A synoptic history of the development, production environmental oversight of hydropower in Brazil, Canada and Norway

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Abstract

Sustainable global energy production is back-stopped by hydropower which is responsible for a significant share of the green energy produced worldwide. Hydropower, however, does not come without some environmental impacts, but has worked to reduce those impacts. Here we discuss the historical, legislative and design configurations of hydropower facilities located in three of the world's most important producers: Brazil, Canada and Norway. The background is intended to inform the collection scientific papers from each country aimed at assessing and improving the sustainability of hydropower production that form the core of this special issue on sustainable hydropower. We review the development and key legislative history for hydropower in each country and to point out the common backgrounds and interests each nation has in the continued sustainable development of its hydropower resources.

Introduction

Global hydro-electricity generation has now reached more than 4 000 TWh per year and matches that of nuclear, wind and solar electricity production combined (IEA, 2019). Globally, hydro-electric generation capacity has an estimated overall technical potential of four times the current production (16 400 TWh/yr), with installed capacity having risen sharply since the early 1970s. Since 2000, the rise in global generation ability has been particularly marked as a result of the rapid development of unexploited Asian, African and South American potential and the need to provide backstop generation capacity to other green energy approaches in Europe and North America (IEA 2019). Consequently, there are an estimated 3,700 dams either planned or under construction that are capable of producing in excess of 1 MW, primarily in developing nations where the demand of electricity is growing fastest (Zarfl et al. 2015).

Hydropower is the most important renewable electrical energy source worldwide and is typically seen as "green" energy that can be generated in an environmentally sustainable manner. Nevertheless, hydropower comes with a set of associated environmental impacts that can be both diverse and complex including: reduced ecosystem connectivity (Brown et al. 2013), habitat alterations resulting from reservoir construction (Sabater 2008), downstream effects associated with dam operation, i.e. hydrograph alterations (Poff et al. 1997; Forsberg et al. 2017), facilitation of species invasions and/or distributional shifts (Gherardi & Padilla 2014), alteration of watershed nutrient dynamics (Pokhrel et al. 2017, Moran et al. 2018), increases in contaminant levels (Rosenberg et al. 2000; Pringle 2001), possible loss of biodiversity in adjacent terrestrial habitats (Benchimol & Peres 2015), and potential greenhouse gas emissions from reservoirs (Prairie et al. 2018). As a result, since 1990 there has been an exponential rise in scientific studies associated with documenting and mitigating the more obvious environment impacts of hydropower production (Figure 1), with both the problems and approaches varying depending on where and how the hydropower potential is exploited.

In this special issue we focus on the issues associated with the assessment of hydro-power impacts on aquatic ecosystems by comparing and contrasting the development experience of three of the world's largest producers: Brazil, Canada and Norway, who combined produce 21.6% of the world’s hydro-electric output (IEA 2019). While each country produces the same basic product, each has a different approach to production (i.e., run-of-the-river versus pump storage) and do so at different scales (predominantly large versus small) and in different biogeographic regions (Figure 2). Nevertheless, each approach often encounters many of the same problems with the study and insurance of environmental integrity. By comparing and contrasting experiences, we hope to gain insights into commonly emerging problems and what needs mitigating to ensure sustainable hydropower production. To provide a basis for comparison, we first review the hydropower production systems within each country and the associated regulatory regime within which hydropower producers operate, as both have implications for the ways in which the costs and benefits of hydropower production are viewed in each country.

Brazil: A Synopsis of the Production and Regulatory Regime

History

The development of the Brazilian hydropower industry parallels that of many areas of the world, having begun in the 1900s as a result of private initiatives to provide electric power for lighting and transportation services to local cities such as São Paulo and Rio de Janeiro. Initial investment was largely foreign, with foreign entities controlling 70% of hydropower generation capacity by 1915 (Burrier 2016). The enactment of the Water Codes in 1934 set out a framework for hydropower regulation reflecting government intent to place future hydropower development under public ownership, with Federal and State owned utilities growing significantly after 1945 to become the leaders in the development, financing and construction of hydropower dams (Leite 2009). Eletrobras, established in 1961 as an autonomous agency of the Federal Government, continued that trend and was charged with the completion of studies to finance and construct electric power projects and operate electric power plants and transmission lines. With co-ordinated planning came the realization that installed capacity and potential in the heavily populated southeastern parts of Brazil could not meet the growing demand for electricity. Thus beginning in the 1960s, and continuing through to 1980, there was increased investment in the construction of large hydropower plants with the addition of over 22,000 MW of installed capacity (Burrier 2016), much of it occurring in the relatively underdeveloped Amazon (Harvey, 1976; von Sperling, 2012) that contains six of the world's largest 25 rivers (FAO, 2014).

Production

Brazil is endowed with a geography that lends itself to hydropower production, in particular because it receives an estimated 12% of the world's surface precipitation (de Souza 2007) and controls approximately 7% of the world's freshwater supplies (Burrier 2016). Consequently, Brazilian electric power is generated largely by hydropower, with hydropower plants providing 61.15% (109 GW) of installed capacity (ANEEL, 2020) as compared to the 16% global average (IEA 2019). Despite the high reliance on hydropower in the energy matrix, the percentage has decreased substantially in the last decade (from 84% in 2009) as the share of solar, wind and biomass sources have risen. Most electricity generation in Brazil is provided as a public service through government agencies (83.2%), with private producers accounting for the remainder. In all there are 1,368 hydropower plants in Brazil: 217 large (i.e. > 30 MW), 420 small (1-29 MW) and 731 micro-generation facilities (up to 1 MW), providing up to 102 GW, 5.3 GW and 0.8 GW, respectively (ANEEL, 2020). Most hydropower plants within the mix are classified as medium head (15-150m) facilities (von Sperling 2012).

Brazil is now home to some of the largest hydropower plants in the world, including Itaipu on the Paraná River between Brazil and Paraguay (14,000 MW, world's second largest), followed by the Amazonian dams at Belo Monte on the Xingu River (11,233 MW, world's fourth largest) and Tucuruí on the Tocantins River (8,370 MW, world's sixth largest). The highest concentration of hydropower, however, is in the midwest, south and southeast regions of the country (Dias et al., 2018), where the geographic relief is composed predominantly of small mountains and plateaus that create rivers with vertical drop suitable for the formation of large storage reservoirs (de Souza 2008). In contrast, in the Amazon Basin, hydropower projects are predominantly run-of-river that use bulb turbines that combine the turbine and generator is a single sealed unit and smaller reservoirs to minimize some of the negative social and environmental effects of hydropower development (von Sperling, 2012). In the run-of-river schemes the costs of per unit of energy are higher, since during the dry season hydropower production is reduced. For example, while installed capacity at Tucuruí is 8,370 MW, guaranteed capabilities are rated at only 49% of that (4140 MW) as a result of precipitation-driven variations in the availability of water for hydropower generation (de Souza 2008). Thus, despite having one of the world´s largest and most efficient grids for transferring electricity across regions, Brazil often has to use energy from thermal plants to meet energy demand because of the hydropower system's dependence on rainfall (Prado Jr. et al., 2016). Analyses of potential climate change impacts on the Brazilian hydropower system have indicated that climate change may drastically affect the ability of the system to meet energy demands and consequently, the system's capability to supply enough power (Soito & Freitas, 2011; Dias et al., 2018),

In the south and southeast regions of Brazil, which concentrates >55% of Brazil's population, the hydroelectric potential is nearly exhausted (Dias et al., 2018) and has been compromised recently by droughts which have negatively affected production (Semertzidis et al 2018). For example, 2001 and 2002 drought conditions precipitated the institution of rolling blackouts and compulsory rationing aimed at reducing consumption to compensate for that drought-induced reduction in generation capacity (Burrier 2016). As a result hydropower expansion came to be the centre piece of a federally funded economic growth initiative named Programa de Aceleração do Crescimento (Program of Accelerated Growth), launched in 2007. The program supported the construction of 55 new dams that nearly doubled Brazil's hydropower output, much of it concentrated in the Amazon Basin. In 2018, Brazil´s hydroelectric potential was estimated at 246,240 MW (Eletrobrás, 2018), with 40% of that located in the Amazon Basin. There are 416 operational or under construction dams and 334 planned/proposed dams in the Amazon Basin. Hydropower development in the region is currently constrained by limited infrastructure and low regional energy demand, with most dams located in upland tributaries (Winemiller et al., 2016). Furthermore, the environmental sensitivity of one of the world's most biodiverse regions and the presence of indigenous populations has raised concerns over the continued rapid expansion of Amazonian hydropower potential. According to the National Energy Plan for 2030, 62% of the hydroelectric potential in the basin is now subject to social-environmental restrictions due to the presence of protected areas, such as Conservation Units and Indian Reservations (Britto et al., 2015). Nevertheless, dams such as Belo Monte have been the focal point of both national and international protests centred on the preservation of the environment and indigenous land rights.

Regulation and Permitting

Brazil's Federal structure makes hydropower resource development governance complex given the sometimes competing interests and jurisdictions of Federal, State and Municipal authorities. In the context of licensing hydropower development, the most important body is the Brazilian Institute of Environment and Renewable Sources (IBAMA), which was created in 1989 and subsequently linked to the Ministry of Environment. IBAMA is responsible for environmental policy, monitoring, implementation of Federal environmental policies and the environmental licensing, quality control and inspection of hydropower facilities (de Britto et al. 2015). In Brazil, environmental licensing is required for any potentially polluting activity and/or activities that can cause impacts to the environment, such as hydropower dam construction. Licensing is regulated under the auspices of the National Environmental Policy (instituted in 1981) and should be preceded by an Environmental Impact Assessment (EIA) (World Bank, 2008). The licensing process differs according to the energy production. For hydropower plants > 30 MW, the Federal portion of licensing in Brazil is a tiered, three-phase process which must be matched with obtaining complementary authorizations from State or Municipal authorities. In the first phase a Provisional License must be obtained and is issued as part of preliminary planning for the project. The Provisional License approves project location, environmental viability and sets out construction conditions which are developed as part of the completion of environmental impact and risk analyses aided by public hearings. Following the Provisional Licence, an operator must obtain an Installation License that permits project construction and requires the meeting of previously determined conditions for project construction and the completion of any required complementary environmental studies. As part of the Installation Licence, environmental mitigation measures for the project are determined and approved. Before operations can begin, an Operating License must be obtained. The operating licence permits hydropower generation and sets out the conditions under which generation can occur. For example, low flow or reservoir level condition may be imposed. The Operating License further ensures that the conditions determined in the previous licensing phases have been met and will set out final environmental monitoring and control measures that must be implemented (de Britto et al. 2015). The process is not wholly bureaucratic as the Federal or State interest can intervene to defend the public interest or if there is evidence to suggest laws have been broken (de Britto et al. 2015). Accordingly, public hearings may become part of the licensing process.

Canada: A Synopsis of the Production and Regulatory Regime

History

From its beginnings in 1881 at Chaudieres Falls on the Ottawa River, Canada's hydropower capacity has grown steadily and Canada was the world's 3rd largest producer of hydropower (386 TWh) in 2019, just behind Brazil (398 TWh International Energy Association, 2020). Canada has an installed capacity of 81,000 MW, with approximately 155,000 MW of undeveloped potential (Canadian Hydropower Association, 2020). Hydropower accounts for 60% of all electricity generated in Canada and provides >80% of Canada's renewable energy supply. Hydropower production occurs in nearly all Canadian provinces and territories, and accounts for >90% of energy production in Quebec, Manitoba, Yukon, Newfoundland and Labrador and British Columbia, with Quebec (48%) and British Columbia (18%) being the largest producers.

Given the large size of the country and the associated variety of landscapes, Canadian hydropower production is diverse, including more than 500 facilities, ranging from pico- (<5kw) and micro-scale (<100kw) off channel run-of-the-river projects, to vast multi-dam projects with a large generation capacity. For example the James Bay complex in Northern Quebec features 11 dams and has an installed generation capacity of 16,527 MW (Canadian Mining and Energy, 2020). Many of Canada's largest hydropower dams were built in the latter half of the 20th century, for example BC Hydro's WAC Bennet Dam (1968, 2876 MW) and Labrador's Churchill Falls Dam (1974, 5428MW). However, some large dam construction is currently ongoing in Canada, including BC Hydro's Site C dam on the Peace River (1,100 MW), Labrador's Muskrat falls project on the Churchill River (824 MW), Manitoba Hydro's Keeyask project on the Nelson River (695MW) and Quebec's Romaine River 4 project (245 MW) which will increase the installed generation capacity for the La Romaine Complex to 1550MW. Given the northern location of much of Canada's production and potential and the concentration of its population in south, power transmission across long distances remains a challenge for the hydropower industry.

Production

The majority of Canadian facilities are comprised of traditional storage systems that rely on a combination of dams to increase the head of a waterfall and reservoirs that allow flexibility in production. Some of these storage dams are very large and have a high head height, such as Canada's tallest dam, Mica (240m head height, 2800 MW installed capacity) located on the Columbia River in the Rocky Mountains of British Columbia, and Canada's largest dam, the Robert-Bourassa Dam (5,616 MW 162m head height, 2,835m wide), which is part of the James Bay Complex and located on the La Grande River in Northern Quebec (Canadian Mining and Energy, 2020).

There are several large stand-alone run-of-the-river type hydropower facilities in Canada, including some of Canada's oldest and longest running, for example Beauharnois (1929) on the St. Lawrence River, Sir Adam Beck 1 (1922) on the Niagara River (1600 MW) and La-Grande-1 at James Bay (1436 MW). However, the majority of run-of-the-river dams in Canada are typically part of cascade systems, which occur immediately downstream of large storage dams, such as the Revelstoke Dam (2876 MW) located below the Mica Dam in British Columbia. Canada has just one pumped storage facility, the 174 MW Sir Adam Beck Pump Generating Station on the Niagara River, in Ontario. However, plans and proposals are in place to develop more pumped storage facilities, including a 1000 MW facility in Ontario (TC Energy, 2020) that will pump water from Lake Huron (Georgian Bay) to the height of the Niagara escarpment and the expansion to 900MW capacity at the existing Brazeau River facility in Alberta. Canada also has numerous small low head hydropower (<50MW) facilities with a total installed capacity of 3400 MW, which account for 4.5% of total hydropower production (Natural Resources Canada, 2020). Given that most of the feasible sites for large hydropower production are already utilized in Canada and there is an estimated 15,000 MW of undeveloped potential for small hydropower, small hydropower construction is expected to increase in the coming years in Canada (Natural Resources Canada, 2020).

Regulation and Permitting

The majority shareholders for hydropower projects in Canada are Provincial or Territorial Crown Corporations (i.e. government-owned or controlled enterprises) such as BC Hydro, Hydro Québec and Yukon Energy Corporation. While these corporations are responsible for most of the hydropower generation in Canada (Natural Resources Canada, 2019), a small proportion of hydroelectric power is produced from privately-owned companies. All hydroelectric producers must abide by the regulatory schemes enacted by both Federal and Provincial governments, although principal control rests with Provinces as a result of the constitutional prerogative for the exercise of legislative control over the management of natural resources found within their territories (Pineau et al. 2017). Federal authority is exercised directly only where waterways are interprovincial or international, although such waterways will in practice be jointly managed. Federal authority is also exercised indirectly through the National Energy Board which regulates energy exports and has limited jurisdiction over inter-provincial trade in energy. Accordingly, it is Provincial governments through their control licenses for hydropower production and royalty regimes that essentially control the development of hydropower potential across Canada and control is exercised through a variety of Provincial Ministries and Agencies. As a consequence, the rules governing hydropower development and management vary by province and invariably reflect the importance of hydropower in the economic development of the province as a whole. Thus, the 1960s saw provincially driven expansions of hydropower systems with politicians actively supporting hydropower with the aim of making electrical utilities a cornerstone of the provincial economy that would promote the growth of secondary industrial manufacturing activity.

Federal regulation impacts hydropower operations principally through environmental regulation, and all relevant Federal regulations must be adhered to by all hydropower companies, particularly those applied under the auspices of Canadian Environment Assessment Act that are designed to minimize project construction impacts, or those applied under the auspices of the Fisheries Act designed to protect fish and fish habitat. Additional regulations may be enacted at the Provincial level depending on the socioecological values of various jurisdictions. Many regulatory requirements are shared between the Federal and Provincial governments, so joint review panels may be formed to expedite review processes. Prior to 2019, at the successful completion of the environmental review process an 'authorization' to operate indefinitely was issued, although renovations or additional construction required new authorization. Since 2019, the revised *Fisheries Act* has included language permitting the Federal government to suspend, modify, or cancel an authorization under certain conditions.

The primary Federal legislative acts affecting the development and operation of hydropower in Canada are the *Canadian Environmental Assessment* (CEA) *Act,* the *Fisheries Act* and the *Species at Risk Act*. The *CEA Act* ensures that an appropriate assessment of all potential environmental consequences is completed for a project, with the objectives of ensuring environmentally sustainable development and minimizing the consequences of the project for affected socioecological systems. An important component of the *CEA* is accounting for the cultural and socioeconomic impacts of development on aboriginal peoples. *The Fisheries Act* has a general emphasis on protecting fish habitat and fisheries productivity (*No person shall carry on any [...] activity that results in serious harm to fish (death of fish or any permanent alteration to, or destruction of, fish habitat) that are part of a commercial, recreational or Aboriginal fishery, or to fish that support such a fishery*; Section 35(1)). Under the Act, the Minister of Fisheries may also request incorporation of fish passage structures or methods, screens or diversions at water intakes, and the release of adequate quantities of water if they consider that doing so is necessary to ensure the free passage of fish or the prevention of harm to fish and fish habitat. Design and construction issues are the major driver of Federal regulations in Canada (e.g. reservoir size, total dam footprint, head height), with operational regulations generally being covered at the Provincial level under the auspices of water management plans. Provincial regulations, however, may also limit or restrict work around water. For example, Ontario's *Public Lands Act* has a land use planning process that allows the Ministry of Natural Resources and Forestry to reject or accept a proposal based on its environmental consequences. Overall, the regulatory scheme for hydropower constructions in Canada is most likely to halt projects if they impact aboriginal communities, critical fisheries or fish habitat, migratory birds, or endangered species listed under the *Species at Risk Act*, which must be adhered to under all circumstances Notably, and despite the environmental oversight of hydropower development, gaining and sustaining public acceptance of large energy projects has become increasingly difficult in

Canada, with increased levels of protest and public opposition in the media being observed. And while most such activities have focused on hydrocarbon projects, large hydropower projects such as BC Hydro's Site C have faced similar treatment.

Norway: A Synopsis of the Production and Regulatory Regime

History

Most Norwegian hydropower (approx. 90 %) is publicly owned (by state, county municipalities or municipalities). The first hydropower plant in Norway began operation in 1885 in Skien (Tellefsen et al. 2020). New projects developed steadily in the following decades, with the construction of hydropower plants playing a critical role in development of industrial and economic growth in Norway (Meld.St.25 2016-2016, p. 30). In 1909, the Norwegian Parliament implemented a licensing system which both secured national control over hydropower resources and provided an institutional framework for their management (Auestad et al. 2018). State control was strengthened in 1921 with the establishment of a government agency, now called the Norwegian Water Resources and Energy Directorate (NVE), that over time grew to have scientific, advisory and supervisory responsibilities for Norwegian river systems and the production of electricity in general (Auestad et al. 2018). Beginning in the 1950s and lasting for nearly 30 years, there was an intense period of hydropower development, which slowed as conflicts between hydropower development and environmental concerns escalated. The Mardøla conflict in the summer of 1970 represented a significant turning point for Norwegian hydropower development with the mobilization of a broad social coalition opposed to further large-scale hydropower development. Although the project was completed, one outcome of the conflict was an increased emphasis on the ecological consequences of hydropower development, with the Norwegian Water Resources and Energy Directorate undertaking a number of large-scale applied research projects that focused on the environmental effects of hydropower (Auestad et al. 2018). The Alta-Kautokeino project similarly had a large impact on Norwegian hydropower development and came to be the largest single environmental controversy in Norwegian history (MacDougald 2008). In addition to worries about its effects on Atlantic salmon (*Salmo salar* Linnaeus 1758) populations and local sources of income, concerns coalesced around the loss of control over culturally important lands which belonged to the indigenous Sami people (MacDougald 2008).

These large political conflicts ultimately led to the creation of the Master Plan for Water Resources aimed at making hydropower development more predictable (NVE 2020). Potential for development is also regulated through national plans for protecting water courses from hydropower development, with four plans having been developed between 1973 and 1993 (Halvorsen, et al. 1998) and a final supplement plan issued in 2005.

Production

Around 94% of the energy production in Norway comes from hydropower and the total mean annual production is estimated at 135 TWh (NVE, 2020). The topography and climate of Norway are well suited for hydropower production given the steep terrain and high annual precipitation and that approximately 40% of the Norwegian landmass lies more than 600 metres above sea level (Graabak et al. 2017). Thus, the main part of the Norwegian system (around 80%) consists of high head plants with storage reservoirs at higher elevations connected via tunnels to power plants at lower altitudes. The configuration uses the large elevation difference between intake and turbine and results in smaller production discharges as compared to traditional run-of-the-river power plants. Run-of-the-river plants that utilise large river discharges and a relatively low head are mainly found in the larger rivers of south-eastern Norway. One notable effect of the reliance on high-head structures is that the majority of Norwegian hydropower plants are underground with powerhouse turbines and generators housed in mountain caverns linked to the reservoir and outlet point with tunnels. Reliance on high-head structures also skews the distribution of hydropower plant size toward smaller sizes (<10MW), 1175 plants falling in the 0-10MW size range, 255 plants in the 10-100MW range and 80 power plants larger than 100MW responsible for 80% of total hydropower production (Thaulow et al. 2016).

The Norwegian hydropower system has more than 1000 reservoirs with a storage capacity of about 85 TWh (Graabak et al. 2017), which represents about 50% of the European storage capacity (Lehner et al. 2005; Tellefsen et al. 2020). The capacity makes the Norwegian power system very flexible and capable of adapting quickly to the variable market demands for electricity. Initial connections to the broader Scandinavian market were undertaken in the 1960s, largely as a means of offsetting the variations in reservoir inflows that occurred between wet and dry years (Tellefsen et al. 2020). Interconnection with the continental European market has since developed with the aim of using Norwegian hydropower capacity as a battery for balancing the production capabilities of European renewable energy sources. In 1991, the Norwegian Energy Act deregulated the energy market and electricity is now traded through the Nordic power exchange, Nord Pool, with the Nordic market having expanded with connections to Germany and the Netherlands. With the transition to a renewable energy system, the flexibility of the Norwegian system has been proposed as a battery for balancing intermittent European renewable resources through increased connection with Europe (Graabak, et al. 2016). In such a system, energy could be imported to Norway during periods of high production and low prices in the European market to facilitate pumping to higher reservoirs in the Norwegian system as a means of storing generation potential for periods of high demand and low production in Europe (Charmasson et al. 2018).

Another important component in the Norwegian system are transfers and brook intakes where smaller rivers and streams are taken into the tunnels and transferred to reservoirs or directly to the power plants. Over the last decades, several hundred small hydropower plants (<10 MW) have been built with a total estimated production potential of 10.7 TWh. Most of these have very little to no storage capacity but are still of the high head type (Figure 2D) where the production is mainly controlled by the head.

An effect of the high head power plants that use long intra-basin transfer tunnels and brook intakes (Figure 2A and 2D) is that a considerable parts of natural river reaches are bypassed by the tunnel systems, resulting in reduced river flows over long distances in many rivers. Some of larger Norwegian hydropower systems also use inter-basin transfer where water is transferred between river basins leaving the donor basin with a permanent reduction in runoff downstream of the point from where water is transferred.

Regulation and Permitting

The technical potential for hydropower in Norway is estimated to be 212 TWh, of which 132 is constructed and 50 is protected due to environmental concerns (Meld.St.25 2016-2016, p. 158). Approximately 70 % of Norwegian watersheds and 15 of the 20 highest waterfalls are currently affected by hydropower (Norwegian Environment Agency 2020). Due to the high cultural and economic value of Atlantic salmon, mitigating environmental effects of hydropower in Norway has mainly been concentrated on salmon rivers and there is now a well-developed tradition for collaboration between hydropower companies, nature managers and scientists. Approximately 32 % of Norwegian salmon populations are found in rivers regulated for hydropower (Anon. 2018). Environmental mitigation targeting other riverine species or lake (reservoir) ecosystems, however, are less developed. Since 2007, Norway has implemented the EU Water Framework Directive (WFD) and is committed to achieving "good ecological status" in all waterbodies.

Regulation and management of hydropower production in Norway involves a number of different ministries and directorates, the most important of which are: the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Environment Agency (NEA). The legal framework under which hydropower is developed is complex, with regulations enshrined in a number of parliamentary acts, the most important of which include: the Watercourse Regulation Act (1917), the Water Resources Act (2000), the Planning and Building Act (1965-2009) and the Water Framework Directive (2006). To operate a hydropower plant, a licensee must have a hydropower license that depends on the size and age of the facility, i.e. large hydropower projects > 10MW, small hydropower projects <10 MW installation, and revisions that apply to the terms and conditions of older hydropower licenses. All licensing must be transparent and include sufficient opportunity for public consultation, meaning that considerable time and resources are usually devoted to the process of obtaining a licence.

The licence grants permission to develop and run both the power station and any associated dam and includes conditions and rules for operation and specific requirements for the mitigation of environmental impacts (Thaulow et al. 2016). All license conditions must meet the requirements of the Water Framework Directive which focus on the biology and chemistry of the affected waters, but can be broader if tailored to meet local social and environmental concerns as outlined under Norwegian legislation. For example, licenses regulate how much water can be stored in, or released from, reservoirs with the aim of limiting the maximum and minimum water levels, although there is no consideration given to how rapidly or frequently water level fluctuates within these limits and/or the ecological consequences of fluctuating water levels. Some power producers operate with environmental restrictions that set minimum flows, environmental flows and reservoir level restrictions. However, in 2013 less than 15% of hydropower affected rivers had minimum flow restrictions, and a review of 187 watersheds operating under historical regulations indicated that 54% of those did not have any environmental restrictions (Sørensen 2013).

Licences issued after the 1970s usually include general terms and conditions which allow NVE to impose environmental regulations aimed at avoiding or minimize the negative environmental effects of hydropower. Such regulations are typically aimed at controlling loss of biological diversity, mitigating reservoir impoundment effects (i.e., sedimentation, water quality, modified hydrological regimes), or ensuring fish passage migration and river habitat connectivity. Some mitigation regulations, however, have been implemented for the benefit of landscape and other important societal values (Thaulow et al. 2016). While most of the environmental regulations are managed by NVE, those directly targeting fish, ecology and outdoor life are managed by the Norwegian Environment Agency and the County Governors (OED 2012). Although many watersheds do not have such general terms and conditions yet, this is expected to change due to the ongoing process of revising the terms of hydropower licenses. The terms of more than 400 licenses in 187 watersheds are expected to be opened for revision before 2022, with the main goal being the improvement of river and watershed environmental conditions. Nevertheless, the over-arching aim will be to ensure a sustainable balance between environmental considerations and the goal of minimizing the power production losses (Sørensen 2013).

Conclusions

Geographically separated and dominated by generation design differences that owe much to their respective geographies, Brazil, Canada and Norway would appear to have few similarities in terms of their experiences with, and concerns for, hydropower generation. Such a conclusion, however, would not account for the similarities in their histories of development, particularly the role that hydropower has played in the development of each countries resource and industrial base. Such a conclusion would also overlook the social conflicts that have determined, and are determining, the course of hydropower developments in each country. Endowed with great hydropower potential, each country has recognized its importance as an engine of economic growth and latterly as a source of "clean" energy. And there are growing connections between the countries, for example, Norway's leading hydropower producer Statkraft has recently made significant investments in Brazilian Hydropower having purchased 450 MW of capacity with plans to continue its operations in Brazil. Such investments will bring with them technology transfers, including those developed elsewhere to help ensure the ecological integrity and sustainability of generation projects. Accordingly, the comparison and contrast of existing studies regarding hydropower development in the three countries, as here, should contribute both to the debates about "green energy" and the development of a consensus about how hydropower can continue to best contribute to its production.

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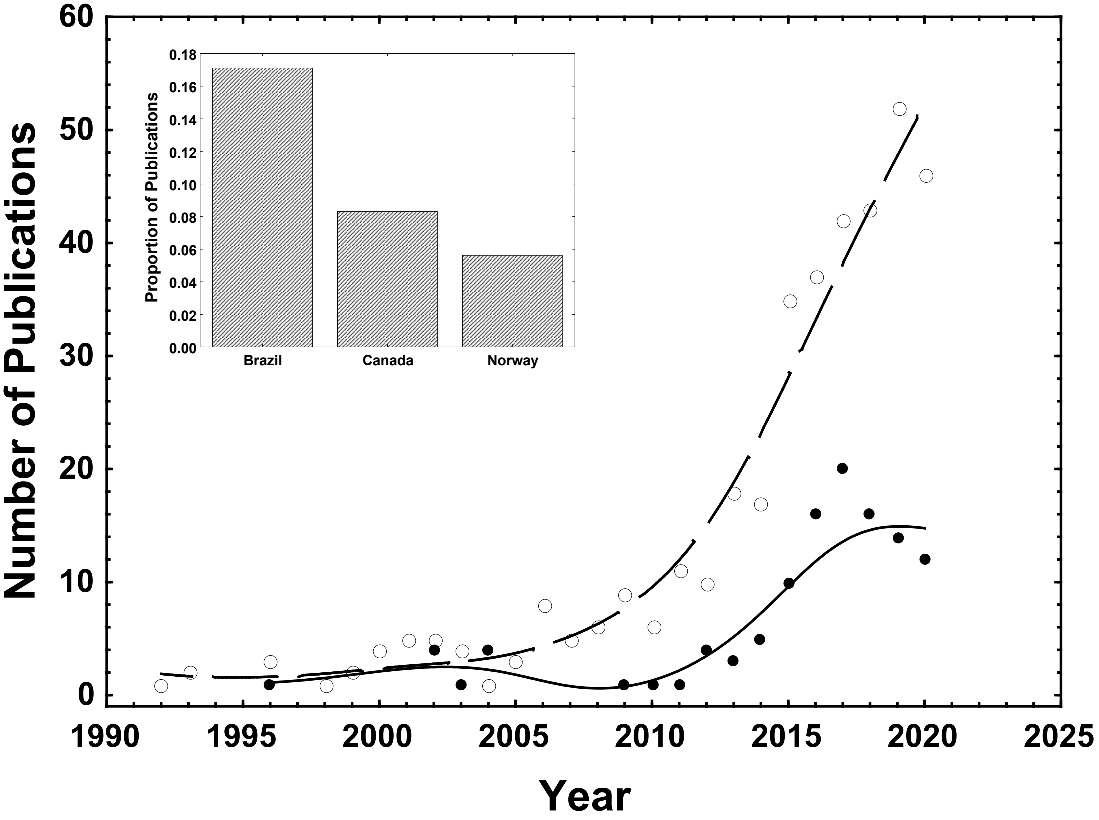

Figure 1: Annual number of peer-review papers published between 1990-2020 (dashed line) as obtained from the Web of Science using the search terms "hydro-power" and "environmental impacts" and the same trend (solid line) for Brazil, Canada and Norway combined depicting the recent exponential rise in research efforts focused on the environmental impacts of hydropower. Inset shows the relative proportion of all papers published that focus on hydro-power issues in Brazil, Canada and Norway.

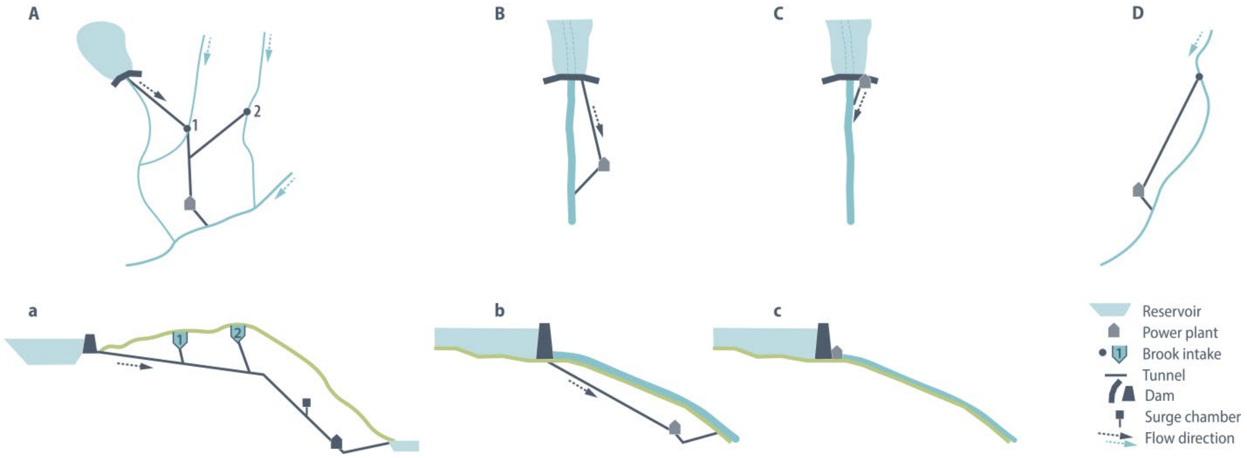

Figure 2: Schematic bird's eye (upper case) and cross-sectional (lower case)views of the different possible hydropower configurations that dominate in Brazil, Canada and Norway. A,a) High head system with reservoir and river intakes and underground power plant common in Norway; B,b) Medium head power plant with river reservoir and underground power plant also common in Norway and Canada; C,c) Run-of-the-river power plant with power house at the dam common in Brazil and Canada; and, D) High head power plant with no storage, typical for small hydropower systems in all countries. Legend, lower right corner, defines the key features of hydropower stations.