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The impact of shadow flicker or pulsating shadow effect, caused by wind turbine blades, on Atlantic salmon (*Salmo salar*)

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Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes and Research Institutes supported by MASTS. The Centre is funded by the Scottish Government.

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Please reference this report as follows: Dodd, J.A. & Briers, R.A. (2021)
The Impact of Shadow Flicker or Pulsating Shadow Effect, Caused by Wind Turbine Blades, on Atlantic Salmon (*Salmo salar*) CD2020_08. Scotland's Centre of Expertise for Waters (CREW).
Available online with supporting documents at: crew.ac.uk/publications

ISBN Number: 978-0-902701-90-8

Dissemination status: Unrestricted

Acknowledgements: The authors would like to thank the project steering group: Colin Bean (NatureScot), Emily Bridcut (Marine Scotland Science), and Andy Gowans (SEPA) for their support.

Cover photographs courtesy of: Jennifer Dodd (Edinburgh Napier University) and Marine Scotland Science.

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Glossary

Term	Definition
Adult	The stage at which an individual salmon can produce offspring.
Alevin	Newly hatched salmon up to a few months of age.
Anadromous fish	A species of fish that reproduce in freshwater and migrate to the sea to take advantage of the better growing conditions.
Aspect	The orientation of an area relative to the compass, for example, an area with a southern aspect would be facing south and would therefore receive more direct sunlight.
Benthos	The flora and fauna found associated with the bottom of a lake, river or stream.
Catchment	The area of land from which water drains into a lake, river or stream.
Catchment topography	The physical form of the catchment including the slope of the land over larger and smaller scales.
Circadian rhythms	The approximately 24-hour pattern of various activities seen in most animals.
Conspecifics	Individuals of the same species.
Diadromous fish	A species of fish that reproduce in freshwater and migrate to the sea to take advantage of the better growing conditions or vice versa, i.e., the species will spawn in the ocean and migrate to freshwater to grow and mature.
Diffraction/Diffracted	The change of the direction of a wave, in this case light, when it encounters an object (e.g., a branch over hanging a river or a boulder on the riverbed).
Exogenous feeding	When an animal starts to feed on external food (i.e., not dependant on yolk).
Fry	The life stage of an Atlantic salmon that spans from hatching to one year of age.
Geographic range	The physical area over which the species is found globally.
Innate pathways	In the context of this report, a cognitive pathway of behavioural response that is inborn, i.e., the behavioural pathway has been inherited (compare with learned pathways).
Learned pathways	In the context of this report, a cognitive pathway of an individual resulting in a behavioural response which has been learned following exposure to external stimuli (compare with innate pathways).
Macroinvertebrates	Invertebrates which can be seen without the use of a microscope. The term is mostly associated with aquatic organisms.
Migrate/Migration	The process of movement from one area to another for the purposes of growth and/or reproduction.
Ontogenetic development	The development of an individual from fertilisation of the egg to adulthood.
Parr	The life stage of an Atlantic salmon that spans from approximately one year of age to the point at which the animal smolts (i.e., changes to the seaward migratory stage).
Photoreceptors	Organs or sensors which detect the presence of light.
Phototactic	When an animal shows a response to light - positive phototaxis means an individual is attracted to light, negative phototaxis means an individual is repelled by light.
Refraction/Refracted	The change in the direction of a wave, in this case light, as it passes from one medium into another (e.g., air into water).
Riparian habitat	The habitat immediately surrounding a river.
Riverbed	The bed of the river, composed of hard material like sand, pebbles or boulders, or soft materials like silt.
r-strategists	An organism which produces a large number of offspring, generally to compensate for high offspring mortality. In Atlantic salmon there are larger relative losses at the egg stage compared with losses at the adult stage.
Smolt	The life stage of an Atlantic salmon where the animal undergoes internal changes to its biology and external changes to its appearance in preparation for life in saltwater. The animal also exhibits changes in behaviour.
Smoltification	The process by which an individual parr (the preceding life stage) undergoes internal changes to its biology and external changes to its appearance in preparation for life in saltwater. The animal also exhibits changing in its behaviour.
Snell's Window	The restricted window through which fish see terrestrial and aerial objects owing to the refraction of light entering water.
Stock-recruitment curve	The relationship between the number of returning adult spawning fish and the number of individuals recruited to the population in a defined area.
Turbidity	The degree of cloudiness or opacity of a liquid, due to occurrence of suspended matter in the water.
Water caustics	The reflection and refraction of light at an interface between media (here air-water) and the resultant pattern projected on a surface.

1 Executive summary

1.1 Research questions

1. What are the potential biological and ecological impacts/responses of shadow flicker on Atlantic salmon at an individual level, at each life-stage, within a river system?
2. Do Atlantic salmon habituate to repeated disturbance and may that increase susceptibility to other pressures, such as predation risk?
3. Can the impact of shadow flicker be extrapolated to the whole Atlantic salmon population of an affected river?
4. Are there ways in which this issue can be successfully mitigated?

1.2 Background

Onshore wind farm developments have become a common sight within the Scottish landscape, and the installed capacity of onshore wind-generated electricity has expanded, to meet climate adaptation needs. Impacts from the installation of wind turbines near rivers and streams may include changes to water quality caused by runoff from construction and drainage of land, or damage to vulnerable freshwater habitat (such as gravels used by fish for spawning) during construction of stream and river crossings or through inadvertently creating barriers to fish migration. The potential impact of shadow flicker on freshwater fish (a flickering or pulsating light to shadow cast effect caused by the motion of wind turbine blades as they pass in front of the sun) has not previously been investigated.

Atlantic salmon (*Salmo salar*) are undergoing a significant decline across their natural range. They are a qualifying feature within 17 Special Areas of Conservation (SACs) designated under the EU Habitats Directive in Scotland. Furthermore, Atlantic salmon also support other qualifying features for SACs, for example, freshwater pearl mussels are dependent on the presence of salmonids to complete their lifecycle. The extent to which Atlantic salmon may be exposed to, and potentially impacted by, shadow flicker from wind turbine blades is not well understood.

1.3 Aim and objectives

The overall aim of this project was to review the available literature (peer-reviewed and grey from national and international sources) relating to the impact of shadow flicker caused by wind turbine blades on freshwater fish, with a particular focus on Atlantic salmon in rivers. The conclusions of this review may, depending on the evidence available, inform policy in relation to the placement of wind turbines in areas adjacent to rivers in the Scottish context. This report answered the four research questions to specifically address the following project objectives:

- Review the current literature on 'shadow flicker' on freshwater fish with a particular focus on Atlantic salmon;
- Use examples from the literature to provide insights into the actual biological impact that shadow flicker may have on Atlantic salmon in rivers;
- Suggest ways in which this issue, should it be shown to be significant, can be mitigated or used to inform wind turbine placement near rivers.

1.4 Key findings

The review of the available peer-reviewed and grey literature from national and international sources found:

- While there is some information available about the response of Atlantic salmon to changes in light intensity (e.g., responses to strobe light or artificial light at night), there is no published information about the responses (biological or behavioural) of Atlantic salmon, or any fish species, to artificial light patterns of the characteristics associated with shadow flicker;
- Based on extrapolation of the available evidence and the authors' opinion (formed with low confidence due to the lack of available information), there is not sufficient evidence to support or refute any impact of shadow flicker on Atlantic salmon in rivers;
- The literature review has highlighted a research gap relating to the responses of freshwater fish to patterns of varying light intensity.

Atlantic salmon are exposed to multiple stressors in the freshwater environment (e.g., exploitation, invasive non-native species and increasing water temperatures). The literature review identified one life stage, parr, of Atlantic salmon which might be exposed to shadow flicker. Against the background of natural light patterns arising from, for example, distortions to the water surface, movement of bankside vegetation and cloud-cover, it is the authors' opinion that, the addition of shadow flicker is unlikely to result in a change at the population level.

1.5 Recommendations

The responses of Atlantic salmon, or indeed any fish species, to changes in the dynamic pattern of natural light has not been significantly investigated. We note that there have been recent work investigating responses to artificial light sources (e.g., associated with street lighting or the use of strobe light in aquaculture). As such, any extrapolation of the effects of shadow flicker on Atlantic salmon at the individual and population level has been guided, following a review of the literature, by expert opinion alone.

Appropriate mitigation can only be drawn up when a significant impact is evident. To remediate possible impacts associated with shadow flicker from wind turbine blades, any changes to wind turbines associated with operational wind farms or published guidelines relating to the construction of new wind farm developments must be based on evidence of a biological impact on salmon populations which, at this stage, we do not have. A biological impact would be measured as fish lost, resulting in a measurable impact to the population, which is directly attributed to shadow flicker (alone or in conjunction with another stressor). Further research is needed to address the project questions fully and inform potential policy development if required. These include:

- Fundamental research and modelling to investigate natural light patterns in rivers and how this is influenced by the shadow flicker from single or multiple wind turbines;
- Applied research on the effects of changes in light, both pattern and intensity, on Atlantic salmon at different life-stages;
- Investigation of the potential use of riparian planting as a mitigation measure to shield rivers from the effects of shadow flicker.

2 Introduction

2.1 Background and scope

In response to a changing climate and attempts to reduce emissions from the burning of fossil fuels, renewable energy infrastructure continues to grow. For example, the Renewable Energy Directive in 2009 (2009/28/EC) and subsequent amendments has driven the increase in renewable energy production across Europe. Targets for Scotland are that 100% of energy production by 2050 will be delivered by the renewable energy sector (Scottish Government, 2017). Onshore wind farm developments have become a common sight within the Scottish landscape to meet climate adaptation needs. Scotland now has over 4,500 wind turbines, relating to schemes in excess of 100 kW (i.e., not small wind turbines associated with domestic properties), in operation (Unpublished NatureScot data, up to December 2019) although there is no definitive source for details of their location, size, and design. Onshore wind-generated electricity has expanded within a decade and provided approx. 70% of installed capacity of renewable energy since 2016 (Figure 1). This renewable energy picture is constantly evolving as more onshore wind farms become operational and the electricity generating capacity changes with improving technology, repowering assets as supply reaches lifespan end, and increasing proportion of offshore wind farms.

The growing number of wind farms has, in some circumstances, caused unease to the wider public, mostly due to perceived impacts on people and the environment. Distances between wind turbines and human habitation has been driven by the visual impacts of wind turbines on residents living close to a wind farm development, as well as potential impacts of noise, and shadow cast, from the motion of wind turbine blades. For example, a specific concern relates to the risk of photoconvulsive attacks, which may be induced by the flickering light from wind turbine blades (Harding et al., 2008). The role of shadow flicker, or pulsating shadow effect, in relation to potential impacts on human habitation has recently been included as part of the planning consent process in Scotland (ClimateXChange, 2015; ClimateXChange, 2017). Current guidance advises that wind turbines should be placed outwith a ten-rotor diameter distance of human habitation (ClimateXChange, 2015), but the evidence base to support this as a threshold for the effect of shadow flicker on human habitation is not robust (ClimateXChange, 2017).

Shadow flicker has been defined as :

"*Under certain combinations of geographical position, time of day and time of year, the sun may pass behind the rotor and cast a shadow over neighbouring properties. When the blades rotate, the shadow flicks on and off; the effect or impact is known as "shadow flicker"***."** (ClimateXChange, 2017)

The impacts of wind farm installation, in proximity to Scottish inland waters (e.g., rivers, streams), on freshwater and diadromous fish and their associated fisheries has been highlighted by Marine Scotland Science (Scottish Government, 2018). These include changes to water quality and sediment loading caused during the construction phase through the release of, for example,

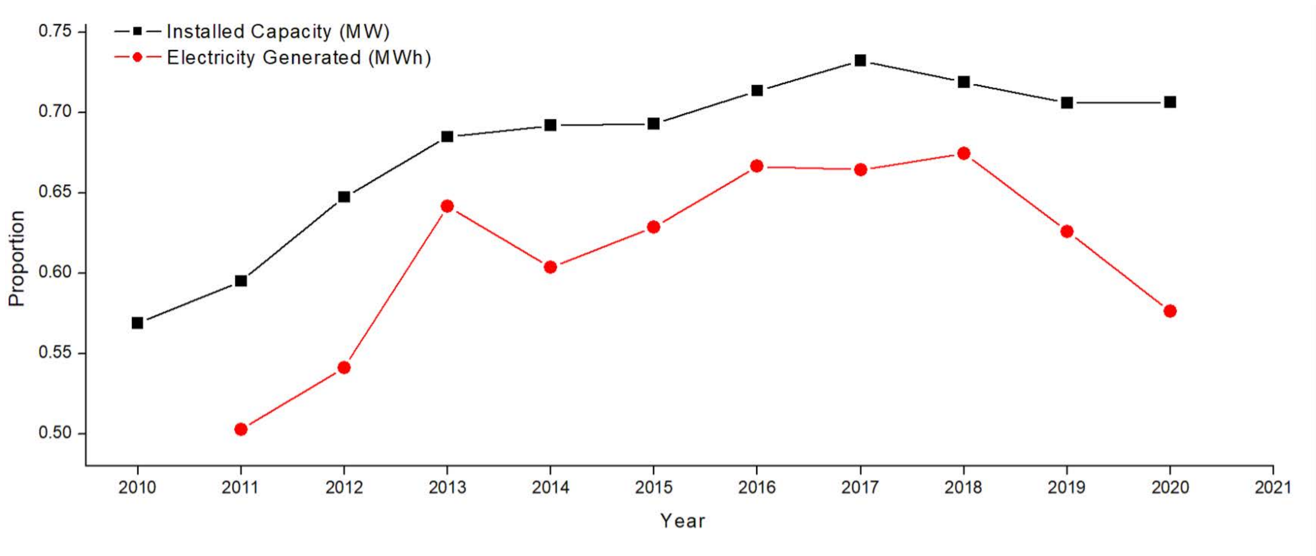

Figure 1: Onshore energy generation in Scotland. Cumulative installed capacity (MW) as a proportion of total installed capacity (black) and the proportion of energy generated (MWh) from onshore wind farming (red). Figures from National Statistics, 2021.

fine sediments and runoff from drainage of land or pollution incidents. Damage may also occur to vulnerable freshwater habitats (such as gravels used by fish for spawning) in areas where stream and river crossings are constructed, or through habitat loss if barriers to fish migration are inadvertently created. Potential issues associated with shadow flicker effects on freshwater fish, regarding the placement of onshore wind farm installations, are a more recent consideration and have not been investigated previously.

The impact of shadow flicker from new onshore wind turbines, and the installation of replacement wind turbines during the repowering of established wind turbines at onshore sites, situated in proximity to river systems, may have the potential to impact a range of freshwater fish. The focus of this review investigates potential shadow flicker impacts on the biology and ecology of Atlantic salmon (*Salmo salar*). The extent to which Atlantic salmon may be exposed to, and potentially impacted by, shadow flicker from wind turbine blades is not well understood. Atlantic salmon are already undergoing significant decline throughout its natural range (Rikardsen et al., 2021). They are a qualifying feature within 17 Special Areas of Conservation (SACs), designated under the EU Habitats Directive, in Scotland. Furthermore, Atlantic salmon also support other qualifying features for SACs, for example, freshwater pearl mussels are dependent on the presence of salmonids to complete their lifecycle. In 2019, Scottish Government published a list of twelve high-level pressures affecting Atlantic salmon in freshwater and at sea (Scottish Government, 2019). Of these, eleven relate to freshwater habitats: exploitation (the removal of individuals from the population by humans); predation/competition (the removal of individuals from the population by other animals); fish health (the effects from disease and parasites on individual survival); genetic introgression (the effect of altering the genetic integrity of a population through inter-breeding with intentionally stocked or escaped farm salmon); invasive non-native species (multiple effects at the individual and population level); water quality (the impacts of pollutants entering the lake, river or stream); water quantity (the impacts from changes to the flow patterns in rivers from sources such as abstraction and large scale rainfall patterns); water temperature (impacts from changes to the temperature profiles of rivers through, for example, losses in riparian shading); instream habitat (impacts from changes to the cover provided in the river in the form of, for example, substrate and large woody debris); riparian habitat (impacts from losses of riparian vegetation and conifer plantations in areas already under pressure from acidification); migration barriers (loss of habitat through restriction of access via in-river structures). There is no current evidence that any of these eleven high-level pressures consider possible impacts of shadow flicker on Atlantic salmon.

There is a breadth of water policies relating to the conservation and management of Atlantic salmon in Scotland. Statutory obligations to protect Atlantic salmon are undertaken through SACs (via the EU Habitats Directive), through the maintenance and protection of freshwater biodiversity (via the EU Water Framework Directive), and through the management of Atlantic salmon populations (via various statutory commitments delivered by Marine Scotland Science and the District Salmon Fishery Boards). Atlantic salmon are also protected under Appendix III of the Bern Convention, listed as a UKBAP (UK Biodiversity Action Plan) Priority species and in the Scottish Biodiversity Plan (spring stock component only) which has succeeded the UKBAP under the Post-2010 Framework, the status of the stock is monitored by NASCO (North Atlantic Salmon Conservation Organisation), ICES (International Council for the Exploration of the Sea) and OSPAR (Oslo-Paris) Convention. Furthermore, the Scottish Government has been tasked with the delivery of the Wild Salmon Strategy, which is currently under development and is expected during 2021.

This literature review will be used to inform Scottish conservation and environmental regulatory agencies, as well as other relevant stakeholders, on the available evidence of shadow flicker impacts on Atlantic salmon, outline areas where more research is needed, and where further work may be recommended. These project outputs may have implications for policies supporting overall renewable energy development in relation to efforts to tackle climate change in Scotland, and the applied water policy context. For example, managing interactions between wind turbine placement (such as proximity to a river system, including wind turbine size, density, and screening) and the maintenance of conservation features within designated sites, as well as wider fisheries management.

2.2 Aim and objectives

The overall aim of this project was to review the available literature (national and international peer-reviewed and grey) relating to the impact of shadow flicker caused by wind turbine blades on freshwater fish, with a particular focus on Atlantic salmon in rivers. The conclusions of this review may, depending on the evidence available, inform policy in relation to the placement of wind turbines in areas adjacent to rivers in the Scottish context. This report specifically addressed the following project objectives:

- Review the current literature on 'shadow flicker' on freshwater fish with a particular focus on Atlantic salmon;
- Use examples from the literature to provide insights into the actual biological impact that shadow flicker

may have on Atlantic salmon in rivers;

- Suggest ways in which this issue, should it be shown to be significant, can be mitigated or used to inform wind turbine placement near rivers.

To achieve the above objectives, four research questions were investigated, reviewed, and answered, these were:

- What are the potential biological and ecological impacts/responses of shadow flicker on Atlantic salmon at an individual level, at each life-stage, within a river system?
- Do Atlantic salmon habituate to repeated disturbance and may that increase susceptibility to other pressures, such as predation risk?
- Can the impact of shadow flicker be extrapolated to the whole Atlantic salmon population of an affected river?
- Are there ways in which this issue can be successfully mitigated?

2.3 Research approach

To assess the state of current knowledge regarding the possible effects of shadow flicker on Atlantic salmon, a review of the available literature (peer-reviewed and grey) was undertaken. Two databases were used (Web of Science and Google Scholar) to identify published scientific articles and web-search engines (Google™ & Bing™) to identify grey literature containing the best available evidence to investigate potential effects of shadow flicker. There was no direct evidence available, either as laboratory experimentation or field observation relating to the project questions, thus extrapolation of available knowledge was made using the authors' opinion[1], to address the project goals.

3 Current research

The review of the available literature highlighted a complete lack of any evidence relating to the effects of shadow flicker in an experimental or field setting on the biology and ecology of any freshwater fish species, including Atlantic salmon. Current knowledge relating to the effect and impact of artificial light on fish species has included: the use of strobes to alter fish behaviour in aquaculture (Bui et al., 2013), the use of strobes as a deterrent to riverine obstacles for migrating fish (Fjeldstad et al., 2012), and the impacts of artificial light at night (ALAN; Riley et al., 2012). Current literature investigating the impact of shadow flicker (in the form of flickering light) from wind turbine blade motion relates only to research on possible human impacts (Harding et al., 2008).

3.1 Sources of natural light pattern within the river environment

In rivers, natural variation in illumination or light patterns (the movement of light and transmission of light within the environment) below the water surface comes from a range of sources which may have different temporal and spatial scales and, predictability. Hours of daylight and solar intensity follow predictable annual seasonal cycles which will also vary across the geographic range of the Atlantic salmon. Within these annual cycles, less-predictable, shorter-term cycles of natural light patterns are associated with local weather conditions in the form of cloud cover which show a greater degree of predictability at seasonal compared with daily scales (Matuszko, 2012).

Overlaying these temporal patterns, are spatial patterns which vary in their extent relative to river habitats. Shading results from a varying amount of light reaching the water surface. The form of the river channel and the wider riparian habitat influences the natural pattern of shading. The height of the riverbank, relative to the wetted width of the river, will influence the proportion of shadow cast on the river surface (Hill et al., 1995). The height, form and density of riverbank vegetation will also influence the proportion and nature of the shadow pattern cast. For example, shadow (light dapple) patterns cast by tall mature trees will be different from those cast by dense shrub. Furthermore, the degree of shadow contrast will be linked with sunlight intensity whilst wind strength will impact the dynamic nature of the dappling pattern through its influence on the motion of vegetation. The substrate of the riverbed also plays a role in the light-shadow pattern on the riverbed/surface, with large boulder substrates creating more complex shadow-patterns compared with smaller pebble substrates. The aspect of the river reach and wider catchment topography will also play a significant, and predictable, role in river light patterns, with southern facing habitats receiving higher annual solar radiation. The underlying soils, geology and land use can add colour (e.g. via dissolved organic carbon) and suspended particles to water, disrupting the optical properties of river water (Effler et al., 2010). Changes to river flow and depth can also affect light penetration which is often exacerbated by increased turbidity at high flows.

1 Authors' opinion has been formed based on a review of the literature and previous experience gained through a foundation of research in the freshwater environment. The opinions expressed have been formed with low confidence due to the level of extrapolation required resulting from to the lack of information and evidence available.

Natural light patterns also arise from the physical state of the water itself. Water surface conditions play a significant role in the pattern of light entering the river habitat. Water caustics (or wave-induced flicker) are the optical phenomena of fluctuations and spatial patterns of the refraction of light through a disturbed water surface (McFarland & Loew, 1983). As light is transmitted through a surface (e.g., moving from air to water) it is refracted and is diffracted when it encounters an object (e.g., a branch overhanging a river) resulting in light rays diverging and converging to form variable patterns of light (Lock & Andrews, 1992). In rivers, the water surface can be disturbed in response to wind strength but is more predictably disturbed in response to channel form. Decreasing depth and increasing substratum roughness results in an increase to the amount of distortion of the water surface (Branch et al., 2021). Furthermore, the velocity of water over the substrate will also change the water surface conditions. The interplay between the light reaching the water surface and the degree of surface distortion results in variations to the intensity of light at any specific location and hence variation in the visual 'noise' experienced by an individual organism. Under similar local lighting conditions, due to the increase in water surface distortion, fish in a riffle would experience higher water caustics and thus increased visual noise compared with a fish in a pool. Natural light patterns within a river thus arise from a number of spatial drivers (i.e., river aspect, river channel form and catchment topography, local vegetation cover, substratum and water surface conditions) which are modified over long and short time scales (i.e., seasonal and weather effects).

3.2 Sources of artificial light pattern within the river environment

Variation in illumination or light pattern of a habitat is important for the visual interpretation of available resources by animals (Théry, 2001). Artificial alterations to natural light patterns can come from a variety of sources. For example, the impact of artificial light at night (ALAN) on aquatic organisms has received significant recent attention (Riley et al., 2015). ALAN focusses on the effects of light level and temporal variation and not light pattern, which is the focus here. One possible source of impact on the pattern of light in rivers is the flickering light-to-shadow effect from the blades of wind turbines as they cross sunlight. This effect is commonly referred to as 'shadow flicker'. There are numerous spatio-temporal influences (e.g., geographical position, time of day and time of year) which will contribute to both the *occurrence* of shadow flicker and the *frequency* and *pattern* of shadow flicker. Medium and large wind turbines, most with two or three blades, have a rotation rate of between 30 and 60 revolutions per minute, translating to a shadow flicker frequency in the range of 1 to 3 Hz (Clarke, 2001). The recommendation for the upper limit to shadow flicker frequency is 2.5 Hz (Verkuijlen & Westra, 1984, as cited in Harding et al., 2008) which has been identified from previous work investigating the limits of photoconvulsive (epileptic) response in humans to the frequency of flickering light (Wilkins et al., 1980). However, in impact assessments of shadow flicker for proposed wind farms (see Bolton, 2007; Duckworth, 2010; Duckworth, 2012), only the occurrence of shadow flicker was assessed and not the frequency of shadow flicker. In the context of wind farms with multiple wind turbines, it is likely that both synergistic and antagonistic interactions will occur to the light passing between the blades of adjacent wind turbines, with the potential of producing shadow flicker across a broad range of frequencies, albeit not for sustained periods. This effect is likely to occur more frequently with increasing wind farm size. To the best of the authors knowledge, there has been no report detailing the frequency and pattern of shadow flicker in installed or proposed wind farms. The magnitude of shadow flicker (occurrence of- and frequency of-) and how this interacts with existing natural light patterns to change the dynamics of light in running waters has not been investigated.

3.3 Light-pattern perception by Atlantic salmon

To interact with the environment an organism needs to perceive resources in space and time. Light perception in Atlantic salmon is achieved through two photosensory pathways; the eyes, employing rod and cone photoreceptors which mediate object detection and, extraretinal photoreceptors (e.g., pineal organ), which use environmental light cues for a number of tasks including, regulation of circadian rhythms, ontogenetic development (Jonsson & Jonsson, 2011), growth (Metcalfe & Thorpe, 1990) and changes to body colouration (Shand & Foster, 1999). There are two ways in which shadow flicker could have an influence on Atlantic salmon via these perceptual pathways. Firstly, through changes to the photoperiod perceived by an individual via the loss of total light reaching the animal as a result of increased total shadow. The potential interruption to daylight on a river surface, from shadow flicker, has been calculated as between 5% in May to 3.2% in March for the River Thurso (information supplied by Lomond Energy Ltd. to NatureScot). The total loss of light would be much lower due to the small area of the wind turbine blades (which would cast a shadow) relative to the total swept area of the entire rotor blade. Given the low proportion of relative light loss from shadow flicker, it is highly unlikely that shadow flicker would have any biologically significant impact on perceived photoperiod. The second source of impact from shadow flicker could arise from behavioural change arising from exposure to the rhythmic disturbance from shadow flicker (*cf*. natural light patterns) which could impact, for example, prey detection or predator avoidance. It is this disturbance to the natural light pattern and any visual stimulus from wind turbines that have been considered in this review.

3.3.1 Effects of natural light patterns

While the role of absolute light in resource use by Atlantic salmon is well documented (Jonsson & Jonsson, 2011), the role of light *pattern* is not well understood. However, useful studies are beginning to emerge for other species. For example, Matchette et al. (2018) demonstrated that human participants were significantly slower and more error prone when capturing prey items in a dynamic light environment. Newly hatched domestic fowl (*Gallus gallus*) exhibited lower successful attack and prey acquisition rates in dappled light compared with constant light (Matchette et al., 2019). In studies on Picasso trigger fish (*Rhinecanthus aculeatus*), Matchette et al. (2020) demonstrated that increasing visual noise impacted prey location by this visual reef predator and Attwell et al. (2021) showed that three spined sticklebacks (*Gasterosteus aculeatus*) increased their swimming speed and spent less time being stationary in environments with increased visual noise. Extrapolation of these results to Atlantic salmon may indicate increased energetic costs associated with increased movement and potential onward impacts from higher energetic costs.

How these results translate to Atlantic salmon in a natural setting is unclear. Rivers are highly dynamic environments with high amounts of natural visual noise. Without any information relating to the interplay between natural visual noise and shadow flicker it is not possible to assess whether there would be any behavioural or physiological change in Atlantic salmon.

3.3.2 Effects of artificial light patterns

The effect of flickering light on salmonids has been investigated. Flicker fusion frequency is the frequency at which an individual can no longer detect flicker in a light source. In Atlantic salmon parr, flicker fusion frequency has been measured and varies linearly with temperature and light intensity (Hanyu & Ali, 1964), for example, at a light intensity equivalent to an overcast day (~1000 lux), at a temperature of 5 °C the flicker fusion frequency for Atlantic salmon was measured at ~20 Hz, at 15 °C was ~30 Hz and, at 25 °C was ~40 Hz (Hanyu & Ali, 1964). While these experiments were undertaken on immobilised fish in an unnatural experimental setting, it is likely that the flicker fusion frequencies for Atlantic salmon are above the maximum allowable under wind farm construction regulations (Hanyu & Ali, 1964). Therefore, shadow flicker frequency from wind turbine blades is well within the flicker frequency perceptible by Atlantic salmon. However, there has been no subsequent research to investigate whether the perception of flicker fusions frequencies results in any impact to the animal (e.g. alters behaviour or causes physiological change).

Some experimental work on salmonids has been undertaken to investigate the effect of artificial light flicker, in the form of strobe light. The use of strobe light to deter Atlantic salmon smolts from a hydropower intake, (Fjeldstad et al., 2012) demonstrated that strobe light (no detail of frequency reported) deterred Atlantic salmon smolts from entering a hydropower intake. In an aquarium study, Jesus et al. (2019) investigated the behavioural response of trout (*Salmo trutta*; mean total length = 161 mm ± 23 mm) exposed to two different strobe frequencies (5.83 Hz and 10 Hz; both higher than maximum wind turbine flicker frequency) for 60 minutes under day and night conditions. Fish exposed to the faster (10 Hz) strobe demonstrated a greater repellent effect than the slower (5.83 Hz) strobe. In an aquarium (170-240 mm fish fork length) and field study (580-1396 g fish mass) of the effects of a low frequency strobe (3 Hz; close to critical wind turbine frequencies) on whitefish (*Coregonus laveratus*), Könïgson et al. (2002) demonstrated that fish swam significantly faster and, in a direction, away from the stimulus. In a night-time field study, Hamel et al. (2008) demonstrated that strobe light (7.5 Hz) at two intensities (2634 & 6585 lumens) repelled rainbow smelt (*Osmerus mordax*) to a distance of 21 metres for up to four hours after strobe activation.

The time taken for fish to return to a 'pre-disturbed' condition has also been investigated following exposure to artificial light. Atlantic salmon were observed returning to pre-exposure behaviours within a few minutes of exposure to medium (26.8 $\mu mol \cdot m^{-2} \cdot s^{-1}$) and high (35.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$) light intensities (Bui et al., 2013). In the ten minutes following the cessation of a strobe light stimulus, trout movement patterns were returning to a level similar to that observed during the pre-stimulus period (Jesus et al., 2019). Using blood plasma cortisol as a measure of stress response, Richards & Chipps (2007) showed that Chinook salmon (*Oncorhynchus tshawytscha*) exposed to 1.43 Hz strobe light, returned to similar stress levels as a control group seven hours after exposure (cortisol levels were measured at one hour and seven hours after strobe exposure).

Fish response to strobe lighting reviewed above is almost certainly due to the startle response to the sudden and rapid change in light levels. The study of the effects of strobe lighting on Atlantic salmon smolts by Fjeldstad et al. (2012) showed that strobe light effects under dark conditions were not significant compared with those under daylight (however, the number of fish moving during the day was very low (n=8), thus the statistical validity of a dark/light difference is this study is borderline). The study on trout by Jesus at al. (2019) showed greater responses under light conditions compared with dark. When acutely exposed to three light levels (low, 0.8 µmol m^{-2} s^{-1}; medium, 26.8 µmol m^{-2} s^{-1}; high, 35.4 µmol m^{-2} s^{-1}), sea caged Atlantic salmon under all treatments swam to deeper depths but did not exhibit the stress related behaviours (fast swimming and jumping) observed in the fish exposed to the medium and high light treatments (Bui et al., 2013). Anecdotal evidence in Heggenes & Dokk (2001) reported that when young Atlantic salmon were caught in torchlight, as part of an observational study of night-time behaviours (observers were trying not to startle the fish), fish tended to hold their position without sign of any activity or, they sank towards the bottom of the river. Furthermore, fish not directly caught in torch light, but observable, were more often seen to be feeding. The strobe frequencies and light intensities in the above studies are both greater than that experienced via shadow flicker.

To date, there have been no studies investigating the shadow flicker frequencies and light intensities associated with wind turbines.

The literature review highlighted only a few very recent studies investigating the biological and ecological effects of natural light patterns on freshwater fish species. It also highlighted a complete lack of evidence relating to the biological and ecological effects of artificial light patterns with the characteristics associated with shadow flicker from wind turbine blades.

4 Key findings

4.1 What are the potential biological and ecological impacts/responses of shadow flicker on Atlantic salmon at an individual level, at each life-stage, within a river system?

There are six life stages of Atlantic salmon identified and considered in this report (Figure 2). Each of these have been assessed separately for potential impact from shadow flicker. Atlantic salmon are an anadromous fish species. After spending one, two or three years maturing in the marine environment, mature adults return, most often to their natal rivers, and lay eggs in a nest called a redd between November and January. Salmon redds are most often created in the faster flowing water as a pool moves to a riffle, here the gravel is flushed of sediment and there is a high level of oxygen dissolved in the water. Eggs incubate until March/April when the newly hatched animals (alevin) are dependent on their yolk sac for food and remain buried within the gravel. Young alevin are relatively immobile, but as they absorb their yolk sac they become more mobile and eventually emerge from the gravel as young fish, commonly referred to as fry. Fry generally inhabit the faster flowing parts of the river, usually the riffle sections, and start to feed on small prey

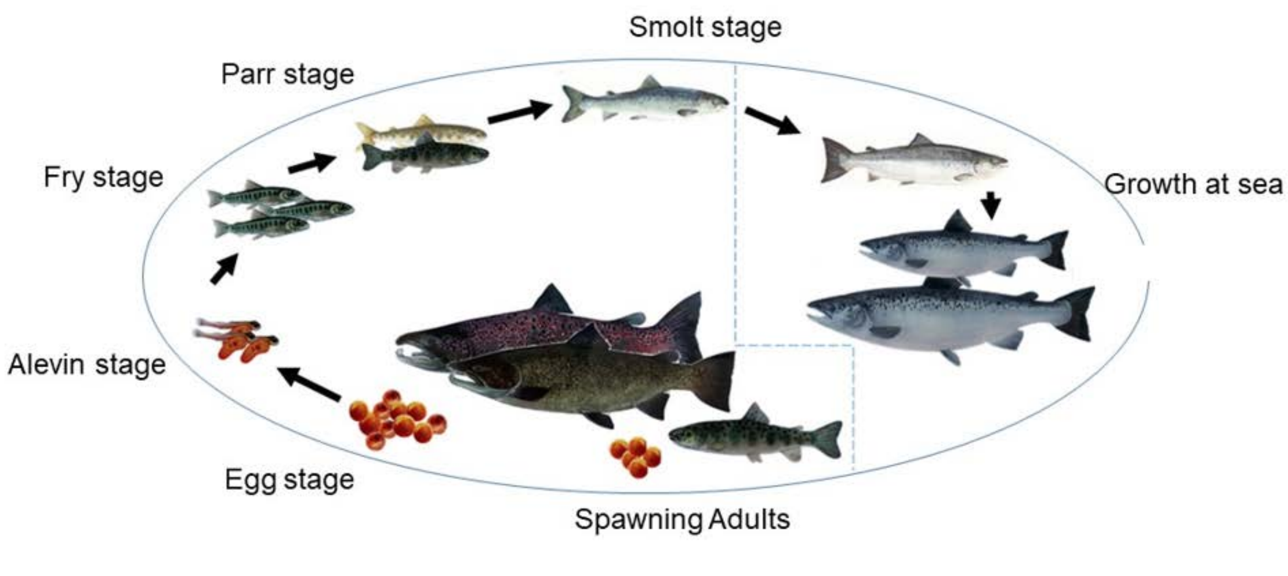

Figure 2: Life cycle of Atlantic salmon (*Salmo salar*). Note that six life stages to the left side of the dotted blue line occur in freshwater, and are the focus of this project's scope, whilst the right side of the dotted blue line involve life stages at sea. Colin Bean, 2021.

items, usually macroinvertebrates from the water column. After a year of growth, the animals have reached a size of about 70 mm or larger and are referred to as parr. Atlantic salmon parr continue to grow in the river until they attain a size large enough to trigger the process of smolting. The process of smolting changes the animal's physiology, morphology (shape) and behaviour as an adaptation to life in the marine environment. When the animal starts to become silver and migrates towards the marine environment, typically in April to June, the animal is referred to as a smolt. Smolts then feed at sea where they grow, mature, and return as adult fish.

4.1.1 Egg

Atlantic salmon bury their eggs in a nest called a redd (can be a single nest or a series of nests in a row), in the tail end of a pool where the water becomes shallower and faster, during the months from approximately November to January. Eggs are buried at depths of between 10 and 30+ centimetres (Crisp & Carling, 1989; Armstrong et al., 2003) to protect them from predators, high water flow and light (Armstrong et al., 2003). Atlantic salmon eggs are thus not exposed to natural light conditions and would therefore not be impacted by shadow flicker.

4.1.2 Alevin

The newly hatched animal, called an alevin, are relatively immobile (due to a large yolk sac) and are negatively phototactic (avoiding light) for the first few weeks following hatching. As time progresses and they absorb the yolk sac, the fish become positively phototactic and emerge from the gravel and leave the redd. In an experimental manipulation, Brännäs (1987) showed that under natural conditions (i.e., a dark only cycle), compared with exposure to light, there was little evidence of a photoperiod effect on alevin emergence. Field studies of alevin emergence have shown that most alevins move away from the redd during the hours of darkness (Brännäs, 1988; Fraser et al., 1994; Riley & Moore, 2000). Furthermore, Garcia De Leaniz et al. (1993) observed newly emerged alevin moving downstream through the river gravels up to a twenty-metre distance. Both experimental and field evidence suggests that the alevin stage up to the point of emergence shows negative phototaxis (i.e., a behavioural response to move away from bright light and seek areas with no or low light levels). Atlantic salmon alevin are thus not exposed to natural light conditions and would therefore not be impacted by shadow flicker.

4.1.3 Fry

After the alevin has moved out of the gravel and absorbed most of the yolk sac, it begins active swimming, facing into the current, and undertaking exogenous feeding (Symons, 1979a; Jonsson & Jonsson, 2011). This stage is commonly referred to as fry. Dispersal of fry within stream habitats has been shown to follow diel patterns with most of the movement away from the redd location happening at night (Jonsson & Jonsson, 2011). Atlantic salmon fry disperse from the redd location in upstream and downstream directions usually within tens of metres (Rodríguez, 2002; Eisenhauer et al., 2020). Diurnal differences in upstream and downstream movements have been detected in some salmonid species. For example, higher upstream movements in Sockeye salmon (*Oncorhynchus nerka*) fry (Clarke & Smith,1972) and rainbow trout (*Oncorhynchus mykiss*) fry (Northcote, 1962) were observed during daylight hours. To the best of our knowledge, diel directional differences in the movement of Atlantic salmon fry have not been quantified. If Atlantic salmon dispersal follows similar diel patterns as detailed for other salmonids, then larger fry (which are associated with upstream movements; Eisenhauer et al., 2020) would be exposed to daylight shadow flicker. However, fry are found in stream areas which are shallower, faster flowing and with coarser substrate (Armstrong et al., 2003) resulting in high levels of water surface distortion. While the levels of light transmission to these areas is high, impacts from shadow flicker on Atlantic salmon fry are likely to be low due to a highly dynamic light environment arising from high water caustics.

4.1.4 Parr

After a year of growth, the animal typically moves from riffle habitat to deeper run/glide habitat. Experimental observation of the interaction of water depth and shade availability has shown that in shallow water (24-29 cm depth) Atlantic salmon parr (60-150 mm fork length) were significantly more likely to be found in shaded areas, while in deep water (43-50 cm) fish did not show a distribution relative to light levels (Gibson & Power, 1975). This suggests that the perception of absolute light influences habitat choice, as increased water depth is perceived as cover due to decreasing light levels. In shallower areas, where exposure to shadow flicker would be more likely, individuals would be inhabiting areas with more shade and thus less likely to be exposed to shadow flicker. In deeper areas, parr would be less likely to be exposed to shadow flicker due to the associated decrease in light levels.

Evidence to support diel movement patterns in parr is conflicting. Several studies have shown significant patterns of periodicity (e.g., Fraser et al., 1993; Stickler et al., 2007; Boavida et al., 2017) while others have not (e.g., Scurton et al., 2005; Berland et al., 2004; Puffer et al., 2015). Atlantic salmon parr movement during daylight hours would have the potential to be exposed to shadow flicker to a greater extent.

4.1.4.1 Prey acquisition

Behavioural responses are linked to an individual's ability to interpret the environmental signal to noise ratio (Galloway et al., 2020). For example, predator avoidance through use of camouflage, will be more successful if the background visual noise is greater than the visual signal caused by an individual's camouflage pattern. Successful prey acquisition by a visual predator is reliant on a large signal to noise ratio of the prey, i.e., the prey is more easily seen in an environment.

Atlantic salmon fry and parr are sit-and-wait visual predators. Their diet typically consists of benthic macroinvertebrates inhabiting the riverbed and macroinvertebrates drifting downstream; drifting macroinvertebrates are composed of organisms from the benthos and organisms of terrestrial and aerial origin. Faster flowing points within the river are correlated with a larger supply of invertebrate food (Elliot, 1967) and fish have the greatest access to food if they maintain a vantage point in the fastest flowing water while taking advantage of slacker water near stones and cobbles (Metcalfe et al., 1997). This strategy is based on the fish being able to detect and intercept a food item before it is swept past the individual. Detection of food items is related with flow (the faster the flow, the shorter the time an individual has to detect and capture the food item; Hughes & Dill, 1990) and light intensity (Metcalfe et al., 1997). Juvenile Atlantic salmon can detect drifting prey down to lux levels similar to twilight, but their detection performance decreases rapidly under light conditions similar to night (Fraser & Metcalfe, 1997).

The interaction of dappled light and water caustics was shown to adversely affect prey detection by human participants (Matchette et al., 2018) and by reef fish (Matchette et al., 2020) and three-spined sticklebacks were less likely to respond to virtual prey in environments with increased visual noise (Attwell et al., 2021). There is clear evidence that increasing visual noise from natural light flickering can negatively impact prey acquisition in fish. However, shadow flicker is rhythmic and therefore predictable, under some circumstances shadow flicker may interact by increasing visual noise, making prey acquisition more challenging, or the rhythm of the shadow flicker may decrease visual noise, making prey acquisition less challenging. Whether this effect would occur is not clear and would need to be investigated experimentally.

4.1.4.2 Territory defence

Parr and fry are territorial and competition for territories is a dynamic process (Jonsson & Jonsson, 2011). Cutts et al. (1999) observed that those fry which established territories earlier were more dominant and individuals with larger body size were more likely to displace a resident individual. Observations of parr in a natural setting have shown that prior residency impacts the distribution of individuals in a Norwegian river system (Kvingedal & Einum, 2011). Being able to locate and defend a territory is a critical part of this life stage (Jonsson & Jonsson, 2011).

Light levels have been shown to impact territory size. Atlantic salmon have been shown to defend smaller territories on darker nights (Jonsson & Jonsson, 2011) and under low light levels, equivalent to starlight, Valdimarsson & Metcalfe (2001) demonstrated that parr were observed tolerating competing individuals in closer proximity than under daylight conditions. The impact of light pattern on territory related behaviours is however not well understood. Three-spined sticklebacks were shown to avoid areas with increased visual noise (Attwell et al., 2021) but were more likely to be found in the company of conspecifics in presence of increasing visual noise (Matchette & Herbert-Read, 2021). Unlike three spined sticklebacks, Atlantic salmon are not shoaling fish at the fry and parr life stages, thus any extrapolation of these observations must be taken with caution.

The degree to which change to light patterns impact territory defence by Atlantic salmon is therefore not clear. However, it could be hypothesised that increased visual noise, associated with shadow flicker, would make an individual less obvious to a conspecific via changes to the individual's signal to noise ratio (Matchette et al., 2020) ultimately changing territory defence behaviour. The onwards impacts of these changes to behaviour and thus survival are unknown.

4.1.5 Smolt

The mechanisms associated with the onset of smoltification, the process by which an individual parr undergoes physiological, morphological and behavioural changes to adapt for survival in the marine environment, have been the subject of much debate (e.g., Thorstad et al., 2012; Morera et al., 2021) but are linked with body size, condition and age (Jonsson & Jonsson, 2011). Smolts migrate through the river towards the estuarine and marine environments, with the majority of migratory movement occurring at night (Thorstad et al., 2012) but an increase in daytime migration has been observed in the latter stages of the seaward migration phase (Moore et al., 1995; Moore et al., 1998; Ibbotson et al., 2006).

During daylight hours, Atlantic salmon smolts did not show a response to strobe light used to deter them from a hydropower intake (Fjeldstad et al., 2012), although the total low number (n=8) of smolts moving during daylight in this study makes the reliability of this result low. During their downstream migrations, Atlantic salmon smolts, if this life stage is exposed to shadow flicker, it would only be for a very short period and unlikely to be impacted by shadow flicker.

4.1.6 Adult

After a period of one or more years at sea, the mature Atlantic salmon return to their natal rivers. During this upstream river migration and in the period prior to spawning, adult salmon will rest in deep pools during daylight (Armstrong et al., 2003) or under logs and tree branches (Witzel & MacCrimmon, 1983) to avoid bright sunlight (Crisp 1996). In pools, fish have been observed remaining close to the bottom during the day (Keenleyside, 1962) and farmed fish in sea cages have been shown to avoid light (Huse & Holm, 1993).

Although the spawning behaviour of Atlantic salmon is well described, evidence to support any diel timing in the spawning patterns for Atlantic salmon is surprisingly lacking. Using tagged adult lake dwelling trout, Finlay et al. (2020) showed that movements to spawning areas were correlated with ambient light conditions and that adults most often moved to spawning areas at night-time and under darker lunar conditions. Post spawning, a small proportion of the population will survive and move downstream (Bardonnet & Baglinère, 2000). While some individuals will migrate directly to the marine environment, most will spend several months in the river before migrating, but little is known about their behaviour or habitat usage during this time (Bardonnet & Baglinère, 2000). Returning adults, tend to remain in deep, dark sections of the river in advance of their movement onto the spawning areas. During their movement to the spawning areas, which happen during the winter months, Atlantic salmon adults would likely only be exposed to shadow flicker for brief periods. Furthermore, those individuals which do survive following spawning quickly move downstream to deeper sections of the river. It is unlikely that the adult stage of Atlantic salmon would be impacted by shadow flicker.

4.1 Key findings:

The following findings are based on the authors' opinion[2] following the review of the available literature relating to the life stages of Atlantic salmon:

- It is **highly unlikely** that the **egg stage** of Atlantic salmon would be impacted by shadow flicker under any local habitat conditions.
- It is **highly unlikely** that the **alevin stage** of Atlantic salmon would be impacted by shadow flicker under any local habitat conditions.
- Under a typical habitat distribution for fry, in their preferred riffle habitats of a stream, that it is **unlikely** that the **fry stage** of Atlantic salmon would be impacted by shadow flicker.
- While fry of Atlantic salmon are typically found in riffle habitats, individuals found outwith riffle habitat may experience greater exposure to shadow flicker than those found in riffles.
- The evidence available to establish whether shadow flicker would impact the **parr** life stage of Atlantic salmon is **inconclusive but possible**.
- Shadow flicker is **unlikely** to impact the **smolt stage** of Atlantic salmon.
- However, while that majority of Atlantic salmon smolts in a population migrate during the darker hours, there is a change in the pattern of migration towards the end of the migration period. Atlantic salmon smolts migrating later in the migration period may be exposed to shadow flicker, however, the impacts of the exposure are currently unknown. It is likely that any impact from exposure would be low due to the limited exposure an individual would be exposed to as it moved seaward.
- It is **unlikely** that the **adult stage** of Atlantic salmon would be impacted by shadow flicker. Spawning is undertaken during the winter months when days are short and those animals which do survive spawning tend to move downstream to larger, deeper river sections.

2 Authors' opinion has been formed based on a review of the literature and previous experience gained through a foundation of research in the freshwater environment. The opinions expressed have been formed with low confidence due to the level of extrapolation required resulting from to the lack of information and evidence available.

4.2 Do Atlantic salmon habituate to repeated disturbance and may that increase susceptibility to other pressures, such as predation risk?

As is evident from the previous section (4.1), the direct evidence available to quantify any effect of shadow flicker on freshwater fish is lacking. Therefore, this section focusses on possible habituation to the visual motion of wind turbine blades.

An animal's response to a stimulus is based on whether the stimulus is novel or established and whether experience of the stimulus results in reward or penalty (Lieberman, 1999). The response of fish towards a predator has been shown to arise through innate-pathways (i.e., a response expressed in its entirety upon first exposure to the signal from the predator) and learned-pathways (Ferrari et al., 2010; Lau et al., 2021). Innate-pathways have been shown in salmonids through an association with alarm cues (i.e., chemicals released by conspecifics injured by a predator; Chivers & Smith, 1998). For example, Scheurer et al. (2007) demonstrated that rainbow trout showed an innate response to a chemical alarm cue after 100 years (~15 generations) in a predator-free environment. Innate-pathways have also been shown in salmonids' response to odour cues (i.e., chemicals released by a predator). For example, Hawkins et al. (2004) showed that naïve, newly hatched Atlantic salmon alevins responded to the odour from a predator (pike, *Esox lucius*). Learned-pathways differ from innate via a modification or enhancement of the response to the first exposure to the predation signal (Alcock, 1993). The ability of salmonids to form a learned association with olfactory cues has been demonstrated in rainbow trout (Brown et al., 2013; Ferrari et al., 2010), brook trout (Mirza & Chivers, 2000) and Atlantic salmon (Leduc et al., 2007; Lau et al., 2021). The innate- and learned-pathways summarised above relate to an individual's response to olfactory cues (i.e., chemicals in the water) that have been released by either conspecifics or predators.

Responses to visual stimuli from in-water predator models have been demonstrated in Atlantic salmon. For example, experimental stimulation has shown that under pressure from predation, in the form of an in-water visual cue, juvenile Atlantic salmon change their method of prey acquisition, by delaying attacks until prey reached its closest point, assumed to be a response to predator avoidance (Metcalfe et al., 1987) and socially dominant individuals wait for subordinates to resume feeding before doing so themselves (Gotceitas & Godin, 1991).

Terrestrial predators are visually perceived by fish through Snell's window. Light transmission through water is governed by refraction and reflection. Light entering the water is refracted through the water surface and is also reflected against the underside of the water surface. These two processes result in the phenomenon called Snell's window where, objects above the water surface are seen through a cone of about 97 ° (Lynch, 2015). Outwith Snell's window, a fish will only see what is reflected by the underside of the water surface. Atlantic salmon exposed to the visual cue from wind turbine blades would also view these through Snell's window.

Responses to terrestrial predators (i.e. aerial visual cues) has been demonstrated in Atlantic salmon fry (Houde et al., 2010; de Mestral & Herbinger, 2013). The degree to which responses to aerial visual cues are learned has also been investigated. Lau et al. (2021) demonstrated that Atlantic salmon from three populations exhibited no innate response to a visual terrestrial predator cue but did show an innate response to an olfactory cue. This suggests that responses to predation risk from terrestrial visual cues are not innate in Atlantic salmon but are learned. While other studies have shown that Atlantic salmon do respond to visual terrestrial predation cues (Houde et al., 2010; de Mestral & Herbinger, 2013) these were often experienced in conjunction with an associated surface disturbance. This could indicate that in Atlantic salmon, the response to a terrestrial predator is learned from a combination of visual cues and motion in the form of surface disturbance (Lau et al., 2021), which may result in alarm cues from conspecifics.

Habituation occurs when repeated exposures to stimuli reduces responsiveness, for example, through learning that an initially startling stimulus is not followed by harm (Lieberman, 1999). A lack of habituation to olfactory cues has been demonstrated. For example, in an aquarium experiment, Arctic charr (*Salvelinus alpinus*) were shown not to habituate to the chemical odours of the predatory pikeperch (*Sander lucioperca*) after four exposures (Vilhunen, 2006). Habituation to natural and artificial visual cues has been demonstrated in minnow (*Phoxinus phoxinus*) response to a pike model (Magurran & Girling, 1986) and in three-spined stickleback (*Gasterosteus aculeatus*) to a goldfish (*Carassius auratus*) predator (Huntingford & Coutler, 1989) and, in chum salmon (*Onchorhynchus keta*) response to a plastic predator model (Kanayama, 1968). Habituation to strong light stimulus has been demonstrated in Atlantic salmon parr (Folkedal et al., 2010). Parr exposed to strong light showed habituation to the changes in light intensity, but a residual stress response, in the form of oxygen consumption rate, was evident 43 days after the treatment began (Folkedal et al., 2010).

In response to predation olfactory cues, juvenile salmonids have demonstrated a memory ranging from ten days (brook trout, *Salvelinus fontinalis*; Mirza & Chivers, 2000) to 21 days (rainbow trout; Brown & Smith, 1998). Experimental manipulation has shown that when trained to associated different levels of risk (high and low conspecific alarm cues) with the same predator cue, predator-naïve juvenile rainbow trout were shown to have longer memory towards the predation cue when there is a higher threat associated (Ferrari et al., 2010). If the movement of wind turbine blades were not perceived as a threat (as they did not result in attack *cf*. surface disturbance), and extrapolating Ferrari et al.'s (2010) result, individuals within a stretch of river exposed to the motion of wind turbine blades would not likely perceive them as a threat and would retain this information, in a similar fashion as olfactory memory, over time. However, to the best of our knowledge, there is no evidence to support or refute that Atlantic salmon have the cognitive ability to extrapolate this information across spatial scales. At this stage, we cannot answer the question if an object displaying a similar motion (e.g., the beating wings of an aerial predator) would be ignored by an individual at a different time or location along the river.

The other route through which an individual may experience predation pressure and not respond naturally, would be if an aerial predator was to share the same Snell's window as a rotating wind turbine blade. To be successful in differentiating these two different visual cues, an individual needs the visual ability to resolve objects with enough definition and cognitive ability to differentiate between them. To the best of our knowledge, there is no evidence to support or refute the ability of Atlantic salmon to achieve this.

4.2 Key findings:

The following findings are based on the authors' opinion[3] following the review of the available literature:

- It is **likely** that Atlantic salmon will become habituated to the visual motion of wind turbine blades.
- However, there is no evidence available to support whether this learned knowledge could be transferred by Atlantic salmon to a novel situation, for example, an individual experiencing wind turbine blade motion in a different section of the river or an individual experiencing a movement pattern similar to wind turbine blade motion (e.g., an aerial predator).

3 Authors' opinion has been formed based on a review of the literature and previous experience gained through a foundation of research in the freshwater environment. The opinions expressed have been formed with low confidence due to the level of extrapolation required resulting from to the lack of information and evidence available.

4.3 Can the impact of shadow flicker be extrapolated to the whole Atlantic salmon population of an affected river?

The number of individual Atlantic salmon has declined across the species range (Rikardsen et al., 2021). It is therefore important that any possible impacts at the individual level (e.g., see sections 4.1 and 4.2) are understood and quantified at the population level.

Atlantic salmon are *r*-strategists and thus losses of individuals across ontogenetic development phases decrease with increasing life-stage (i.e., Atlantic salmon, like most freshwater fish, have higher losses at the egg stage compared with the adult stage). After losses at the egg stage, mortality to the parr stage is controlled by density dependence (Milner et al., 2003). Survival after the parr stage is usually described as density-independent, meaning there is a positive correlation between smolt output and the number of returning adults (Jonsson et al., 1998; Thorstad et al., 2012). The freshwater component of Atlantic salmon production is therefore modelled based on the availability of suitable habitat in rivers linked with the parr life stage (Symons, 1979b; Solomon, 1985). In other words, given natural population losses expected prior to reaching the parr stage and the lack of density-dependence following this stage, the parr stage can be viewed as the maximum production supported by a specific river. As such, stock-recruitment curves (the relationship between the number of adults spawning in a system and the number of individuals recruited to the population), capture this information as the freshwater component of population models and are used as the basis for exploitation and control (e.g., Marine Scotland Science, ND). Predictions about the carrying capacity of river systems for Atlantic salmon have been undertaken based on the physical characteristics of a river (Moir at el., 2005; Bjørnås et al., 2021). These models use physical measurements of the river channel and assign them habitat units. Assumptions are made about the carrying capacity of each habitat unit for specific life stages, which can be adjusted to match known river population conditions based on stock recruitment curves, and calculations are then undertaken to predict Atlantic salmon production for given areas.

The review of available evidence about the impacts of shadow flicker has highlighted the parr stage as being the most likely to be exposed to shadow flicker. Although there is no evidence available to support any indication of biological or ecological impact. However, *assuming* that this was the case, it may be possible to modify existing stock assessment models (as the parr stage already plays a dominant role in stock assessment) to account for impacts at the parr stage to the whole population level. However, this is reliant on two key pieces of information: (a) if there is an impact from shadow flicker, the magnitude must be quantified as individual parr mortality arising solely from shadow flicker and not from another source (for example the eleven high-level pressures affecting Atlantic salmon, Scottish Government, 2019) and, (b) the spatial and temporal extent of the shadow flicker on known parr habitat, i.e., the spatial extent and the time over which shadow flicker may be cast on the water surface must be calculated for each individual wind turbine. These variables could be added to existing recruitment models and any losses of Atlantic salmon, arising from shadow flicker, from population of interest could be quantified. However, as the parr stage is the most likely to be exposed to shadow flicker, the number of Atlantic salmon parr lost from a river system as a direct and sole result of shadow flicker impacts from wind turbine blades, would have to be first quantified.

4.3 Key findings

The following findings are based on the authors' opinion[4] following the review of the available literature:

- Given the available information about existing stock-recruitment models and their use for exploitation and control, it would be possible to make some adjustments to existing models and extrapolate impact from shadow flicker to the whole Atlantic salmon population of an affected river.
- However, the number of Atlantic salmon parr lost from a river system as a direct and sole result of shadow flicker impacts from wind turbine blades, would have to be quantified.

4.4 Are there ways in which this issue can be successfully mitigated?

Some key life stages and behaviours of individual salmon have been identified which may be impacted by shadow flicker or the appearance of wind turbine blades within Snell's window (the restricted window through which fish see terrestrial or aerial objects). However, there is a need to ensure that this information is used appropriately and proportionately, for example, the actual time during which shadow flicker may be cast on any single location in a river is likely to be low in most realistic scenarios. Any changes, to remediate possible impacts associated with shadow flicker, to existing wind turbines associated with operational wind farms or wind farm published guidelines relating to the construction of wind farm developments must be based on evidence of a biological and ecological impact on Atlantic salmon populations which, at this stage, we do not have.

Appropriate mitigation can only be drawn up when a significant impact is evident. However, if evidence of an impact was identified or to emerge, mitigation strategies to avoid and/or minimise shadow flicker related impacts associated with **existing** wind farms may be achieved through two routes: **(a)** changes to the operation of the wind turbines (adjacent to watercourses switched off during periods of potentially high shadow flicker impact). Fishery managers may also play a role in the development of situation-appropriate mitigation measures. Due to the high levels of variability between the life stages across Scottish catchments (Malcolm et al., 2019), local knowledge of the river systems would be key to understanding whether mitigation was indeed required and the best way to achieve this option and/or, **(b)** introduction of screening, in the form of planting riparian vegetation between the wind turbines and the watercourse. As identified (section 4.1), the Atlantic salmon parr life stage is the most likely to be exposed to shadow flicker cast by wind turbine blades in motion. As these fish are present within rivers through the year, it would not be possible to operate the wind turbine without resulting in the exposure of shadow flicker to the river. Neither may it be attainable to adjust operational usage of wind turbines, given a regular parr presence in Atlantic salmon rivers. This is combined with a need to produce sufficient renewable energy for climate adaptation purposes in Scotland. Option **(b)**, the use of screening using riparian vegetation, is a more achievable mitigation measure and has multiple added benefits, including lowering stream temperatures (Garner et al., 2014), stabilising river banks, and improving biodiversity through the provision of new habitat (SEPA, 2009) and a source of terrestrial food. Consideration of the species and community composition of any newly created riparian habitats should follow best practice and in conversation with local biodiversity officers, landowners, and fishery managers (River Restoration Centre, 2020). Two further mitigation measures may be considered for **proposed** wind farm developments including: **(c)** locating wind turbines at an appropriate distance from the watercourse such that they are unlikely to have a shadow flicker related impact on Atlantic salmon populations. New models could be developed for taking advantage of recent evidence about the geographical relationships between solar energy and wind speeds for Britain (Bett & Thornton, 2016) and existing models which calculate shadow flicker cast based on the parameters of the wind turbine as well as

4 Authors' opinion has been formed based on a review of the literature and previous experience gained through a foundation of research in the freshwater environment. The opinions expressed have been formed with low confidence due to the level of extrapolation required resulting from to the lack of information and evidence available.

the latitude and longitude of the wind turbine placement (Danish Wind Industry Association, ND); and **(d)** an appropriately sized wind turbine stem (which is increasing in size with advances in technology) such that the wind turbine blades are not able to cast shadow flicker on the water surface.

4.4 Key findings:

The following finding is based on the authors' opinion[5] following the review of the available literature:

- Should evidence of a significant impact be identified on the biology and ecology of Atlantic salmon in Scottish rivers, then there are four possible measures available to mitigate the impact of shadow flicker cast from wind turbine blades on the water surface and fish populations:
    - For **existing** wind farms:
        a. Changes to the operation of existing wind turbines.
        b. The use of riparian screening to prevent shadow flicker reaching the water surface.
    - For **proposed** wind farm developments:
        c. Locating new wind turbines at far enough distances to prevent shadow flicker casting on the water surface.
        d. Use appropriately sized wind turbine stem, such that wind turbine blades are not able to cast shadow flicker on the water surface.

5 Authors' opinion has been formed based on a review of the literature and previous experience gained through a foundation of research in the freshwater environment. The opinions expressed have been formed with low confidence due to the level of extrapolation required resulting from to the lack of information and evidence available.

5 Conclusions

The literature review indicated that there is no evidence to support or refute any biological or ecological impact of shadow flicker from wind turbine blades on Atlantic salmon. As such, an extrapolation of the literature material investigating the effects that changes to light may have on six life stages of Atlantic salmon in freshwaters resulted in the following key findings:

It is the authors' opinion[5] that at an individual level:

- It is **highly unlikely** that the **egg stage** of Atlantic salmon would be impacted by shadow flicker under any local habitat conditions.
- It is **highly unlikely** that the **alevin stage** of Atlantic salmon would be impacted by shadow flicker under any local habitat conditions.
- Under a typical habitat distribution for fry, in their preferred riffle habitats of a stream, that it is **unlikely** that the **fry stage** of Atlantic salmon would be impacted by shadow flicker.
- While fry of Atlantic salmon are typically found in riffle habitats, individuals found outwith riffle habitat may experience greater exposure to shadow flicker than those found in riffles.
- The evidence available to establish whether shadow flicker would impact the **parr** life stage of Atlantic salmon is **inconclusive but possible**.
- Shadow flicker is **unlikely** to impact the **smolt stage** of Atlantic salmon.
- However, while that majority of Atlantic salmon smolts in a population migrate during the darker hours, there is a change in the pattern of migration towards the end of the migration period. Atlantic salmon smolts migrating later in the migration period may be exposed to shadow flicker, however, the impacts of the exposure are currently unknown. It is likely that any impact from exposure would be low due to the limited exposure an individual would be exposed to as it moved seaward.
- It is **unlikely** that the **adult stage** of Atlantic salmon would be impacted by shadow flicker. Spawning is undertaken during the winter months when days are short and those animals which do survive spawning tend to move downstream to larger, deeper river sections.
- It is likely that Atlantic salmon will become habituated to the visual motion of wind turbine blades.
- However, there is no evidence available to support whether this learned knowledge could be transferred

by Atlantic salmon to a novel situation, for example, an individual experiencing wind turbine blade motion in a different section of the river or an individual experiencing a movement pattern similar to wind turbine blade motion (e.g., an aerial predator).

It is the authors' opinion[6] that, at a population level:

- The findings from the literature review identified the parr life stage as the life stage which had the greatest possibility of being exposed to shadow flicker from wind turbines. As the parr life stage is also a key life stage in stock recruitment models, it would be possible to use existing stock recruitment models and extrapolate impact from shadow flicker to the Atlantic salmon population of an affected river. However, the number of parr lost from a system as a direct result of shadow flicker, and no other factor, would have to be quantified.

Mitigation can only be drawn up when a significant impact has been found. Should evidence of a significant impact be identified on the biology and ecology of Atlantic salmon in Scottish rivers, then there are four possible measures available to mitigate the impact of shadow flicker cast from wind turbine blades on the water surface and fish populations:

- For **existing** wind farms:
    a. Changes to the operation of existing wind turbines.
    b. The use of riparian screening to prevent shadow flicker reaching the water surface.
- For **proposed** wind farm developments:
    c. Locating new wind turbines at far enough distances to prevent shadow flicker casting on the water surface.
    d. Use appropriately sized wind turbine stem, such that wind turbine blades are not able to cast shadow flicker on the water surface.

6 Authors' opinion has been formed based on a review of the literature and previous experience gained through a foundation of research in the freshwater environment. The opinions expressed have been formed with low confidence due to the level of extrapolation required resulting from to the lack of information and evidence available.

5 Key conclusions

The following conclusions are based on the authors' opinion[6] following the review of the available literature:

- There is no specific evidence available to support or refute any biological or ecological impact of shadow flicker from wind turbine blades on Atlantic salmon.
- The parr life stage of Atlantic salmon was identified as being most likely to be exposed to shadow flicker, but there is no evidence to suggest this would impact the biology or the ecology of the individual.
- There is no evidence available to support whether any habituation to the visual motion of wind turbine blades would impact on the response of an Atlantic salmon to potential predators.
- If an impact was identified, this would need to be interpreted in terms of the number of fish lost as a result of the effects of shadow flicker in comparison to any of the multiple stressors currently facing Atlantic salmon in our rivers.
- Should an impact be identified, various forms of mitigation were identified to prevent shadow flicker being cast on river surfaces.

6 Recommendations

The literature reviewed in this report represents studies undertaken across the geographic range of Atlantic salmon. Many aspects of the life history of Atlantic salmon vary, relatively predictably, across latitude (Power, 1981) and less predictably at smaller geographical scales (Malcolm et al., 2019). The application of the results of this review must therefore take this into consideration. Furthermore, Riley et al. (2012) advises that comparisons between studies using different species, study sites and lighting treatments, as has been necessary here due to the paucity of studies, must also be made cautiously.

The review has highlighted that our understanding of salmonid responses to light has focussed to the greatest extent on behavioural responses to acute changes in light intensity with emerging work in the last few decades on responses to strobe light, focussed on high frequency changes in light intensity. Only since 2019 has evidence about fish behavioural response to more natural light patterns started to emerge. Furthermore, there is a lack of evidence to assess the cognitive abilities of Atlantic salmon to transfer information (i.e., habituation to the movement of wind turbine blades) to a novel setting within the river environment. The lack of these critical pieces of evidence has meant that the review of the evidence base, has made the delivery of robust conclusions problematic. As such, we highlight the following key areas of research (which may be prioritised alongside other key knowledge gaps as part of the preparation of the Wild Salmon Strategy) to address the issue of the potential effects of shadow flicker on Atlantic salmon and possible habituation from the visual stimulus from wind turbine blades:

- Determine the range and distribution of shadow flicker frequencies, actual and modelled, that would be experienced by fish in rivers in Scotland.
- An investigation of what shadow flicker frequencies may cause behavioural change in Atlantic salmon.
- Investigate whether rhythmic disruptions to light patterns have different effects on Atlantic salmon than more natural light patterns.
- Investigation of the cognitive capacity of Atlantic salmon to transfer knowledge to novel situations.

Further recommendations

- Investigation of the potential use of riparian planting as a mitigation measure to shield rivers from the effects of shadow flicker from wind turbine blades, and its findings to inform relevant policy development, if impacts can be demonstrated.
- Continued review and development of best practice guidelines relating to the mitigation of shadow flicker impacts from wind turbine blades situated next to rivers or streams, by Scottish environmental regulators and conservation agencies, in response to new emerging evidence and existing frameworks. For example, the Forests and Water Guidelines (Forestry Commission, 2011) and UK Forestry Standard (Forestry Commission, 2017) provide information relating to buffer zones around rivers in relation to the planting of conifer trees for forestry. While the scientific evidence base supporting the establishment of minimum buffer zones and how to manage existing forestry is considerable, this guidance may provide a source of exploratory material as it relates to appropriate buffer zones between rivers and forestry plantations.
- Consideration of the development of a Scotland wide map-based tool containing details of onshore wind turbine locations, their size, and design. This could be used to prioritise sites in proximity to inland waters for further research purposes and/or inform proposed wind farm development near rivers which support Atlantic salmon populations should impacts of shadow flicker on fish be demonstrated in the future.
- Gathering of insights from all relevant stakeholders such as river-based practitioners (e.g., Fisheries Trusts and District Salmon Fishery Boards), specialist engineers, and the renewable energy sector may provide additional novel suggestions for mitigation strategies for shadow flicker impacts from wind turbine blades not covered in this report. It may be appropriate to draw on this broad base of expertise and experience, through consultation and knowledge-exchange opportunities (e.g., workshops), which is most often not available through published peer-reviewed nor easily accessible grey literature.
- Investigation of the impacts of wind turbines regarding anglers' perceptions of shadow flicker and any potential loss to the amenity value of Atlantic salmon rivers, as this was beyond the project scope.
- Investigation of the impacts of shadow flicker associated with offshore wind farm installations on Atlantic salmon life stages at sea, as this was beyond the project scope.

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CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes and Research Institutes. The Centre is funded by the Scottish Government.