0% n = 153	55.9% 44.1% n = 1085	0.182 (small) p < .0001
<b>Years of education</b> (mean, SEM)	13.37 (0.33) n = 143	13.21 (0.12) n = 1072	p = .659
<b>Job situation</b> Employed Unemployed Retired Scholar/student	65.0% 0.0% 30.0% 5.0% n = 140	58.8% 11.9% 26.7% 2.6% n = 990	0.134 (small) p < .0001
<b>Duration of residency</b> (years, mean, SEM)	25.39 (1.22) n = 191	21.450 (0.49) n = 1068	0.239 (small) p = .002
<b>Financial participation in wind project</b> No Yes	93.2% 6.8% n = 146	97.9% 2.1% n = 876	0.103 (small) p = .003

Table 4: Perception of impacts from WTs

	DK	G-S	Effect size (w) p-value (Chi <sup>2</sup> -test)
	Percentage (Number)		
<b>Obstruction light inside the house</b>	73.1% n = 128	30.0% n = 467	medium (0.390) p < .0001
<b>Obstruction light outside the house</b>	89.2% n = 157	37.7% n = 176	medium (0.460) p < .0001
<b>Shadow perception outside the house</b>	2.0% (3) n = 153	11.0% (51) n = 462	small (0.138) p = 0.001
<b>Shadow perception inside the house</b>	1.3% (2) n = 153	8.8% (41) n = 465	small (0.127) p = .002
<b>Noise perception outside the house</b>	17.6% (27) n = 153	41.0% (275) n = 671	small (0.188) p < 0.0001
<b>Noise perception inside the house</b>	10.5% (16) n = 153	23.9% (162) n = 678	small (0.127) p < 0.0001

Table 5: Annoyance induced by WT impacts and other local sources (single item scale 0 to 4; 0='not at all')

	DK	G-S	Effect size (d) p-value (t-test)
	mean (SEM)		
<b>Annoyed by day obstruction marking (white LED or Xenon or coloured stripes)</b>	0.86 (0.09) n = 169	0.69 (0.04) n = 810	p = .092
<b>Annoyed by day obstruction marking (white LED or Xenon)</b>	0.86 (0.09) n = 169	1.00 (0.07) n = 339	p = .232
<b>Annoyed by night obstruction marking</b>	1.88 (0.13) n = 169	1.14 (0.05) n = 817	small (0.463) p < .0001
<b>Bothered / annoyed by shadow casting</b>	1.33 (0.88) n = 3	1.98 (0.23) n = 152	p = .514
<b>Bothered / annoyed by landscape change</b>	2.11 (0.15) n = 110	1.39 (0.05) n = 1093	small (0.454) p < .0001
<b>Bothered / annoyed by WT noise</b>	2.75 (0.25) n = 24	1.43 (0.08) n = 283	large (1.009) p < .0001
<b>Agricultural machinery noise</b>	2.11 (0.15) n = 110	1.39 (0.05) n = 1093	small (0.454) p < 0.0001



Table 6: Frequency of annoyance by obstruction lights depending on the time of day and weather conditions

	DK	G-S	Effect size (w) p-value (Chi <sup>2</sup> -Test)
	Percentage (number)		
<b>Annoyed by obstruction lights during daylight</b>	26.6% (45) n = 169	5.9% (25) n = 423	small (0.289) p < .0001
<b>Annoyed by obstruction lights at night</b>	54.4% (92) n = 169	31.2% (132) n = 423	small (0.216) p < .0001
<b>Annoyed by obstruction lights: clear sky</b>	47.9% (92) n = 169	7.3% (31) n = 423	medium (0.468) p < .0001
<b>Annoyed by obstruction lights: cloudy</b>	43.2% (73) n = 169	8.3% (35) n = 423	medium (0.468) p < .0001
<b>Annoyed by obstruction lights: rainy</b>	37.3% (63) n = 169	8.3% (35) n = 423	medium (0.468) p < .0001
<b>Annoyed by obstruction lights: misty/foggy</b>	32.5% (55) n = 169	10.2% (43) n = 423	small (0.271) p < .0001

Table 7: Negative impact of obstruction lights on daily activities (scale 0 to 2)

	DK	G-S	Effect size (d) p-value (t-test)
	mean (SEM)		
<b>Garden/fields</b>	0.52 (0.05) n = 168	0.58 (0.04) n = 278	p = .390
<b>In the house</b>	0.41 (0.05) n = 168	0.20 (0.02) n = 411	small (0.374) p < .0001
<b>Taking a walk</b>	0.88 (0.07) n = 168	0.49 (0.04) n = 411	small (0.495) p < .0001
<b>Doing sports</b>	0.42 (0.05) n = 168	0.29 (0.03) n = 354	small (0.206) p = .031
<b>Relaxing</b>	0.69 (0.06) n = 168	0.49 (0.04) n = 410	small (0.263) p = .006
<b>Driving a car</b>	0.72 (0.06) n = 168	0.39 (0.03) n = 399	small (0.453) p < .0001
<b>Watching TV</b>	0.29 (0.05) n = 168	0.23 (0.02) n = 411	p = .252
<b>Reading</b>	0.26 (0.04) n = 168	0.29 (0.03) n = 411	p = .517
<b>During conversations</b>	0.33 (0.05) n = 168	0.22 (0.02) n = 419	small (0.198) p = .042
<b>While hosting guests</b>	0.51 (0.05) n = 168	0.24 (0.03) n = 418	small (0.432) p < .0001

Table 8: Annoyance Stress-Scale (scale 0 to 4)

	DK	G-S	Effect size (d) p-value (t-test)
	mean (SEM)		
<b>Obstruction Lights Annoyance Stress-Level</b>	2.16 (0.09) n = 170	1.27 (0.04) n = 1038	medium (0.777) p < .0001
<b>Shadow Casting Annoyance Stress-Level</b>	0.24 (0.06) n = 153	0.72 (0.03) n = 927	medium (0.648) p < .0001
<b>Landscape Change Annoyance Stress-Level</b>	2.36 (0.08) n = 110	1.42 (0.03) n = 748	large (1.199) p < .0001
<b>Noise Annoyance Stress-Level</b>	0.29 (0.07) n = 130	0.77 (0.04) n = 749	medium (0.544) p < .0001

Table 9: Percentages of strongly annoyed residents based on the AS-Scale (level 4)

	DK	G-S	Effect size (w) p-value (Chi <sup>2</sup> -test)
	Percentage (number) of strongly annoyed residents		
<b>Strongly annoyed participants induced by obstruction lights</b>	6.1% (12) n = 153	3.0% (27) n = 890	p = .370
<b>Strongly annoyed participants induced by shadow casting</b>	0.0% (0) n = 197	0.0% (0) n = 467	not calculable
<b>Strongly annoyed participants induced by landscape change</b>	0.5% (1) n = 197	0.4% (2) n = 467	p = 1.00
<b>Strongly annoyed participants induced by WT noise</b>	2.5% (5) n = 197	5.9% (40) n = 679	p = .061
<b>Strongly annoyed participants induced by at least one emission</b>	6.6% (13) n = 197	6.1% (67) n = 1102	p = .780

Table 10: Percentages of behavioural and cognitive coping to reduce lightning annoyance

	DK	G-S	Effect size (w) p-value (Chi <sup>2</sup> -test)
	Percentage (number)		
<b>Changing location of outdoor activities (already done)</b>	18.5% (30) n = 162	33.5% (105) n = 313	small (0.158) p = .001
<b>Moving away (already done) or thinking about it</b>	1.9% (3) n = 162	3.6% (15) n = 415	small (0.217) p < .0001
<b>Resigning/getting used to it (already done)</b>	27.8% (45) n = 162	51.7% (213) n = 412	p = .274

Table 11: Comparison of attitudes and planning process moderator variables

	DK	G-S	Effect size (d) p-value (t-test)
	mean (SEM)		
<b>Attitudes toward the local wind farm (scale -3 to +3)</b>	1.00 (0.14) n = 158	1.00 (0.05) n = 987	p = .834
<b>Attitudes toward WTs in general (scale -3 to +3)</b>	1.67 (0.12) n = 156	1.62 (0.04) n = 1093	p = .687
<b>Community interests have been heard to a sufficient degree (scale 0 to 4)</b>	1.20 (0.11) n = 160	1.77 (0.06) n = 590	small (0.414) p < .0001
<b>My personal interests have been heard to a sufficient degree (scale 0 to 4)</b>	1.12 (0.11) n = 160	1.38 (0.06) n = 578	not relevant (0.180) p = .035
<b>Stressed during planning and construction process (scale 0 to 4)</b>	1.34 (0.15) n = 111	0.68 (0.04) n = 1071	small (0.480) p < .0001

Table 12: Sensitivities and general stress (scale 0 to 4)

	DK	G-S	Effect size (d) p-value (t-test)
	mean (SEM)		
<b>Light sensitivity</b>	1.80 (0.12) n = 111	0.88 (0.03) n = 520	large (0.861) p < .0001
<b>Noise sensitivity</b>	1.68 (0.12) n = 111	1.81 (0.03) n = 672	p = .315
<b>Acute stress</b>	0.63 (0.10) n = 80	1.20 (0.03) n = 1078	medium (0.571) p < .0001
<b>Chronic stress</b>	0.41 (0.08) n = 80	1.08 (0.03) n = 1074	medium (0.696) p < .0001

Table 13: Multiple regression prediction of obstruction lights annoyance stress (OLAS-Scale)

	DK R <sup>2</sup> adjusted = 0.661 n = 75, all VIF < 5.2		G-S R <sup>2</sup> adjusted = 0.555 n = 360, all VIF < 5.7	
	Beta	p-value	Beta	p-value
<b>Landscape Change Annoyance Stress-Scale</b>	<b>0.570</b>	< .0001	0.054	.204
<b>Attitudes towards the local wind farm</b>	-0.002	.984	-0.136	.105
<b>Attitudes toward WTs in general</b>	0.021	.822	-0.115	.174
<b>Community interests have been heard to a sufficient degree</b>	<b>0.389</b>	.014	-0.048	.416
<b>My personal interests have been heard to a sufficient degree</b>	<b>-0.665</b>	< .0001	-0.076	.180
<b>Stressed during planning and construction process</b>	<b>0.191</b>	.047	<b>0.279</b>	< .0001
<b>Light sensitivity</b>	0.046	.529	<sup>a</sup>	<sup>a</sup>
<b>Number of WTs visible from home</b>	0.119	.150	<b>0.291</b>	< .0001
<b>Duration of residency</b>	0.039	.667	0.052	.208
<b>Age</b>	<b>0.220</b>	.010	0.021	.605
<b>Gender</b>	-0.069	.336	0.116	.001
<b>Years of Education</b>	0.045	.553	-0.065	.093
<b>Distance to nearest WT / light mast</b>	-0.025	.728	-0.044	.235

<sup>a</sup> No variable available; the number of respondents is too small.

Note: A VIF below 7 is considered as an indication of low collinearity between predictor variables.