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Lubricant Oil Consumption and Opportunities for Oil-Free Turbines in the Hydropower Sector: A European Assessment

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Abstract: Lubricant oil is used in hydropower units to minimize friction, improving the turbine efficiency and reducing the wear. However, oil production is a pollutant process, while eventual spills may affect water quality and damage freshwater ecosystems. In this study, the lubricant oil consumption of the European hydropower fleet was estimated (considering its installed capacity of 254 GW). The energy required to extract and process the oil was also estimated based on available literature data. The oil consumption was estimated to be 22×10^3 tons/year, and the associated CO_2 emissions are 10^5 tons/year. The lubricant oil costs EUR 116 million per year. Although this is only 0.0022% of the oil consumed as a primary energy source in the European context, and less than 0.4% of the European industry consumption of lubricant oil, results show that new bearing types and oil-free turbines (e.g., self-lubricating or water-lubricated turbines) can improve the sustainability of the hydropower sector, minimizing the risks and impacts associated with incidental oil spills and leakages. The provided data can also be used for Life Cycle Assessment analyses.

Keywords: bearing; hydropower; lubricant; oil-free; turbine

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1. Introduction

Hydropower accounts for 1360 GW of installed power worldwide and 254 GW in Europe, and globally generates 4250 TWh/year [1]. Hydropower is a renewable energy technology and it provides flexibility to the electric grid and ancillary services. Multipurpose reservoirs provide several additional benefits, e.g., water storage and flood control. On the other hand, the alteration of aquatic ecosystems is perceived to be the main cause of hydropower-related impacts, with risks imposed on migrating fish and biodiversity. Therefore, hydropower needs to achieve a good balance between electricity generation, social benefits and impacts on the ecosystem and biodiversity, limiting the conflict with the environmental objectives of water policies. Within this context, novel emerging technologies are discussed in [2–4], where their benefits in a European context are estimated. The implementation of these technologies can mitigate the impacts of hydropower on the environment, while generating renewable energy and providing flexibility.

The impacts associated with turbine operation may be relevant in certain contexts. The turbine may affect water quality (e.g., oxygen deficit and oil spills) and may damage migrating fish which pass through it. With the aim of reducing these impacts, environmentally enhanced turbines (EETs), e.g., auto-venting turbines, self-aerated draft tubes, oil-free turbines and the so-called "fish-friendly" turbines, have gained attention in the past two decades [5]. However, although the benefits of these turbines (e.g., the reduced fish mortality of fish-friendly turbines), and the risks of traditional turbines, are clear and evident, the quantitative estimation of some of them is challenging on a large scale.

Among other things, the impacts of lubricant oil have not been quantitatively estimated yet on a large scale, e.g., in Europe. Oil lubricates the runner blade trunnion bearing and sliding parts of the operating mechanism in the hub [6], e.g., in the case of adjustable turbines (Kaplan and Deriaz turbines). Oil is also used in the gearbox, if present. The production of lubricant oil is highly pollutant and requires energy for extraction, production, maintenance and transport. González-Reyes et al. (2020) [7] discussed the different types of oil, distinguishing between mineral, biodegradable and synthetic. Biodegradable oil is a better option in terms of energy and CO_2 equivalent emissions than mineral or synthetic oils. However, biodegradable oil may pose potential risks in contact with water. Oil needs to be changed regularly, which entails a break in generation, causing economic losses. Furthermore, lubricant oil must be managed as a dangerous waste, with inherent risks of spillage during handling, that can generate negative impacts on the environment, and has some operational and maintenance problems [7–9]. In Francis turbines, the hydraulic oil system does not come into contact with the open water cycle, hence oil spills from the turbine directly to the open water are avoided. Oil spills may instead occur in the hydraulic cylinders of the intake gates. In Kaplan turbines, oil spills are more common, especially in the runner, because the blades are adjustable and the seals are not 100% tight. In older turbines, the whole runner is filled with hydraulic oil, whereas, in new runners, only parts of the runner are filled with oil [8].

Since most hydropower units use lubricant oil, the estimation of the annual amount of oil used is of high interest. This is especially valid for Europe, where the target of 100% renewables has been set by 2050 in the European Union (EU). Therefore, in this study, the lubricant oil consumption of the turbines installed in the European hydropower fleet is quantified, and the benefits that oil-free turbines can entail are quantified as well. Section 2 describes the implemented method to estimate oil consumption and impacts. Section 3 describes the results and Section 4 discusses the related implications. The European Union (EU) includes Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden. Europe also includes: Albania, Andorra, Belarus, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Greenland, Iceland, Kosovo, Liechtenstein, Macedonia, Moldova, Monaco, Montenegro, Norway, San Marino, Serbia, Switzerland, Turkey, Ukraine, United Kingdom.

2. Materials and Methods

The open source JRC (Joint Research Centre) hydropower database, including 4030 European hydropower plants, 2429 of which are located in the European Union, was used in this study to carry out the calculations. The database mainly includes hydropower plants with installed power above 1 MW and from hereinafter called hydropower database. The hydropower database specifies, for each plant, the country, the type (run of river—ROR-, reservoir hydropower plant—RHP-, pumped hydropower storage—PHS), the installed power (P, kW), the gross head (H_{gross}, m) (in most cases, but not for all), the annual energy generation (E, kWh) and, for some of them, the reservoir volume (V, Mm^3). In this database, 194 GW are included, with respect to the total European installed power of 254 GW; therefore, although the database is not complete and was completed in 2019, it is a statistically representative sample of the hydropower fleet (the missing data are mainly related to small hydropower plants and to some countries where data are not available). This database was used in [3] to assess the potential of modernization strategies and in [10] to assess the energy potential associated with the recovery of the wasted energy (hydrokinetic energy at the tailrace, heat from the generators and degassing methane).

The number of units (to calculate the flow and power per unit) and the turbine type were estimated as described in [10], mostly considering indications and collected data from the hydropower company Voith Hydro (Figure 1 and Table 1). Therefore, we suggest referring to [10] for more information, where the methodology was validated and proved to adequately estimate these technical characteristics.

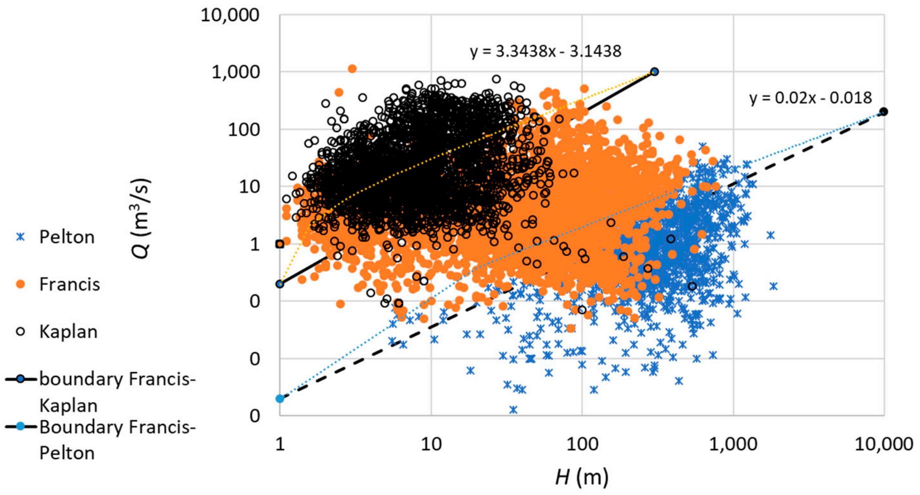

Figure 1. Range of Kaplan, Francis and Pelton turbines in the EU, based on flow rate *Q* and head *H* ([10], based on Voith Hydro), but without indication of the location.

Table 1. Average number of units (No.) per power class (K = Kaplan, F = Francis, P = Pelton) (Source: Voith Hydro).

Power Class *P* (MW) (Overall Installed Power per Plant)									
P	**1–10**	**10–20**	**20–50**	**50–100**	**100–200**	**200–500**	**500–750**	**750–1000**	**1000–1500**
No. of units	1 (K, P), 2 (F)	1.8	2.1	2.3	2.5	3.2	3 (K, P), 5 (F)	3.7	6.0

The required oil in each unit was estimated considering the power per unit, the number of units and the turbine type, according to Table 2 (RD 34.10.559 [11]) RD is a regulatory document that establishes rules and procedures for actions in a particular field of activity and is approved in accordance with the procedure established in the industry. This guidance document was developed by the production association for the adjustment, improvement of technology and operation of power plants and networks. RD 34.10.559 are designed to determine the annual oil consumption during the operation of hydraulic units for turbines of different types and capacities. The annual oil consumption is made up of its consumption for topping up during the operation of the hydraulic unit, for replacement and for compensation of losses during the overhaul.

Table 2. Oil consumption in hydropower units [11].

Turbine Type	**Power, MW**	**Turbine Oil Consumption Rates (Tons per Year)**				
		Topping Up	**Replacement**	**Compensation of Losses**	**Total Annual**	**Collection Amount**
Francis turbine Propeller hydraulic turbine Pelton turbine	from 1 to 5 (incl.)	0.63	0.34	0.13	1.1	0.28
	from 5 to 16 (incl.)	0.74	0.47	0.29	1.5	0.39
	from 16 to 85 (incl.)	0.84	1.09	0.39	2.32	0.92
	from 85 to 650 (incl.)	0.96	2.06	0.80	3.82	1.75
Kaplan turbine (Vertical)	from 1 to 5 (incl.)	0.7	0.23	0.3	1.23	0.19
	from 5 to 20 (incl.)	1.58	0.79	0.4	2.77	0.67
	from 20 to 40 (incl.)	1.99	1.42	0.5	3.91	1.20
	from 40 to 85 (incl.)	2.38	3.14	0.58	6.10	2.66
	from 85 to 220 (incl.)	2.67	4.92	0.9	8.49	4.18
Kaplan turbine (Horizontal)	from 19 to 48 (incl.)	1.4	1.42	0.5	3.32	1.20

Topping-up oil compensates for losses due to cleaning, evaporation, foam formation, leakage through leaks in the oil system and through the seals of the runners of Kaplan turbines, and when sampling for analysis. Oil consumption rates for topping up and compensation for irretrievable losses during the operation of hydraulic units are estimated by a statistical method. Oil consumption rates for replacement are estimated by an analytical method, taking into account the capacity of the oil system and the service life of the oil. Based on the results of a survey of hydroelectric power plants, the average oil service life for low-capacity oil systems is 8–10 years; for large ones it is 15 years. Oil losses during the overhaul of hydraulic units consist of losses in the form of an oily residue and emulsion at the bottom of the oil pans of the guide and thrust bearings of the turbine and generator when draining oil, as well as oil consumption for flushing the baths of the lubrication system and control units. Oil losses during overhauls are included in the oil consumption rates, taking into account the overhaul period of the hydraulic unit. When oil is replaced in the equipment, waste oil is collected. The collection of oil per unit during periodic replacement is determined by taking into account that the collected waste oil is about 0.85 of the volume of oil for replacement (from the normative RD 34.10.559 [11]).

The energy (MWh) used to manufacture and transport the oil was quantified according to [8]. The former was estimated as 8.26 kWh/L and the latter as 1.37 kWh/L, as average among mineral, synthetic and biodegradable oils. The associated emissions are 3.18 $kgCO_2/L$ for the manufacturing, and 0.53 $kgCO_2/L$ for the transport (the conversion factor from kWh to $kgCO_2$ is 0.385). The transport is very site-specific, and in this study, an average distance of 87 km was assumed. The average cost is estimated 4.3 EUR/L and a density of 0.8 kg/L was assumed. The emissions resulting from extraction and transport are insignificant compared with those related to the energy used in the manufacturing of the oil.

3. Results

Data of Table 2 were used to perform the assessment, implementing them to the European hydropower fleet data. Table 3 depicts the cumulative power per power class and the estimated turbine type (Figure 1) of the European hydropower fleet. Table 4 shows the oil consumption for each power class and turbine type. The composition of the European fleet has proven to be adequate for large-scale assessments, as already discussed in [3,10]. The Francis turbine is the most widely used in the European context, thanks to its wide operating range. It is the most suitable turbine for the typical European topographic/hydrologic context.

Table 3. Cumulative power P (MW) for each power range and turbine type.

	<5 MW	**5 < P < 16**	**16 < P < 20**	**20 < P < 40**	**40 < P < 85**	**85 < P < 220**	**220 < P < 500**
Pelton	1115	1550	194	2282	5244	9669	1269
Francis	3665	13,527	5466	26,820	37,436	48,219	11,176
Bulb	14	0	0	0	0	0	0
Kaplan	45	900	676	3361	9547	9969	2879

Table 4. Cumulative oil consumption (tons/year) for each power range and turbine type.

	<5 MW	**5 < P < 16**	**16 < P < 20**	**20 < P < 40**	**40 < P < 85**	**85 < P < 220**	**220 < P < 500**
Pelton	574	260	26	172	223	298	11
Francis	4028	2091	691	2069	1559	1413	168
Bulb	4	0	0	0	0	0	0
Kaplan	29	230	108	439	1043	662	93

The aggregated results at the European scale show that the amount of oil used in the European context is 16,200 tons/year with a required energy of 0.19 TWh/y and CO_2 emissions of 75,075 tons/year. The total cost is estimated to be EUR 87 million per year. These results refer to 195 GW, and can be extrapolated linearly to the whole 254 GW of European installed capacity. For the whole European context, the consumed oil is 21,665 tons per year and the required energy is 0.26 TWh/y, which represents 0.04% of the hydropower generation in Europe, roughly corresponding to one third of the maximum potential of hydrokinetic turbines in EU rivers estimated in [4]. The CO_2 emissions are 100,473 tons/year. The investment cost per year to satisfy the oil requirement becomes EUR 116 million per year. In the EU, the annual consumed oil is estimated to be 12,575 tons/year, corresponding to 0.0022% of the oil consumed as a primary energy source (582 Mtons per year).

Topping-up oil compensates for losses due to cleaning, evaporation, foam formation, leakage through leakages in the oil system and through the seals of the runners of Kaplan turbines, and when sampling for analysis. These losses and compensation for irretrievable losses represent 59% of the total amount of used oil. The collection amount is 85% of the replaced oil, which ranges between 15% and 49% (average, 34%) of the annual oil consumption of each unit.

4. Discussion

The impact of oil consumption in the European hydropower sector was assessed, identifying impacts in terms of CO_2 emissions, energy and costs. According to Mordor Intelligence (2022), in the most contributory European countries (France, Germany, Italy, Russia, Spain, United Kingdom), the lubricants market stood at 5.83 billion liters in 2021 and is projected to reach 6.53 billion liters in 2026. The automotive industry is the largest segment by end-user industry, accounting for around 49% of the total lubricant consumption in the region. Power generation is likely to be the fastest-growing end-user industry in the market, with a compound annual growth rate (CAGR) of 2.54% over the period 2021–2026, followed by automotive (2.49%). In Europe, the expanding power generation capacity, especially that of renewables, is likely to drive the consumption of lubricants in the power generation industry. The hydropower sector counts for less than 0.42% of the European lubricant oil consumption in the industrial sector [12].

The estimated values include the oil that is spilled into the environment (part of topping up item and losses, Table 1), that generally occurs as a consequence of incidents or in the form of oil droplets and oil mist leakage due to the centrifugal force and high temperatures [6]. However, the problem of oil mist leakage from bearings is complex, and it is difficult to assess exactly how much of this oil is spilled into the environment. Data collected in [7] show that this amount can reach 68 l/y/MW for a Kaplan turbine, with negative effects on the environment downstream, for example on fish, birds, mammals and plants. Spilled oil can contaminate the fish respiratory organs. Eggs and fish larvae can absorb toxic components from the oil. Spilled oil may stick to bird feathers; hence they may lose thermal insulation and waterproofing. The fur of mammals may become contaminated with oil, and it may also lose thermal insulation. In vegetation, a reduction in transpiration may occur, with a consequent reduction in photosynthesis. However, it must be noted that, according to [13], oil presence in aquatic ecosystems may not solely and mainly be attributed to the hydropower sector. Furthermore, other sectors, in addition to wind turbines, involve rotating components and desalination plants require oil [8,14].

The main solutions for minimizing the use of oil are (1) using oil free solutions, such as oil free bearings and oil free hubs, or water-lubricated turbines, and (2) implementing more environmental friendly solutions, such as an ester-based oil or other biodegradable oils, oil/water-based enhanced nano-lubricants, oil/greases and additives [15–17]. Sun et al. (2022) [6] discussed further conventional engineering measures to deal with oil mist leakage: reduction in the operating pad and oil temperature, optimization of the oil circulation loop in the oil tank, improvement of the sealing performance, and design of the oil mist emission device. Self or water-lubricated turbines can help in minimizing impacts, minimizing eventual environmental damages due to unexpected oil leakages and spills. Water-lubricated guide bearings also contribute to increasing the overall plant efficiency by reducing friction losses by about 50% and limiting maintenance in comparison to oil-lubricated ones [17]. To date, several Kaplan bulb and Francis turbines have been upgraded so as to make them work free from oil [5], but this technology can also be extended to Deriaz and Pelton turbines [5]. New materials and lubricants are being developed [18,19]. These technologies are developing more and more, especially in the European context. Some examples of their implementation are described in [20,21]. We suggest referring to the abovementioned references for further details.

However, some challenges exist. Given the low viscosity of water, bearings lubricated with water tend to operate in a boundary or mixed lubrication regime for relatively longer periods [5], especially when considering low sliding speeds and start/stop cycles. This can significantly increase friction while shortening the effective wear life of bearing components. Therefore, the use of water-based lubrication introduces several engineering challenges, foremost of which is the material choice for bearing surfaces. New materials are mainly at the development and R & D stage and have not fully met the operation and endurance targets set by the hydropower industry [19]. Oil-free rotor support systems have also enabled a broad range of high-speed machineries outside the hydropower sector, from air cycle machines, compressors and blowers to turbochargers, microturbines and small gas turbine engines [22].

Although, in this study, the impacts associated with oil consumption in hydropower plants was assessed, hydropower should not be regarded only in terms of impacts, especially when compared with the solar photovoltaic (PV) and wind sectors. For example, hydropower equipment does not contain critical materials such as lithium and cobalt (used in electric vehicles), or neodymium, praseodymium, and dysprosium (used in electric vehicles and wind power plants), or silver and silicon (used for photovoltaics). Hydropower is the best renewable energy for reducing pressure on mineral resources. The Extraction of Mineral Resources indicator is measured in kilograms of antimony equivalent (kgeq.Sb) per kilogram extracted to take into account existing reserves, the rate of extraction and the “depletion” of each mineral substance; the value for hydropower is 0.017, whereas it is 0.04 for coal, 0.3 for wind and 14 for solar PV [23]. Therefore, any energy technology should be comprehensively considered with regard to its impacts and benefits. Tables with sustainability indicators for each clean energy technology, benefits and impacts, with focus on the European Union, can be found in [24], and in [25] for the hydropower sector.

5. Conclusions

Hydropower benefits and impacts are at the center of major discussions. In order to mitigate the impacts, mitigation measures have to be developed and implemented.

In this study, a European assessment was carried out to estimate the oil consumption, and related impact, associated with hydropower operation. The aggregated results at the European scale show that the amount of oil used in the European context is 21,665 tons/year with a required energy of 0.26 TWh/year and CO_2 emissions of 100,473 tons/y. The total cost was estimated to be EUR 116 million per year. The required energy to satisfy the oil demand corresponds to 0.05% of the hydropower generation in Europe, roughly corresponding to one third of the maximum potential of hydrokinetic turbines in the EU rivers. In the EU, results reveal 12,575 tons/year of oil used, which is 0.0022% of oil consumption as a primary energy source and less than 0.42% of the lubricant oil production in the European industry.

This figure indicates that the pollution associated with the use of oil in the hydropower sector is marginal if compared with other sectors. Anyway, oil-free hydropower units could have positive impacts on the ecological status of rivers, supporting the clean and renewable energy targets set by the European Commission, and making hydropower further amendable, especially in light of the modernization needs of the European hydropower fleet.

Large-scale impact assessments should be also performed for the other sectors (e.g., wind and solar), whose impacts on the environment have been less studied, especially the impact of critical materials extraction and use.

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