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Influence of cooling water of power stations on the water availability in the Rhine Basin

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Summary

Multiple sources report that approximately half of the extracted water within the Rhine Basin is currently used for cooling water purposes by power plants. How much of this water is actually consumed, and not returned to the Rhine River after extraction and use, is a question that has become more relevant now that periods of droughts in Western Europe have caused extreme low river discharges. Moreover, it is expected that such drought periods with low water levels and low freshwater availability show increased return periods with potentially more severe extremes due to climate change. In this research, we estimated the cooling water consumption by power plants within the Rhine Basin. This information can be used for calculations on water availability and low flow in the Rhine River and its main tributaries. It should provide useful background information for the Socio-Economic Scenarios formulated by the International Commission for the Hydrology of the Rhine Basin (CHR) and the update of the Dutch Delta Scenarios by the Dutch Delta Programme. The quantitative information is also valuable for e.g. the water allocation model for the Rhine Basin, that was set up by Deltares using RIBASIM software as part of the Socio-Economic Scenario project for the CHR and that will also be used in the EU Stars4Water project.

First, general abstraction and consumption values of cooling water for different types of power plants and cooling systems are determined. The different types of power plants include coal-fired power plants, diesel-fired power plants, gas-fired power plants, and nuclear power plants, as these generate the most energy. Thereafter, an overview is created of the power plants within the Rhine Basin, which are located within 3 km of the Rhine River or its tributaries; use fossil/nuclear fuel to generate power; use surface water; have a capacity larger than 20 MW; and are in operation. The 3km bound is used as this distance includes the most important and largest capacity power plants, combined with the fact that the chance to abstract water from the Rhine reduces to close to nihil at this distance. For each of these power plants their capacity, and type of cooling water system are determined. This was first done by looking at the Global Power Plant Database (Byers et al., 2019); Wikipedia (n.d.); and Weibezahn et al. (2020). Additional information was, thereafter, looked for in company or government documentation. For several power plants assumptions had to be made about the type of cooling system used, as it was not stated in the documentation. In this case, satellite imagery was used: when coolers or a cooling tower were identifiable on site, it was assumed that there was a closed-cooling system present, otherwise a once-through cooling system was assumed to be present. Combining this information with the earlier identified abstraction and consumption values of cooling water for different types of power pants and cooling systems, gives the cumulative water abstraction and consumption within the Rhine Basin.

We discern four types of cooling systems, which are once-through cooling; closed-loop cooling; air cooling; and hybrid cooling. These all abstract and consume different amounts of cooling water for different types of power plants. Once-through cooling systems abstract the most cooling water, especially at nuclear power plants. Closed-loop cooling systems consume the most cooling water, especially in nuclear power plants and oil-fired power plants.

Within the Rhine Basin, there are 2 relevant power plants located in France, 2 in the Netherlands, 3 in Switzerland, and 50 within Germany. The two power plants within the Netherlands are eventually also excluded from the calculations, as these power plants are located downstream of Lobith, which is the point of comparison.

Even though the largest share of included power plants is made up of closed-loop cooled gas power plants, half of the total calculated abstraction of 89 m^3/s within the Rhine Basin can be attributed to nuclear power plants. The total consumption within the Rhine Basin when the power plants would be operating at maximum capacity amounts to approximately 15 m^3/s, of which coal and nuclear power plants together consume the most. When comparing this cooling water consumption by power plants in the Rhine Basin to the lowest water discharge measured at Lobith, the share amounts to 2.4%. It is important to note that there is still a large uncertainty present regarding the type of cooling water systems used at individual power plants within the Rhine Basin, as such information is not generally publicly available. The uncertainty analysis displays that the total abstraction within the Rhine Basin can also amount to 235 and 332 m^3/s through different calculation approaches using demographic and statistical data. The three calculated abstraction values in this report make up 13.7-51.1% of the lowest measured discharge at Lobith. It is important to note that these are abstraction values, and not consumption values as were used in previous sections.

The water abstraction and consumption are in practice lower than the above-mentioned estimates, as 31-54% of the total installed power generation capacity is actually used. As a result, we estimate that the total water consumption rate in the Rhine basin by power plants is between about 4.8 and 8.1 m^3/s differing per season. Variations between seasons are to be expected because some power plants could switch between once-through and closed-loop cooling depending on water availability and river water temperatures. Further, there will be variations in water consumption because electricity demand varies, and power plants can only produce so much electricity as demanded as there is hardly buffering in the electricity system. The estimated realistic consumption values vary with the seasons and in summer make up about 0.8-1.1% of the lowest measured discharge at Lobith.

It is important to mention that several future developments could influence the water use and consumption within the Rhine Basin both on the short-term and longer-term. These are climate change, socio-economic changes, the *Energiewende*, innovations, Carbon Capture and Storage, and alternative cooling methods and/or sources. For future research on water consumption by power plants and future projections of this, it is recommended to consider these different developments and explore various scenarios in a pathway study. The main recommendation for future research is, however, to reduce the uncertainty of this study either by validating the estimated abstraction and consumption numbers or by validating the types of cooling water system used. Lastly, it is recommended to further research the effect of the distribution of power plants within a country on their vulnerability to factors such as water shortage and higher water temperatures.

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1 Introduction

1.1 Problem description

The Rhine River is one of the most intensively used rivers in Europe, one of the most important waterways in the world, and it connects important economic regions between the Alps and the North Sea. The Rhine water is used for many different purposes, such as for drinking water, irrigation, industrial production, and cooling water for power generation. Moreover, the river discharge is also important for environmental flow and for inland navigation (Ruijgh et al., 2019; Van der Krogt et al., 2021; Stahl et al., 2016; Jiang, 2022).

Jiang (2022) and Statistischen Bundesamt (2018) report that 46% to 53% of the total extracted water within the Rhine Basin is currently used for power supply. Within Germany alone this is already equal to 12 to 13 billion m^3 of water abstracted per year, which is almost exclusively used for cooling purposes (98.8%; Jiang, 2022; Statistiches Bundesamt, 2018; Umwelt Bundesamt, 2019). Climate changes, such as low-flow situations, and socio-economic changes could influence the future water availability and consequently the cooling capacity within the Rhine Basin (Damveld, 2022; Byers et al., 2014). How much of this water is consumed, and not returned to the Rhine River after extraction and use, is a question that has become more relevant now that periods of droughts in Western Europe have caused extreme low river discharges. Moreover, such drought periods with low water levels and low freshwater availability are expected to increase in return periods with potentially more severe extremes due to climate change (Görgen et al., 2010; Stahl et al., 2022).

In this context, we note that in publications and media, the difference between abstraction and consumption is often not clearly made, even though differences between the two are generally substantial (Byers et al., 2014). In this report we will be using the following definitions: Water use can either mean water abstraction or water consumption. Abstraction is the total volume of water extracted from ambient waters such as the Rhine River of which, depending on the cooling system almost all to virtually none is returned to the original water source. Consumption, on the other hand, is the total volume of water that is not returned to the original water source after being abstracted (Reig, 2013).

1.2 Relevance and research aim

Scenarios (SES) project of the International Commission for the Hydrology of the Rhine Basin (CHR). Within this project, a RIBASIM water allocation model is developed, which makes it possible to explore various scenarios and strategies regarding water availability, water demand and use and water allocation for the Rhine Basin in a quantitative way.

The aim of this research is to estimate the cooling water consumption by power plants within the Rhine Basin and put that in perspective with the total Rhine discharges at Lobith. If this would prove to be relevant, data on the water abstraction and consumption for cooling purposes within the Rhine Basin, should be considered in future scenario analyses on water availability, water use and water allocation, for example using the RIBASIM model (Van der Krogt et al., 2021).

Different factors affect the abstraction and consumption of power plants, such as the location of the plants, electric capacity, the type of power plant, and the type of cooling systems. These factors will be assessed in this research for each power plant within the Rhine Basin and are used for calculations on water availability and low flow in the Rhine River and its main tributaries.

The generated information and conclusion could be useful for the formation of the Socio-Economic Scenarios (SES) set-up by the CHR (Ter Maat & Van Aalst, 2022) and to update the Dutch Delta Scenarios by the Dutch Delta Program. The quantitative information is also valuable for e.g. the water allocation model for the Rhine Basin, that was set up by Deltares using RIBASIM software as part of the Socio-Economic Scenario project for the CHR and that will also be used in the EU Stars4Water project.

1.3 Objectives

The objective of this study is to estimate the water consumption by power plants in the Rhine Basin and to put that consumption in perspective by comparing it with typical Rhine discharges at Lobith. Resulting water consumption estimates could be used for assessing potential impacts on freshwater availability and on Rhine water levels, particularly in periods of droughts in further studies.

Supporting questions are set-up to fulfil the aim and objectives:
1 How do different types of power plants and their cooling systems work?
2 Where are the power plants located within the Rhine Basin?
3 What is the energy generating capacity of these power plants and how much cooling water do these power plants abstract/consume from the Rhine River and its tributaries?
4 How does this impact the total water use (abstraction/consumption) within the Rhine Basin?
5 What future developments are important to be aware of? In particular, what kind of impacts will these developments have on the water abstraction/consumption?

1.4 Approach and outline

Chapter 2 first gives an overview and description of the Rhine Basin. Chapter 3 describes the different power plant types, the different cooling water systems, and their main characteristics. Typical values are given for the abstraction and consumption of cooling water. Chapter 4 provides an overview of the power plants along the Rhine and data on their electricity generation capacity, the fuel type, and the type of cooling water system. Chapter 5 combines the general data on water abstraction and consumption with the overview created in Chapter 4. This gives an overview of the total water use in the Rhine Basin. Chapter 6 considers the uncertainty during the calculation process. Lastly, Chapter 7 identifies future developments that could change the potential for water abstraction/consumption in the Rhine Basin through existing literature. Based on this, recommendations for future research are given.

2 The Rhine Basin

The Rhine River originates in the Swiss Alps and flows over a distance of approximately 1300 km through mainly Germany and Switzerland to the Netherlands into the North Sea. The main contributors to the Rhine's water supply are its tributaries Aare, Neckar, Main, Moselle and Saar. We, therefore, do not solely consider the main river, but also its tributaries. The Rhine Basin itself spans an area of 190.000 km^2, of which the majority is located in Germany. There are, however, eight other countries it flows through: Switzerland, Austria, Italy, Belgium, France, Liechtenstein, Luxembourg, and the Netherlands (see Figure 1; Jiang, 2022; Stahl et al., 2016). We, thus, chose to include power plants from all countries located within the boundaries of the Rhine Basin.

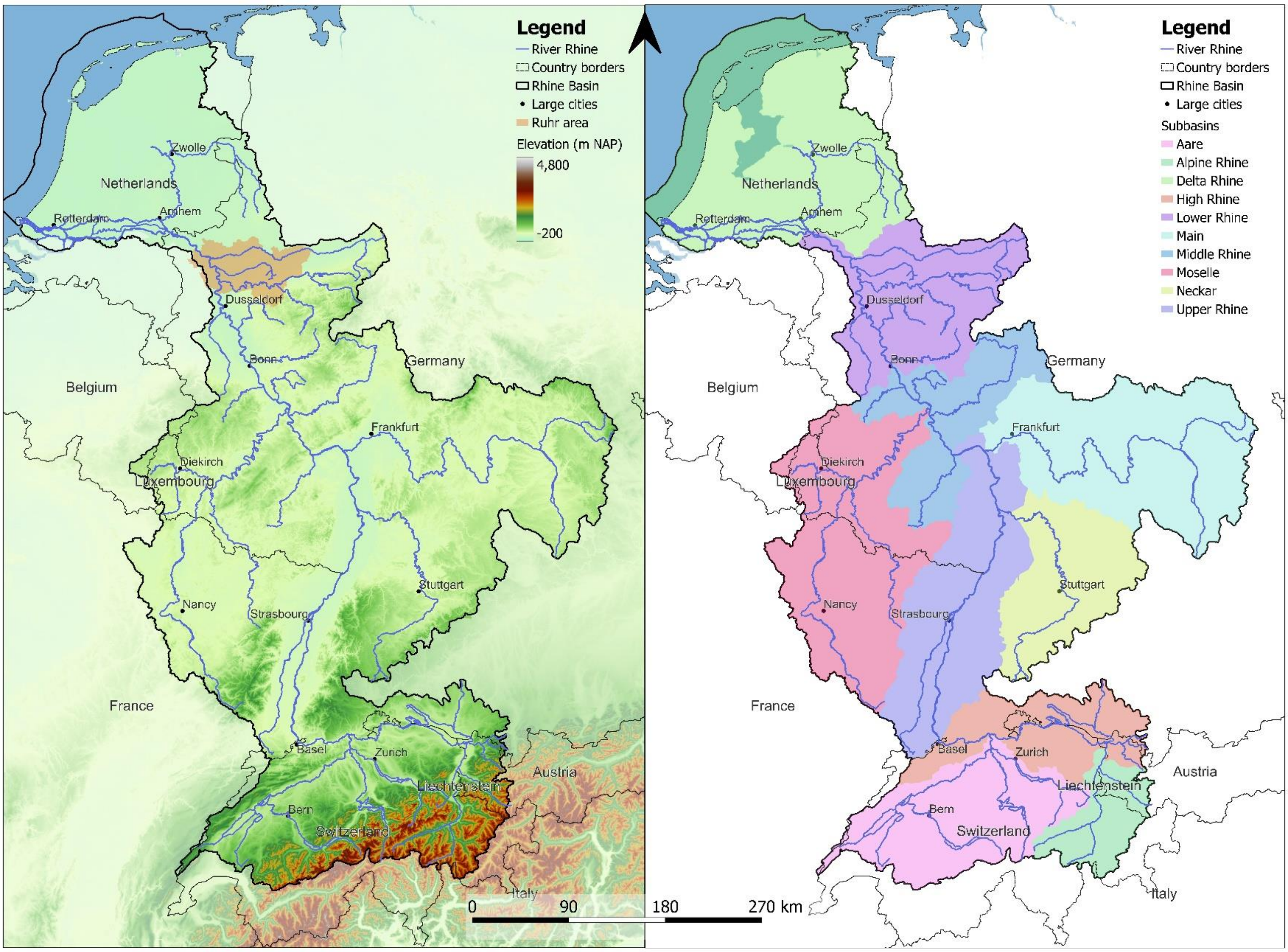

Figure 1: The Rhine Basin, its subbasins, and orography.

3 Different types of power plants and their cooling systems

There are several types of power plants, and they all require cooling systems. In this study, the coal-fired power plants, diesel-fired power plants, gas-fired power plants, and nuclear power plants are taken into consideration. It was chosen to do so, because the first analysis of the power plants within the Rhine Basin showed that these generate the most energy, while solar power plants, hydroelectric plants, geothermal plants, biomass plants, and wind power plants do either not use cooling systems, do not generate electricity larger than 20 MW or are not present within the 3km proximity of the Rhine River (Fraunhofer, 2022; NS Energy, 2020). The 3km bound is used as this distance includes the most important and largest capacity power plants, combined with the fact that the chance to abstract water from the Rhine reduces to close to nihil at this distance.

Coal-fired, diesel-fired, and gas-fired power plants use fossil fuels to generate electricity. Gas-fired power plants burn natural gas, and its combustion is much lower than from coal or oil. Another type of plant, which can be categorized under the gas-fired power plant, is the combined-cycle power plant. It uses both gas and steam turbines, which produces higher amounts of energy than a single fuel source. The nuclear power plant is the only low-carbon energy source considered in this study and uses uranium in a nuclear fission reaction to generate energy (NS Energy, 2020).

All considered power plants use technology in which turbines convert the thermal heat from the combustion or nuclear fission processes into mechanical energy, which in turn is used to produce electoral power via generators. By thermodynamic laws of physics, it is unavoidable that a substantial amount of heat generated in this process cannot be turned into electrical energy. In terms of energy amount, such excess heat is of the same order as the energy turned into electrical power. Large systems providing effective cooling are therefore required to avoid accumulation of heat in the power plant and overheating of the systems. When steam turbines are used, and this is mostly the case, exiting steam from the turbines needs to be cooled and condensed in large heat exchangers called condensers before again being used as water in the turbines. In power plants such cooling is achieved by water cooling, air-cooling or a combination of both. Excess heat is released by heating (ambient) water through evaporation, air draft, or a combination of these. These cooling principles require different systems with different amounts of ambient feed water. The main type of cooling systems (Byers et al., 2014) are described below.

1 *Once-through cooling or open loop cooling*. This type of cooling system withdraws large volumes of water from a running water source, such as a river. Hereafter, the water takes up the heat, after which this warmed-up water is discharged back into the running water source. This is visualized in Figure 2 (Webber, n.d.). The cooling is based on the principle that heating water requires energy. To increase the temperature of 1kg of (fresh) water with 1˚C, a fixed amount of energy of 4,18kJ is required, which is called the specific heat of water. To increase 1kg of water with 1˚C per second requires therefore 4,18kW power (for 1 m^3, this is 4,18MW). For such so-called thermal discharges environmental regulations are in place which generally limit the maximum temperature above ambient water conditions, prescribe efficiency of mixing at the discharge location, and prescribe the maximum extents of the so-called mixing zone.

Because of this, the temperature rise between withdrawal and discharge induced by the power plant is mostly between 4˚C and 7˚C. Recirculation of heat between outfall and intake, and therefore accumulation of heat must be minimized at all times to limit ecological damage, as organisms can solely reproduce within a certain temperature range. Water temperatures higher than 25ºC can cause (oxygen) stress for flora and fauna, also resulting in a shorter life expectancy (IKSR, 2014; IKSR, 2013-a; IKSR, 2013-b). Additionally, higher water temperatures due to recirculation have indirect effects, and can lead to increased evaporation in the water bodies from which the water is extracted. This has, amongst others, been researched by the ICPR-STEMP-group, an expert group on changes in water temperatures within the International Commission for the Protection of the Rhine (ICPR; IKSR, 2014).
It is estimated that this type of cooling system abstracts between 48-168 liter water per kWh produced electricity by the power plant. For a medium size installation producing 100MW of electricity output, this gives an abstraction between 1.3 m^3/s and 4.7 m^3/s. Between 0% and 1% of this abstracted water is consumed and almost all is returned to the water source with a higher temperature. This means that whereas the total withdrawal quantities are large, the consumption is relatively small. This type of cooling system is often preferred, as these are financially the most optimal. However, due to the large amounts of water required, for larger power plants (>100MW), this type is generally only applied along coasts and estuaries where sufficient cooling water is available.

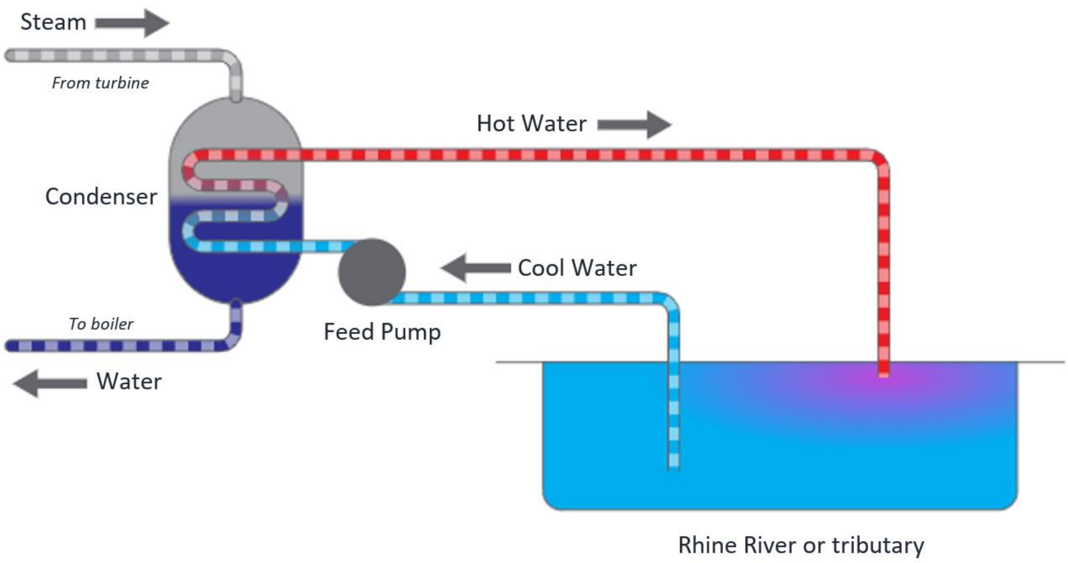

Figure 2: The open-loop or once-through cooling process in a power plant (Adapted from Webber, n.d.).

2 *Closed-loop cooling or re-circulatory cooling*. In this type of cooling system, water is pumped from the Rhine River into a condenser. Herein the water warms up, after which it flows into the cooling tower. The airflow in the tower cools the water, after which the cooled down water returns to the condenser. Less water from the Rhine River needs to be pumped in, as solely make-up water is required to replace the water lost by evaporation in the cooling tower. This is visualized in Figure 3 (Webber, n.d.). The cooling thus makes use of the principle that evaporating water requires energy. Evaporating 1 kg of (fresh)water requires 2,26 $\cdot 10^3$ kJ of energy, the so-called evaporation heat of water (note that this is about 540 times larger than heating 1 kg of water with 1˚C, the principle used in once-through cooling). In a truly closed-loop system there are no thermal discharges to the river. Water withdrawn from the river system is called make-up water. It is estimated that this type of cooling system abstracts between 1-5 liter water per kWh produced output electricity. For a medium size installation producing 100MW of electricity output, this gives an abstraction between 0.03 m^3/s and 0,14 m^3/s. Between 61-95% of

this abstracted water is lost from the river system (consumed) and moves on as water damp in the air when a tower is used, compared to 4-9% in a cooling pond. Hence, especially cooling towers consume a relatively large volume of the water withdrawn from the river, but the amount of cooling water abstracted to generate one kWh of power is limited. This type of cooling system is often used for coal-fired power plants.

Capital and operational costs of this system are generally higher than for once-through type cooling systems, but since the system requires much less water, and it is easier for meeting environmental regulations, it is often applied at places where less surface water is available, such as at inland locations or along (smaller) rivers. Once-through and closed-loop cooling systems are sometimes combined in order to produce cheaper electricity. This is solely possible when there is sufficient water available for (partly) closed-loop cooling, as the ability to switch to evaporative cooling is not possible due to limited water available in dry times or hot summer days.

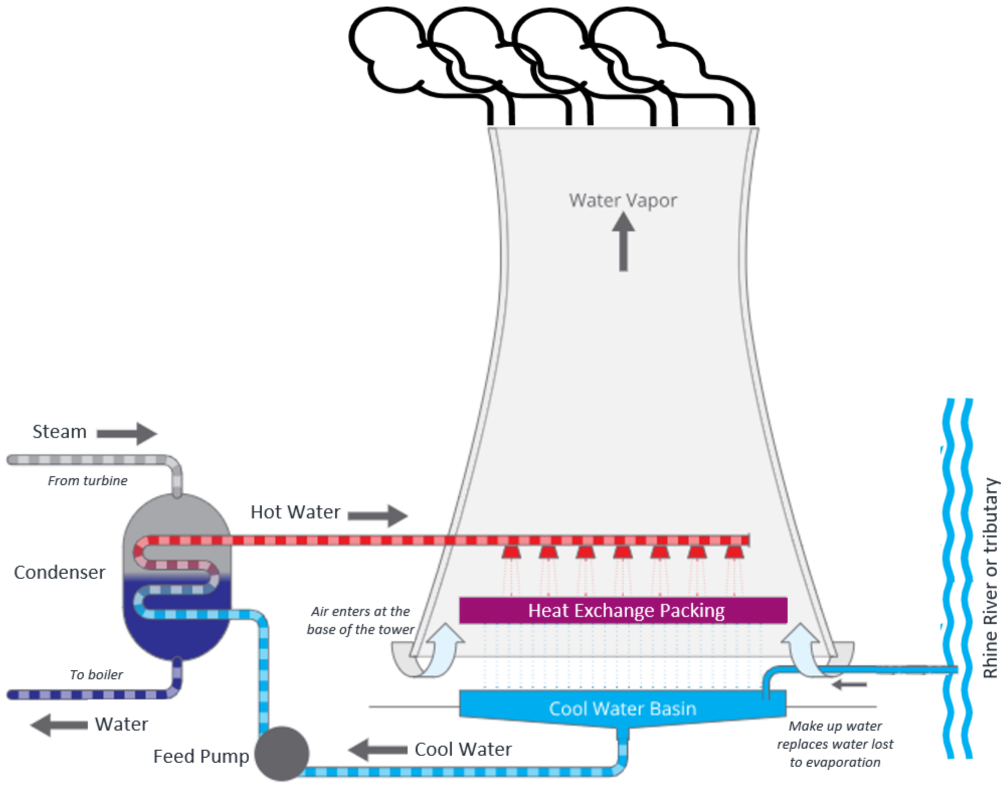

Figure 3: The closed cooling or re-circulatory cooling in a power plant (Adapted from Webber, n.d.).

3 *Air-cooled*. This type of cooling system uses fans and radiators to remove heat air through air circulation. Water does not need to be abstracted for this type of cooling system. Air cooling does, however, uses 40% more energy than closed loop cooling to generate energy, as there is not evaporative heat transfer from cooling water.

4 *Hybrid cooling*. This type of cooling system can operate with and without cooling water and is a combination of the air-cooled cooling and closed cooling systems described above. It combines either a wet-dry cooling tower, or a dry-wet system in series (Figure 4). It is estimated that this type of cooling system abstracts between 0-67 liter water per kWh. 61-95% of this abstracted water is lost, meaning the cooling water is less efficiently used.

It is important to note that power plants can have multiple cooling systems installed, and in that case can switch between these systems based on meteorological circumstances and water availability. This can result in a power plant using a once-through cooling system when water is available, while using closed cooling when water availability is limited. This complicates determining the cooling water system(s) in place for power plants (European Commission, 2014).

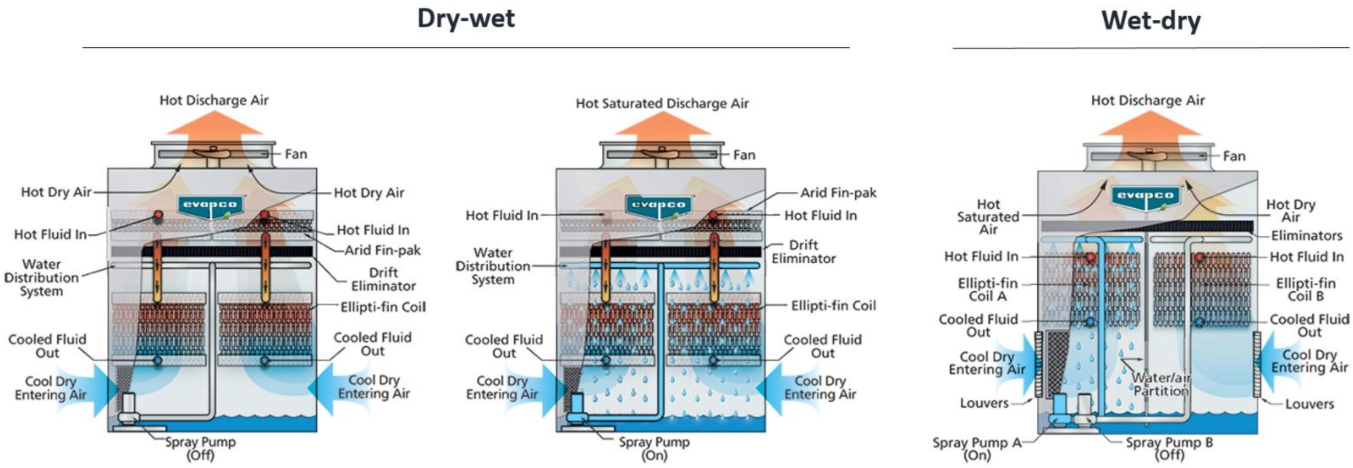

Figure 4: Hybrid cooling system: both dry-wet and wet-dry (Evapco, n.d.).

At some locations, part of the excess heat from power generation is used for district heating. This can be combined with several of the above described cooling systems.

In the table below, Byers et al. (2014) have estimated how much water is abstracted and consumed per type of power plant. This abstraction is given in liter per kWh and in Megaliter per GWh, as these units are inherently the same. For example, the table displays that an open-loop nuclear power plant abstracts 164 liter water per kWh, or 164 megaliter water per GWh, while consuming 1.27 liter water per kWh, or 1.27 megaliter water per GWh. The CCGT power plant in the table is a combined cycle power plant, which is an effective type of power generation in which the excess heat from a first turbine is used for fueling a second. +CCS indicates that a Carbon Capture and Storage system is added to the power generation process. This process captures CO_2 at the site of the power plant, after which it is transported to an injection site, and sequestrated for long-term storage. CCS can capture 85-95% of the CO_2 produced at the power plant. This, however, increases the water abstracted, for two reasons. First, the chemical and physical processes to capture and separate CO_2 require large volumes of cooling and scrubbing water. Second, a power plant with CCS requires approximately 10 to 40% more energy, which again increases the required abstraction of cooling water (Eldardiry & Habib, 2018). CCS can, therefore, significantly increase the amount of water abstracted (Byers et al., 2014).

This overview shows that for the three cooling systems using water, there are large differences in the amounts of water abstracted, however, smaller differences in water consumed.

Table 1: Abstracted and consumed water in the different types of power plants. O=Open loop; C=Closed loop; H=Hybrid cooling (35% dry, 65% wet; Byers et al., 2014).

Litres/kWh ML/GWh	Nuclear			Oil-fired (steam)			CCGT			Coal (sub-critical)			CCGT + CCS			Coal + CCS (super-critical)		
	O	C	H	O	C	H	O	C	H	O	C	H	O	C	H	O	C	H
Abstraction	164	3.88	2.52	134	2.08	0.68	47.6	0.93	0.59	118	2.11	1.33	90.0	1.82	1.19	220	4.29	2.79
Consumption	1.27	2.66	1.71	1.14	1.82	0.59	0.38	0.72	0.47	0.78	1.77	1.17	0.90	1.36	0.88	2.10	3.22	2.09

4 Inventory of power plants within the Rhine Basin

An overview of the locations and characteristics of the power plants in the Rhine Basin is difficult to obtain, as coherent information, particularly details concerning the cooling systems, is scarce (Schleifer & Luo, 2018). The locations of the power plants, name, country, type of power generated, capacity and generated energy were obtained through the Global Power Plant Database (Byers et al., 2019); Wikipedia (n.d.); and Weibezahn et al. (2020; see Table 2 and the extended Table in the Appendix). The remaining information in the Appendix was collected through company or government documentation and satellite imagery. For several power plants assumptions had to be made about the type of cooling system used (indicated by ** in the Tables), as it was not stated in the documentation. In this case, satellite imagery was used: when coolers or a cooling tower were identifiable on site, it was assumed that there is a closed-cooling system present, otherwise a once-through cooling system was assumed to be present. Solely the power plants remained that 1) are located within 3 km of the Rhine River or its tributaries; 2) use fossil/nuclear fuel to generate power; 3) use surface water; 4) have a capacity larger than 20 MW; and 5) are in operation. The 3km bound is used as this distance includes the most important and largest capacity power plants, combined with the fact that the chance to abstract water om the Rhine reduces to close to nihil at this distance. The numbers in Figure 5 correspond to the IDs in Table 2 and Table I in the Appendix. Table I in the Appendix also lists power plants that we looked into, but did not meet these criteria, and were therefore removed. The reason of removal is stated. The power stations and consequently the data, are subject to relatively fast changing conditions. It is, therefore, important to mention that this inventory and further calculations in this report are done in the year 2022. These are based on the, at this time, most recent and best available data collectable within the time and boundary conditions of the project.

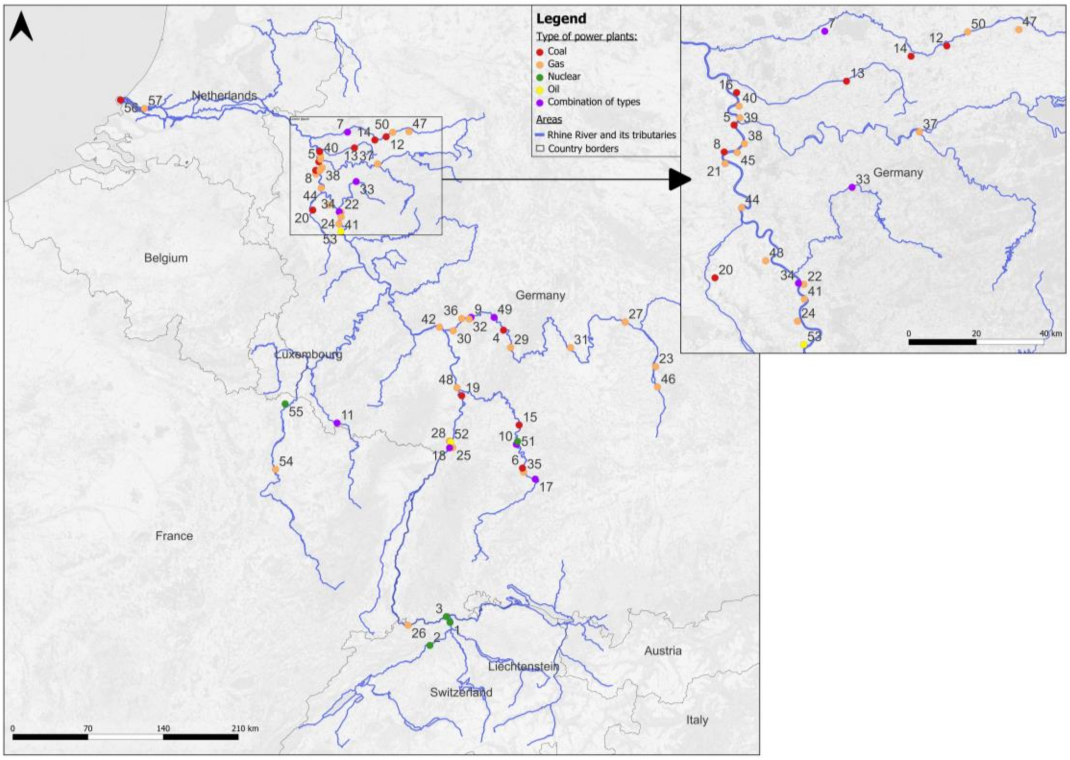

Figure 5: Power plants within the Rhine Basin, which 1) are located within 3 km of the Rhine River or its tributaries; 2) use fossil/nuclear fuel to generate power; 3) use surface water; 4) have a capacity larger than 20 MW; and 5) are in operation.

Table 2: Overview of locations and characteristics of the power plants within the Rhine Basin.

ID	Country	Name	Type of power generated	Capacity (MW)	Type of cooling water system
1	CH	Kernkraftwerk Beznau	Nuclear	760	Once-through cooling
2	CH	Kernkraftwerk Gösgen	Nuclear	1035	Hybrid cooling (dry-wet cooling tower)
3	CH	Kernkraftwerk Leibstadt	Nuclear	1245	Closed cooling (cooling tower)
4	DE	Heizkraftwerk der Sappi Stockstadt GmbH	Coal	24.8	Closed cooling** (chillers)
5	DE	HKW Sachtleben	Coal	27.5	Closed cooling** (chillers)
6	DE	Stuttgart-Muenster	Coal	184	Once-through cooling
7	DE	Chemiepark Marl Power Station	Coal (180) and Gas – CCGT (136)	316	Closed cooling (chillers)
8	DE	Kraftwerk N230/L7/Krefeld-Uederingen	Coal	234	Once-through cooling**
9	DE	HKW West (Mainova)	Coal (124) and Gas – CCGT (120)	244	Closed cooling** (chillers)
10	DE	Kraftwerk Walheim	Coal (275) and oil (116)	391	Once-through cooling**
11	DE	HKW Fenne GrubenNatural Gaskraftwerk	Coal (424) and gas (42)	466	Closed cooling** (cooling towers)
12	DE	Bergkamen power station	Coal	717	Closed cooling** (water tower)
13	DE	Herne power station	Coal	729	Closed cooling** (chillers and water tower)
14	DE	Trianel Kohlekraftwerk Lünen	Coal	746	Closed cooling** (water tower)
15	DE	Heilbronn power station	Coal	778	Closed cooling** (water tower)
16	DE	KW Walsum	Coal	1200	Closed cooling
17	DE	Altbach/Deizisau power station	Coal (783) and gas (253)	1036	Hybrid cooling (wet and dry)
18	DE	Rheinhafen-Dampfkraftwerk (Karlsruhe)	Coal (1351) and Gas – CCGT (365)	1716	Closed cooling (water tower)
19	DE	GKM (Mannheim) power station	Coal	1958	Closed cooling** (chillers)

ID	Country	Name	Type of power generated	Capacity (MW)	Type of cooling water system
20	DE	Neurath power station + BoA2	Coal	4211	Closed cooling (water towers)
21	DE	KWK-Anlage Krefeld DT	Gas - CCGT	25.8	Closed cooling** (chillers)
22	DE	X-Kraftwerk in Currenta chempark Leverkusen	Gas - CCGT	27	Closed cooling** (chillers)
23	DE	HKW Erlangen (Natural Gas)	Gas - CCGT	28.5	Closed cooling** (chillers)
24	DE	HKW Köln Südstadt	Gas - CCGT	35	Once-through cooling**
25	DE	Heizkraftwerk West – Karlsruhe	Gas - CCGT	37	Once-through cooling**
26	DE	Kraftwerk Grenzach-Wyhlen	Gas - CCGT	40	Once-through cooling**
27	DE	HKW Eltmann	Gas - CCGT	57	Closed cooling** (chillers)
28	DE	HKW Wörth / Papierfabriek Palm	Gas - CCGT	59	Closed cooling (chillers)
29	DE	Obernburg	Gas - CCGT	100	Once-through cooling**
30	DE	GuD-Anlage Rüsselsheim Opel	Gas - CCGT	112	Once-through cooling**
31	DE	Heizkraftwerke an der Friedensbrücke	Gas - CCGT	122	Closed cooling** (chillers)
32	DE	HKW Niederrad	Gas - CCGT	126	Closed cooling** (chillers)
33	DE	HKW und Spitzenlastanlage Barmen	Gas – CCGT (82) and oil (60)	142	Once-through cooling
34	DE	Merkenich (Nord) power station / Cologne-Merkenich power station	Gas – CCGT (94) and coal (72)	166	Closed cooling** (chillers)
35	DE	Heizkraftwerk Stuttgart-Gaisburg	Gas - CCGT	195	Closed cooling (chillers)
36	DE	Heizkraftwerk Industriepark Höchst	Gas -- CCGT	248.5	Closed cooling (chillers)
37	DE	Heizkraftwerk Hagen-Kabel	Gas - CCGT	230	Closed cooling** (chillers)
38	DE	HKW III/B (Duisburg-Wanheim)	Gas - CCGT	279	Closed cooling** (water tower)
39	DE	Duisburg Ruhrort (Hermann Wenzel)	Gas - CCGT	315	Closed cooling** (chillers)

ID	Country	Name	Type of power generated	Capacity (MW)	Type of cooling water system
40	DE	Duisburg Hamborn	Gas - CCGT	385	Closed cooling** (water tower)
41	DE	HKW Niehl 2	Gas - CCGT	413	Hybrid system (dry-wet)
42	DE	Kraftwerk Mainz-Wiesbaden (KMW)	Gas - CCGT	434.2	Closed cooling** (chillers)
43	DE	Dormagen	Gas - CCGT	586.3	Closed cooling** (chillers)
44	DE	GuD Lausward	Gas - CCGT	595	Closed cooling (chillers)
45	DE	Huckingen	Gas - CCGT	606	Closed cooling** (water tower)
46	DE	Franken 1	Gas - CCGT	823	Closed cooling** (water towers)
47	DE	Trianel's Hamm-Uentrop Natural Gaskraftwerk	Gas - CCGT	838	Closed cooling** (chillers)
48	DE	BASF_Ludwigshafen power plant = Kraftwerk Süd + Kraftwerk Mitte	Gas - CCGT	880	Closed cooling** (coolers)
49	DE	Staudinger power station	Gas (622) and coal (510)	1132	Closed cooling** (water towers)
50	DE	Gersteinwerk	Gas - CCGT	2005	Closed cooling** (water towers)
51	DE	NECKARWESTHEIM-2	Nuclear	1400	Hybrid cooling (dry cooling tower)
52	DE	MiRO	Oil	70	Closed cooling** (chillers and cooling towers)
53	DE	Raffineriekraftwerk Köln Godorf	Oil	80	Closed cooling (chillers)
54	F	BLENOD 5	Gas - CCGT	427	Closed cooling** (chillers)
55	F	CATTENOM	Nuclear	5200	Closed cooling (cooling towers)
56	NL	Maasvlakte 3*	Coal. Possible to stoke max 30% biomass	1100	Once-through cooling**
57	NL	Rijnmond II*	Gas - CCGT	810	Hybrid cooling

** = Power plants located downstream of Lobith.*
*** = Assumption made about the type of cooling system based on satellite data, as it was not disclosed in the documentation*
Country abbreviations: Germany = DE; Netherlands = NL; France = F; Switzerland = CH.

5 Impact of power plants on total water use in the Rhine Basin

Combining the abstraction and consumptive water losses from Table 1 with the power plant data in Table 2, generates the following overview given in Table 3. Power plants 56 and 57 from Table 2 were excluded when generating this overview, as these power plants are located downstream of Lobith, which is the point of comparison (see the next paragraph for the comparison). Hence, when speaking of all power plants hereafter, all power plants excluding 56 and 57 are meant. The estimated total abstraction within the Rhine Basin when all power plants would simultaneously operate at maximum capacity amounts to approximately **89 m^3/s**, of which half can be attributed to the nuclear power plants (see Figure 6). The total consumption within the Rhine Basin when all power plants would operate at maximum capacity amounts to approximately **15 m^3/s**, of which coal and nuclear power plants together consume most (see Figure 6). Even though gas plants are in higher numbers present than both coal and nuclear power plants, their total consumption is much lower due to their higher efficiency (Table 1).

Table 3: The total water abstraction and consumption per type of power plant and type of cooling system within the Rhine Basin, excluding the power plants within the Netherlands.

	Nuclear			***Oil-fired***			***Gas - CCGT***			***Coal***			***Combined***
	Open	***Closed***	***Hybrid***	***Open***	***Closed***	***Hybrid***	***Open***	***Closed***	***Hybrid***	***Open***	***Closed***	***Hybrid***	
Number of power plants	1	2	2	2	2	0	6	28	2	3	15	1	**64: 9 plants have 2 fuel types**
Total capacity (MW)	760	6445	2435	176	150	-	406	10671.3	666	693	13052.3	783	**36,238**
Total abstraction (m^3/s)	34.62	6.95	1.70	6.55	0.087	-	5.37	2.76	0.109	22.72	7.65	0.289	**88.81**
Total consumption (m^3/s)	0.268	4.76	1.16	0.056	0.076	-	0.043	2.13	0.087	0.15	6.42	0.254	**15.40**

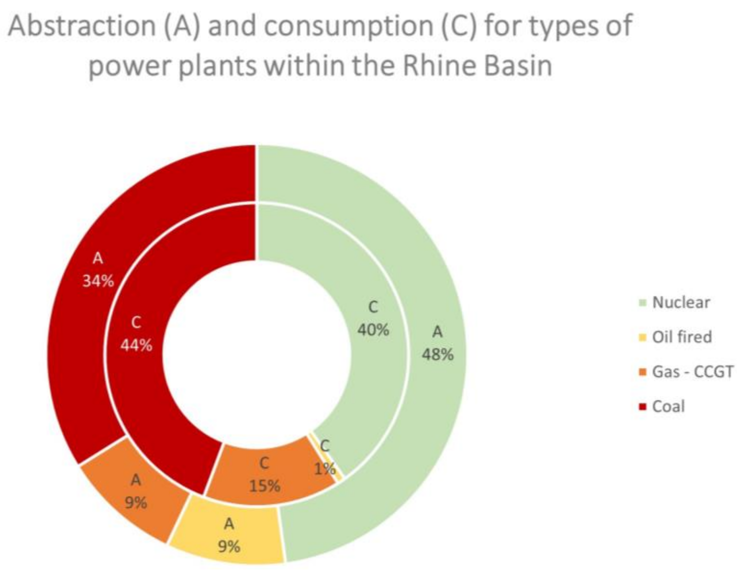

Figure 6: The share of each type of power plant in the total abstraction (A) and consumption (C) upstream of Lobith within the Rhine Basin.

This cooling water consumption by power plants within the Rhine Basin can be compared to the water discharges at Lobith. Lobith is located on the border between Germany and the Netherlands, where the amount of Rhine water entering the Netherlands is measured. Regular discharges at Lobith lie between 1000-4450 m^3/s (Rijkswaterstaat, n.d.), of which the cooling water consumption by power plants makes up 0.3-1.5%. During the summer of 2022, the water discharge at Lobith dropped to a record low of 650 m^3/s, which had only happened twice before in 1976 and 1949 (NL Times, 2022). When comparing the water consumption to this discharge, the percentage increases to 2.4%.

6 Uncertainty

There is uncertainty in the calculation method used in this report, as data about the type of cooling water systems installed and their specific control settings are not publicly available for many of the power stations within the Rhine Basin. This can affect the estimated total abstraction and consumption by power plants to a large extent.

We, therefore, also use two different calculation approaches in which data, provided by the German Federal Institute of Hydrology, are used.

In the first approach, the water use of non-public water suppliers is derived from Destatis (2018), amounting to 18.7 billion m^3. 16.6 billion m^3 or 526 m^3/s of this water is used for cooling purposes in the whole of Germany. As we want this for the Rhine Basin area and not the whole area of Germany, a reduction factor is set-up. The area of the Rhine up to Lobith is 159896 km^2, while the area of Germany is 357256 km^2. Dividing these results in a reduction factor of 0.447. Multiplying this factor by 526 m^3/s leads to a cooling water demand of 235 m^3/s for the Rhine Basin excluding the Netherlands.

In the second calculation approach, demographic data and energy data of the Rhine Basin and Germany are used. The water use for energy/inhabitant (E) using data from Germany is 6.42×10^{-6} $m^3/s/E$ (IKSR, 2003). There are approximately 60 million people living in the Rhine Basin (IKSR, n.d.), and when combined with the previously calculated number for water use per E, results in 385 m^3/s cooling water used in the Rhine Basin. This does include the Dutch inhabitants; therefore, we add a correction factor to this number. The Rhine area up to Lobith is 159896 km^2, while the total area of the Rhine Basin is 185300 km^2. This results in a correction factor of 0.86, and thus a cooling water use of 332 m^3/s within the Rhine Basin, excluding the Netherlands.

Table 4 displays the different outcomes when using the three calculation approaches. When using the methodology within this report based on the cooling system type, the water use/water abstraction is lower compared to the methodologies in which statistical data and demographic data us used. This does indicate there is a rather large uncertainty surrounding the water use within the Rhine Basin calculated within this report.

Table 4: Comparison outcomes of the three calculation approaches

Calculation approach	**Water use (m^3/s)**
Cooling system type	89
Statistical data Germany - Destatis	235
Demographic data - IKSR	332

When comparing the three outcomes for water abstraction to the water discharges of 1000 m^3/s at Lobith (low end of regular discharge for the Rhine River (Rijkswaterstaat, n.d.)), the share ranges from 8.9-33.2%. For the water discharge of 4450 m^3/s (high end of regular discharge for the Rhine River (Rijkswaterstaat, n.d.)), the share of consumption ranges from 2-7.5%. When comparing this uncertainty range for the water consumption to the low discharge which occurred in 2022, the percentage increases to 13.7-51.1%. These values, thus, do deviate much from the values determined before when uncertainty was not considered, however, can be attributed to the fact that here water abstraction is used to calculate the percentages instead of water consumption.

There are also other studies besides Byers et al. (2014), which have determined abstraction and consumption values for the different types of cooling systems, such as Jin et al. (2019) and Macknick et al. (2012). These values are displayed in Table 5 and 6. Considering these values, also leads to slightly different values for the total abstraction and consumption for cooling water purposes by power plants (see Table 5 and 6). Figure 7 displays the different values for the studies alongside one another, which shows that the values do not deviate largely and, therefore, do not have a significant effect on the earlier determined total water abstraction and consumption upstream of Lobith within the Rhine Basin.

Table 5: Displays the abstraction and consumption values derived from Jin et al. (2019). These values are multiplied by the earlier calculated capacities, leading to the total cooling water abstraction and consumption upstream of Lobith within the Rhine Basin.

		Nuclear			**Oil-fired**			**Gas - CCGT**			**Coal**		
		Open	**Closed**	**Hybrid**	**Open**	**Closed**	**Hybrid**	**Open**	**Closed**	**Hybrid**	**Open**	**Closed**	**Hybrid**
Abstraction and consumption values derived from Jin et al., 2019	*Water abstraction (L/GWh)*	155	4.19	No value	178	4.55	No value	75.7	1.78	0.36	103	2.54	1.78
	Water consumption (L/GWh)	1.02	2.54	No value	1.10	2.65	No value	0.56	0.91	0.36	0.40	2.08	1.48
Capacity values derived in Section 4	*Total capacity (MW)*	760	6445	2435	176	150	-	406	10671.3	666	693	13052.3	783
Calculated water use within Rhine Basin using values from Jin et al., 2019	*Total abstraction (m^3/s)*	32.7	7.50	No value	8.70	0.19	-	8.54	5.28	0.067	19.83	9.21	0.39
	Total consumption (m^3/s)	0.22	4.55	No value	0.054	0.11	-	0.063	2.70	0.067	0.077	7.54	0.32

Table 6: Displays the abstraction and consumption values derived from Macknick et al. (2012). These values are multiplied by the earlier calculated capacities, leading to the total cooling water abstraction and consumption upstream of Lobith within the Rhine Basin.

		Nuclear			**Oil-fired**			**Gas - CCGT**			**Coal**		
		Open	**Closed**	**Hybrid**	**Open**	**Closed**	**Hybrid**	**Open**	**Closed**	**Hybrid**	**Open**	**Closed**	**Hybrid**
Abstraction and consumption values derived from Macknick et al., 2012	*Water abstraction (L/GWh)*	168	4.17	No value	No value	No value	No value	43.0	0.97	No value	103	2.22	No value
	Water consumption (L/GWh)	1.02	2.54	No value	No value	No value	No value	0.38	0.78	No value	0.43	1.81	No value

Capacity values derived in Section 4	*Total capacity (MW)*	760	6445	2435	176	150	-	406	10671.3	666	693	13052.3	783
Calculated water use within Rhine Basin using values from Macknick et al., 2012	*Total abstraction (m^3/s)*	35.5	7.47	No value	No value	No value	No value	4.85	2.88	No value	19.83	8.05	No value
	Total consumption (m^3/s)	0.22	4.55	No value	No value	No value	No value	0.043	2.31	No value	0.083	6.56	No value

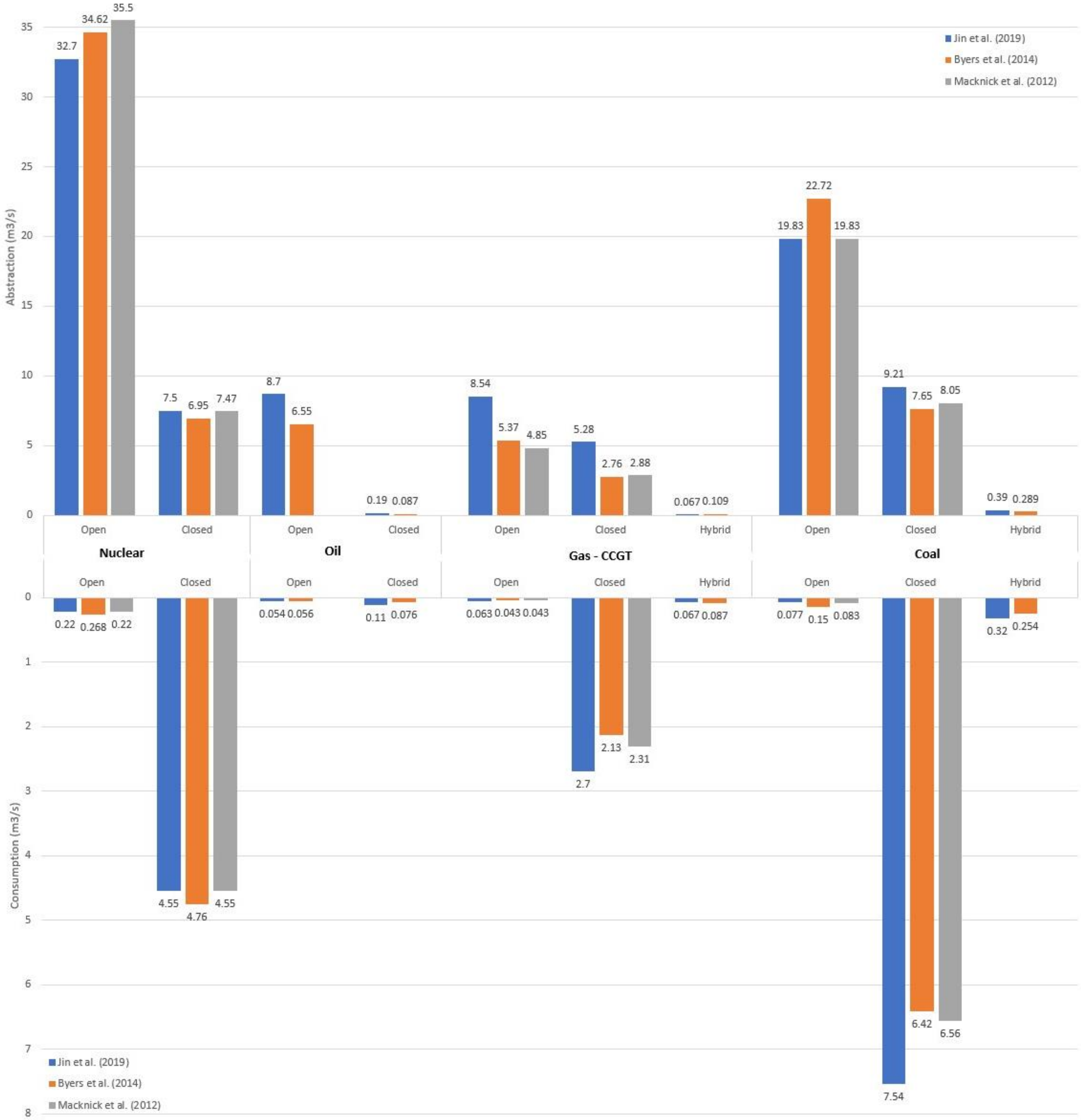

Figure 7: Total abstraction and consumption for cooling water by power plants upstream of Lobith within the Rhine Basin based on the abstraction and consumption values of three different studies: Jin et al., 2019; Byers et al., 2014; and Macknick et al., 2012.

As was mentioned above, abstraction and consumption are calculated for the situation in which the power plants operate at full capacity. This is however not the case in practice: there is much more power generation capacity installed than normally used to be able to supply power at any time, also during maximum peak demand. To estimate the effect on the above total water abstraction and consumption estimates, the actual power generated is compared to the total installed power generating capacity in each month for power plants in Germany. This is displayed in Table 7, which shows that from November to January the net power generated is approximately half of the total capacity, whereas this decreases to approximately 30-35% over the summer months. Combining these percentages with the abstraction values found results in an actual abstraction of approximately 27-47 m^3/s during the winter months, and an actual abstraction of 31-40 m^3/s during the summer months. Combing these percentages with the consumption values found, results in an actual consumption of approximately 4.8-8.1 m^3/s during the winter months, and an actual consumption of 5.4-6.9 m^3/s during the summer months.

Table 7: Displays the share of electricity production in the net power generation capacity for power plants in each month (Appunn et al., 2022; IEA, 2022).

Month	Natural gas (GWh; IEA, 2022)	Oil (GWh; IEA, 2022)	Coal (GWh; IEA, 2022)	Nuclear (GWh; IEA, 2022)	Other combustible non-renewables (GWh; IEA, 2022)	Total electricity production per month (GWh)	Net power generation capacity per month (GWh; Appunn et al., 2022)	Percentage of total capacity (%)
January	9687.8	386.6	17551.1	5925.7	501.6	34052.8	64728	52.6
February	8870.5	403	12618.4	5369.2	488.2	27749.3	58464	47.5
March	8766	382.9	12723.1	5503.6	487.4	19974.6	64728	30.9
April	8066.3	403.2	11570.8	5147.6	536.2	25661.1	62640	41.0
May	5538.5	376.1	8647.2	5279.4	520.5	20361.7	64728	31.5
June	5934.4	363.6	11902.7	4943.8	517.6	23662.1	62640	37.8
July	5463.2	369.3	11387.9	5517	540.1	23277.5	64728	36.0
August	4222.7	358.6	11677.5	5792.3	535.5	22586.6	64728	34.9
September	5505.8	362.9	16259.3	5456.1	517.6	28101.7	62640	44.9
October	5422.7	405.5	15246.1	5303.1	525.7	26903.1	64728	41.6
November	8771.7	484.4	17977.6	5604	533.5	33735.2	62640	53.9
December	8620.2	470.8	17378	5599.5	509.4	32577.9	64728	50.3

7 Future developments and future research

Future developments could change the amount of water abstraction and consumption within the Rhine Basin. These developments are discussed below.

7.1 Low flows and higher temperatures due to climate change

Climate change, already on the short-term, leads to extremes in temperature and rainfall, and consequently extremes in the Rhine River flow. Winters will be wetter, while summers will be dryer. Dry summers were thus far mitigated by the snowmelt and glacial meltwater of the alps, but this will decrease on the long-term due to climate change (Damveld, 2022). Low flow situations will therefore more often occur during Spring and Summer, leading to insufficient cooling water capacity and reduced electricity output to maintain a safe and efficient operation. This situation has already occurred in several countries, such as Germany and Spain (Byers et al., 2014), and has recently occurred for nuclear power plants in France (Damveld, 2022). The impact of low flows on power generation is higher for coal power plants than gas power plants, as its water consumption and downstream impacts are twice as high. Higher air temperatures, resulting from climate change, lead to higher water temperatures, which reduces the thermal efficiency and cooling potential of power plants (Byers et al., 2014). In a study performed by the ICPR-STEMP group, it became evident that the temperature of the Rhine will increase by 1-1.5ºC in August for 2021-2050 compared to 2001-2010. This increase will amount to 3-3.5ºC for 2071-2100 compared to 2001-2010 (IKSR, 2014). The cooling water could thus become warmer than permits allow, requiring the power plants to temporarily shut down. This has already occurred in 2015 for nuclear power plants in France. It could also occur that the permitted temperatures of the cooling water are heightened by the government, which also occurred in 2015 for the nuclear plants in France. The French government allowed the cooling water temperature to be as high as 28 ºC, surpassing the allowed level of 25 ºC in Switzerland and Germany. This can lead to unsafe situations (Damveld, 2022).

7.2 Socio-economic factors

The water demand within the Rhine Basin is expected to increase due to population growth, economic growth, a higher demand for food production, and a higher number of air conditioners. This increases the general water demand, leading to less available cooling water. The demand for power will also increase due to the socio-economic factors mentioned (Damveld, 2022; Byers et al., 2014). Additionally, the demand for power will increase due to electrification, meaning the transition away from fossil fuels towards electricity. Electrification is connected to the European Green Deal, which consists of policy initiatives set by the European Commission to make the European Union climate neutral in 2050. Amongst these policy initiatives are strategies to move towards sustainable and smart mobility, and strategies to move towards a clean and circular economy. This will lead to a shift in the type of electricity used and consequently change the power demand (European Commission, 2019 & 2020)

7.3 Die Energiewende

Die Energiewende is the term representing the energy transition occurring in Germany towards renewable energy sources. The current energy supply is largely reliant on nuclear power and fossil fuels; however, these are being replaced by wind power, solar power, hydropower, biomass, and geothermal energy sources. This transition is occurring due to multiple factors, such as the high risk of nuclear plants; large carbon emissions in the fossil

fueled power plants; the scarcity of fossil fuels; and the ability to produce more local energy using renewables.
The transition has been fixed by law in the Renewable Energy Sources Act, where the phasing-out of nuclear energy by 2022 and 40-45% of electricity consumption coming from renewable energy developments by 2025 have been set (Federal Ministry for Economic Affairs and Climate Action, n.d.).
The war in Ukraine has, however, caused both the postponement of closing nuclear power plants, and the phasing out of coal power plants. Postponement of closing the Neckarwestheim, the one nuclear power plant in Germany that uses Rhine Water, was also announced. The war in Ukraine has affected Germany's ability to ensure sufficient energy, as Germany is largely dependent on natural gas exports from Russia. The climate crisis, on the other hand, has caused droughts and reduced water levels, which reduces the potential for hydroelectric power in neighboring countries, as well as complicating the transport of coal to the power plants. For now, Germany says to have no other option than to continue with nuclear power and coal to ensure sufficient power for the winter demand in 2022. The plans to close the last nuclear power plants and to reduce fossil fuels are still on the agenda, but postponed (CNBC, 2022). It is important to be considerate of these changes, as the Energiewende is occurring and, thereby, largely altering the type of power plants used. It, therefore, also alters the abstraction and consumption of cooling water within the Rhine Basin.

7.4 Innovation

On the short-term, increases in efficiency for cooling water purposes will occur due to multiple or circular uses. Thereby, technical optimizations of the power plants will occur, leading to a higher efficiency of water use. This is going to influence the water demand for cooling by a large extent, as conversion efficiency is most frequently mentioned as a key driver for the cooling water demand (Jin et al., 2019). This will reduce the demand for cooling water (Umwelt Bundesamt, 2019). Developments in combined heat and power (CHP) can possibly also reduce the cooling requirements of power plants, as waste heat can be supplied to industrial, commercial, and domestic users through district heating (Byers et al., 2014).

7.5 Carbon Capture and Storage (CCS)

CCS is currently added as an additional step in power plants to capture carbon during the combustion process. CCS might be good to reduce CO_2 emissions to the environment, but costs substantially more water per kWh generated. CCS namely reduces the net plant efficiency. Thereby, the marginal water used for cooling the CCS system exceeds the water used to cool the steam cycle of the power plant itself (Byers et al., 2014; Jin et al., 2019).

7.6 Alternative cooling methods and/or sources

When a shift occurs from open loop cooling to closed loop cooling or hybrid cooling, freshwater abstractions will be reduced. This will have beneficial effects on the thermal pollution and ecology, but will also result in higher consumptive losses, dependent on the type of power plant. It is, thereby, likely that both abstraction and consumption will increase in the middle-term future, as the number nuclear power plants as well as CCS-methods will increase. There will likely also occur a shift from the use of freshwater cooling sources towards saline sources on tidal and coastal locations. This shift is due to the limited abstraction licenses for freshwater being handed out (Byers et al., 2014; Jin et al., 2019).

7.7 Recommendations for future research

For future research, it is recommended to reduce the uncertainty of this study either by validating the estimated abstraction and consumption or by validating the types of cooling

water system used. This could be for example be done through contacting the power plants directly. It is also worth mentioning that there is an official statistical databank available on the national level of the Rhine riparian countries, which could further reduce the uncertainty of this study. This should be considered in future studies (personal communication P. Krahe, BfG).
For future research, it is additionally useful to consider the different developments on the cooling water capacity in the Rhine Basin, mentioned above. These developments could potentially alter the water use and therefore the results of this study. Especially the Energiewende can alter the cooling water use already on the short-term, as fossil and nuclear power plants included in this study are going to be shut down in the upcoming years. To consider the different developments, future scenarios considering climate change and socio-economic factors affecting the Rhine water supply, could be included, resulting in a pathway study.
For future research on the warming Rhine water or recirculatory use, it is important to be aware of the influence these have on the evaporative capacity of the water body, as was explained in Section 3 (IKSR, 2014).

Lastly, it could be useful to look at the distribution of power plants over different water sources within a country. When all power plants are primarily located adjacent to the same river, it increases the vulnerability of the power plants to the occurrence of unforeseen problems, such as water shortage or higher temperatures. This cascade effect could be further explored in future research.

8 Conclusion

In this study, we combine typical cooling water abstraction and consumption values for different types of power plants with an overview of power plants within the Rhine Basin, to estimate the total cooling water consumption by power plants within the Rhine Basin.

The results are subject to uncertainties; nevertheless, several conclusions can be drawn. There are four types of cooling water systems, which are once-through cooling; closed cooling; air cooling; and hybrid cooling. Once-through cooling systems abstract the most cooling water, while closed cooling systems consume the most cooling water. When the typical abstraction and consumption values for such systems from literature are combined with the power capacity of the 55 relevant power plants upstream of Lobith within the Rhine Basin, we find an estimated total abstraction of 89 m^3/s and estimated consumption of 15 m^3/s. These numbers only change slightly when general abstraction and consumption values from other literature studies are used. When comparing this cooling water consumption by power plants in the Rhine Basin to the lowest water discharge measured at Lobith, the share amounts to 2.4%.

There is, however, uncertainty on the type of cooling water system used at each power plant. Considering different calculation approaches for the cooling water use by power plants within the Rhine Basin, leads to values of 235 and 332 m^3/s. The three calculated abstraction values in this report make up 13.7-51.1% of the lowest measured discharge at Lobith. It is important to note that these are abstraction values, and not consumption values as were used in previous sections.

The abstraction and consumption values in this report were generated by using the full capacity values of the power plants. It is, however, important to come to realistic values, whereby the actual electricity production and the variation compared to the total installed capacity is considered. This resulted in an actual abstraction of 27-47 m^3/s and consumption of 4.8-8.1 m^3/s during winter months, and an actual abstraction of 31-40 m^3/s and consumption of 5.4-6.9 m^3/s during summer months. The thus estimated realistic consumption values vary with the seasons and in summer make up 0.8-1.1% of the lowest measured discharge at Lobith.

Several future developments could influence the water use and consumption within the Rhine Basin both on the short-term and long-term. These are climate change, socio-economic changes, the Energiewende, innovations, Carbon Capture and Storage, and alternative cooling methods and/or sources. It is recommended to set-up a pathway study for future research, in which the influence of these developments, such as changes in the electricity generated, on the water use within the Rhine Basin could be studied. The main recommendation for future research is, however, to focus on reducing the uncertainty of this study. Thereby, the effect of the distribution of power plants within a country on their vulnerability to water shortage could also be studied further.

9 References

Appunn, K., Haas, Y., & Wettengel, J. (2022, 3 August). *Germany's energy consumption and power mix in charts*. Retrieved from Germany's energy consumption and power mix in charts | Clean Energy Wire

Byers, E. A., Hall, J. W., & Amezaga, J. M. (2014). Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, *25*, 16-30.

Byers, L., Friedrich, J., Hennig, R., Kressig, A., Li, X., McCormick, C. O. L. I. N., & Valeri, L. M. (2019). A global database of power plants. *World Resources Institute, Washington, DC, available at: https://www. wri. org/publication/global-database-power-plants (last access: 26 August 2020)*.

CNBC. (2022, 6 September). *Germany to keep two nuclear plants available as a backup and burn coal as it faces an energy crisis brought on by war and climate change*. Retrieved from Germany to keep two nuclear plants available as a backup, burn coal (cnbc.com)

Damveld, H. (2022, 14 July). *Kerncentrales maken Frankrijk kwetsbaar door veiligheidsproblemen en klimaatcrisis.*

Deltares. (2021, 14 January). *RIBASIM River Basin simulation model of the Rhine – Volume 1 Main Report*. Deltares report 11205564-000-ZWS-0002. Delft, January 2021.

Destatis. (2018). *Umwelt: Nichtöffentliche Wasserversorgung und nichtöffentliche Abwasserentsorgung.* Retrieved from https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/Wasserwirtschaft/Publikationen/Downloads-Wasserwirtschaft/wasser-abwasser-nichtoeffentlich-2190220169004.pdf?__blob=publicationFile

Eldardiry, H., & Habib, E. (2018). Carbon capture and sequestration in power generation: review of impacts and opportunities for water sustainability. *Energy, Sustainability and Society*, *8*(1), 1-15.

European Commission. (2019, 11 December). *Annex to the communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions.* Retrieved from EUR-Lex - 52019DC0640 - EN - EUR-Lex (europa.eu)

European Commission. (2020, 8 July). C*ommunication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Powering a climate-neutral economy: An EU strategy for Energy System Integration.* Retrieved from IMMC.COM%282020%29299%20final.ENG.xhtml.2_EN_ACT_part1_v9.docx (europa.eu)

European Commission. (2014, 10 July). *Pilot project on availability, use and sustainability of water production of nuclear and fossil energy – Geo-localised inventory of water use in cooling processes, assessment of vulnerability and of water use management measures.* Retrieved from CESNL13784_InventoryCoolingWaterUse_EndReport_FinalPubl140714s (europa.eu)

Evapco. (n.d.). *What is hybrid cooling?* Retrieved from Hybrid Cooling 101 | EVAPCO

Federal Ministry for Economic Affairs and Climate Action. (n.d.). *Renewable Energy*. Retrieved from BMWK - Renewable Energy

Fraunhofer. (2022, September). *Energy-Charts*. Retrieved from Interaktive Karte | Energy-Charts

Görgen, K., Beersma, J., Brahmer, G., Buiteveld, H., Carambia, M., de Keizer, O., Krahe, P., Nilson, E., Lammersen, R., Perrin, C. and Volken, D. (2010). Assessment of Climate Change Impacts on Discharge in the Rhine River Basin: Results of the RheinBlick2050 Project, CHR report, I-23, 229 pp., Lelystad, ISBN 978-90-70980-35-1.

IEA. (2022, 3 October). *Monthly Electricity Statistics*. Retrieved from Monthly Electricity Statistics – Data Tools - IEA

IKSR. (2013-a). *Aktueller Kenntnisstand über mögliche Auswirkungen von Änderungen des Abflussgeschehens und der Wassertemperatur auf das Ökosystem Rhein und mögliche Handlungsperspektiven.* Retrieved from rp_De_0204.pdf (iksr.org)

IKSR. (2003, May). *Bestandsaufnahme der Emissionen prioritärer Stoffe 2000*. Retrieved from https://www.iksr.org/fileadmin/user_upload/DKDM/Dokumente/Fachberichte/DE/rp_De_0134.pdf

IKSR. (2013-b). *Darstellung der Entwicklung der Rheinwassertemperaturen auf der Basis validierter Temperaturmessungen von 1978 bis 2011.* Retrieved from Titelseite Publikation 209d.indd (iksr.org)

IKSR. (2014). *Estimation of the effects of climate change scenarios on future Rhine water temperature development Extensive Version.* Retrieved from Microsoft Word - 214 en (iksr.org)

IKSR. (n.d.). *Siedlungen.* Retrieved from https://www.iksr.org/de/themen/nutzungen/siedlungen?no_cache=1&sword_list%5B0%5D=einwohner&cHash=3e32ddb3b8d5e415ad491bc158fc5733

Jiang, Y. (2022, May 2). *Template Project Proposal Form*.

Jin, Y., Behrens, P., Tukker, A., & Scherer, L. (2019). Water use of electricity technologies: A global meta-analysis. *Renewable and Sustainable Energy Reviews*, *115*, 109391.

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. *Environmental Research Letters*, *7*(4), 045802.

NL Times. (2022, 18 August). *Rhine falls to record low water level at Dutch entry point; Measures readied for waterways*. Retrieved from Rhine falls to record low water level at Dutch entry point; Measures readied for waterways | NL Times

NS Energy. (2020, 23 November). *What are the different types of power plants used to generate energy*. Retrieved from What are the different types of power plants used to generate energy? (nsenergybusiness.com)

Reig, P. (2013, 12 March). *What's the difference between water use and water consumption*. Retrieved from What's the Difference Between Water Use and Water Consumption? | World Resources Institute (wri.org)

Rijkswaterstaat. (n.d.). *Rijkswaterstaat Waterinfo: Lobith*. Retrieved from Lobith - Rijkswaterstaat Waterinfo (rws.nl)

Ruijgh E., 2019. Integrated Overview of the effects of socio-economic scenarios on the discharge of the Rhine. Deltares report 11201722-000-ZWS-0005, version 1.1. Delft, May 2019.

Schleifer, L., & Luo, T. (2018, 4 January). *Power Plants Use Water, But We Have No Idea How Much*. Retrieved from Power Plants Use Water, But We Have No Idea How Much | World Resources Institute (wri.org)

Stahl, K., Weiler, M., Kohn, I., Freudiger, D., Seibert, J., Vis, M., ... & Bohm, M. (2016). The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change. *Synthesis Report I-25, International Commission for the Hydrology of the Rhine Basin, Lelystad, Netherlands*, *10*.

Stahl, K., Weiler, M., van Tiel, M., Kohn, I., Hänsler, A., Freudiger, D., Seibert, J., Gerlinger, K., Moretti, G. (2022): Impact of climate change on the rain, snow and glacier melt components of streamflow of the river Rhine and its tributaries. CHR report no. I 28. International Commission for the Hydrology of the Rhine basin (CHR), Lelystad.

Statistisches Bundesamt (Destatis). (2018, 14 August). *Nichtöffentliche Wasserversorgung und nichtöffentliche Abwasserentsorgung*. Retrieved from Non-public water supply and non-public wastewater disposal - Series 19 Series 2.2 - 2016 - Federal Statistical Office (destatis.de)

Ter Maat, J., Van Aalst, M. (2022, 11 August). *Socio-Economic Scenarios narratives for the Rhine River Basin.* Deltares Memo 11082022 Version draft 0.3. Delft, August 2022.

Umwelt Bundesamt. (2019, 26 November). *EW-R-4: Water efficiency of thermal power plants*. Retrieved from EW-R-4: Water efficiency of thermal power plants | Federal Environment Agency (umweltbundesamt.de)

Van der Krogt, W., et al. (2021, January). RIBASIM River basin simulation model of the Rhine. Deltares report 11201722-000-ZWS-0005. Delft, January 2021.

Webber, M.E. (n.d.). *Thermal Power Plants.* Retrieved from Thermal Power Plants - Resourcefulness (stem.guide)

Weibezahn, J., Weinhold, R., Gerbaulet, C., & Kunz, F. (2020, 1 October). *Conventional power plants*. Retrieved from Data Platform – Open Power System Data (open-power-system-data.org)

Wikipedia. (n.d.). *List of power stations in Germany.* Retrieved from List of power stations in Germany - Wikipedia

A Appendix

Table I: (Additional) Information about the included and excluded power plants within the Rhine Basin.

Included power plants within the Rhine Basin								
ID	***Country***	***Name***	***Type of power generated***	***Capacity (MW)***	***(Estimated) generation (GWh)***	***Type of cooling water system***	***Surface water use***	***Sources***
1	CH	Kernkraftwerk Beznau	Nuclear	760	5107.44	Once-through cooling	40 m^3/s surface water from the Aar River, a tributary of the Rhine River.	Byers et al., 2019 Beznau Nuclear Power Plant - Wikipedia Beznau Nuclear Power Plant, Doettingen, Switzerland (nsenergybusiness.com)
2	CH	Kernkraftwerk Gösgen	Nuclear	1035	6955.52	Hybrid cooling (dry-wet cooling tower)	2.2 m^3/s surface water from the Aar River, a tributary of the Rhine River.	Byers et al., 2019 Gösgen Nuclear Power Plant - Wikipedia KKG_TB_englisch_2016.pdf
3	CH	Kernkraftwerk Leibstadt	Nuclear	1245	8366.79	Closed cooling (cooling tower)	4 m^3/s of surface water from the Rhine River.	Byers et al., 2019 Leibstadt nuclear power plant (alpiq.com) KKL_TB, engl WWW.indd
4	DE	Heizkraftwerk der Sappi Stockstadt GmbH	Coal	24.8	121.92	Closed cooling** (chillers)	6.643.172 m^3/year from the Main, a tributary of the Rhine River.	Byers et al., 2019 2020-Werk-Stockstadt-Umwelterklärung-(EMAS).pdf (sappi.com) E014-HAAN-P02-(Informationsbroschüre DE-2022-01) (enertec.at)
5	DE	HKW Sachtleben	Coal	27.5	135.2	Closed cooling** (chillers)	Surface water from the Rhine River.	Byers et al., 2019 https://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKE widlI7xmrf6AhVSgf0HHYBDCJkQFnoECA0QAQ&url=https%3A%2F%2Fwww.akwasser.de%2Fdownload%2Ffile%2Ffid%2F59&usg=AOvVaw35MwaRWyEbi_eXu0Ar22fd
6	DE	Stuttgart-Muenster	Coal	184	786.12	Once-through cooling	No information available, however, it lies directly at the Neckar, a tributary of the Rhine River. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Stuttgart-Muenster power station - Global Energy Monitor (gem.wiki) Fuel change at the Stuttgart-Münster power plant | EnBW Broschu?re_Innens_Broschu?re_Innens (enbw.com) https://www.bdew.de/energie/waermewende/waerme-schafft-effizienz/gro%C3%9Fwaermepumpe-als-baustein-fuer-klimaneutrale-fernwaerme/

7	DE	Chemiepark Marl Power Station	Coal (180) and Gas – CCGT (136)	216	Unknown	Closed cooling (chillers)	64% of the cool water is derived from surface from from the Lippe, a tributary of the Rhine River.	Byers et al., 2019 Chemiepark Marl power station - Global Energy Monitor (gem.wiki) Marl Chemical Park - Wikipedia https://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwivmcLC2sP6AhWohf0HHUjyA3wQFnoECAsQAQ&url=https%3A%2F%2Fwww.chemiepark-marl.de%2Fde%2Fattachment%2F1454%3Frev%3D1&usg=AOvVaw3AbuqZYvBKp2jf3K3Full4
8	DE	Kraftwerk N230/L7/Krefeld-Uederingen	Coal	234	Unknown	Once-through cooling**	Surface water from the Rhine River.	Byers et al., 2019 CBG - Climate Killer (cbgnetwork.org) Krefeld-Uerdingen power station - Global Energy Monitor (gem.wiki)
9	DE	HKW West (Mainova)	Coal (124) and Gas – CCGT (120)	244	Unknown	Closed cooling** (chillers)	Surface water from the Main, a tributary of the Rhine River.	Byers et al., 2019 Mainova West power station - Global Energy Monitor (gem.wiki) Heizkraftwerk West (mainova.de) Who powers Frankfurt? A look at Mainova. - SKYLINE ATLAS Kraftwerksbroschure.pdf (ifkomhessen.de) EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
10	DE	Kraftwerk Walheim	Coal (275) and oil (116)	391	Unknown	Once-through cooling**	8 m^3/s surface water abstracted from Neckar, a tributary of the Rhine River.	Byers et al., 2019 Heat influences energy supply: First power plants reduce output (handelsblatt.com) Broschu?re_Innens_Broschu?re_Innens (enbw.com) EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com) https://akwasser.de/sites/default/files/dateien/BUND%20Abwa%CC%88rmestudie%20Rhein.pdf
11	DE	HKW Fenne GrubenNatural Gaskraftwerk	Coal (424) and gas (42)	466	Unknown	Closed cooling** (cooling towers)	1 million m^3 / year of water is used from the reservoir in Nonnweiler. This reservoir is fed by the Prims, a small tributary of the Rhine. Part abstracted from the Saar.	Byers et al., 2019 Fenne Power Plant - Wikipedia, the free encyclopedia Nonnweiler Talsperre water reservoir - Bostalsee & Sankt Wendeler Landgo STEAG - Völklingen-Fenne Power Plant
12	DE	Bergkamen power station	Coal	717	3525.03	Closed cooling** (water tower)	Surface water from the Datteln-Hamm Canal, which receives water from the Lippe, a tributary of the Rhine and the Rhine River itself.	Byers et al., 2019 Steag - Wikipedia, the free encyclopedia Datteln-Hamm Canal - Wikipedia STEAG - Kraftwerk Bergkamen
13	DE	Herne power station	Coal	729	3584.03	Closed cooling** (chillers and water tower)	Surface water from the Rhine-Herne Canal, a canal connected to the Rhine River.	Byers et al., 2019 Kraftwerk Herne - Wikipedia, the free encyclopedia

14	DE	Trianel Kohlekraftwerk Lünen	Coal	746	3667.6	Closed cooling** (water tower)	Surface water from the Dattel-Hamm Canal, which receives water from the Lippe, a tributary of the Rhine and the Rhine River itself.	Byers et al., 2019 Lünen-Stummhafen power plant - Wikipedia, the free encyclopedia Lünen Coal-Fired Power Plant - Power Technology (power-technology.com)
15	DE	Heilbronn power station	Coal	778	3824.93	Closed cooling** (water tower)	23 m^3/s surface water abstracted from Neckar, a tributary from the Rhine River.	Byers et al., 2019 Rhine and Neckar: Low water level hits BW energy supply - CHR Aktuell Flyer_Bestand_HN.indd (enbw.com) Heilbronn Power Plant - Wikipedia, the free encyclopedia https://akwasser.de/sites/default/files/dateien/BUND%20Abwa%CC%88rmestudie%20Rhein.pdf
16	DE	KW Walsum	Coal	1200	5899.63	Closed cooling (Natural train wet cooling tower, previous only continuous cooling required, now also tower)	Surface water from the Rhine River.	Byers et al., 2019 Duisburg-Walsum power plant – The last one makes the shaft light off! (der-letzte-macht-das-schachtlicht-aus.de) rutten.pdf (d1rkab7tlqy5f1.cloudfront.net)
17	DE	Altbach/Deizisau power station	Coal (783) and gas (253)	1036	Uncertain	Hybrid cooling (wet and dry)	Surface water from Neckar, a tributary from the Rhine River.	Byers et al., 2019 Broschu?re_Innens_Broschu?re_Innens (enbw.com) Altbach Power Station - Wikipedia
18	DE	Rheinhafen-Dampfkraftwerk (Karlsruhe)	Coal (1351) and Gas – CCGT (365)	1716	Unknown	Closed cooling (water tower)	24-27 m^3/s surface water abstracted from the Rhine River.	Byers et al., 2019 RDK (Karlsruhe) power station - Global Energy Monitor (gem.wiki) Rheinhafen-Dampfkraftwerk Karlsruhe - Wikipedia, the free encyclopedia The World-Class Coal Power Efficiency of Rheinhafen-Dampfkraftwerk Block 8 (powermag.com) broschuere-rheinhafen-dampfkraftwerk-karlsruhe.pdf (enbw.com) Broschu?re_Innens_Broschu?re_Innens (enbw.com) Environmental associations against the water permit of TPM 7 - INKA Stadtmagazin Karlsruhe (inka-magazin.de)
19	DE	GKM (Mannheim) power station	Coal	1958	9626.24	Closed cooling** (chillers)	Surface water from the Rhine River.	Byers et al., 2019 GKM (Mannheim) power station - Global Energy Monitor (gem.wiki) Mannheim | large-scale power plant Technology (gkm.de) https://www.gkm.de/media/?file=91_die_technik_im_gkm.pdf&download
20	DE	Neurath power station + BoA2	Coal	4211	Unknown	Closed cooling (water towers)	Surface water from the Erft River, a tributary of the Rhine River.	Byers et al., 2019 Neurath lignite-fired Power Station (rwe.com) Neurath Power Station - Wikipedia RWE Power Lignite-Fired Plant, Neurath, Grevenbroich - Power Technology (power-technology.com) Water Pollution XI - C. A. Brebbia - Google Boeken

21	DE	KWK-Anlage Krefeld DT	Gas - CCGT	25.8	99.98	Closed cooling** (chillers)	No information available, however, it lies directly at the Rheinhafen Krefeld, connected to the Rhine River. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Anlage Krefeld DT power station - Global Energy Monitor (gem.wiki) EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
22	DE	X-Kraftwerk in Currenta chempark Leverkusen	Gas - CCGT	27	104.63	Closed cooling** (chillers)	Surface water from the Rhine.	Byers et al., 2019 Rundgang CHEMPARK Leverkusen - www.chempark.de global-power-plants: global-power-plants: 1 row where owner = "Currenta GmbH & Co. OHG" and primary_fuel = "Gas" (datasettes.com) From Rhine to pure water - www.chempark.de EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
23	DE	HKW Erlangen (Natural Gas)	Gas - CCGT	28.5	110.44	Closed cooling** (chillers)	No information available, however, it lies directly at the Regnitz, a tributary of the Main, which connects to the Rhine. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Erlangen power station - Global Energy Monitor (gem.wiki)
24	DE	HKW Köln Südstadt	Gas - CCGT	35	135.63	Once-through cooling**	No information available, however, it lies directly at the Rhine. High likelihood it uses surface water from the Rhine River. RheinEnergie AG also explains they use surface water from the Rhine for cooling in their processes.	Byers et al., 2019 Heizwerk Köln-Südstadt - Wikipedia, the free encyclopedia CHK Nachhaltigkeitsbericht 2017 (stadtwerkekoeln.de)
25	DE	Heizkraftwerk West - Karlsruhe	Gas - CCGT	37	143.38	Once-through cooling**	Surface water from the Rhine harbor.	Byers et al., 2019 Heizkraftwerk-West – Stadtwiki Karlsruhe https://www.ka-news.de/region/karlsruhe/alb-in-gefahr-stadtwerke-leiten-kuehlwasser-ein-buerger-fuerchten-zu-viel-waerme-art-1058174
26	DE	Kraftwerk Grenzach-Wyhlen	Gas - CCGT	40	155.01	Once-through cooling**	No information available, however, it lies directly at the Rhine. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Grenzach-Wyhlen: DSM commissions new power plant for climate protection | SÜDKURIER (suedkurier.de) Grenzach-Wyhlen power station - Global Energy Monitor (gem.wiki)
27	DE	HKW Eltmann	Gas - CCGT	57	220.89	Closed cooling** (chillers)	No information available, however, it lies directly at the Main. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Eltmann power station - Global Energy Monitor (gem.wiki) EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)

28	DE	HKW Wörth / Papierfabriek Palm	Gas - CCGT	59	228.64	Closed cooling (chillers)	Surface water from the Rhine River.	Byers et al., 2019 Immission control amendment approval according to § 16 Federal Immission Control Act (BImSchG) as well as premature construction § 8a Abs. 1 BImSchG Palm Power GmbH & Co. KG in Wörth am Rhein - UVP (uvp-verbund.de) EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
29	DE	Obernburg	Gas - CCGT	100	387.54	Once-through cooling**	No information available, however, it lies directly at the Main, a tributary of the Rhine River. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Akzo Obernburg power station - Global Energy Monitor (gem.wiki)
30	DE	GuD-Anlage Rüsselsheim Opel	Gas - CCGT	112	434.43	Once-through cooling**	No information available, however, it lies directly at the Main, a tributary of the Rhine River. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Anlage Rüsselsheim power station - Global Energy Monitor (gem.wiki) The Opel – Rüsselsheim Power Plant – RheinMain Regional Park (regionalpark-rheinmain.de) Opel plant in Rüsselsheim makes in-house power generation more flexible | Wind Power Journal (windkraft-journal.de)
31	DE	Heizkraftwerke an der Friedensbrücke	Gas - CCGT	122	472.79	Closed cooling** (chillers)	60 million m^3/year surface water from the Main, a tributary of the Rhine River.	Byers et al., 2019 Heizkraftwerk Würzburg – Wikipedia Application_20110330 (districtenergyaward.org)
32	DE	HKW Niederrad	Gas - CCGT	126	488.3	Closed cooling** (chillers)	Surface water from the Main, a tributary of the Rhine River.	Byers et al., 2019 Heizkraftwerk Niederrad – Wikipedia Kraftwerksbroschure.pdf (ifkomhessen.de) waerme-stromerzeugung-mainova-kraftwerke-data.pdf
33	DE	HKW und Spitzenlastanlage Barmen	Gas – CCGT (82) and oil (60)	142	Unknown	Once-through cooling	Surface water from the Wupper, a tributary of the Rhine River.	Byers et al., 2019 Heizkraftwerk Barmen – Wikipedia B_Kapitel 12_hauptnutzer punktförmig (wupperverband.de)
34	DE	Merkenich (Nord) power station / Cologne-Merkenich power station	Gas – CCGT (94) and coal (72)	166	Unknown	Closed cooling** (chillers)	Surface water from the Rhine River.	Byers et al., 2019 Ihr Energieversorger aus der rheinischen Region | RheinEnergie
35	DE	Heizkraftwerk Stuttgart-Gaisburg	Gas - CCGT	195	Unknown	Closed cooling (chillers)	Surface water from Neckar, a tributary of the Rhine River.	Byers et al., 2019 Broschu?re_Innens_Broschu?re_Innens (enbw.com) Combined heat and power plant Stuttgart-Gaisburg - Wikipedia, the free encyclopedia hkw-stuttgart-gaisburg-allgemeinverstaendliche-kurzbeschreibung.pdf

								(enbw.com) EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
36	DE	Heizkraftwerk Industriepark Höchst	Gas -- CCGT	248.5	Unknown	Closed cooling (chillers)	Surface water from the Main River.	Byers et al., 2019 Combined heat and power plant Industriepark Höchst - Wikipedia, the free encyclopedia Veröffentlichung BImSchG-Bescheid nach der Industrieemissionsrichtlinie (hessen.de)
37	DE	Heizkraftwerk Hagen-Kabel	Gas - CCGT	230	891.34	Closed cooling** (chillers)	Surface water from the Lenne, a tributary of the Rhine River.	Byers et al., 2019 Hagen-Kabel combined heat and power plant - Wikipedia, the free encyclopedia Hagen-Kabel power station - Global Energy Monitor (gem.wiki) https://www.enervie-gruppe.de/Home/Wer-wir-sind/enervie-gruppe/mark-e/Erzeugung-Kraftwerke.aspx/usetemplate-print/
38	DE	HKW III/B (Duisburg-Wanheim)	Gas - CCGT	279	1061.85	Closed cooling** (water tower)	Surface water from the Rhine River.	Byers et al., 2019 Duisburg-Wanheim combined heat and power plant - Wikipedia, the free encyclopedia CHDU - Kraft-Wärme-Kopplung (stadtwerke-duisburg.de)
39	DE	Duisburg Ruhrort (Hermann Wenzel)	Gas - CCGT	315	1220.75	Closed cooling** (chillers)	Surface water from the Rhine River.	Byers et al., 2019 Hermann Wenzel Power Plant - Wikipedia, the free encyclopedia Hermann Wenzel Power Plant, Federal Republic of Germany | SpringerLink EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
40	DE	Duisburg Hamborn	Gas - CCGT	385	1492.02	Closed cooling** (water tower)	No information available, however, it lies directly at the Rhine River. High likelihood it uses surface water from the Rhine River.	Byers et al., 2019 Hamborn combined heat and power plant - Wikipedia, the free encyclopedia EWI_Merit_Order_Tool_2021_en_v2021_3.xlsm (live.com)
41	DE	HKW Niehl 2	Gas - CCGT	413	1600.54	Hybrid system (dry-wet)	Surface water from the Rhine River.	Byers et al., 2019 Cologne-Niehl combined heat and power plant - Wikipedia, the free encyclopedia Combined heat and power plant Cologne-Niehl (de-academic.com)
42	DE	Kraftwerk Mainz-Wiesbaden (KMW)	Gas - CCGT	434.2	1682.69	Closed cooling** (chillers)	Surface water from the Rhine River.	Byers et al., 2019 Power plants Mainz-Wiesbaden - Wikipedia, the free encyclopedia Mainz: Green data center planned on the Ingelheimer Aue (fr.de) Kraftwerke müssen Flusswassernutzung zur Kühlung drosseln - NATURSCHUTZ UND LANDSCHAFTSPLANUNG (nul-online.de)
43	DE	Dormagen	Gas - CCGT	586.3	2272.14	Closed cooling** (chillers)	Surface water from the Rhine River.	Byers et al., 2019 Dormagen CCGT plant (rwe.com) Dormagen power station - Global Energy Monitor (gem.wiki)

44	DE	GuD Lausward	Gas - CCGT	595	Unknown	Closed cooling (chillers)	Surface water from the Rhine River.	Byers et al., 2019 GuD-Kraftwerk Düsseldorf Lausward mit der Fernwärmeauskoppelung - drei Weltrekorde / CCGT power plant with district heating extraction in Lausward, Düsseldorf – three world records - Made-in-Europe.nu lausward-brochure.pdf (siemens.com) Lausward power station - Global Energy Monitor (gem.wiki) Lausward Power Plant - Wikipedia, the free encyclopedia Slide deck for the “CCPP Fortuna” reference in Lausward, Düsseldorf (flux50.com)
45	DE	Huckingen	Gas - CCGT	606	2348.49	Closed cooling** (water tower)	Surface water from the Rhine River.	Byers et al., 2019 Duisburg-Huckingen (rwe.com) Duisburg-Huckingen power plant - Wikipedia, the free encyclopedia
46	DE	Franken 1	Gas - CCGT	823	3189.45	Closed cooling** (water towers)	Surface water from the Rednitz, a tributary from the Rhine River.	Byers et al., 2019 Franken 1 power station - Global Energy Monitor (gem.wiki) Kraftwerk Franken I - Wikipedia, the free encyclopedia ApplNotes_SLD_EON_Franken_I_de (ott.com)
47	DE	Trianel’s Hamm-Uentrop Natural Gaskraftwerk	Gas - CCGT	838	3247.58	Closed cooling** (chillers)	Surface water from the Datteln-Hamm Canal, which receives water from the Lippe, a tributary of the Rhine River and the Rhine River itself.	Byers et al., 2019 Hamm-Uentrop-Rev-3.pdf (he-water.co.uk)
48	DE	BASF_Ludwigshafen power plant = Kraftwerk Süd + Kraftwerk Mitte	Gas - CCGT	880	Unknown	Closed cooling** (coolers)	Surface water from the Rhine River.	Byers et al., 2019 Kraftwerk BASF-Ludwigshafen – Wikipedia Water - BASF Report 2021
49	DE	Staudinger power station	Gas (622) and coal (510)	1132	5565.32	Closed cooling** (water towers)	Surface water from the Main, a tributary of the Rhine River.	Byers et al., 2019 Staudinger power station - Global Energy Monitor (gem.wiki) Microsoft Word - Asset Finder_Staudinger_1206.doc (uniper.energy) Staudinger Power Plant - Wikipedia, the free encyclopedia
50	DE	Gersteinwerk	Gas - CCGT	2005	7768.23	Closed cooling** (water towers)	Surface water from the Lippe, a tributary from the Rhine River.	Byers et al., 2019 Elektriciteitscentrale Gersteinwerk - Wikipedia Gersteinwerk CCGT power plant (rwe.com)
51	DE	NECKARWESTHEIM-2	Nuclear	1400	9408.61	Hybrid cooling (dry cooling tower)	45.2 m^3/s of surface water abstracted from the Neckar, a tributary of the Rhine River.	Byers et al., 2019 kernkraftwerk_neckarwestheim_abschlussbericht_eu-stresstest.pdf (enbw.com) Neckarwestheim Nuclear Power Plant - Wikipedia Neckarwestheim GKN II nuclear power plant | Portal on Nuclear Safety (nuklearesicherheit.de) https://akwasser.de/sites/default/files/dateien/BUND%20Abwa%CC%88rmestudie%20Rhein.pdf

52	DE	MiRO	Oil	70	104.5	Closed cooling** (chillers and cooling towers)	Surface water from the Rhine River.	Byers et al., 2019 https://www.google.nl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKE widlI7xmrf6AhVSgf0HHYBDCJkQFnoECA0QAQ&url=https%3A%2F%2Fwww.akwasser.de%2Fdownload%2Ffile%2Ffid%2F59&usg=AOvVaw35MwaRWyEbieXu0Ar22fd
53	DE	Raffineriekraftwerk Köln Godorf	Oil	80	119.43	Closed cooling (chillers)	14.500 m^3/hour surface water from the Rhine River.	Byers et al., 2019 broschuere-power-plant-new-building-godorf.pdf (shell.de) Rheinland Raffinerie - Wikipedia, the free encyclopedia Shell refinery in Cologne-Godorf: Cooling towers are being gradually dismantled | Kölner Stadt-Anzeiger (ksta.de)
54	F	BLENOD 5	Gas - CCGT	427	1717.88	Closed cooling** (chillers)	Surface water from Moselle.	Byers et al., 2019 Registre national des installations de production et de stockage d'électricité (au 31 décembre 2018) — Open Data Réseaux Énergies (ODRÉ) (opendatasoft.com)
55	F	CATTENOM	Nuclear	5200	31442.07	Closed cooling (cooling towers)	0.89 km^3/year surface water from Moselle, a tributary of the Rhine River.	Byers et al., 2019 Cattenom Nuclear Power Plant - Wikipedia Cattenom Nuclear Power Plant - Super Engineering Website (reduper.com)
56	NL	Maasvlakte 3*	Coal. Possible to stoke max 30% biomass.	1100	6370.67	Once-through cooling**	Abstracts 33.2 m^3/s surface water from the Nieuwe Waterweg (Delta-Rhine).	Byers et al., 2019 Centrale Maasvlakte - Wikipedia MPP3 – 'Nederland heeft nu de schoonste kolencentrale ter wereld' | FluxEnergie 1745-103effectennatuur.pdf (commissiemer.nl)
57	NL	Rijnmond II*	Gas - CCGT	810	1777.65	Hybrid cooling	Surface water from the Nieuwe-Maas (Delta-Rhine).	Byers et al., 2019 Mothballed Rijnmond power plant acquired by GSO - Power Engineering International Rijnmond Energie - Wikipedia

Excluded power plants within the Rhine Basin

Country	*Name*	*Type of power generated*	*Capacity (MW)*	*(Estimated) generation (GWh)*	*Type of cooling water system*	*Reason for exclusion from the dataset*	*Sources*
CH	Kernkraftwerk Mühleberg	Nuclear	390	2620.92	Once-through cooling**	**Closed in 2019.**	Byers et al., 2019 Kerncentrale Mühleberg - Wikipedia
DE	Huerth Ville / Berrenrath power station	Coal	52	255.65	Closed cooling** (cooling tower and chillers)	6 km from Erft, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019 Huerth Ville - Berrenrath power station - Global Energy Monitor (gem.wiki)
DE	Hkw Offenbach power station	Coal	54	265.48	Once-through cooling**	5 km from the Main, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019
DE	Industrie-Kraftwerk / Rheinberg power plant	Coal	79	388.39	Closed cooling** (chillers)	**Coal plant is replaced by a biomass plant.**	Byers et al., 2019 Solvay Woodpower Project, Rheinberg - NS Energy (nsenergybusiness.com)
DE	Wuppertal-Elberfeld power station	Coal	85	417.89	Closed cooling** (chillers)	**Decommissioned in 2018.**	Byers et al., 2019 Wuppertal-Elberfeld combined heat and power plant - Wikipedia, the free encyclopedia
DE	HKW I – Stadtwerke Duisburg (Hochfeld)	Coal	95	467.05	Uncertain	**Decommissioned in 2018.**	Byers et al., 2019 Combined heat and power plant of Stadtwerke Duisburg in Hochfeld opens its doors to visitors for the last time - Rundschau Duisburg (rundschau-duisburg.de)
DE	Wachtberg power station	Coalv	118	580.13	Closed cooling* (chillers)*	No information available, but located 5.5 km from the Rhine River. **Unlikely that surface water is used.**	Byers et al., 2019 Wachtberg power station - Global Energy Monitor (gem.wiki)
DE	Kraftwerk Werdohl-Elverlingsen	Coal	310	1524.07	Closed cooling** (water tower)	**Decommissioned in 2022.**	Byers et al., 2019 Werdohl-Elverlingsen Power Station - Wikipedia Abriss des Kraftwerks Werdohl-Elverlingsen: Verhandlungen mit Investoren (come-on.de) 3537-kohlereader_englisch-final.pdf (ecologic.eu)
DE	Kraftwerk Ensdorf	Coal	389	1912.46	Closed cooling** (water tower)	**Decommissioned.**	Byers et al., 2019 Kraftwerk Ensdorf - Wikipedia, the free encyclopedia

DE	Lünen power station (KSBG)	Coal	473	2325.44	Closed cooling** (water tower)	**Decommissioned in 2019.**	Byers et al., 2019 Lünen power station (KSBG) - Global Energy Monitor (gem.wiki)
DE	Frimmersdorf power station	Coal	562	2762.99	Closed cooling** (water towers)	**Decommissioned.**	Byers et al., 2019 Water Pollution XI - C. A. Brebbia - Google Boeken Frimmersdorf Power Station - Wikipedia
DE	Kraftwerk Bexbach	Coal	721	3544.69	Closed cooling** (water tower)	**Since 2017, it has been standing still** and will only be ramped up if there are bottlenecks in the power supply.	Byers et al., 2019 Broschu?re_Innens_Broschu?re_Innens (enbw.com) Cooling water supply of power plants – Nonnweiler Dam (talsperrenverband-nonnweiler.de) Nonnweiler Talsperre water reservoir - Bostalsee & Sankt Wendeler Land Bexbach Power Plant - Wikipedia, the free encyclopedia SR.de: Kohlekraftwerke aus der Reserve holen?
DE	Scholven power station + Buer power station	Coal	816	Unknown	Closed cooling** (water towers)	No information available, but located 7 km both from the Lippe and the Rhein-Herne Canal. **Unlikely that surface water is used.**	Byers et al., 2019 Scholven power station - Global Energy Monitor (gem.wiki) Scholven | Uniper
DE	Westfalen	Coal	1049	5157.26	Closed cooling** (water towers)	**Decommissioned.**	Byers et al., 2019 Kraftwerk Westfalen - Wikipedia, the free encyclopedia
DE	KW Voerde	Coal	1390	6833.74	Closed cooling** (water tower)	**Decommissioned.**	Byers et al., 2019 STEAG - Weiher Power Plant Elektriciteitscentrale Voerde - Wikipedia
DE	Niederaussem power station	Coal	3900	16863.13	Closed cooling (water tower)	5 km from the Erft, a tributary of the Rhine River, unlikely that this surface water is used. **Information is unavailable**.	Byers et al., 2019 kraftwerk-niederaussem-englisch-download.pdf (uni-lj.si) Without water, the power plant stands still | Kölnische Rundschau (rundschau-online.de)
DE	Bochum	Gas	20.7	80.22	Closed cooling (cooling towers)	**Decommissioned in 2018.**	Byers et al., 2019 Bochum power station - Global Energy Monitor (gem.wiki) Hagedorn kauft ehemaliges Heizkraftwerk Bochum - Unternehmensgruppe Hagedorn (unternehmensgruppe-hagedorn.de)
DE	INEOS Solvents Moers Kraftwerk	Gas	24	93	Closed cooling	**Groundwater** supplied by the Links Nieder rheinische Entwässerungsgenossenschaft (LINEG).	Byers et al., 2019 JOINT ENVIRONMENTAL STATEMENT PDF Free download (docplayer.org)
DE	Dortmund	Gas	26	100.76	Closed cooling** (cooling tower)	**Decommissioned in 2022.**	Byers et al., 2019 Dortmund cogeneration plant (rwe.com) Dortmund combined heat and power plant goes off the grid ahead of schedule - energate messenger.com (energate-messenger.com)

DE	HKW Pfaffenwald – University of Stuttgart	Gas - CCGT	36	139.51	Closed cooling** (chillers)	8 km from Neckar, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019 Technik | Heizkraftwerk | Universität Stuttgart (uni-stuttgart.de)
DE	Natural Gas und Dampfturbinenanlagam Standord Heizkraftwerk Südraum	Gas - CCGT	38.6	149.59	Closed cooling** (chillers and small cooling tower)	2.5 km from Saar, **unlikely that this surface water is used**. Information is unavailable.	Byers et al., 2019 Combined cycle plant at the CHP plant Süd | Stadtwerke Saarbrücken (saarbruecker-stadtwerke.de)
DE	HKW Hiltrop	Gas - CCGT	44	170.51	Closed cooling** (chillers)	6.5 km from Emscher, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019 Hiltrop combined heat and power plant - Wikipedia, the free encyclopedia
DE	DS Smith Aschaffenburg Mill power station	Gas - CCGT	47	182.14	Closed cooling** (chillers)	2.1 km from Main, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019 DS Smith Aschaffenburg Mill power station - Global Energy Monitor (gem.wiki)
DE	HKW 1 + HKW 2 Alt-Oberhausen	Gas	47.6	Unknown	Closed cooling** (chillers)	2.5 km from Rhein-Herne Kanal, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019 Alt-Oberhausen combined heat and power plant - Wikipedia, the free encyclopedia Oberhausen-Sterkrade combined heat and power plant - Wikipedia, the free encyclopedia
DE	Holthausen – Henkel Kraftwerk	Gas	84	325.53	Closed cooling** (chillers)	1.5 km from Rhine River, **unlikely that this surface water is used.** Information is unavailable.	Byers et al., 2019
DE	Heizkraftwerk Karlstraβe 2 / Heizkraftwerk Nord (Bonn)	Gas - CCGT	95	368.16	Closed cooling (chillers)	10 million m^3 **groundwater** per year.	Byers et al., 2019 ChP Plant North (Bonn) - Wikipedia, the free encyclopedia Kraftwerk an der Karlstraße: Das ist Bonns größte Heizung (ga.de)
DE	HKW Sandreuth	Gas	150	581.31	Closed cooling** (chillers)	More than 4 km to the Rednitz River, so **unlikely water from the Rhine River is used**.	Byers et al., 2019
DE	Knapsack Natural Gas	Gas - CCGT	1230	4766.74	Closed cooling** (chillers)	6 km from the Erft, a tributary of the Rhine River, **unlikely that this surface water is used**. Information is unavailable.	Byers et al., 2019 Knapsack Gas power station - Global Energy Monitor (gem.wiki) DE11CWL_Knapsack_en.pdf (amiblu.com)

DE	PHILIPPSBURG -2	Nuclear	1468	9865.6	Closed cooling** (water towers)	**Shut down / decommissioned.**	Byers et al., 2019 Philippsburg Nuclear Power Plant - Wikipedia Germany shuts down Philippsburg 2 - Nuclear Engineering International (neimagazine.com)
DE	Kraftwerk + Natural Gas Turbine #9	Oil (66.3) and gas (51.9)	118.2	Unknown	No satellite imagery available	No satellite imagery available. 1.5 km from Rhine River, **unlikely that this surface water is used**. Information is unavailable.	Byers et al., 2019
DE	DK Kraftwerk	Other	21	69.43	Once-through cooling**	**Recycles residues** from steel industry.	Byers et al., 2019 DK Recycling and pig iron - Wikipedia, the free encyclopedia
DE	Oxea GmbH	Other	38	125.63	Hybrid cooling	**Uses the oxo synthesis process to form energy** (or hyroformylation).	Byers et al., 2019 oxea-bwk-12-2017-sd-siemens-eng.pdf (siemens-energy.com) Rental refrigeration for flexible use | CHEManager (chemanager-online.com)
DE	O10	Other	94.2	311.44	Closed cooling** (chillers)	Previous lignite power plant, but is **now part of the 560 MW-dormagen power plant.**	Byers et al., 2019 Dormagen CCGT plant (rwe.com)
DE	GichtNatural Gaskraftwerk Dillingen	Other	95	281.03	Closed cooling (cooling tower system)	Blast furnace gas, **not a regular gas plant.** Also 2 km distance to the Saar, so **surface water use is unlikely.**	Byers et al., 2019 Blast furnace gas power plant Dillingen (steag-newenergies.com) GuD-Kraftwerk Dillingen - GWT - Wasser und Wärmetechnik
F	Croix-de-Metz	Gas – CCGT	413	1661.55	Closed cooling** (chillers)	Uses water from the **public drinking water network.**	Byers et al., 2019 Microsoft Word Viewer - P1-Cx_de_Metz (eib.org) Croix-de-Metz (Toul) power station - Global Energy Monitor (gem.wiki)
F	FESSENHEIM	Nuclear	1760	10641.93	No satellite imagery available	Shut down in 2020 (**decommissioned).**	Byers et al., 2019 Fessenheim Nuclear Power Plant - Wikipedia End of the line for Fessenheim as France's oldest nuclear plant shuts down (france24.com)
LU	Esch-sur-Alzette CCGT Power Plant Luxembourg	Gas - CCGT	385	908.11	Air-cooled / dry cooling system	**Use of air-cooled system**, so no surface water is required.	Byers et al., 2019 Esch-sur-Alzette CCGT Power Plant Luxembourg - DEO (globalenergyobservatory.org) EUR 80 mio for a new power plant at Esch-sur-Alzette (eib.org)
NL	DELDERLAND*	Coal	590	3416.99	Closed cooling** (chillers)	**Closed in 2015.**	Byers et al., 2019 Gelderland power station - Global Energy Monitor (gem.wiki)

NL	Maasvlakte (MV1 and MV2)*	Coal	1040	6023.18	Closed cooling**	**Closed in 2017.**	Byers et al., 2019 List of power stations in the Netherlands - Wikipedia Centrale Maasvlakte - Wikipedia
NL	HARCULO*	Gas - CCGT	349	1452.93	Closed cooling** (chillers)	**Decommissioned.**	Byers et al., 2019 Harculo HC60 (IJssel Centrale) Power Plant Netherlands - DEO (globalenergyobservatory.org)

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