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# Global freshwater thermal emissions from steam-electric power plants with once-through cooling systems

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ABSTRACT

Large quantities of heat are rejected into freshwater bodies from power plants employing once-through cooling systems, often leading to temperature increases that disturb aquatic ecosystems. The objective of this work was to produce a high resolution global picture of power-related freshwater thermal emissions and to analyse the technological, geographical and chronological patterns behind them. The Rankine cycle was systematically solved for ~2400 generating units with once-through cooling systems, distinguishing between simple and cogenerative cycles, giving the rejected heat as a direct output. With large unit sizes, low efficiencies, and high capacity factors, nuclear power plants reject 3.7 GW heat into freshwater on average, contrasting with 480 MW rejected from coal and gas power plants. Together, nuclear and coal-fuelled power plants from the 1970s and 1980s account for almost 50% of the rejected heat worldwide, offering motivation for their phasing out in the future. Globally, 56% of the emissions are rejected into rivers, pointing to potential areas of high thermal pollution, with the rest entering lakes and reservoirs. The outcome of this work can be used to further investigate the identified thermal emission hotspots, and to calculate regionalized water temperature increase and related impacts in environmental, energy-water nexus studies and beyond.



## 1. Introduction

Steam-electric power generation requires copious amounts of cooling water. Broadly speaking the heat absorbed in the cooling water is either removed by means of a (wet/dry) cooling tower, a cooling pond, or rejected directly into a water body. The latter is known as once-through cooling and is responsible for power-related thermal pollution of freshwater bodies. The deleterious effects of temperature increase on aquatic ecosystems have been reported in numerous publications [1–8]. The need to abate thermal pollution, problems of fish impingement and entrainment, as well as to reduce the dependency on large quantities of cooling water withdrawals has, in cases, led to a shift away from once-through cooling. Once-through cooling systems are rarely permitted for new power plants in the United States [9], and compliance with the Clean Water Act [10] has led to the installation of helper cooling towers, or even complete retrofits in existing facilities with once-through cooling systems [11]. Section 316(a) of the U.S. Clean Water Act [10] is dedicated to thermal discharges and requires the "protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife" in the receiving water body. Maximum acceptable water temperatures vary according to the State, but many impose a 32 °C upper temperature threshold for surface water, a limit which is very often exceeded [12]. The European Freshwater Fish Directive requires downstream temperatures from the point of discharge not to exceed 21.5 °C and 28 °C (or 1.5 °C and 3 °C above natural temperatures) in salmonid and cyprinid waters, respectively [13].

These regulations reflect the importance of preventing freshwater thermal pollution in many regions, and several works have studied the effect of power-related heat emissions on ecosystems and on the ability of the steam-electric power plants to operate at the desired capacity. In a study investigating the vulnerability of electricity supply under climate change scenarios, head dumps were calculated by assuming the temperature difference between cooling water discharges and the river water was 3 °C [14]. The Thermoelectric Power and Thermal Pollution Model (TP2M) is a rounded tool developed to model the power output and thermal loading of rivers as a function of efficiency loss arising from river flow and temperature fluctuations for steam-electric power plants

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with all types of cooling [15]. The TP2M enables a holistic examination of this aspect of the water-energy nexus, however, the estimates of efficiency and thermal emissions are not the outcome of the thermodynamic cycle of each generating unit [15]. The TP2M has been included in the regional biophysical model FrAMES, providing a high resolution analysis of the tradeoffs and effects of thermal pollution, including river temperature increase, and has been applied in studies centred in Northeastern United States [16,17]. In terms of coverage, all retrieved studies of power plant-related freshwater thermal pollution have so far been restricted to U.S. and European power plants [12,14,16,17].

In view of the impacts caused by elevated river water temperatures, which in the future could be aggravated by a combination of increased energy demand and the effects of climate change [16,18,19], of the reliance of previous work either on set differences between cooling water discharge and river water temperatures or on efficiency loss equations for the calculation of thermal emissions, and of the lack of a comprehensive study on a global scale, the objective of this work is to produce a global picture of current power-related heat emissions into freshwater bodies by systematically solving the relevant thermodynamic cycles on a power generating unit level for all units with once-through cooling systems worldwide. A further objective is to analyse these emissions geographically, temporally and in terms of the technological characteristics of the generating units. By making the data from this work available, there is ample opportunity for their utilization as input to river temperature models, whether localized or broader in scale, to estimate river temperature increase and associated environmental impacts.

## 2. Methods

### 2.1. Characterizing steam-electric facilities & filling in the gaps

In order to calculate the thermal emissions to freshwater bodies, information on power plant design and location were required. The Platts UDI WEPP (World Electric Power Plants Database) version March 2012 [20] was the principal data source for the power plant analysis. The WEPP database was selected insofar as it offers worldwide coverage and information on a power generating unit level, including the type of cooling system, steam conditions, boiler and fuel type and more, which are necessary for the calculation of freshwater heat emissions. Data are provided for over 60,000 operational power plants made up of approximately 127,000 generating units, amounting to 5.2 TW of gross generating electrical capacity, 60% of which (3.1 TW) comes from the subset of the thermoelectric sector (10,000 operational power plants, 21,700 units), selected for the purposes of this work. The exact numbers as well as the steam-electric technology types selected from the categories available in the WEPP database are presented in Tables S1 and S2 of the Supplementary Information.

The coverage of steam-electric facilities in the WEPP database was considered overall satisfactory, the only major drawback being a so-classified "comprehensive" as opposed to "complete" coverage of fossil fuel burning units above 50 MW in China, where "comprehensive" is interpreted in the database documentation as 75% or more coverage of facilities. High facility inclusion notwithstanding, the gaps in the different types of data offered for each generating unit are larger. This can be seen in Table 1, which presents the percentage coverage in terms of total units and in terms of the total gross generating electrical capacity of the steam-electric sector for a selection of parameters necessary for the calculation of thermal emissions. Cooling system information is provided for only 40% of all steam-electric units, however, the installed capacity of these units amount to 74% of the total generating capacity of all steam-electric units. This is largely explained by the fact that the database is heavily populated by small units – indicatively over a third of the steam-electric units have a capacity below 25 MW – for which many pieces of information are missing.

#### 2.1.1. Location and cooling system identification

No exact geographic locations are available for the entries of the WEPP database, with the highest resolution being city or post-code. To this extent, in the first of a two-step process, the coordinates of all units with a cooling system specified by the WEPP database as belonging to the once-through freshwater umbrella of cooling systems (Table S3) were determined by specific plant information retrieved from internet searches, and the coordinates were subsequently validated via Google Earth imagery [21]. Examination of aerial imagery of the power plants enabled the recording of the receiving water body (river, lake or reservoir), and ensured that erroneously labelled once-through freshwater cooling systems were excluded from the study (e.g. facilities that had undergone retrofits and operated with cooling towers etc.). In the second step, the coordinates of large units with no information under cooling system and with capacities above 100 MW were retrieved and their cooling system was determined via Google Earth imagery, by following a similar procedure for aerial imagery cooling system identification to that described by the USGS [22]. At the end of these two steps the cooling system information was completed for over 3800 additional units, raising the corresponding share from 74% to 92% of the total installed capacity of all steam-electric facilities (Table 1). Some 750 of the newly identified units fell under the umbrella of once-through freshwater cooling systems, raising the initial share of generating capacity of all units with this cooling system from 14% to 19% of the entire steam-electric sector as documented in the WEPP database (Table 1).

From the available categories in the WEPP database, the cooling system types considered relevant for this work are presented in Table S3 and include once-through freshwater cooling and combined/mixed cooling. With the focus being on freshwater thermal pollution, coastal or estuarine thermal emissions were excluded from this study. Accordingly, in all references to once-through cooling hereafter, the receiving compartment is assumed to be a freshwater body. Thermal emissions into artificially constructed cooling ponds were excluded, inasmuch as they occur in what is generally a tightly controlled small-scale purpose-built environment, as were emissions from wet cooling tower blowdown, which are negligible compared to those from once-through cooling [17]. A total of 2399 units with once-through cooling systems or similar, pertaining to 754 steam-electric power stations worldwide were retained for further analysis of their freshwater thermal emissions.

#### 2.1.2. Steam temperature and pressure at the high turbine entry

Steam conditions at the turbine entry are part of the main drivers of performance when it comes to steam-electric power cycles [23]. To fill in the gaps, empirical relationships were set up utilizing information from units with complete sets of steam condition-related data, regardless of the cooling system type, because the method of heat rejection has no influence on the steam conditions at the turbine entry. The scatterplot in Fig. 1 shows the steam temperature plotted against steam pressure at the entry of the high pressure turbine (if there are multiple turbines) for all steam-electric generating units. The data are colour-coded according to the group of fuel to which they belong (see Table S4 for fuel group breakdown), and their shape reflects the state of the steam at the given temperature and pressure (subcritical – supercritical – ultrasupercritical). The limiting factor for steam conditions is the maximum temperature that the turbine metallurgy can withstand [23], which is evident by the plateau reached in the