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Review

Is clean growth really all that clean? A review of the cumulative effects associated with renewable energy clean growth initiatives in Canada and beyond

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Abstract

Clean growth (also known as green capitalism, green economy, or green growth) is an economic theory in which economic expansion occurs in an environmentally and ecologically sustainable manner. Technologies such as hydropower, wind energy, small nuclear reactors, and solar power have been championed as important aspects of the transition and transformation needed to address the climate crisis. Although many of these projects are inherently more environmentally friendly than traditional approaches to energy development, the cumulative effects of clean growth technologies have not been reviewed before. Cumulative effects (the additive impacts of multiple minor stresses such as many small wind turbines or their complex synergistic effects) can create significant threats to the environment. This review aimed to understand the individual and cumulative effects of clean growth technologies, and provide examples of how these cumulative effects are being quantified and mitigated in Canada and beyond. In general, cumulative effects in clean growth technologies are understudied with little knowledge regarding how they are impacting the environment and society. Understanding the societal and cultural impacts of multiple clean growth projects, in addition to the environmental impacts, particularly in traditional Indigenous lands and territories, is a necessity prior to undertaking further development. We recommend investing in long-term monitoring of clean growth technologies as well as ensuring adequate baseline data to better understand potential impacts. Furthermore, we recommend that impact assessments consider long-term and future stressors to allow managers to understand how cumulative effects will manifest in a changing world. Ensuring the use of consistent terminology and varied indicators and/or endpoints for research involving cumulative effects and clean growth, and considering the activity in its broader context (e.g., considering spatial and temporal aspects), will enable more robust research and more comprehensive understanding of impacts. Finally, we suggest documenting best practices for evaluating and monitoring the cumulative effects in clean growth to support decision makers.

Key words: cumulative effects, clean growth, environmental assessment, hydropower, wind energy, hydrokinetic

1. Introduction

Over the last few centuries, human-induced impacts on the natural environment have increased so rapidly scientists have termed our current geological epoch (late 18th century to present) the "Anthropocene" (Crutzen and Stoermer 2000; Crutzen 2002). Impacts to the environment, such as climate change, biodiversity loss, natural resource extraction, and land use changes are a result of a rapid increase in the human population (Crutzen 2002). Many necessary activities that drive economic growth, such as manufacturing, the extraction of natural resources, and the transport of goods, negatively impact the environment. Clean growth (or green capitalism, green economy, or green growth) is an economic theory in which economic expansion is done in an environmentally and ecologically sustainable way. Originating from the 2005 Ministerial Conference on Environment and Development in Seoul, South Korea, members from Asia and Pacific adopted the idea of "green growth" to combine economic growth with environmental sustainability. The United Nations defines clean growth as economic growth that is energy efficient, uses sustainable agricultural practices, and uses renewable energy technologies with "Affordable and Clean Growth" being one of the 17 sustainable development goals (United Nations 2018). The premise of clean growth is simple; with appropriate application of science and technological innovation and by establishing relevant market incentives that include environmental considerations, environmental degradation can be mitigated, while yielding new opportunities for capital accumulation and economic growth (Sapinski 2015; Dale et al. 2016).

Furthermore, the economic benefits of clean growth are anticipated to improve the well-being of people and communities, helping them be resilient to the anticipated impacts of climate change (Lee 2021). The Pan-Canadian Framework on Clean Growth was released by the Canadian federal government in partnership with several provinces and territories in 2016 and serves as a roadmap for achieving clean growth. Throughout the Framework, clean growth initiatives encompass a wide variety of activities, including the increased use of renewable resources, reducing coal-fired electricity, updating current infrastructure, modernizing systems, using cleaner fuels in transportation, and encouraging the use of green vehicles (Environment and Climate Change Canada 2016).

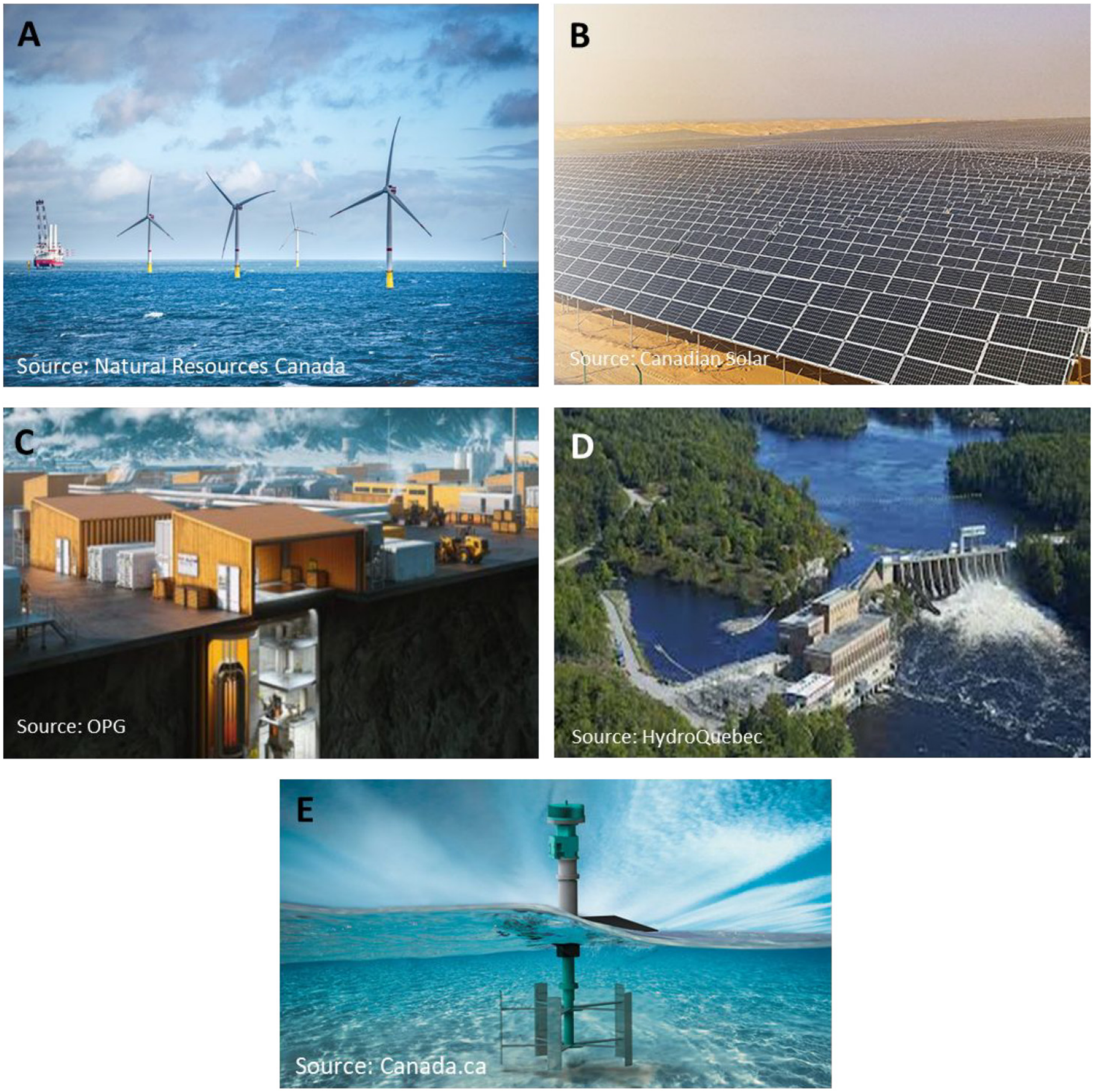
Prior to the implementation of projects that fit the criteria specified by federal or provincial governments, an environmental impact assessment (EIA) is conducted as a planning and decision-making tool to understand the effects associated with implementing new, major projects. Initially introduced in 1969 in the United States, some form of EIAs is now mandated in almost all nations globally (Senate and House of Representatives of the USA 1969; Morgan 2012; Pope et al. 2013). In Canada, a project will trigger an EIA if it is "determined to have the greatest potential for adverse and complex effects in areas of federal jurisdiction related to the environment" under the *Impact Assessment Act* (IAAC 2019). Within the last two decades, a sub-category within EIAs has emerged to understand the collective effects associated with these projects (Seitz et al. 2011). Cumulative environmental effects can be defined in many ways (Spaling 1994). For the Impact Assessment Agency of Canada (IAAC), the accepted definition for cumulative effects is "changes to the environment that are caused by an action in combination with other past, present, and future human actions" (CEAA 2012). The concept recognizes that not only multiple minor stresses (e.g., many small wind turbines) can add up to create significant threats to the environment, but also that different activities can combine in complex ways to produce aggregate effects that may differ from the additive effects of individual activities (CEAA 2012; Master et al. 2009). IAAC's definition of cumulative effects also recognizes that complex human impacts (e.g., climate change, forestry, and urbanization) can affect multiple features of ecosystems through interacting, synergistic, and often indirect processes. Many of the methods that proponents may use to quantify single adverse effects also apply for cumulative effects (Canadian Environmental Assessment Agency 2014). For example, consideration of valued components, temporal and spatial scales, baseline reporting, surveying and modeling methodologies, and considerations for the physical environment, wildlife, landscape, human health, socio-economic impacts, and Indigenous rights and interest can be used for both environmental impact and cumulative effect assessments in Canada. Consideration of effects on Indigenous People can encompass health and socio-economic changes, physical and cultural heritage, use of lands and resources for traditional purposes or any structural disturbance (Government of Canada 2012). Overall, Canada assesses cumulative effects through the "Policy Framework for Assessing Cumulative Effects under the Impact Assessment Act", and this is guided by the "Cumulative Effects Assessment Practitioners" Guide'. This guide outlines a five-step process that practitioners must complete while assessing cumulative effects: scoping, analysis, mitigation, significance, and follow-up (CEAA 1999). Yet, there are also major policy gaps as it relates to the intersection of cumulative effects and clean growth in Canada (Tedeschi et al. In Press) and beyond.

The aim for this review was to understand and report on the cumulative effects of clean growth activities throughout Canada and globally. Despite a plethora of clean growth technologies, this review focuses solely on the renewable energy technologies of hydropower, solar, wind energy, hydrokinetic energy, and small nuclear energy due to their popularity, global presence, and being relatively well documented. We focused primarily on the information on these cumulative effects of these technologies throughout Canada while also noting examples of how these technologies are being monitored globally. The cumulative effects of clean growth projects remain a relatively novel focus, yet it is extremely important given an increasing rate of clean growth projects, and because some of the emerging actions and technologies could yield a variety of unanticipated synergistic environmental impacts. Failure to consider these cumulative effects during the early phases of the clean growth "revolution" could impede the ability to meet targets and reduce the environmental and socio-economic benefits that are promised by clean growth. Findings of this study may help policy makers, managers, and practitioners to understand the current status of cumulative effects in renewable energy technologies in Canada and beyond and how cumulative effects can be integrated into impact assessments.

2. Approach

We examined various scientific and gray literature that discussed clean growth and cumulative effects with main focus on five types of clean growth projects (hydropower, solar, wind energy, marine hydrokinetic, and small nuclear energy; Fig. 1). We acknowledge that other growth and extraction initiatives that contribute to cumulative effects exist, such as green transport, critical minerals, and energy transmission (as identified through conversation with the IAAC) but we have focused our efforts on renewable energy technologies. Similarly, we acknowledge that there is a growing literature on the economic and financial aspects of clean growth, including complex trade-offs (e.g., Wang and Lee 2022), which were also beyond the scope of our review. Primary literature searches were conducted between 15 September 2023 and 31 January 2024. Relevant scientific literature was found using academic journal databases (Google Scholar, Web of Science, and Scopus) and online search engines (e.g., Google Scholar and Google). Resources were found using relevant keywords (e.g., 'cumulative effects', "cumulative effects in clean growth" in conjunction with other search terms like "hydropower", "solar power", "wind energy", and other related terms), as well as reading and collecting citations found

Fig. 1. Examples of clean growth activities in Canada: (A) wind energy including onshore and offshore (source: Natural Resources Canada), (B) solar energy (source: Canadian Solar), (C) small nuclear reactors (source: OPG), (D) hydropower (source: HydroQuébec), and (E) marine kinetic (source: Canada.ca). All images available for re-use via Creative Commons.



in relevant papers. Searches were restricted to English. We acknowledge that because we limited our search to English, we undoubtedly missed literature from some regions, including Russia where there is a reasonable amount of research on this topic (see Dregulo (2023) for an English example of Russian scholarship).

Due to the nature of clean growth and the associated projects, research and information was mostly available in gray literature including government websites and government documents. Searches used keywords specific to each initiative (e.g., "onshore wind energy") to identify results from government webpages.

3. Findings

3.1. Hydropower

3.1.1. Potential cumulative effects in small hydropower

Four general pathways for cumulative effects in hydropower have been proposed: single-source additive effects, single-source interactive effects, multi-source additive effects, and multi-source interactive or synergistic effects (Cada and Hunsaker 1990). "Additive effects" denotes the total impact equaling the sum of the effects, and "interactive effects" refers to an impact greater than the sum (Cada and Hunsaker 1990). Few papers explicitly studied the types of cumulative effects associated with Small Hydropower (SHP) projects such as run-of-river hydroelectric power (directly using the natural flow of a river, RoR), although general effects (not additive) from a single source of RoR SHPs and cumulative effects of dam-and-reservoir SHPs or large hydropower (LHP) can be used as proxies. Overall, there are inconsistent terminologies regarding both the field of cumulative effects and the category of "SHP" and a lack of contextualized evidence frequently impedes studies and practices that could assist in understanding the cumulative effects of hydropower on the environment (Ross 1998; Jones 2016; Kelly-Richards et al. 2017; Couto and Olden 2018).

Broadly, the cumulative effects of RoR SHP infrastructure can span hydrology, topography, bathymetry, water and soil chemistry, biodiversity and abundance, and anthropic land usage (See Table 1 in Supplementary Materials; Bracken and Lucas 2013; Anderson et al. 2015; Bilotta et al. 2016; Gibeau et al. 2017; Kelly-Richards et al. 2017; Thorstad et al. 2017; Kuriqi et al. 2021). Some effects that could combine to form cumulative impacts include SHP construction and operation that can alter flow and appropriate land- and soundscapes, resulting in many effects, including increased turbidity and sedimentation, noise pollution, flooding, degradation of water quality, habitat loss, changes in community structure, and the decline or extirpation of species (Anderson et al. 2015; Zhang et al. 2015; Kelly-Richards et al. 2017; Kuriqi et al. 2021). Humans may experience displacement, a loss of food and water security, and harm to recreational, aesthetic, and culturally significant resources (Pinho et al. 2007; Abbasi and Abbasi 2011; Başkaya et al. 2011; Hennig et al. 2013). Additionally, like all hydropower projects, the turbines associated with RoR SHP can entrain or strike animals passing through them, causing injury or mortality (Bracken and Lucas 2013; Thorstad et al. 2017). Also, the impounded section of a waterway which is required to create the water head can obstruct animal movement, potentially resulting in mortality or other impacts such as genetic fragmentation or widespread delays to seasonal migrations (Lucas et al. 2009; Gauld et al. 2013; Anderson et al. 2015; Lange et al. 2018). One study observed a 1.5% injury rate in lampreys passing a "fish friendly" RoR turbine (Bracken and Lucas 2013), and another study observed a more severe mortality rate of 5%–8% combined (turbine and impoundment) for salmon smolts at a different RoR facility (Thorstad et al. 2017). These effects may be small in isolation but would quickly accumulate in an additive or interactive way with the presence of several facilities on the same watershed.

It is unknown if the impacts of a singular LHP are more severe than a singular SHP, but there is currently no evidence to support that SHPs are less impactful than LHPs in a cumulative or per-mega watt (MW) sense (Gleick 1992; Kibler and Tullos 2013; Premalatha et al. 2014; Kelly-Richards et al. 2017; Couto and Olden 2018). In fact, SHPs may exhibit significantly greater environmental harm (e.g., direct conflicts with endangered species) and require more civil works per MW than LHPs (Bakken et al. 2014; Zhang et al. 2015). Specific types of SHPs or technologies used for SHPs may be favourable over other types of SHPs, but common terminologies defining SHPs do not adequately capture this nuance. Due to a variety of these factors, there is regulatory favour granted to SHPs as seen in British Columbia, India, Chile, and Turkey, proliferating these developments with little oversight and deeper understanding on SHP effects (Başkaya et al. 2011; Jaccard et al. 2011; Islar 2012; Kumar and Katoch 2014; Susskind et al. 2014; Shaw et al. 2015; Konak and Sungu-Eryilmaz 2016; Kelly-Richards et al. 2017; Couto and Olden 2018).

While the general adverse effects of RoR SHPs have been studied, the explicitly cumulative perspectives are not well articulated; therefore, we draw upon literature focused on the cumulative effects of other types of hydropower (Premalatha et al. 2014; Couto and Olden 2018; Lange et al. 2018). Environmental deterioration through destruction of land, forests, and degrading of aquatic ecosystems increases with the addition of SHPs in a watershed, such that the total impacts are likely greater than the sum of effects (Kelly-Richards et al. 2017). The reliance, however, on extrapolating from project-level effects indicates that almost all anticipated impacts are derived from single-source additive effects, with poor knowledge of multi-source synergistic effects (Cada and Hunsaker 1990; Johnson et al. 2016; Kelly-Richards et al. 2017).

3.1.2. Cumulative effects in small hydropower in Canada and beyond

Cumulative effects assessment (CEA) for hydropower in Canada tends to be incorporated into regional assessments (RA) and strategic environmental assessments (assessments looking at overall strategies such as policies and SEA) rather than EIAs for individual projects. Ideally, an RA occurs at the watershed scale or higher for hydropower and related activities (Kristensen et al. 2013). A summary of twelve CEA studies over eight years at Hydro-Quebec was consistent with the concept of an RA (Bérubé 2007). They outlined a seven-step process common across all forms of impact assessment: (1) scoping, (2) identification of relevant activities (past, present, and future), (3) description of effects, (4) description of a baseline, (5) description of historical trends, (6) significance determination, and (7) mitigation. In addition, they highlighted the difficulties in locating sufficiently detailed baseline data for meaningful comparisons, the lack of a consistent threshold for significant effects, questions around how to mitigate the cumulative effects identified (e.g., water quality, air quality, and noise), difficulties in quantifying cumulative effects when project-level effects were minimal, and the difficulty of considering future undertakings in cumulative effects projections.

Manitoba Hydro (2015) also undertook an RA on their activities in the Nelson River sub-watershed in the form of a 50-year retrospective. They compiled historical environmental reports, contemporary EIA reports, and post-project monitoring reports, and analysed the data to provide a comprehensive analysis. This approach was hindered by in-

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adequate baseline and historical data (and conflation of the two), methodological inconsistency over time which complicated pre- and post-development comparisons, and the adversarial nature of early environmental assessments, leading to divergent findings regarding the magnitude and scope of the effects. This report failed to consider how the effects of hydropower development synergized with other activities in the region, such as mining and forestry, and was entirely retrospective in nature, therefore offering little insight regarding cross-sectoral or synergistic effects, nor value for guiding future development in the region (Scrafield et al. 2018).

Strategic environmental assessments (SEAs) are based on the understanding that implementing public-private partnerships (PPPs) without comprehensive foresight effectively predetermines what projects will occur, relegating project-level assessment to a regulatory hurdle (Halseth et al. 2016). For example, the decision to incentivize small hydropower in Newfoundland (NL) using PPPs in the 1990s could have used an SEA framework but did not (Bonnell and Storey 2000). At the policy level, by choosing to incentivize private-sector development of small hydro, the NL government was effectively pre-determining that small hydro facilities would be built without considering whether small hydro was the best option for the energy needs of NL, especially in light of existing effects from past and present hydroelectric facilities. SEAs at the policy level would have evaluated the projected effects of small hydro facilities against potential alternatives before incentivization. At the plan level, Newfoundland Hydro (NLH) decided to purchase up to 50 MW of power, with little consideration regarding the quantity or location of these facilities. SEAs for this plan could have estimated the number of small hydro facilities needed to reach this maximum, facilitating the estimation of cumulative effects. The SEA would also have allowed the opportunity to ensure that these projects avoided spatial overlap with past, existing, and potential future undertakings to minimize synergistic and/or compounding effects. At the program level, NLH approved four new developments. SEAs at this level would look very similar to a proponent-driven project-level EA, except NLH would undertake the assessment with a top-down view of all approved activities in tandem with activities in other industries. This would allow a better estimate of the sum of all effects of these new developments and a more effective analysis of potential cross-sectoral effects (Bonnell and Storey 2000).

Challenges and complicated phenomena are associated with undertaking a SEA. Multiple policies may act in unforeseen ways, requiring policy-level SEAs to consider past, concurrent, and potential future policies in the same manner a project-level EA would (Bonnell and Storey 2000; Kelly-Richards et al. 2017). If the NL government did consider alternatives to small hydropower, the diverse risks associated with different electricity generation methods would make comparisons difficult (Bonnell and Storey 2000), though comparative frameworks for some technologies have since been developed (e.g., SHP and wind power; Bakken et al. 2014). Administrative fragmentation between NLH and the NL government will continue to inhibit watershed- or regional-scale planning of SHP development. For the cumulative effects of SHP to be properly addressed, extensive cooperation among all regulators, proponents, and stakeholders are essential at the earliest stages of SEAs (Bonnell and Storey 2000).

The current model for how cumulative effects are dealt with is fundamentally inadequate, and there has been a call for broad and revolutionary, rather than incremental or evolutionary, change in the field (Halseth et al. 2016; Johnson et al. 2016; Jones 2016). These changes should advance evaluation and monitoring of cumulative effects, past project-based thresholds, and fine-scale legalism, and work towards a spatially planned, cumulative-minded development framework (e.g., Jager et al. 2015; Winemiller et al. 2016; Erikstad et al. 2020) that is fully integrated with economic and regulatory decisions and incentives (Halseth et al. 2016; Johnson et al. 2016; Kelly-Richards et al. 2017; Lange et al. 2018). By considering ecological and environmental processes in spatial planning tools, and by recognizing the pressure economic and regulatory processes exert on individual developments, efforts can more adequately focus on holistic environmental, community, and individual health (Halseth et al. 2016; Johnson et al. 2016; Jones 2016). Without change, the current rate of SHP construction could lead to the rapid proliferation of negative impacts worldwide (Kelly-Richards et al. 2017).

Beyond Canada, cumulative effects of small hydropower facilities have been investigated in Europe, the United States, South America, and Asia. Reviews of cumulative impact assessment noted important “lessons learned” from case studies throughout Canada, the United States and Europe (Canter and Atkinson 2011; Canter and Ross 2010). Throughout the European Union, recent incentives have resulted in the increase in renewable energies, in particular hydropower. However, a review of hydropower in Romania noted significant individual and cumulative effects associated with small hydropower facilities and the lack of mitigation measures for native aquatic fauna (Costea et al. 2021). A study in Scotland showed the presence of multiple small hydropower facilities inhibits the spawning migrations of fish species (Gowans et al. 2003). Throughout South America, understanding the need to incorporate cumulative effects assessments have been historically neglected in planning and policy documents, particularly throughout rivers in the Amazon (Athayde et al. 2019). Despite Asia being home to over half of the hydropower capacity in the world, cumulative impacts assessment in hydropower needs to be improved. For example, the Mekong River Commission, an inter-governmental basin-wide organisation consisting of Cambodia, Laos, Thailand, and Vietnam, has been criticized for the lack of integrated assessment of cumulative impacts, particularly on tributary hydropower facilities (Keskinen et al. 2012; Ziv et al. 2012). Furthermore, the cumulative biophysical impacts of small and large hydropower developments in the Nu River in China associated with small hydropower projects may exceed those of large projects, particularly regarding habitat and hydrologic change (Kibler and Tullos 2013). Overall, the evaluation and monitoring of cumulative effects of small hydropower facilities world-wide is lacking in EAs and the scientific literature. Further studies are needed to understand the cumulative effects of this technology, thus providing information that can be implemented in EAs in the hopes that the cumulative effects of small hydropower facilities are reduced.

3.2. Wind energy (onshore and offshore)

3.2.1. Potential cumulative effects of wind energy

Practitioners have continued to struggle with implementing standard processes to assess the cumulative environmental effects of wind energy (Gill and Hein 2022), and evaluating and monitoring these effects are essentially absent from environmental assessments globally (Sinclair et al. 2017). Individual effects of wind energy are rarely studied outside of the context of turbine collisions with avian (and sometimes bat) fauna, and cumulative effects are therefore not assessed or assessed poorly. We can therefore begin by exploring individual wind energy impact assessments to understand how they fit into the larger scope of cumulative effects. The impact of wind energy developments on wildlife can be placed into three categories: (i) disturbance-induced displacement, (ii) direct mortality from collision with turbine components, or (iii) habitat loss (Tosh et al. 2014). Identifying the sources or effect pathways of hazards is important when considering the effects on wildlife and the environment, especially considering the impacts to species, which species are vulnerable, individual species thresholds, and understanding temporal and spatial boundaries for exposure or animal movement (Goodale and Milman 2016), all of which are complex and difficult to assess.

The EIAs of wind energy projects are still largely focused on birds (Tosh et al. 2014). Operational wind farms can impact bird populations across a multitude of species (e.g., Scottish Natural Heritage 2018). While there is no clear definition or methodology on how to assess wind energy impacts on birds, commonly used assessments focus on direct impacts through collisions with components of the wind turbine (e.g., Drewitt and Langston 2008), trauma from being caught up in turbine turbulence (Winkelman 1992), disturbance caused by habitat loss (Larsen and Masden 2000; Pearce-Higgins et al. 2008; Marques et al. 2014; Laranjeiro et al. 2018), or the creation of a barrier which increases energy expenditure when individuals avoid the turbine (Winkelman 1985; Still et al. 1997; de Lucas et al. 2004; Hötker et al. 2006; Masden et al. 2009; Sugimoto and Matsuda 2011). While there are plenty of studies that report the impacts of wind project on birds, there are not a lot of studies exploring cumulative effects of several wind projects or wind projects in conjunction with other alterations. In Canada, assessment of cumulative effects on birds includes both direct collisions and species' disturbance (Environment Canada 2007). Bird collisions can be measured through field surveys of bird carcasses (e.g., Environment Canada 2007) or predicted using a variety of modeling techniques, the most popular of which is the Band Model (Band et al. 2007). Assessing collision risk or displacement of birds is especially difficult as a number of outcomes affected by the ecology and behaviour of each individual bird species need to be predicted using modeling (Smallwood et al. 2009; Carette et al. 2012; Herrera-Alsina et al. 2013; Scottish Natural Heritage 2018), which will likely under or over estimate collision risks, while not reflecting the true biology of the species (Scottish Natural Heritage 2018).

Similarly, between 2002 and 2014, over 70 peer-reviewed publications have focused on wind energy project impact on bats, with a majority of these (58%) originating from the United States and Canada (Tosh et al. 2014). In 2010 and 2011, up to 1.3 million bats were estimated to be killed by wind turbines in North America (Arnett et al. 2013). Bats are killed through collision and barotrauma (Baerwald et al. 2008) as they are attracted to a variety of visual, thermal, or acoustic cues from the turbines, with the presence of foraging habits and roost locations nearby an additional factor in mortality risk (Dürr and Bach 2004; Szewczak and Arnett 2006; Kunz et al. 2007; Cryan 2008; Cryan and Barclay 2009). There are currently few examples of cumulative effect assessments for bats due to a variety of challenges. For example, bat studies generally do not include mortality surveys across multiple wind farm sites simultaneously to look at temporal or spatial patterns (Arnett et al. 2008), lack population data at larger spatial scales (O'Shea et al. 2003; Jansen 2023), and lack standardization of methodologies for measuring bat fatalities (E. Baerwald and R. M. R. Barclay, University of Calgary, unpublished data). In Canada, if bat mortality exceeds ten bats per turbine, per year, then the cut-in speed of the turbines has to be reduced or blades feathered below the speed of 5.5 m/s (Tosh et al. 2014), although it is unknown if these changes alter bat mortality. Overall, there are a lack of standard methodologies for measuring bat mortality, even outside of the context of cumulative effects.

Outside of birds and bats, there is limited literature to suggest that wind turbines have an impact on other terrestrial biodiversity. One Norwegian study explored the impact of wind turbines on habitat avoidance and displacement in reindeer and found it varied depending on the time of year (Eftestøl et al. 2023). In general, wind turbine impacts could be more prominent in species with a narrow habitat range (Swihart et al. 2003; Munday 2004; de Baan et al. 2013). Furthermore, barrier effects, noise, vibration, shadow flickers, and electromagnetic field generation could all impact terrestrial wildlife (Bennun et al. 2021), although these have rarely been studied in isolation or as cumulative effects.

The impact of the noise created by onshore wind energy projects and their effect on humans is debated in the literature. Some researchers found that noise due to wind turbine operation can cause auditory annoyances (Bolin et al. 2011) or even some health issues (Dai et al. 2015), while others report no major health concerns (Bolin et al. 2011; Ladenburg 2015). In other studies, there is a reported psychological (due to individuals seeing turbines often; Pederson and Waye 2004) reaction (resulting in nervousness; Colby et al. 2009) in the presence of wind turbines.

Some studies have described the visual annoyance and/or disturbance of turbines to humans as well as the overall impacts that wind energy projects have on how we interpret the visual landscape. The visual impacts of wind turbines continue to be extremely difficult to evaluate due to its subjectivity (Leung and Yang 2012). For example, acceptance of wind turbines is negatively correlated with how many turbines are seen daily by individuals (Ladenburg and Dahlgaard 2012).

Two types of landscape effects are direct effects, where turbine development damages existing landscape components (e.g., removal of trees), and secondly, effects on the landscape due to the addition of new features (e.g., wind turbines visible) (White Consultants 2013). UNESCO recommends in the construction of windfarms that the distance between windfarms, the distance they are visible, the design of the windfarm, and the overall character of the landscape, as well as considering the location of views and how the landscape is experienced from those views as these can cumulatively interact to produce the overall aesthetic experience should be considered (White Consultants 2013; UNESCO n.d.). Methodologies for assessing visual impacts are lacking, indicating a potential lack of interest in this topic, and also fail to consider other developments in their cumulative effect assessment structure.

Other singular, adverse environmental impacts due to wind farms are not well understood but wastewater and oil from wind turbine construction could have negative impacts on the surrounding soil (Dai et al. 2015). While there are no studies that examine impacts on peatland by wind energy structures, in general, disturbances of the peat layers (major carbon sinks) can impact ecosystems close to the disturbance and beyond. For example, disturbance of peat can lead to decreases in water quality and impacts to aquatic life (Nayak et al. 2010; Bain et al. 2011) through increased run-off and sediment and nutrient leaching (Leeks and Roberts 1987; Roberts and Crane 1997; Lindsay and Bragg 2005; Dykes and Jennings 2011; Muller and Tankere-Muller 2012). Furthermore, some evidence suggests that large-scale wind projects may have impacts on local microclimates. For example, a study in Texas found that large wind farms increase the average surface temperature of nearby nonwind farm areas by 0.72 °C over the course of a decade which can impact local precipitation (Zhou et al. 2012), and another study noted that wind farms could increase average surface temperatures over time (Wang and Prinn 2010), although it is clear that more research needs to be completed focusing on wind turbine effects on microclimate. It is possible that direct impacts such as mortality and larger-scale environmental impacts such as changes in microclimate and habitat disturbances can all impact wildlife and ecosystems cumulatively. Additionally, visual and auditory annoyances in humans could work synergistically to impact health. Although these are currently just hypotheses as studies of cumulative effects processes are not well understood and need to be undertaken to effectively mitigate the environmental effects of wind energy to reduce their overall cumulative effects.

The investment in offshore wind energy is increasing globally, and as such, many institutions are urgently trying to develop frameworks to help explore cumulative effects. Current frameworks for assessing offshore wind energy impacts are still rarely standardized across nations and governing bodies. Impact-producing factors (IPFs, as listed by Gill 2005) can occur during three phases: construction, operation, and decommissioning of the wind project (Gill 2005). Very rarely are all three of these phases considered cumulatively in EIAs (although CEAs are required within this), with most reports focusing on elements during construction (e.g., pile-driving) or operation (e.g., noise). The components of what makes up a "good" framework for offshore wind project EIAs include understanding the range of IPFs and their effects on animal population demographics, the scale of the industry at full capacity, proportion of species population impacted, identifying other stressors that may impact population demographics, and other ecosystem and ecological components (e.g., understanding habitat loss, nutrient availability, alterations at different trophic levels, and altered diversity; Gill 2005; Croll et al. 2022). Overall, the environmental impacts from offshore wind energy are not well understood, and a majority of the research is in its beginning stages. Some studies focus on the single isolated effect of noise created during pile-driving of the benthic floor (Goodale and Milman 2016) as it impacts marine mammals (such as the harbor porpoise in Northern Europe) through hearing damage and changing behaviours (e.g., David 2006; MMS 2007) and negatively impacts fish (Kikuchi 2010), sea turtles (MMS 2007), and birds (Gill 2005), although these taxa have not been extensively studied. Another study examining microclimate changes for offshore wind showed that large deployments of offshore wind energy could cause a slight cooling (0.2 °C) of the ocean surface in wind farm areas (Wang and Prinn 2011), although, again, this is not well studied. Without thorough understanding of these singular effect producing components (IPFs), there is little hope in understanding how these impacts can come together cumulatively to impact individuals and populations.

The same difficulties and limitations that exist for onshore wind energy environmental assessments also plague offshore wind projects. There are substantial limitations with understanding offshore impacts due to exacerbated difficulties with exploring spatial and temporal scales across jurisdictions in marine environments (Masden et al. 2015). As a result, understanding the combined impacts over several different projects is difficult, as assessments of mobile aquatic species are very difficult to conduct (Parsons et al. 2009; Gusatu et al. 2021). For single impacts, there are risks to marine wildlife due to collisions with wind farm structures or displacement and disturbance (via direct or indirect pathways such as electromagnetic disruption), such as for migratory seabirds (e.g., Desholm and Kahlert 2005; Furness et al. 2013), and less so for fish (Perrow et al. 2011; Michel 2013), turtles (MMS 2007), and marine mammals (e.g., porpoises; Tougaard et al. 2005). True collision and displacement risks are not well understood due to the difficulty in measuring interactions between animals and wind farms, and in understanding how wind farms can impact cumulative effects (such as combining collisions with habitat loss or noise displacement as it relates to offshore ecosystems, Masden et al. 2015).

3.2.2. Examples of cumulative effects throughout Canada and beyond

In Canada, wind energy projects are assessed at the provincial level unless wind projects are offshore or within a nationally protected area (McMaster et al. 2021). Provincially, several EIA frameworks mention the importance of cumulative effect consideration, although outside of policy frameworks, there is little guidance on how to complete these (Nova Scotia Environmental Assessment Branch 2021; Newfoundland and Labrador Department of Environment and Climate Change 2023). To date, there are no cumulative effect frameworks for wind energy specifically in Canada, and it is yet to be seen how regional assessments of offshore wind energy in Nova Scotia and Newfoundland and Labrador consider cumulative effects.

One study explored and identified 94 "valued components", understood as similar to IPFs, across Canadian impact assessments of wind farms, with an overwhelming majority of these applicable to the construction and operation phases as opposed to the decommissioning phase (Godinho et al. 2023). Many of these impact assessments looked at traditional isolated biophysical impacts on wildlife, environments, vegetation, and soil (among others), but some socio-economic impacts, including human health and impacts to Indigenous communities were also mentioned. How these impacts relate to cumulative effects was not assessed. Thus, despite CEAs being a part of Canadian EIAs, current EIAs are not prepared to tackle the issue of cumulative effects due to a lack of understanding of how single, isolated impacts to the environment or wildlife act cumulatively (Dutta 2020).

Beyond Canada, many of the frameworks for assessing the cumulative and environmental effects of wind energy projects are similar to those found in Canada. Overall, there is still a lack of guidance for how to assess the cumulative effects in wind energy projects, and without this guidance, it will continue to be difficult for meaningful assessments to occur. Many of the cumulative effect frameworks that exist are focused on a single component (e.g., birds) rather than a holistic picture of how wind farms are impacting ecosystems at large. Needless to say, the consideration of cumulative effects in offshore wind energy projects is becoming more prevalent in research and development (through identification of what isolated impacts need to be considered, e.g., Godinho et al. 2023), meaning that EIAs will become more complicated with the addition of cumulative effects. In the project development world, there is a fear that adopting a more rigorous environmental assessment process will delay renewable energy projects (Jay 2010; Scott et al. 2014) and will have largely negative impacts on meeting climate change goals (Geißler et al. 2013; Schumacher 2017; Ryan et al. 2019; Fischer et al. 2020). Worldwide, consistent practices to assess cumulative effects have not been implemented very successfully (e.g., Willsteed et al. 2018; Gill and Hein 2022) due to difficulties that are preventing practitioners from making practical decisions to assess cumulative effects, including inconsistent use of terminology and definitions (e.g., Judd et al. 2015; Foley et al. 2017), understanding environmental baselines, and the difficulty of understanding spatial and temporal scales for each effect (e.g., Cooper and Sheate 2002; Masden et al. 2010; Duinker et al. 2013; Foley et al. 2017).

Countries under the jurisdiction of the European Union (EU) are required to complete a strategic environmental assessment to establish thresholds and overall environmental impacts on valued components (Renewable UK 2013). Developers must complete an EIA that includes consideration of impacts (direct, indirect, negative, positive, long-term, permanent, or inter/intra-project cumulative effects) a project may have and, where applicable, complete a habitat regulations assessment (HRA), which explores effects on specific habitats or species (Renewable UK 2013). In 1999, the European Commission published guidance for EIA to help streamline the process for individual countries, although each country is responsible for creating their own guidance framework (European Commission 1999). The EIA is the only assessment that is used by decision makers to approve or reject a project. Additionally, while the EIA outlines that impacts should be considered and analyzed, there is a focus on direct, isolated impacts and does not really mention how these isolated impacts could work together cumulatively, which makes assessments of cumulative effects challenging despite the 51 "cumulative" effects assessed between the SEA, EIA, and HRA (Renewable UK 2013). The guidelines for EIAs in various Nordic countries and how they accommodate biodiversity in the European North Sea by considering impacts from offshore wind projects "does well" to consider isolated impacts on the environment (Nordic Energy Research 2022). Environmental permits are required in Sweden and Norway and these look at a variety of isolated environmental impacts and in the Norwegian case, impacts to other socio-economic factors.

Isolated effects of wind farms have been explored extensively and are being considered for cumulative effects in several countries, mostly for offshore wind energy developments and focusing on wildlife. The Netherlands has included cumulative effects for their assessment of offshore wind farms, including through the Nature Conservation Act, which requires cumulative effect assessments and stipulate that adverse cumulative effects must be assessed for individual projects, including wind farms for impacts on targeted species such as bats and birds. How individual effects should be assessed cumulatively are not laid out in either of these acts. As a whole, there are currently no clear cumulative effects scoping methods that explore spatial and temporal scale, methodologies to assess these effects, or centralized database for existing or proposed projects that can help people better understand how isolated effects should be considered cumulatively in the Netherlands (Ministry of Economic Affairs and Climate 2015).

In the wake of increased attention on coastal and marine ecosystems, the French Ministry for Ecology established the "ECUME" scientific working group (WG) in 2018 to help address the impacts of offshore cumulative effects through a risk based strategy of all stressors and potentially impacted proponents of cumulative effects (Brignon et al. 2022). The ECUME WG used a risk-based approach to identify and rank adverse effects that offshore wind farms may produce during construction, operation, and decommissioning, while also identifying at-risk species, how sensitive areas could be affected, and what level of scientific knowledge exists for these interactions. Overall, the working group was able to identify 41 relevant species or groups of species and habitats along with 47 pressures during the three phases of offshore wind development (Brignon et al. 2022), showing a comprehensive way other working groups can begin to identify isolated effects that interact to become cumulative effects, although it is important to note, that similar to other frameworks for cumulative effects, the ECUME WG does not define how isolated effects should be assessed cumulatively, rather states what effects should be considered for each receptor.

In the United States, EIAs are not always required for wind energy projects (Teff-Seker et al. 2022). Interestingly, the United States Environmental Protection Agency recently published a report that calls for more cumulative effects research to be applied to human health outcomes, such as those seen in Pederson and Waye (2004) or Dai et al. (2015) at various socio-economic levels (United States Environmental Protection Agency 2022). The document outlines key questions that should be considered in a human health cumulative effect assessment that can often impact communities differently based on factors of socio-economic status, race, ethnicity, and previous exposure. This report recognizes that there are key research and methodology standardization gaps that need to be fixed to help us understand why some populations are more at risk for cumulative effects (United States Environmental Protection Agency 2022). While this report does not mention wind energy specifically, this brings to the forefront the consideration of cumulative effects across different socio-economic scales that has not appeared in wind energy EIA literature. Thus, moving forward it will be necessary to consider these impacts in addition to the work that is being completed for cumulative effects on wildlife.

Australia has not mandated the assessment of cumulative effects in the context of wind energy but cumulative effects are accounted for under the Environmental Protection and Biodiversity Conservation Act. Despite this, the act does not provide guidance or indicate methodologies that address those cumulative effects (Dales 2011; Dunstan et al. 2020). Cumulative effects so far are focused on the marine environments (Great Barrier Reef Park Authority 2018; Fulton et al. 2021). Australia has taken a number of steps that may pertain to offshore wind energy projects in particular. For example, Australia has produced a national cumulative pressures map that aims to sum all of the 109 identified pressures in their coastal waters (Fulton et al. 2021). Recent work has suggested the type of analysis that should be considered to understand the full scope of cumulative effects, such as qualitative and quantitative assessments of impact and risk, model-data analysis of relationships between activities, impact analysis of the cumulative effects on valued components, risk analysis of the likelihood of effects, and an outcome synthesis on mitigation activities (Dunstan et al. 2020). Of these, most cumulative effect assessment approaches do not actually reflect realized risk but are closer to hazard analyses where risks are identified without further consideration (Stockbridge et al. 2021). Furthermore, if cumulative effects assessments are meant to be fully competent, evaluation of management measures must be included (Cormier et al. 2018; Stelzenmüller et al. 2018). Overall, Australian cumulative effect assessments include the same roadblocks and priorities that exist for frameworks worldwide, including adopting standardized approaches, clarification of terminologies and methods, understanding baselines, thresholds, and standards, understanding spatial and temporal scales, and a call to use more integrated approaches (Great Barrier Reef Park Authority 2018).

3.3. Small-scale nuclear energy

3.3.1. Potential cumulative effects in nuclear energy

Safe, reliable, small-scale nuclear power, also known as small modular reactors (SMRs), has the potential to provide humans with low-emission energy production, but multiple caveats exist that potentially have direct and indirect cumulative effects on ecosystems and humans (Fiorini 2014; Horvath and Rachlew 2016; Prăvălie and Bandoc 2018; Zarębski and Katarzyński 2023). These isolated effects include transportation and disposal of radioactive material, impacts on sensitive ecosystems (e.g., Arctic and sub-Arctic), disturbances to livestock, contamination of freshwater ecosystems, industrial noise and activity, and the potential of nuclear accidents (e.g., meltdowns, decay heat, and equipment failure; Rowan and Rasmussen 1994; Burgherr and Hirschberg 2014; Carless et al. 2016; Kyne and Bolin 2016; Ramana and Ahmad 2016; Brinkmann and Rowan 2018; Hanna et al. 2019; Froese et al. 2020; Malatesta 2021; Krall et al. 2022; Zarębski and Katarzyński 2023). Current studies focused on understanding these effects of SMRs have been conducted in the United States of America, Canada, Germany, Poland, Italy, Australia, and Jordan; however, there is still limited evidence to provide comprehensive knowledge that can be applied across contexts on the impacts of the effects SMRs will have on humans and the environment (Rowan 2018). Due to multiple isolated effects SMRs could have on humans and environment, their production and distribution need to be competently and comprehensively planned. For instance, guidance on how on how these isolated impacts can occur cumulatively through EIAs will need to be developed, likely using existing frameworks around nuclear power plants in Canada, the United States, and other countries, to fully understand the impacts of SMRs (Rowan and Rasmussen 1994; Brinkmann and Rowan 2018; Hanna et al. 2019; Zhang et al. 2023).

The relative footprint of SMRs and the reliance on prefabricated parts make them easy to deploy and allow them to be distributed widely in greater abundances across the landscape compared to larger nuclear projects (Locatelli et al. 2014; Black et al. 2019). This ability makes SMRs a favorable alternative to other noncarbon-based technologies (e.g., small footprint). Deployment of SMRs in high abundance across the landscape, however, could have a cumulative effect on humans and ecosystems, as the impacts may cross multiple spatial scales in comparison to current centralized large scale nuclear power plants. These impacts can include regionally specific changes to ecosystems through deployment (e.g., development of roads, deployment sites, and either centralized or local waste storage sites), operation (e.g., excessive water usage), and the potential for nuclear accidents (e.g., nuclear storage, transportation, and meltdown). As the number of SMRs increases, these regional effects and how they impact each other cumulatively have the potential to become more widespread (e.g., broad-scale habitat loss, warmer surface water, radiation). Therefore, we recommend that the number of deployments, raw material storage, waste facilities, and part manufacture sites needs to be carefully considered by practitioners.

Furthermore, the financial cost-benefits of SMRs as a reliable non-carbon-based source of energy have been contested for remote communities, with current estimates indicating the technology is potentially too expensive to be a viable there (Froese et al. 2020). Communities (Indigenous and non-Indigenous) often located in northern Canada and in remote resource extraction sites such as the Ring of Fire mining operation in Ontario and Alberta and Saskatchewan resource extraction (Buchheit and Smith 2018; Hurlbert 2022; Zhang et al. 2022). These communities and sites are isolated and might not have the proper infrastructure to support safe and reliable SMR development, deployment, and operations. Careful review and consultation of these communities and sites, especially Indigenous communities, needs to be conducted prior to any progress in the implementation of SMRs as an alternative source of clean energy.

3.3.2. Examples of cumulative effects in nuclear energy throughout Canada and beyond

The environmental and societal impacts of SMRs are not fully understood making their current use controversial (Bratt 2022), which also makes their cumulative impacts difficult to assess. Further assessment and research (e.g., government and university) on their impacts may allow SMRs to be safely and responsibly deployed in Canada. Areas of assessment and research could be focused on improving site development practices, using and creating mitigation tools, developing better nuclear material storage methods and facilities, funding studies that evaluate the environmental impacts SMR development and deployment, and amending EIAs to better reflect current and future knowledge on the impacts of SMRs (see Supplementary Materials Table 1).

The Canadian federal government conducted a nationwide study of SMR technology to provide context and guidance on how to proceed with the transition to using this technology as an effective energy source (SMR Roadmap 2018). An annual SMR action plan was developed from that study with the latest update in 2022. This action plan provides regulators, proponents, and the public with information about the cost, development, and legislative frameworks surrounding the deployment and operation of SMRs. The action plan, however, does not discuss cumulative effects that SMRs will have on humans and the environment, therefore failing to provide regulators, proponents, and the public with this information. Currently development, deployment, and operations of SMR that are <200 Megawatt thermal (MWth) are exempted from the federal Impact Assessment Act through Physical Activities Regulations---SOR2019-285, section 27b, which applies to all nine proposed SMRs in Canada (located in Ontario and New Brunswick). Further review of this exemption needs to be considered given the above discussions on the environmental impacts nuclear power and SRMs have in Canada. Furthermore, government priorities could be focused on funding research to better understand the cumulative effects of this technology. Regardless of the exemption, the New Brunswick government has pledged to conduct thorough EIAs for small modular nuclear reactor projects and asked for public input (Government of New Brunswick 2023*a*, 2023*b*). This EIA will hopefully help guide and inform future impact assessments, although cumulative effects are not explicitly assessed, this could be a first step in the consideration of effects for future deployments of SMRs.

The isolated (and cumulative) effects of SMRs in Canada and beyond have not been well documented, studied, or measured, due to this technology being relatively new. Therefore, the majority of the literature base on isolated effects of SMRs has inferred these effects from those known from commercial-sized nuclear reactor power plants (see above); however, further research needs to happen in these countries as most of them are seeking to use the technology as a means of green energy to help reduce carbon emissions. If SMR technology is to be deployed throughout the world and in more remote and sensitive areas (e.g., polar regions), more research and monitoring centered on the individual and cumulative effects is needed. Without policy, EIAs, research, and monitoring, this new technology could have large environmental impacts that could negate its relatively low carbon emissions (i.e., construction) and instead have lasting impacts on the environment and humans.

3.4. Solar energy

3.4.1. Potential cumulative effects in solar energy

The deployment, maintenance, and recycling of solar farms has multiple direct and indirect isolated effects on ecosystems and humans (see Supplementary Material Table 1; Abbasi and Abbasi 2000; Kaygusuz 2009; Hernandez et al. 2014). Solar power stations require the development of vast amounts of land resulting in effects on the surrounding terrestrial landscape, including converting existing cleared land (e.g., agricultural land) or clearing and developing a site to provide efficient and effective sun exposure (Tsoutsos et al. 2005; Gunerhan et al. 2008; Hernandez et al. 2014; Franco and Franco 2025). This development can cause increases in soil erosion and compaction and increase fragmentation of habitats, potentially altering local biodiversity causing populations of intrinsically and economically important species to decline (e.g., pollinators) (Montag et al. 2016; Guiller et al. 2017; Chock et al. 2021; Leskova et al. 2022). Once deployed, solar farms can decrease soil evaporation rates, alter wind and weather patterns, and increase local albedo and heat island effects (Fthenakis and Yu 2013; Hernandez et al. 2014; Hu et al. 2016). These impacts can affect aquatic ecosystems by increasing local water temperatures impacting fish and aquatic organisms, fragment and reduce temporary surface and groundwater networks, and increase mortality rates of aquatic insects and waterbirds as these species are attracted to photovoltaic (PV) cells (Horváth et al. 2010; Kagan et al. 2014; Grippo et al. 2015; Li et al. 2022). Maintenance of solar farms often requires regular removal of vegetation that can decrease native vegetation allowing non-native and invasive vegetation to become more prevalent. Solar farms have often relied on easy to maintain groundcover (e.g., grass or gravel) that could result in the use of machinery or herbicides and pesticides that have effects on terrestrial and aquatic ecosystems (Hernandez et al. 2014, 2019; McCall et al. 2023).

To mitigate the indirect and direct cumulative effects of the deployment and maintenance of solar farms on multiple ecosystems, the location and the potential modifications to the landscape need to be carefully reviewed, especially if sites are located in remote and sensitive ecosystems that are easily disturbed and/or warmed (e.g., Tiega, permafrost, and tundra ecosystems) (Cameron et al. 2012; Valera et al. 2022). Limiting development near important surface- and groundwater systems and/or using already existing cleared land (e.g., agricultural land) might be useful mitigation tactics to reduce the environmental impacts of solar farms (Grippo et al. 2015; Hamidinasab et al. 2023). A recent study created a table to understand the effectiveness of each mitigation tool used to offset the impacts of solar farms on agricultural industries (Hamidinsab et al. 2023). This table is useful for practitioners and researchers as it quantifies the industrial impact and effectiveness of each mitigation tool. Stakeholders (e.g., farmers and producers), however, will need to be consulted and compensated, and an evaluation of the costs and benefits of converting agricultural land to energy production will be needed (Owley and Morris 2019). Techniques used to mitigate the impacts of solar farms on aquatic ecosystems, however, are either currently being assessed for successfulness or have not been assessed at all (Grippo et al. 2015). Further mitigation tactics could include the displacement of agricultural crops, or using recently developed floating PV cells that mitigate local albedo effects produced by land-based solar power stations (Hassanien et al. 2016; Hayibo and Pearce 2022), and multifaceted approaches that can help with restoring damaged systems due to cumulative effects (e.g., land exchanges and habitat offsets) could help further reduce impacts solar power stations have on humans and ecosystems (Cameron et al. 2012; Northrup and Wittemyer 2013; Hernandez et al. 2019).

Solar electrical panels lose their efficiency over time, creating waste that can have a variety of effects on the environment (Aman et al. 2015) that may further come together cumulatively. Waste produced can consist of toxic materials (e.g., cadmium, arsenic, nickel, lead) that have to be disposed of using proper methods, protocols, and policies (Sinha et al. 2008; Turney and Fthenakis 2011). Best practices to handle toxic waste include safe disposal (e.g., containment methods) or recovery methodologies (e.g., acid that allows waste products to either be reused in PV cell manufacturing or limit their impacts on the environment) (Fthenakis and Moskowitz 1995; Wang and Fthenakis 2005; Kwak et al. 2020). Recycling and retaining low-toxicity materials (e.g., fiberglass, glass, coolant, and insulations) used in PV cells is another viable mitigation tool to reduce waste production (Polit et al. 2016; Xu et al. 2018). These materials can be used for future industrial activities or used in producing new PV cells (Padoan et al. 2019; Niekurzak et al. 2023; Song et al. 2023). The effectiveness of recycling methodologies is quite high (i.e., between 80% and 95%); however, current methods are not cost-effective at large scale and need to be refined if they are to be fully implemented (Gerold and Antrekowitsch 2024). Using existing and developing novel methods, protocols, and policies will assist in the mitigation of waste produced by PV cells and solar power plants.

3.4.2. Examples of mitigating cumulative effects in solar energy throughout Canada and beyond

Overall, a multipronged approach is needed to reduce the cumulative effects that solar energy production has on humans and the environment. This approach can be focused on creating policy instruments that result in assessing the impacts that the development (e.g., clearing or converting land) and maintenance of solar power stations have on a particular site (e.g., habitat fragmentation, local albedo effects), working with multiple stakeholders to safely deploy solar power stations on existing cleared land, and using and developing better disposal and recycling methodology ultimately leading to reduced individual, and thus, cumulative effects (Solangi et al. 2011; Hernandez et al. 2014, 2019).

Canada currently uses regulatory frameworks developed and implemented by provincial (e.g., Ontario Ministry of the Environment, Conservation and Park) and federal regulators (e.g., Canadian Council of Ministers of the Environment) to assess the cumulative effects of solar power stations (Canadian Energy Regulator). These frameworks require both assessment of cumulative effects and EIAs as well as stakeholder consultation and engagement (e.g., Indigenous groups, farmers) to occur prior to and throughout the deployment of solar power stations. It is unknown how individual effects should be assessed to be considered cumulatively. Assessments evaluate the impacts that occur to the environment (i.e., soil disturbances, terrestrial habitat fragmentation, and ground-and surface water disturbances) and provide mitigation recommendations and requirements (e.g., site consideration, silt fencing, waste disposal and recycling protocols, planting native plants) for the proponent. Even though environmental assessments and mitigation actions occur, data generated (e.g., changes in biodiversity) from these impact assessments are not compiled into centralized databases to assess the long-term single or cumulative effects and the broad-scale impacts to landscapes. Empirical evidence needs to be used to improve regulatory frameworks to mitigate cumulative effects of solar power stations. Therefore, improved and centralized data collection (e.g., requiring contractors to provide raw data) will assist in making evidence-based decisions. Furthermore, development and research of novel mitigation tools mentioned in the above sections could be implemented in future regulatory frameworks. By improving assessment and mitigation tools, the cumulative effects solar power stations have on the environment and humans can be reduced.

Solar farms are deployed world-wide; however, frameworks used to assess and mitigate the effects of PV farms depend on regional differences in ecosystems and local and federal governmental priorities (Solangi et al. 2011; Kumar Sahu 2015). These frameworks overall have many similarities with assessment and mitigation frameworks used in Canada and include environmental impact assessment and mitigation recommendations, protocols, and requirements (e.g., habitat mediation and rehabilitation, erosion control, waste disposal and recycling protocols, and species-at-risk considerations). For example, European countries, such as England and Spain, have created comprehensive Geographic Information System (GIS) tools that consider legal, political, and environmental criteria to reduce the effects that can occur when deploying PV farms (Watson and Hudson 2015; Guaita-Pradas et al. 2019). Data generated from these types of analysis can further feed into broader land use and energy policy, ensuring that solar farms are deployed and maintained in a manner that reduces the cumulative effects of this technology. Many frameworks, however, currently do not incorporate these types of methodologies and instead focus on single effects such as albedo effects or erosion caused by developing the land. Further research (e.g., academic, governmental) is needed to focus on developing novel technologies, methods, and frameworks that continue to assess and mitigate cumulative effects. Besides providing novel information, this research needs to prioritize communicating findings effectively with decision makers, allowing them to adequately create assessment tools and regulations that reduce the cumulative effects of solar energy, thus making solar farms truly clean energy.

3.5. Marine hydrokinetic

3.5.1. Potential cumulative effects in marine hydrokinetic energy

Cumulative effects have rarely been considered in the context of marine hydrokinetic energy. Assessments of the impacts of various individual stressors, such as on wildlife or sediment and hydrodynamics, rarely look at the entire breadth of potential effects. The greatest knowledge base for environmental impacts that exists for marine hydrokinetics is borrowed from other marine developments (e.g., offshore wind turbine assessments). Thus, here we can speak to some of the potential isolated environmental impacts that should be considered (see Table 1 in Supplementary Material for examples). Impacts on fish, marine mammals, seabirds, sea turtles, and other fauna include direct collisions, displacement, direct disturbance, noise, and electromagnetic fields (e.g., Boehlert and Gill 2010; Tosh et al. 2014; Copping et al. 2021; Oman 2022). As tidal sites can be important foraging or nursery habitats (e.g., Benjamins et al. 2015; Hastie et al. 2017) where individuals gather in large numbers, this increases the potential for direct (e.g., colliding with underwater turbines) and indirect (e.g., through a loss of foraging opportunities created by barriers) interactions with marine energy structures (Onoufriou et al. 2019). Fish movement (Viehman and Zydlewski 2015; Keyser et al. 2016; Gonzalez et al. 2019; Scherelis et al. 2020; Whitton et al. 2020) and schooling behaviour (Fraser et al. 2018; Williamson et al. 2019) can be impacted by the placement of structure as well. For example, the tidal range energy structure of the La Rance on the Rance River in France has disrupted movement of certain salmonids, shads and eels (Frid et al. 2012). Furthermore, wave energy environmental impact research has identified that hydrokinetic structures may affect prey-predator dynamics with prey avoiding these altered habitats causing changes in the predator community (Gill 2005). Certain structures, however, may attract more biodiversity to the area through the artificial reef effect (Langhamer et al. 2009) and thigmotactic response, a behavioural reaction to tactile contact (Brickhill et al. 2005). While this may seem like a positive aspect, it has been debated as the higher biodiversity may also include invasive species (Bulleri and Airoldi 2005; Glasby et al. 2007) and may negatively impact other colonizer or native species (Langhamer et al. 2009).

Structures such as tidal stream turbines can disturb the benthic foundation by stirring up and depositing sediment (e.g., Boehlert and Gill 2010). Impacts of these developments are largely unknown, but it is thought that the movement of sediment can greatly damage invertebrate communities and other benthic organisms and their habitats, such as eelgrass beds, corals, and rocky reefs (e.g., Copping et al. 2021). Construction of large structures such as tidal barrages or turbines can greatly impact tidal and wave energy dissipation (e.g., Neill et al. 2012; De Dominicis et al. 2017; Largier et al. 2008), thereby impacting the tidal range (Goss-Custard et al. 1991; DeDominicis et al. 2017). Sandbanks and other coastal structures are dependent on consistent tidal flows and can be disrupted by development (Neill et al. 2012; Rahman et al. 2022), which would have a negative impact on coastal communities by rendering some ecological processes impossible especially affecting species who are less mobile (Nichols et al. 1978; Last et al. 2011), depend on ocean currents for movement (Boehlert et al. 2007), or less resilient to stress (Burrows 2012). Similarly, tidal projects can impact hydrodynamics of the speed and direction of certain water currents created by tides (Ramos et al. 2013; du Feu et al. 2019; Li et al. 2020). How this impacts the environment is largely unknown, with few studies aiming to understand the larger implications. A study at Ramsey Sound in Ireland demonstrated that nine tidal energy converters cumulatively caused velocity changes over 24 km away from the array and impacted local sand beds up to 12 km away (Haverson et al. 2018). Additionally, eight tidal stream developments in the Irish Sea had a cumulative effect on each other (see more details in the case study below; Haverson et al. 2017). Although results vary, modeling, such as in the studies above, have shown cumulative effects to be possible in various scenarios, despite this not being validated in the field. These preliminary results using modeling highlight the need to better understand the cumulative effects of marine hydrokinetics developments on the local benthic sediment and hydrodynamics using more field-based research, as their true impacts are still unknown.

While no definite cumulative effects studies have been completed, ocean thermal energy conversion (OTEC) projects have the potential to disrupt the natural chemistry (Boehlert and Gill 2010), temperature (Harrison 1987; Levin et al. 2023), and turbulence (Boehlert and Gill 2010; Levin et al. 2023) of

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ocean strata, as part of this technology brings together water from different levels in the water column. Similarly, effluent from salinity gradient developments will result in mixing differing salinity levels at release sites, with unknown impacts on marine organisms, nutrient levels, and their associated food webs (Comfort and Vega 2011; Seyfried et al. 2019). OTECs are thought to enhance phytoplankton growth which can then greatly influence carbon flux on the sea floor and potentially disrupt oxygen and carbon dioxide levels mid-water (Levin et al. 2023). Disruptions to existing thermal structures could also impact climate, such as ice sheet amounts, monsoon severity, El Niño currents, upwelling of ocean waters, and albedo effects (Nickoloff 2023). Directly, species may become entrained within pumping systems (Comfort and Vega 2011; Devault and Péné-Annette 2017), can be impacted adversely by chemical leakages (Devault and Péné-Annette 2017), and can contribute to bio-fouling (accumulation of certain invertebrates on machinery) that can complicate maintenance (Bordbar et al. 2023). While these impacts are plausible given the nature of these developments, the current evidence base is nearly nonexistent for these isolated effects, further compounding the challenges of considering these in cumulative effects.

3.5.2. Examples of cumulative effects in marine hydrokinetic energy throughout Canada and beyond

The marine energy sector in Canada is small and regionalized despite having some of the best potential for various marine hydrokinetic energy projects. For example, the Bay of Fundy boasts the largest tidal range in the world, resulting in quality tidal energy potential (Nova Scotia Department of Energy and Offshore Energy Environmental Research Association 2008). Over 190 tidal power sites have been identified in Canadian coastal waters that could supply at least 63% of the total energy consumption of the country (Government of Canada n.d.), with an estimated 37 000 and 146 500 MW existent off the Pacific and Atlantic coasts, respectively. Nova Scotia has recently invested actively in marine energy to contribute significantly to the electrical grid (Natural Resources Canada 2020). Unfortunately, impacts to flora, fauna, archaeology, tourism, and socio-economics are not well understood, and future consideration of these effects for the eventual consideration of cumulative effects of these projects include energy extraction, exclusion zones, number of developments, ecosystem changes, and site preparation considerations (Nova Scotia Department of Energy and Offshore Energy Environmental Research Association 2008). A lack of sufficient information regarding how wave energy can be used as a resource has hindered its development but has opened up opportunities and initiatives to explore the wave energy potential further (Government of Canada n.d.; Natural Resources Canada n.d.).

Around the world, understanding of individual, and thus, cumulative effects for marine hydrokinetics has lagged, with little information exploring collision risk, displacements, redirections, changes to oceanographic process, or food availability (Grecian et al. 2010). The limited literature on these effects mainly pertains to other types of projects. Additionally, very few EIAs have looked specifically at technologies like wave energy and tidal stream conversion (Michel et al. 2007). As stated previously, much of this technology is still in its early stages of development, and as a result, there is still a large amount of uncertainty about their environmental impacts (Michel et al. 2007), and therefore also cumulative effects.

4. Synthesis and recommendations

Overall, cumulative effects in clean growth technologies are generally understudied for most, if not all, initiatives highlighted in this review. This gap was evident in both research articles and government documents based in Canada but also internationally. In general, all clean growth initiatives require a more substantial evidence base to understand the cumulative effects associated with each type of infrastructure project. This is particularly true for older technologies, with newer technologies, such as marine hydrokinetics, having more examples of where project-specific cumulative effects were considered in environmental assessments. In addition to clean energy technologies highlighted in this review, we acknowledge that other clean energy technologies and cumulative effect causing activities exist and include green transportation (e.g., green vehicles, including personal vehicles and public transport), critical minerals, which are used in the manufacturing of many clean energy technologies, and electricity transmission to name a few.

This synthesis highlights the challenges that each clean growth initiative faces to understand the cumulative effects associated with each type of infrastructure. Understanding cumulative effects is particularly challenging due to inability to properly assess their impact on spatial and temporal scales and the need to predict how impacts will change in the future based on present-day conditions (Tricker 2007). In addition, due to the additive nature of cumulative effects, this can further cause issues when assessing cumulative effects over temporal and spatial scales as they (e.g., emissions of carbon dioxide over centuries; Tricker 2007). For example, some single impacts may occur immediately (e.g., loss of habitat, soil disruption, and mortality), while others may only become evidence in the long term (e.g., population declines associated with mortality), and how these impact each other cumulatively is difficult to assess. Furthermore, understanding how these impacts will be cumulative with clean growth projects that are new or have yet to be implemented is extremely difficult.

Cumulative effects that are socially and culturally connected are grossly underrepresented in cumulative effect assessments (Larsen et al. 2018). Traditionally, cumulative effect assessments have ignored social impacts with the focus being primarily on environmental impacts (e.g., air, water, soil, and pollution; Wang et al. 2003). Furthermore, Indigenous communities and First Nations are particularly at risk of impacts associated with cumulative effects. For example, approximately 73% of industrial disturbance for Site Dam C (BC Hydro) occurred within 250–500 m of Blueberry River

First Nations territory in northern British Columbia (Gialason and Andersen 2016). Similar impacts to First Nations lands also occur internationally. Cumulative effects associated with mining, such as combined impacts of vibration, noise, dust, and larger impacts such as pollution to groundwater and surface structure destruction (Franks et al. 2010) and its associated infrastructure have impacted greatly on the traditional lands of the Sami in northern Sweden, which are used to herd reindeer and other foraging activities such as fishing and hunting (Larsen et al. 2018). These impacts extend beyond the environment and wade into impacting cultural connection and social identity. We recognize that these impacts are extremely important and deserve their own literature review conducted by experts in this field to best address them. Understanding how these impacts from multiple projects interact with each other as well as the interactions between the environmental, social, and cultural aspects is necessary to develop best practices in cumulative effects assessment in clean growth activities.

Globally, embedding cumulative effects of clean energy technologies into impact assessment varies among technology types and among jurisdictions. Learning and sharing across jurisdictions will be necessary to ensure that there are more timely developments in this sphere. Although we focused on a Canadian context, we also sought examples of where/how cumulative effects were being considered elsewhere. In short, there are no standard approaches to doing so, and examples are somewhat haphazard. There is no specific region, country, or sector for which this has been adequately addressed. To that end, we offer the following eight recommendations intended to improve the evidence base to ensure that cumulative effects are adequately considered in impact assessments related to the emerging clean growth sector with the hope that they will support the development of relevant policy in Canada (Tedeschi et al. In Pres) and beyond.

i. Invest in long-term monitoring of clean growth technologies. Many clean growth projects involve emerging technology that have a fairly small evidence base, necessitating long-term monitoring to build better data. Moreover, impacts associated with cumulative effects may not manifest themselves immediately as these effects are a combination of actions from past to future. Due to their inherently complex nature, the importance of long-term monitoring cannot be emphasized more.
ii. Ensure adequate baseline data to contextualize potential impacts. Without adequate baseline data, it is difficult to determine if impacts have occurred and how they may contribute to cumulative effects. Baseline data are best obtained in terms of "pre" (before impact) studies but can also be obtained in parallel through use of appropriate reference systems. In fact, adopting a before-after-control-impact approach is among the most powerful ways to ascertain if any impacts, including cumulative ones, have occurred (Foley et al. 2017).
iii. Future-proof impact assessments by forecasting how cumulative effects will manifest in a changing world. As a result of other human environmental changes that may be entirely independent of a given clean growth technology, it is possible that impacts may change over time. For example, future climate change may magnify impacts or create new cumulative effects. As such, there is a need to use scenarios to project impacts in the future (Greig and Duinker 2007). Any efforts to mitigate (or compensate for) clean growth impacts need to be future-proofed to ensure that such mitigation continues to be effective in the future (Rehman and Ryan 2018).
iv. Embrace consistent terminology for research involving cumulative effects and clean growth technologies. The lack of consistent terminology for cumulative effects assessments has been apparent for some time (Judd et al. 2015). That same issue persists in the clean growth sector (variously termed clean energy, green growth, etc.). To enable researchers and practitioners to locate relevant literature and to ensure that we are comparing "apples to apples", there is need to embrace consistent terminology for both cumulative effects and clean growth.
v. Use varied indicators/endpoints to ensure comprehensive understanding of impacts. Cumulative effects are inherently difficult to study and can be easily missed if inappropriate or insufficient indicators or endpoints are used (Canter and Atkinson 2011). Use of a variety of indicators and endpoints that span systems, disciplines, and domains (e.g., societal, ecological) is encouraged to ensure that there is potential to detect cumulative effects.
vi. Consider cumulative effects assessments for a given clean growth activity in a broader context that is not isolated in space or time. Often times, cumulative effects assessments fail to consider the broader "landscape" and assume that impacts are isolated in space and/or time (Canter and Ross 2010) and treats isolated effects as cumulative in nature. Assessments should occur with an eye on the broader suite of potential impacts that may spill across assumed spatial and temporal boundaries.
vii. Create best practices for assessing cumulative effects of clean growth projects. Managers and regulators responsible for overseeing or undertaking cumulative effect assessments require best practices specific to clean growth projects. Unfortunately, there remain relatively few of these assessments that have been done in a manner that serve to set the "gold standard". More efforts are needed to develop and test best practices.
viii. Identify and share success stories where cumulative effects have been included in impact assessments for clean growth projects. In many ways, that was the goal of this paper. As outlined above, we identified examples of where cumulative effects assessments have been applied to clean growth projects. Rarely, however, do those studies/examples include truly reflective post-hoc assessments where they consider what worked and what did not work in reducing cumulative effects. There is a need for greater sharing of success stories, failures, and lessons learned to help develop or refine the practices of cumulative effect assessment for clean growth projects.
ix. Fund research to advance the science of cumulative effects in the context of impact assessment for clean growth projects. There is a need for dedicated funding to conduct comprehensive, long-term cumulative effect

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studies for all clean growth projects. Funding should focus on studies that embrace some of the best practice principles outlined here to ensure the evidence base is bolstered with the best possible science.

These proposed recommendations are given in hopes they will better ensure cumulative effects are considered in clean growth technologies. Failure to incorporate cumulative effect impacts during the early phases of clean growth projects could impede their ability to meet targets and yield the environmental and socio-economic benefits that are promised by the clean growth movement. Incorporating the above recommendations into cumulative effect impacts in clean growth can provide more complete impact assessments. Ensuring standardized regional, provincial, and/or national-level guidance and policy regarding reporting on cumulative effects in clean growth technologies is needed to facilitate consistent and accurate knowledge.

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Supplementary material

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