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Climate Change Impact on Nuclear Power Production

Master's Thesis

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Chapter 0: Preface

Abstract

Global warming is a result from anthropogenic processes and is a serious issue that is growing and inclining and that results in the climate change. The climate change will result in severe changes in the ecosystem and its components altering the natural phenomena and raising serious environmental concerns. Of the main concerns is the water availability, which will impose a critical problem with the increasing severity of climate change accompanied with an increase in population. Energy sector is one of the most affected sectors by the water availability, and with the increasing water and electricity demand the supply will be severely disrupted. This study focuses on how different future projections will affect the energy sector within the European Union, specifically, the nuclear power production. With these projections representing the possible future scenarios that are expected to occur taking in consideration socio-economic considerations, along to several other factors. Results are then assessed to visualize and understaand the future impact of climate change and global warming on electricity production from nuclear power plants.

Organization Structure

This project is performed under the supervision of Dr. Yiping Fang. Dr. Fang is a member of the industrial Chair Risk and Resilience of Complex System sponsored by big French companies including EDF, SNCF, RATP, ADP and Orange. His theoretical research interests are reliability theory, stochastic models, uncertainty quantification, stochastic and robust optimization, complex network theory. His Application research interests are risk, reliability and resilience assessment and optimization of cyber-physical systems (particularly smart grids and intelligent transportation systems). He is currently an assistant professor at the Industrial Engineering Laboratory, CentraleSupélec, Université Paris-Saclay, France, located in the south of Paris at Gif-sur-Yvette Cedex. This project is performed by myself, Abdalla Habashy, to be submitted as a Thesis for a Master’s degree in Nuclear Energy.

Chapter 1: Introduction

Shedding a focus on the severity of heat waves and droughts, a third of the nuclear power stations of the biggest European electricity exporter, France, were put out of action after power generation dropped significantly (Réseau de Transport d'Électricité, 2010). Cooling shortages were the main issue in summer 2009, where the electricity shortage was later compensated by UK electricity import due to the assistance of the European electricity exchange system. Although this exchange system is set to accommodate the national shortages, yet it is unknown whether this system will be able to cope with the power reduction threats that will continue to rise in Europe due to global warming according to the Intergovernmental Panel on Climate Change (IPCC).

The total gross of water abstraction, fresh surface, and groundwater, in 2010 was 119 billion cubic meters for the EU 28 member states, with 67 billion cubic meters of cooling water intake for the power generation sector only, accounting for 56.30% of the European water demand (ECOFYS Netherlands B.V., 2014). This tends to propose a serious challenge whether or not will the authorities be ready for the future, specially that cooling water shortages has occurred several times in the past in 2009 and 2003, where according to the IAEA more than 30 nuclear power plants had to shut down reduce their production because of limitations in the possibilities to discharge cooling water (IAEA, 2004) and tend to happen in the future.

The electricity grid and exchange system are affected as a whole, due to the interconnection of countries and import-export liability that countries have with one another, where in 2003 France had to import electricity from UK to supply Italy imports, which implies that a functioning power supply infrastructure is an essential aspect for countries on the European grid. Due to the electricity sector being a Critical Infrastructure (CI), information about how the climate change can impact it and about how capable and ready is the infrastructure to the impacts should be assessed. The European Commission (EC) has adopted several communications in favor of the CI against opposing threats that might arise and hazards that may be caused, such as accidents, terrorist attacks, and natural hazards.

The EC has issued a green paper in 2005 stating that the EU would only be responsible for the CIP of those infrastructures whose disruptions would cause cross-border effects, considering the CI a European CI if its disruptions significantly affect at least two EU member states, and that member States have to conduct CIP under a common framework of those infrastructures whose disruptions would mainly affect the state itself (Commission of the Europen Communities, 2005). Information, communication technologies, water, food, health, financial, public and legal order and safety, civil administration, chemical and nuclear industry, and space and research are all considered to European CIs alongside to the energy, which has electricity as a subsector, and transport sectors.

1.1 Project Objective

This study is mainly focused on assessing and analyzing the effects of climate change with a focus on global warming on the European nuclear power generation. The study is a long-term analysis of the of the water demands in accordance with global warming over a 100-year weather projection to provide a final illustration of how the industry is affected and elaborate the risks encountered with the global warming threat. Taking in consideration the worst-case scenarios, alongside to other possible scenarios and projections, aiming to go for the conservative approach for future preparation of the worst. Nevertheless, the conservatism will be according to the logical and practical limits obtained from literature and previous studies on similar matters.

Chapter 2: Theoretical Background

2.1 Climate Change and Climate Variability

According to the World Meteorological Organization (WMO), climate is the statistical description relevant atmospheric quantities and/or meteorological variables over a considerably long period of time, typically defined as 30 years, knowing that weather is the description of the short time-period. Climate can also be understood as the state of the components of the climate system earth, water reservoirs (rivers and oceans), and ice resembling the five major WMO components atmosphere, hydrosphere, cryosphere, land surface, and the biosphere. In addition to the accordance to temperature, humidity, pressure, wind speed, precipitation, and their branched effects, i.e. variability on soil moisture, rate of melting/evaporation, wind properties on various altitudes and pressures, and several more. Thus, we can infer that climate also is the weather and its range of states' statistical description at a defined location (latitude, longitude, and altitude).

In 1966, the WMO proposed the term "climate change" to cover the long time-scale climate variability regardless of its cause, but during the 1970s, the term was enhanced to focus on anthropogenic causes, as it became clear that human-induced activities had a potential to drastically alter the climate (Hulme, 2016). Climate change, nowadays, is still understood as the human-induced change in the weather conditions, and with the commonly used nomenclature, global warming. Rather in literature, global warming is the increase in surface temperatures, including air and stream, regardless the reasons, although it is clearly not a natural process and is anthropogenic, while climate change is total change in the climate properties of which include global warming and several other effects, induced from increase of greenhouse gases. Moreover, organizations such as the WMO and IPCC and the UN Framework Convention on Climate Change (UNFCCC), have emphasized on the understanding of the "climate change" and identified how it relates and originates from the understanding of climate variability.

The sun is the main energy source to earth, sending plenty of energy in the form of radiative energy where it is harvested in the climate system. Due to the reflectivity property of some of the particles present in the climate system, such as aerosols and clouds, not all energy is absorbed, which in turn results in the counter reflection from earths' climate system to outer space. The in-out relation of this phenomena is best described by earth's energy budget, which according to the IPCC, is the measurement of the incoming energy from the sun and outgoing energy to space balance withing earths' atmosphere. Further phenomena experienced withing earth can be understood from the energy budget, such as cooling and warming, which are distinguished by a negative and positive energy budgets, respectively. Weather in such understanding is the result of the of the variation of the energy throughout the climate system on geographic scale and time.

On the long-term, analysis give an indication on a regions' climate, where further changes result in a variability of the climate in that region, which can result in alterations in the energy distribution. According to the IPCC climate variability is the statistical parameter variation, such as occurrence frequency and standard deviation, of the climate on all scales spatial and temporal extending to more than weather variations. This strictly implies that variability occurs not only a periodic or in patterns, but could also occur randomly, which in literature is named "noise". Climate variability could result in dramatic consequences in the life on the planet with major alterations that can harm the plant life and vegetation as well as the wildlife of animal life and humanity, in addition to major changes in the cryosphere with glacier melting and fluctuations in sea level globally.

Generally, the equilibrium temperature within the earth's atmosphere is the difference in rates at which energy is received from the sun to the rate of energy loss to space, the remaining quantity is then formulated in the form of mechanisms that affect the climate in corresponding regions. The climate is dependent on several factors and variations in processes, namely the factors are called "forcing mechanisms" (National Research Council, 2006). The variation in processes can be identified as an internal variability or forcing, which is a stochastic variability, arises from chaotic processes in the climate system and nonlinear interactions between its components. Internal variabilities include ocean-atmosphere variability, life-carbon effects, and provides further studies on the oscillations and cycles, as they might arise although it is a nonlinear stochastic process. This results in an unforced process variation which then might induce changes in the distribution of energy in oceans and the atmosphere.

External variability or forcing includes natural phenomena such as changes in solar output, volcanic eruptions, or anthropogenic, such as the increase of greenhouse gases (Cronin, 2010). Altogether, the external variabilities impose that with variation in forcing, there are certain thresholds which limit the existence of rapid and irreversible change, noting the different response rate of the constituents of the climate system. For instance, oceans and ice caps, respond on a slower rate to climate forcing relative to the volcanic ash accumulation from a volcanic eruption.

We can induce that climate variability includes the climate variations that last longer than weather events, yet relatively still over a smaller timeframe period that could be a month, a season, or a year. Which in turn clarifies that the term climate change, according to the WMO, refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period, typically decades or longer (WMO, 2019). The IPCC definition, similarly, refers to a change in the climates state identified by changes in its properties, persisting for a long time, typically decades or longer, including all causes anthropogenic and natural (IPCC, 2013). The UNFCCC differs by attributing anthropogenic reasons to the alteration of global atmospheric compositions, directly or indirectly, over a long period of time as well (IPCC, 2013).

Moreover, the WMO further provides further understanding of the difference between the climate variability and change by relating them to frequency and significance of event occurrence with respect to the region or location of study. This implies that regions globally will experience different climate variability varying from a strong variability, where conditions can swing across a large range like from freezing to very warm conditions, to a weak variability, where conditions do not vary significantly over a time period. Thus, concluding that only a persistent series of unusual events taken in the context of regional climate parameters can suggest a potential change in climate has occurred (WMO, 2019).

2.2 Climate Change Impacts

Anthropogenic activities resulted in the climate change that the globe is now facing, with increasing global warming conditions we are facing significant outcomes naturally such as glacier melting and thus increase in sea temperature and sea level increase that would result in flooding. Alongside to the natural changes that arise, countries face serious consequences in the sense of power generation. The electricity production sector is dependent on the water sources, whether it was fossil fueled or not, water availability and its properties are significant parameters that need to be assessed and that will suffer later on with the negatively increasing climate change. In 2017, thermoelectric power (fossil fuels and nuclear) contributed to 18,111 million MWh (74.46%) of current electricity generation worldwide and hydropower 4,006 million MWh (16.47%) (U.S. Energy Information Administration, n.d.).

Global warming and its some of the consequences, such as increased heatwave and drought occurrence frequencies, will have a significant impact on power generation facilities from thermoelectric and hydropower, impacting directly the water-energy interdependence (Stucki & Sojamo, 2012). The water demand is set to increase to the double of its current demand within the next four decades (Olsson, 2012) in accordance with the continuous population growth of the world. This increase in demand will be visualized in the electricity production sector and several other sectors as agriculture and the normal daily-use domestic demand which will result in many constraints being imposed to cope with the increase in demand.

Climate change will severely disrupt the electricity power generation on the long term, and capacity reduction will be the main method to cope with increasing electricity demand that is an outcome of the increasing population growth. Capacity reductions will occur during droughts and extreme heats, which is when streamflow is low and temperatures are high, and that is due to the lack of cooling water that is needed for the full capacity power generation of the thermal power plants (fossil fuels and nuclear) as well as hydropower sources. These harsh conditions, depending on the region of interest, are most likely to occur during time periods of increased demand, and this will continue to increase in frequency, duration and intensity until electricity shortages occur (IPCC, 2008). According to the IAEA operational experience, a series of droughts caused electricity shortages in the American Southeast, the Pacific Northwest, and continental Europe, and this is prone of happening again if the capacity reduction is not accounted for.

Current studies are based on historical climate conditions as their effects on power systems are not clearly understood. Although renewable energy technologies are growing rapidly in the markets and gaining more interest, as they are clean and relatively demand less water which makes them less vulnerable towards droughts, yet it is still expected that thermal power plants and hydropower will most likely remain the dominant power-generating technologies during the whole of the twenty-first century (Johansson, Patwardhan , Nakicenovic, & Gomez-Echeverri, 2012) (Davies, Kyle , & Edmonds, 2013). Renewables are also affected by acute changes in atmospheric parameters, such as the streamflow and increasing temperatures, wind speed and air density, and thus, we can deduce that the main parameters for climate change impact assessment on power generation to be streamflow, stream temperature, air temperature, vapor pressure, wind speed and air density. Therefore, climate change will result in extreme heat incidence and drought occurrence, which in turn will result in the limitation of electricity generation, which could be limited to a decrease of up to 3.0% during an annual summer and up to 7.2-8.8% on a ten-year drought for vulnerable power stations (van Vilet , Widberg , Leduc, & Riahi, 2016).

According to Eurostat, the total electricity generation in the EU is 2800 TWh, of which 762 TWh is from nuclear energy, which contributes to 27.21% of the total EU electricity market, therefore, any disruption in the nuclear sector will be significant in the total energy sector of the EU. That makes it the main subject of interest studied in this thesis where the impacts on the nuclear system will also result in undesired effects on the European electricity supply system, and on other critical infrastructures. According to Watts (Watts, 2003), there are interdependencies between different CIs, such as the power grids being affected with communication system disruptions, which shows the dependency of CIs to each other, which in turn increases their vulnerability. Hence, it is essential to put efforts in the long-term consequences that are indirectly associated with the climate change as they result in further cascading consequences and problems. Droughts, for instance, are an indirect long-term consequence that is indirectly connected to the climate change resulting in further effects on the electricity supply with disruptions on the power generation.

2.3 Cooling systems and Water Consumption

Nuclear power plants are a type of water-cooled reactors, which requires the use of water during the internal cooling process, heat extraction, and to dissipate the waste heat. Waste heat is dependent on several factors including plant capacity, efficiency, size, type of technology used. There are seven different cooling system types (ECOFYS Netherlands B.V., 2014), but the focus will be mainly on the three technologies used for nuclear power plants, once-through cooling systems with and without a tower, and a wet closed-circuit cooling systems.

Once-through cooling systems are systems that require a large amount of water supply to be withdrawn from the reservoir to accommodate for the necessary dissipation of waste heat available, and returning later to the same water body, after leaving the condenser, which explains the large quantity demand. Some reactors require a cooling tower to be added to the once-through system available to reduce the heat loads that could arise on the water surfaces, by cooling the water with an air stream contact before being sent back to the water body from the condenser. This added phenomenon will result in a lower amount of water being sent back to the water body than that being withdrawn, due to the evaporation losses that arise. Closed cooling systems are systems that require the cooling fluid, air for dry systems and water for wet systems, through a heat exchanger within the cooling tower to dissipate the heat obtained from the cooling fluid before it gets recirculated back to the condenser. This system comparably has a higher fluid temperature which in turn reduces the total efficiency of the plant, in addition to the higher evaporation rate.

Nuclear power plants use water throughout its lifetime in areas that can best be classified as Water used, which is water used in the cooling systems for the dissipation of waste heat generated including the safety systems, cooling systems and for power generation, and Water consumed, which is water used in the industrial services of the plant, such as demineralized water for circuit make-up, sanitary water, firefighting, irrigation (IAEA, 2012).

Nuclear power plants use water during the construction, commissioning, operation, and decommissioning, which results in some fraction of water consumption of the total water used. During operation the main water use is in the cooling systems, due to the large amount of heat that is required to be dissipated, which varies around 62% depending on the electrical efficiency of the plant and the heat losses that arise. Water quantity to be used is dependent mainly on the cooling water temperature and the margin of increase it can experience from withdrawal to return, alongside to the thermal efficiency of the plant.

The temperature dependency infers that larger quantity of water is needed when the plant is large due to the higher amount of waste heat that needs to be dissipated. The lower the cooling water temperature, the better the plant performance, as it increases the margin of water temperature increase in the return, thus reducing the water consumption. A power plant with a 33% thermal efficiency will need to reject about 14% more heat than one of the same capacities with 36% efficiency (IAEA, 2012). This implies that higher efficiency can be achieved if water temperatures are suitable for a larger temperature increase in the return phase, with current nuclear power plant efficiencies at a range of 31-33%.

Chapter 3: Project Synthesis

3.1 Project Scope

This project aims to a study and analyze the impacts of the increase of water, stream, temperature as a function of increasing air temperature, and view the projection on future water consumption and its effect on power generation on the European nuclear energy generation. Although large fraction of the of the nuclear power plants are in France, yet all the power plants available will be assessed in the study neglecting the German power plants as they are phasing out in 2022 (Breidthardt, 2011). This project will aim on view a projection of the impacts on the long-term, for the next 90 years, up to year 2100. Some plants will be affected by more than others, as they are in land and lye on rivers, yet the corresponding relevant assumptions will be taken in consideration.

3.2 Climate Scenario

Climate projections re studies based on climate scenarios that quantify the concentration of greenhouse gases and aerosols in the atmosphere affecting the climate system. The projection cannot act as a stand-alone output and are used as inputs for further studies on the climate impact. Climate scenario, on the other hand, refers to a constructed future climate that is most prone to occur, using numerical models and relevant data from human-induced climate change and natural climate variability, to investigate climate change consequences (IPCC, 2018).

As future assumptions on human-induced factors are stochastic and unpredictable, climate scenarios tend to describe the emissions in several emission pathways that imply a corresponding human-induced climate forcing. The IPCC Assessment Reports (AR) used two emission scenarios in the General Circulation Model (GCM), which is a numerical model defining the general circulation of climate system components. These two scenarios are Special Report on Emissions Scenarios (SRES), which was used in AR3 and AR4, and Representative Concentration Pathways (RCP), which was used in the AR5 (Rasmus Benestad, 2017).

3.3 Euro-Cordex

Euro-Cordex is the focus on European studies from the international Cordex initiative, a which is a program sponsored by the World Climate Research Program (WRCP) to organize an internationally coordinated framework to produce improved regional climate change projections for all land regions world-wide (Rasmus Benestad, 2017). The Cordex initiative tend to set focus on simulation to produces climate impact assessments and mitigation studies, based on statistical models and several global climate models and scenarios. The Euro-Cordex initially utilized SRES scenarios on a grid-size of 25 km, but now steer the focus on improving the spatial resolution to 12 km, 0.11 degree, and using the RCP scenarios only (Rasmus Benestad, 2017). The IPCC will be utilizing results from the Cordex initiative in the AR5 to be published, which is a strong validation on the data obtained from Euro-Cordex to be used in the current study alongside to the utilization of RCP scenarios. In addition to the implementation of high-resolution Euro-Cordex results, 0.11 degree, for better results, although 50 km (0.44 degree) are being conducted.

3.4 Representative Concentration Pathway (RCP)

RCP's are scenarios developed by research community within the IPCC, after a decision made during the 25th session in Mauritius on 26-28 April, as an effort to switch from coordinating and approving other proposed new scenarios (Richard Moss, 2008). The IPCCs ' main aim of the RCPs were to be used in the AR5, the latest of their assessment reports, alongside to large range of climate change studies, by implementing integrated climate and impact modelling. RCP is based on the pathways of the additional radiative forcing caused by anthropogenic activity till the end of the 21st century, with the value in 1750 as reference, instead of focusing on the socio-economic scenarios used in SRES, in order to focus on the consequence rather the source and why the consequence occurred (Rasmus Benestad, 2017).

There are four sets of sub-scenarios under the RCP that indicate the radiative forcing associated, ranging from RCP8.5, which corresponds to an 8.5 W/m² and a constant increase of greenhouse gas emission, to RCP2.6, which is the optimistic approach that resembles the significant mitigation resulting in possible negative emissions. Lying in between are RCP6.0 and RCP4.5, which represent a stabilization of a given radiative forcing and greenhouse gas emission. In this study as a conservative approach, the RCP8.5 scenario will be chosen as it is the worst case of all the sub-scenarios, and according to the AR5, it is most likely to result in the exceeding of the global surface temperature. Further analysis could be performed on the several available scenarios to assess the variability of each of the scenarios.

3.5 Methodology

It is challenge to get the closest results to reality and assess all the climate change impacts, taking in consideration all affected parameters that are in accordance with nuclear power plants. To have a right approach of such assessment, according to the hierarchy of importance to nuclear power plants, the water temperature is the main parameter of interest, due to the high dependency of cooling systems on it. Water temperature determines the quantity of water demand to be used by the power plant in the cooling process using the following equation:

$$Q^F = \frac{KW * h * 3.6 * \left(\frac{1-\eta_{total}}{\eta_{electrical}}\right) * (1-\alpha) * (1-\beta) * \omega * EZ}{AS * c * \nu} \; ; Closed\ cooling\ systems\ (Eq.1)$$

$$Q^F = \frac{KW * h * 3.6 * \left(\frac{1-\eta_{total}}{\eta_{electrical}}\right) * (1-\alpha)}{AS * c * \nu} \; ; Open\ cooling\ systems\ (Eq.2)$$

where $\boldsymbol{Q^F}$ is the cooling water demand in (m^3), **KW** is the installed capacity in (kW), **h** is the operation hours in (h), **3.6** is a factor to convert kWh to megajoules, $\boldsymbol{\eta_{total}}$ is total efficiency in (%), $\boldsymbol{\eta_{electrical}}$ is he electric efficiency in (%), $\boldsymbol{\alpha}$ is the share of waste heat not discharged by cooling water in (%), $\boldsymbol{\beta}$ is the share of waste heat released into air in (%), $\boldsymbol{\omega}$ is a correction factor accounting for the effects of changes in air temperature and humidity within a year usually ranging between 0.7 - 1.25, $\boldsymbol{\nu}$ is the water density in (t/m^3), **c** is the specific isobaric heat capacity of water in (MJ/t K), **AS** is the permissible temperature increase of the cooling water in (K), and **EZ** is the densification factor usually ranging between 1-4. (Koch & Vogele, May 2009).

This equation allows to assess the effect of the increasing water temperature, and links waste heat production with the demand for cooling water based on the data of efficiencies and the electricity produced, and for closed cooling systems the share of waste heat released into air. It can also be observed in the denominator how the demand is affected by the water temperature, as it is a function of the inverse of density and specific heat capacity, which means with increasing temperatures the density decreases and consequently the demand increases. For closed cooling systems demand, it can be observed that aside from the humidity to air temperature correction factor, and the waste heat to air release factor that there is a densification factor, which is a factor that takes into account the increase of freshwater intake to avoid salinity increase due to the evaporation of water, which infers to the loss of cooling water during in the cooling process. This acts as a problem mainly when there is a limit in the access of freshwater, which will be compromised by the reduction of power, which is contrary to the desired approach with the increase of electricity demand. Therefore, the water availability and the return water heating constraints, which is taken into account by the factor "AS", and from literature we can find that the maximum water discharge temperature is 10 K. The lower the discharge temperature limit the higher the demand that will be needed, yet if the water availability of the is also constrained then the reduction of power production will be the final compromise.

Closed cooling systems, in contrast to open cooling systems, will require less water intake generally yet that might be misleading to the concept of demand. If a cooling tower is used, the waste heat will be released mainly into the air and not into the receiving surface water, thus emerging losses of water due to the evaporation in the cooling tower which requires a higher quantity on the long-term of operation, this is in addition to the previously discussed issue of salinity and mineral build-up in the cooling cycle that needs to be prevented (Koch & Vogele, May 2009). The evaporation losses are greatly dependent on the humidity and air temperature, and the relation between water temperature and air temperature could be described by the following equation:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \quad (Eq. 3)$$

where **Ts** is the stream water temperature (ºC), **Ta** is the air temperature (ºC), $\boldsymbol{\mu}$ is the estimated minimum stream temperature (ºC), $\boldsymbol{\alpha}$ is the maximum stream temperature in (ºC), $\boldsymbol{\gamma}$ is the steepest slope of the function (º), $\boldsymbol{\beta}$ is the air temperature at the inflection point (ºC) (Mohseni, Stefan, & Erickson, 1998). According to Mohseni, the relation between the air and water temperature is a linear regression model, and to obtain the inflection point temperature and the steepest slope of the function a collection of data on the temperatures of the locations and water bodies to be studied should be assembled. To do so, a list of nuclear power plants to be studied was assembled and with locations identified.

3.6 Tools Used

3.6.1 Python

Python is an open source, interactive, object-oriented programming language that incorporates high level dynamic data types, supporting procedural and functional programming, beyond the object-oriented programming. It has many interfaces to several window systems, and is also used as an extension language for applications that need a programmable interface, with ability to run on Linux, Windows, and MacOS. Python was conceived in the late 1980s by Guido van Rossum at Centrum Wiskunde & Informatica (CWI) in the Netherlands, but currently Python Software Foundation (PSF), a non-profit organization, holds the copyright of the Python software (Venners, 2003). Python has a large standard library that gives it the ability to cover a large number of problem classes and areas of study, including software engineering, operating system interfaces, and several more. In this study, Python3.7 will be used for data analysis and visualization, requiring a sophisticated set of software packages, viewed in table 1, to be installed. Jupyter Notebook will be needed for iPython files, and Miniconda will also be required as a project interpreter to install certain packages that face difficulties in current versions of Python, such as Cartopy.

Installed Python Packages		
GeoPy	SciPy	iPython
MatPlotLib	Networkx	NumPy
Pandas	PyYaml	PiP
Seaborn	PyCountry	Cartopy (MiniConda)

Table 1 Required Python packages to be installed for the study.

3.6.2 MATLAB

MATLAB, which stands for Matrix Laboratory, is a programming language developed by MathWorks implementing a numerical computing environment allowing matrix manipulations, and plotting of functions and data. MATLAB allows the creation of an interface with programs created in other languages, in addition to several packages within the MATLAB, that allows the extension of computing abilities, such as Simulink, which adds graphical multi-domain simulation and model-based design for dynamic and embedded systems. Originating in 1984 by J. H. Wilkinson, George Forsythe, and John Todd, MATLAB is currently a full-featured technical computing environment that allows studies in multiple fields to be performed, such as economics, engineering, sciences, and several more. In this study, MATLAB will be used as the numerical solving tool to work on achieving the desired results and will act as an interface to utilize Microsoft Excels result manipulation, by importing and exporting results.

3.7 Euro-Cordex Projection

As previously discussed, the main importance is to obtain water temperature, which will be done by placing the required parameters, which include air temperature, in the equation obtained from Mohseni. As the study aims to simulate the future water demand of European nuclear power plants, future projection of the air temperature on Europe must be obtained, and to do so, several aspects must be determined. The RCP 8.5 scenarios will be chosen as part of the conservative approach of the study. Yet this is not enough to proceed with the data retrieval process, due to the large database that the Cordex initiative provides from studies performed by several institutes internationally, and domestically in Europe. There are more than 150,000 future projections on many different variables, and to narrow it down we focus on the European studies of high resolution, 12 km, namely Eur-11 and Eur-11i, implementing the RCP8.5 scenarios, and focusing on air temperatures only. These choices have narrowed it down to 642 projections, which also needs further filtering.

To narrow down even further on the future projections, it must be well understood and clear what geographical Coordinate Reference System (CRS) needs to be chosen. First of all, CRS is a type of system that uses coordinates locally, regionally, or globally, to geographically locate points of interest defining specific transformations and map projections between different coordinate systems. There are several types of CRS, including Lambert Conformal Conic, Universal Transverse Mercator coordinate system, Equidistant Cylindrical Projection, and many more, where they differ in how the coordinates are to be assigned to points, such as in cylindrical, cartesian, linear, polar. Now to narrow it down, the CRS to be chosen will be the Equidistant Cylindrical Projection, and that is due to it being in a linear projection format that can directly be interpreted without any use of transformation. That decision was after a previous analysis performed on a Lambert Conformal Conic projection performed by the Centre National de

Recherches Météorologiques (CNRM). The analysis was performed using Panoply, which is a NASA developed application that interactively plots georeferenced and other encoded data, in order to visualize the projections of CNRM, and as distortions were found, due to the necessity of a transformation. Therefore, a Lambert Conformal Conic projection is to be chosen, and that would be represented by Eur-11i on the Cordex database, and alongside to choosing a time frequency of monthly analysis of the future projections to be a monthly analysis, the resulting further narrowing is down to 15 projections.

The remaining 15 studies have all been performed by the Swedish Meteorological and Hydrological Institute (SMHI), which is a is a government agency under the Ministry of the Environment with the task of being an expert body in meteorology, hydrology, oceanography and climatology (SMHI, 2019). To obtain the final result, a certain driving model choice is required, where a driving model is the name of the model that produced the boundary conditions. The most recent driving model available is MPI-M-MPI-ESM which stands for Max Planck Institute for Meteorology - Max Planck Institute Earth System Modelling, with the name describing the features of the model. Finally, with this model and choosing to have a temperature at a near-surface, which corresponds to a height between 1.5m to 10.0m, we are able to extract the final set of projections which consists of 10 netCDF (.nc) files where every file is a batch of all European latitudes and longitudes with the corresponding air temperature projection for 10 years. After the visualization and validation of the resulting files, to make sure no transformation is needed we can safely continue with the study.

3.8 Data Assembly

3.8.1 Available Power Plants

To start the analysis, the data and specifications about the available nuclear power plants in Europe should be determined. (Richard Moss, 2008) power plant matching is a toolset for cleaning, standardizing and combining multiple power plant databases, providing a ready-to-use power plant data for the European power system (Gotzens, Heinrichs, Hörsch, & Hofmann, 2019). This dataset allows the ease of access to readily available nuclear power plant data and provides a facilitated process for updating the data when new datasets are released. Figure 1 and Table 2 show the distribution of nuclear power plants within Europe and its details, respectively.

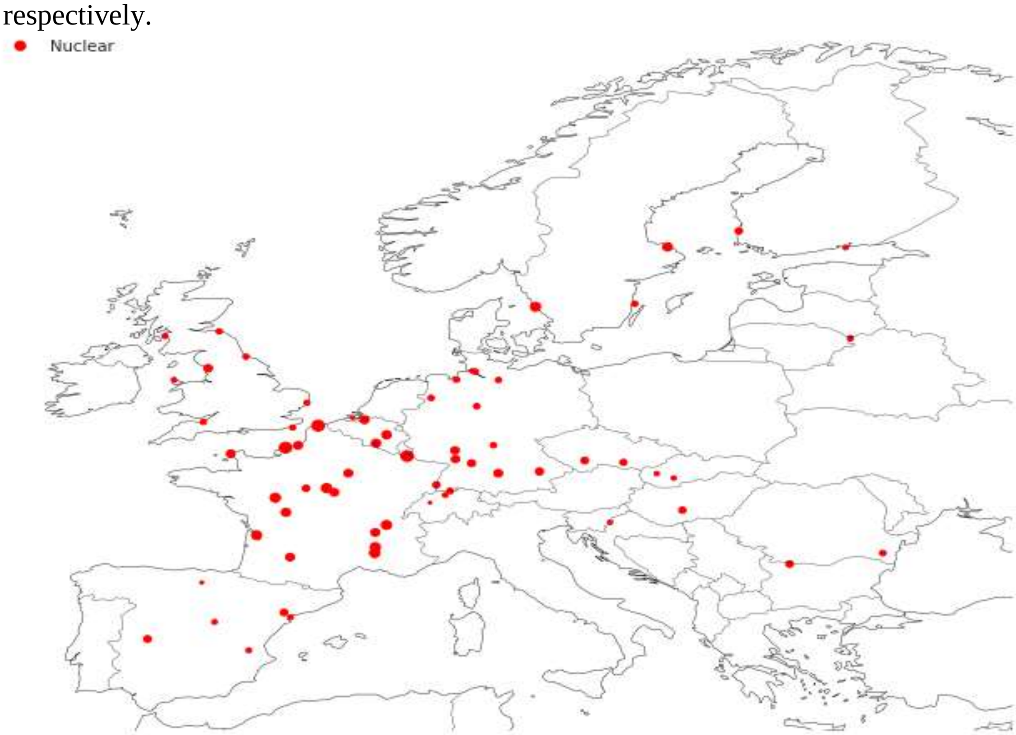

Figure 1 Distribution of nuclear power plants in Europe by country, obtained using power plant matching.

Location	Active Power Plants	Decommissioned Power Plants	Planned to Decommission
Belgium	2	-	-
Bulgaria	1	-	1
Czech Republic	2	-	-
Finland	2	-	-
France	19	1	-
Germany	11	5	6
Hungary	1	-	-
Netherlands	1	-	-
Romania	1	-	-
Slovakia	2	-	-
Slovenia	1	-	-
Spain	6	1	-
Sweden	3	Power Reduction	-
Switzerland	4	1	1
United Kingdom	9	1	7

Table 2 Details of extracted data of the nuclear power plants in Europe, obtained from power plant matching

As can be seen, the total number of power plants is 65, with a majority located in France, and Germany followed by the United Kingdom. Nevertheless, as it is said by the German government to reach a complete phase-out from the nuclear industry by 2023, the whole German market will be neglected from this study as the aim focuses on the next 90 years. The rest of the European nuclear fleet will not be neglected although some power plants have had a reduction in the total power generated and some others are planning on shutdown within the next 3 decades. That is due to the adaptation of the conservative approach, where the demand on water will be considered to be higher to view a projection on the worst, as well as some other countries have possibility of increasing their nuclear fleet within the next decades, and some others are reconsidering the shutting down of nuclear power plants. Further details about the nuclear power plants to be considered in this study can be found in Table 9 in the appendix.

Countries with possibility of power reduction would be Sweden and the United Kingdom, yet regarding the United Kingdom it is more uncertain about this decision as they are currently in the process of constructing a new plant that could roughly be equivalent to two of the current power producing plants. On the other hand, France and Finland have decided to increase the capacity and construct new generation power plants with relatively a high-power generation, which compensates for any future shutdowns. The total power generation, after neglecting Germany and taking would be 115.62 GW produced in Europe from nuclear power with 49 nuclear power plants to be considered.

3.8.2 Water Temperature Parameter Identification

After identifying the considered nuclear power plants and their corresponding locations and the future air temperature projections, the rest of the required parameters of equation 3 are needed. To obtain these parameters, a knowledge on the temperatures of the water bodies used by each power plant needs to know alongside to the air temperature of that location to find a relation and to build a linear regression model to obtain the values. Due to the large amount of water bodies available in the region and the complexity of data retrieval, especially on the rivers and basins located within Europe, this study takes a region and corresponds the largest water body to represent that region. According to (Rubbelke & Vogele, 2011) a value of 0.14 and 16.5ºC could be represented as gamma and beta factors respectively, but that doesn't seem accurate due to the dependency of these factors on the minimum and maximum temperatures of the region, which infers that in the north temperatures are lower than south of Europe. Nevertheless, this assumption will be considered when dealing with central Europe, due to the lack of sufficient temperature data that can be retrieved, if the factors turn out to be relatively out of bound. Although some does not have power plants using it yet it provides an estimation of how water bodies in that region will behave the water bodies to be considered in this study are the Baltic Sea, the North Sea, the Atlantic Ocean, the English Canal, the Loire River, the Danube River, and the Mediterranean Sea. The corresponding coordinates covered by the water bodies and the locations studied for temperature retrieval are in Table 3 and Table 4, respectively.

Water Body	**Latitude**	**Longitude**
Baltic Sea	$L \geq 50$	$10 \leq L$
North Sea	$L \geq 51$	$-2.8 \leq L < 10$
Mediterranean	$L < 41$ $L < 45$	$-8 \leq L$ $-2.8 \leq L$
Atlantic Ocean	$51 \leq L$ $41 \leq L \leq 48$	$L < -2.8$ $L \leq -2.8$
English Canal	$48 \leq L < 51$	$-8 \leq L \leq -2.8$
Danube River	$45 \leq L < 50$	$10 \leq L$
Loire River	$40 < L < 51$	$-2.8 < L < 10$

Table 3 Corresponding latitude and longitudes to be represented by the considered water bodies.

Water Body	**Locations of Interest**
Baltic Sea	*Gdansk*-**Poland**, *Lulea and Gothenburg*-**Sweden**, **Finland**, **Latvia**, *Klaipeda*-**Lithuania**
North Sea	*Esbjerg*-**Denmark**, *Ostend*-**Belgium**, *The Hague*-**Netherlands**, *Newcastle*-**UK**
Mediterranean	*Marseille, Nice and Corsica*-**France**, *Barcelona*-**Spain**, *Rome, Porto Cerro, Caligari*-**Italy**
Atlantic Ocean	*Bordeaux and Brest*-**France**, *Santander and Bilbao*-**Spain**, *Reykjavik*-**Iceland**
English Canal	*Plymouth*-**UK**
Danube River	*Vienna*-**Austria**, *Budapest*-**Hungry**, *Passau*-**Germany**
Loire River	*Nantes, Tours, and Angers*-**France**

Table 4 Locations studied and where temperatures are obtained to find the necessary parameters.

The previous data allows us to obtain the desired parameters related to every water body considered in the study. The results are a linear regression model of the air temperature and water temperature relations performed using Microsoft Excel Solver. To emphasize more on the shape, it is generally an elongated "S" shape, resembling stability at water temperatures on the lowest and highest air temperatures, with a variation in the middle part of the graphs. To obtain a linear regression the set of values is the mid-range was taken and final values were obtained. The following figures and table represent the linear regression model graphs for the corresponding water bodies and the final results to be taken, respectively.

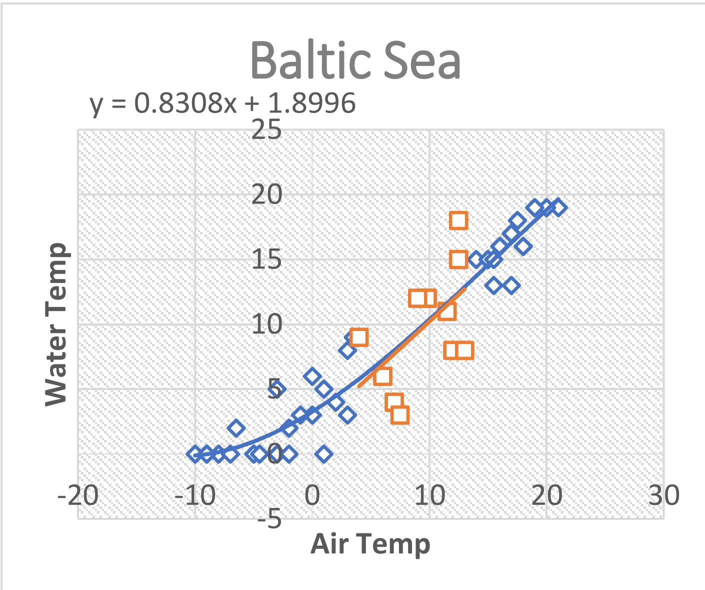

Figure 2 Baltic Sea linear regression model.

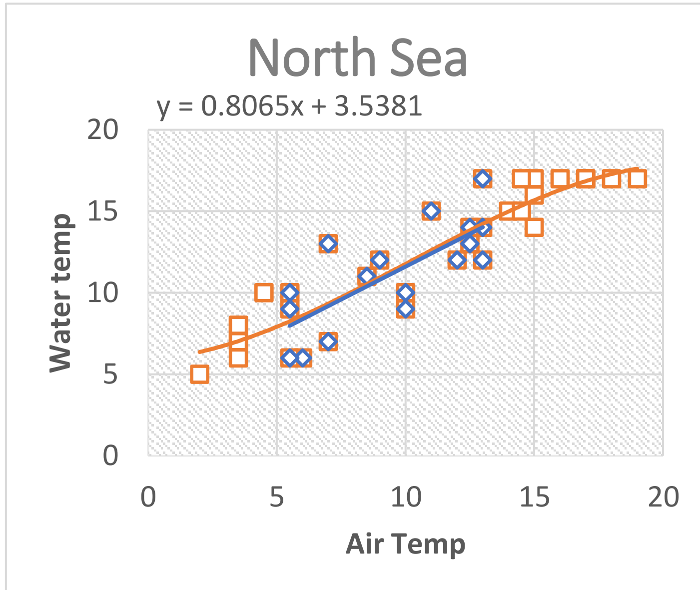

Figure 3 North Sea linear regression model.

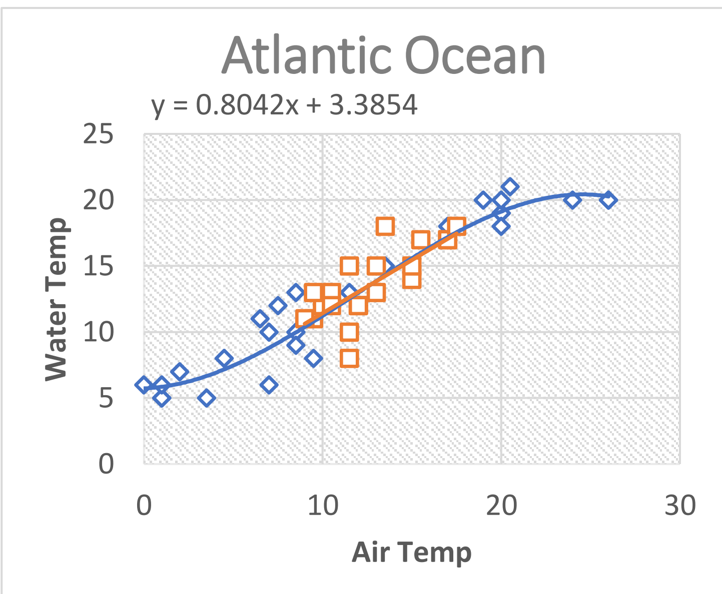

Figure 4 Atlantic Ocean linear regression model.

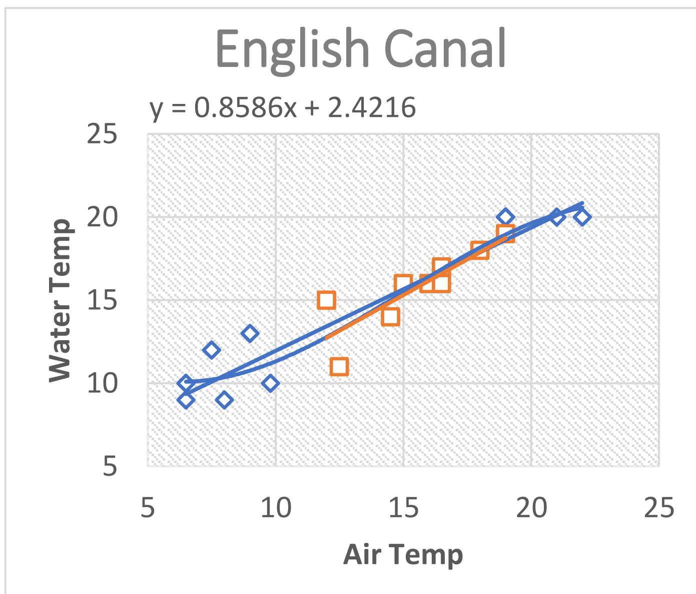

Figure 5 English Canal linear regression model.

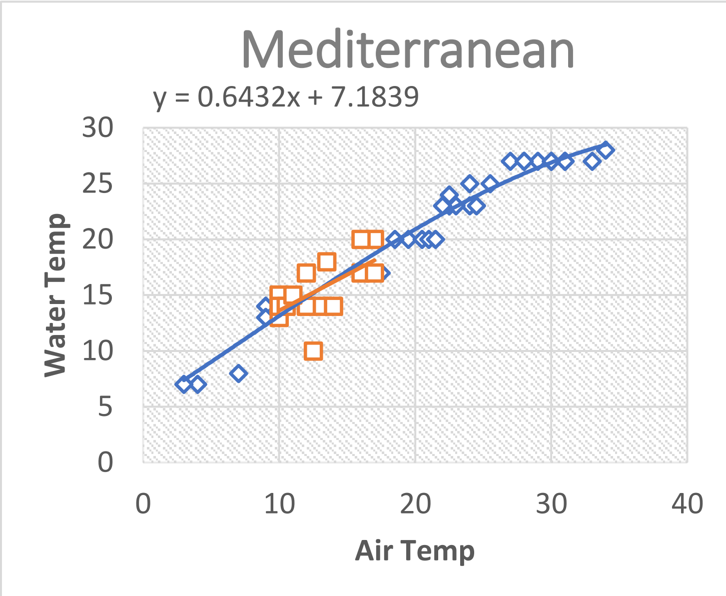

Figure 6 Mediterranean Sea linear regression model.

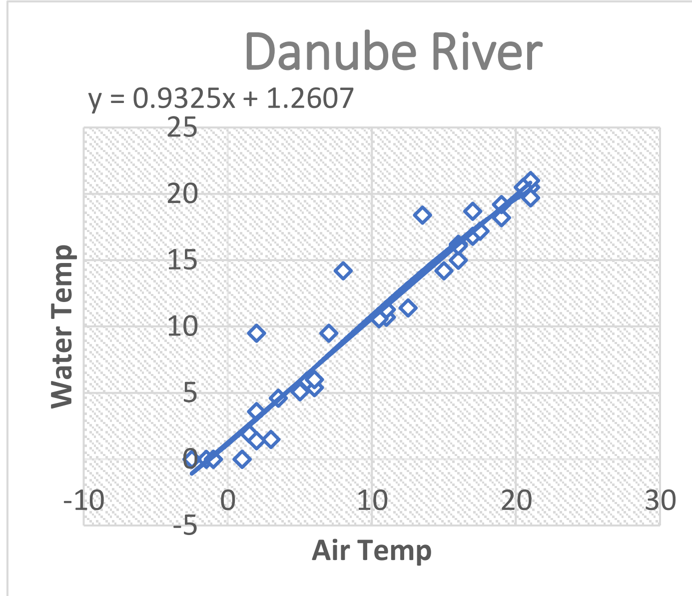

Figure 7 Danube River linear regression model.

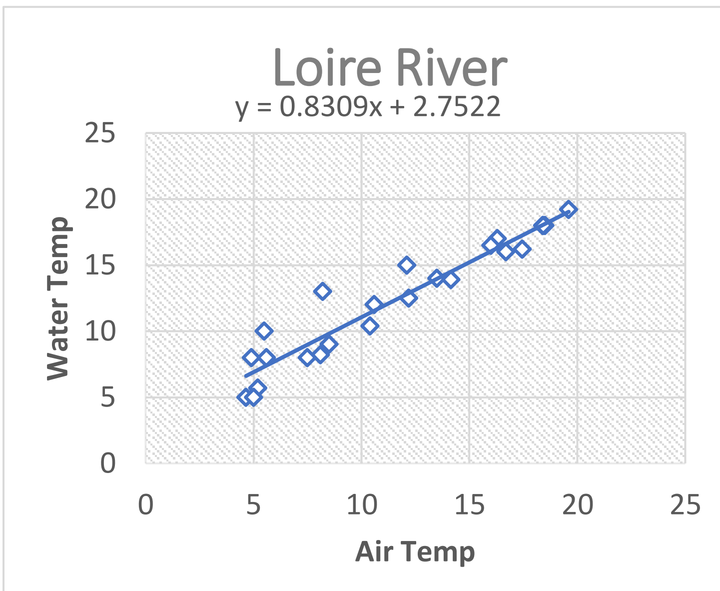

Figure 8 Loire River linear regression model.

Water Body	**Baltic Sea**	**North Sea**	**Mediterranean**	**Atlantic Ocean**	**English Canal**	**Danube River**	**Loire River**
Slope (m)	0.8308	0.8065	0.6432	0.8042	0.8586	0.9325	0.8309
ϑ	0.6932413	0.678692	0.57158	0.677297	0.709466	0.750484	0.6933
$\gamma = \left(\frac{4*slope}{\alpha-\mu}\right)$	0.174905	0.268833	0.1225143	0.20105	0.3122182 (0.14)	0.177619	0.23406
β(Inflec. Temp) $-^{o}C$	15	13	20.5	14	15.5	10	12
α (Max. Temp) $-^{o}C$	19	17	28	21	20	21	19
μ(Min. Temp) $-^{o}C$	0	5	7	5	9	0	5

Table 5 Parameter identification to be used in equation 2 for the projection and analysis.

3.8.3 Water Demand Parameter Identification

With the parameter values of equation 3 obtained, we can now proceed with the determination of the parameters of equation 1 and 2. Initially, the capacity of the considered power plants was obtained through power plant matching, also found in Table 9 in the appendix in MW, yet it needs to be converted to kW. The total hours of operation will be that of a month as the frequency of the obtained projections which is a monthly projection. The total efficiency will be the ratio of the electricity produced to the total heat generated from the power plant, which is a range between 0.75-0.85 (75%-85%), and the electrical efficiency will be taken as the lowest efficiency which is 33%, although there are some plants with a higher efficiency that reaches to 36%, yet as a conservative approach 33% will be chosen, due to the implication that this lower efficiency will require an extra 14% higher heat extraction which in turn a higher demand of water (IAEA, 2012). The density and isobaric specific heat capacities will be arbitrary and constantly determined with every stream temperature calculated from equation 3.

The permissible water temperature increase (AS) will be taken to be 10 K for closed and open cooling systems. The share of waste heat not discharged by cooling water will be taken as 0.01 (1%) retrieved from (IAEA, 2012). Regarding the closed cooling system three additional parameters are required, the share of waste heat released into air, which accounts for the evaporation losses and that will be taken as the ratio of the evaporation losses to the total recirculation cooling water with values obtained from (IAEA, 2012). The correction factor ω, is a factor that accounts for sensible heat transfer increasing in summer and decreasing in winter, and according to (Koch & Vogele, May 2009) it values in a range between 0.7-1.25, and therefore n average will be taken. Finally, the densification factor, which takes into account the densification of water as a resulting effect after evaporation and with the precipitation of minerals, is usually a range between 1-4 (Koch & Vogele, May 2009), but will be taken as 3 according to a previous study performed by (Rubbelke & Vogele, 2011).

Parameter Values	
KW = Values from table 9 in Appendix	**AS** = 10 K
h = 24*30 = 720	**EZ** = 3
$\boldsymbol{\eta_{total}}$ **= 0.75-0.85**	$\boldsymbol{\omega}$ **=** 0.975
$\boldsymbol{\eta_{electrical}}$ = 0.33	$(\mathbf{1}-\boldsymbol{\beta})$= 0.013696
$\boldsymbol{\alpha}$ = 0.01	"$\boldsymbol{c}$" $\boldsymbol{and}$ "$\boldsymbol{\nu}$" =constant value check using XSteam

Table 6 Water demand parameter identification assembly.

The final simulation and run will be performed using MATLAB, as it is more facilitated in the data formatting due to its functionality in matrix logic. This will assist in dealing with the large files and will result in an efficient data storage methodology to a Microsoft Excel file after the simulation has been performed, for further analysis and discussion.

Chapter 4: Results and Discussion

4.1 RCP 8.5

4.1.1 Air Temperature

4.1.1.1 Results

As previously stated, the reactors that will be considered are the 49 reactors across Europe that do not have a future possibility of being decommissioned, or shut down due to any phase or decision taken by the state country. This means that several reactors, that could be currently producing electricity, will not be considered as part of the conservative approach, and to facilitate the simulation of the process which will be on a course of 90 years, 80 upcoming and a previous 10. The approach was performed using the values at the near surface obtained from Euro-Cordex, and using MATLAB, an area of 50 km East-West and 50 km North-South was taken and averaged to obtain the mean air temperature around the rector, which will later correspond to the derived stream temperatures. The following figures illustrate the average of every reactor near surface air temperature per year on the course of 100 years.

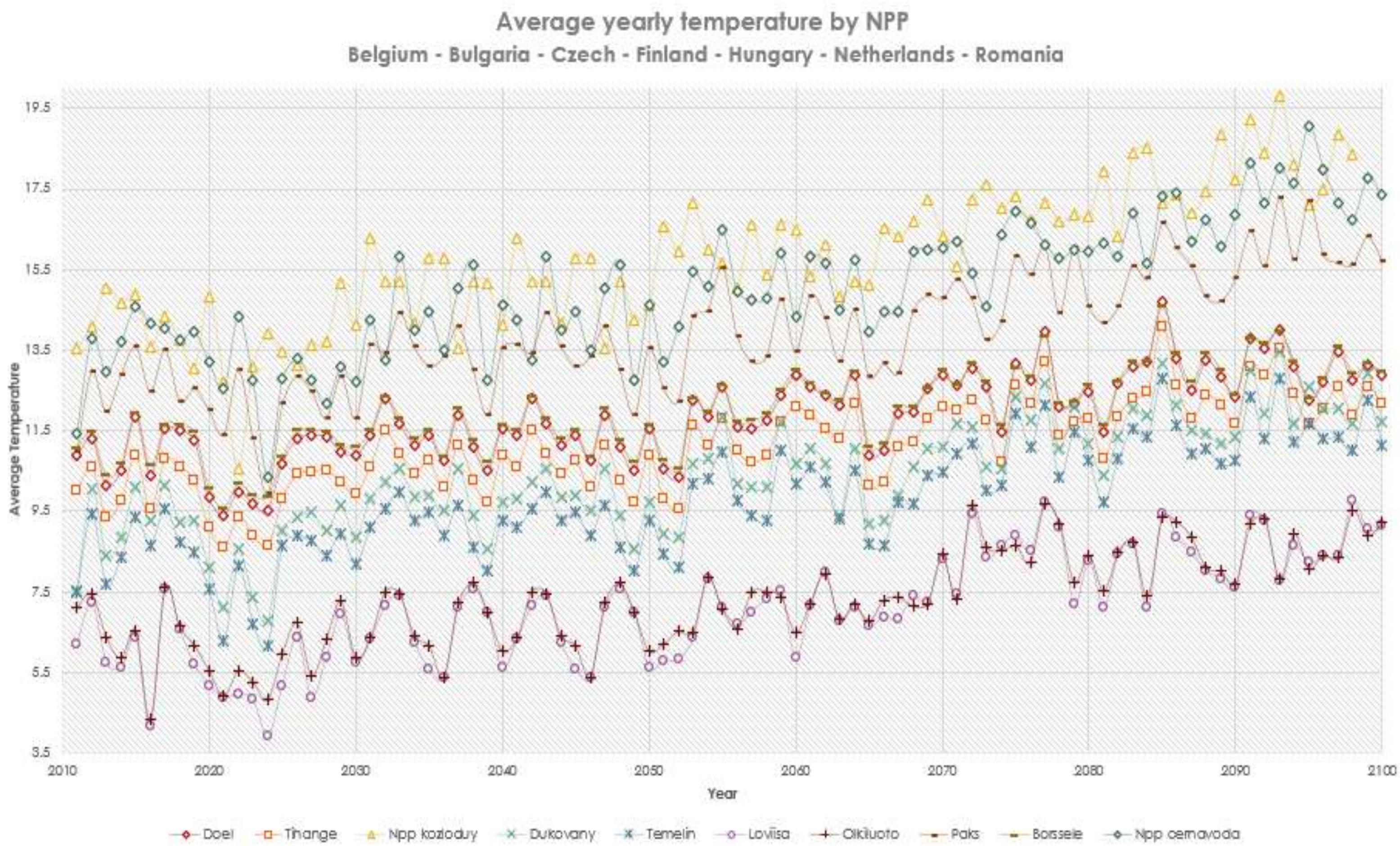

Figure 9 Average yearly near surface air temperature by NPP for following set of countries (a). RCP 8.5.

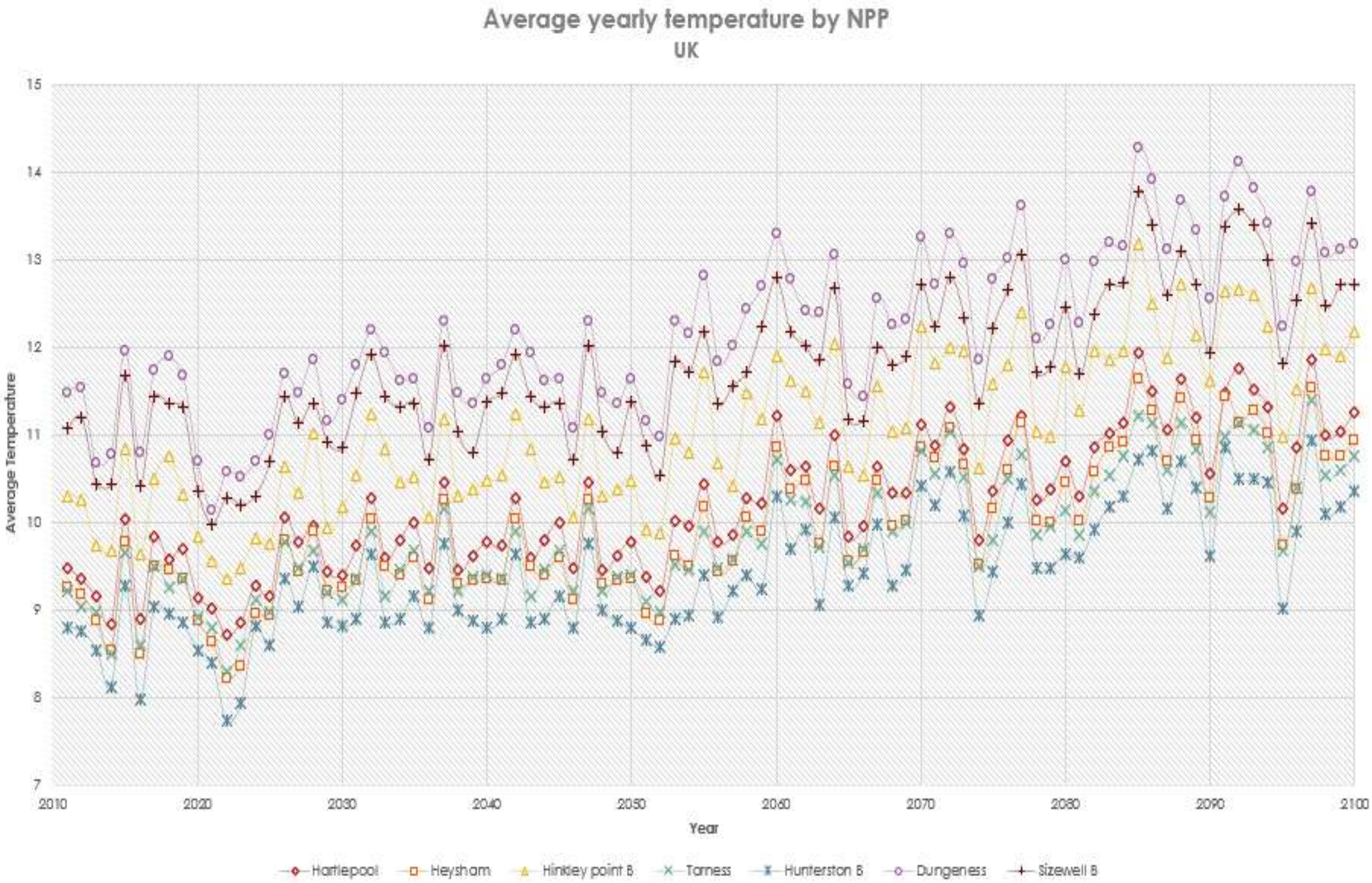

Figure 10 Average yearly near surface air temperature by NPP for following set of countries (b). RCP 8.5.

4.1.1.2 Analysis

The previous figures cover a specific set of reactors within Europe, while the rest can be found in the Appendix, which includes France and most of the southern European region. It is observed that the trend is not periodic trend as it is not seasonal, yet we can observe although the highs and lows the general trend of the behavior is in an increasing manner, which is logical and obvious while using the RCP 8.5W/m^2. We can induce that the behavior generally tends to be similar to all power plants and regions, yet the difference in the values and ranges is mainly due to the location of the power plant, whether it is in the North or South, since the more north the plant is the lower the temperature is, and the more south the plant is the higher the temperature.

4.1.2 Water Temperature

4.1.2.1 Results

After obtaining the air temperatures the next main target is to obtain the stream temperature using the Mohseni equation previously described, alongside to all the obtained parameters in section 3.8.2. Similarly, the stream temperatures were obtained using MATLAB using the monthly values, of the previous process, meaning that the temperatures used are the averaged temperatures, to obtain the monthly stream temperature. The following figures illustrate the average of every reactor stream temperature per year on the course of 100 years after obtaining the monthly values and averaging them on a yearly frequency.

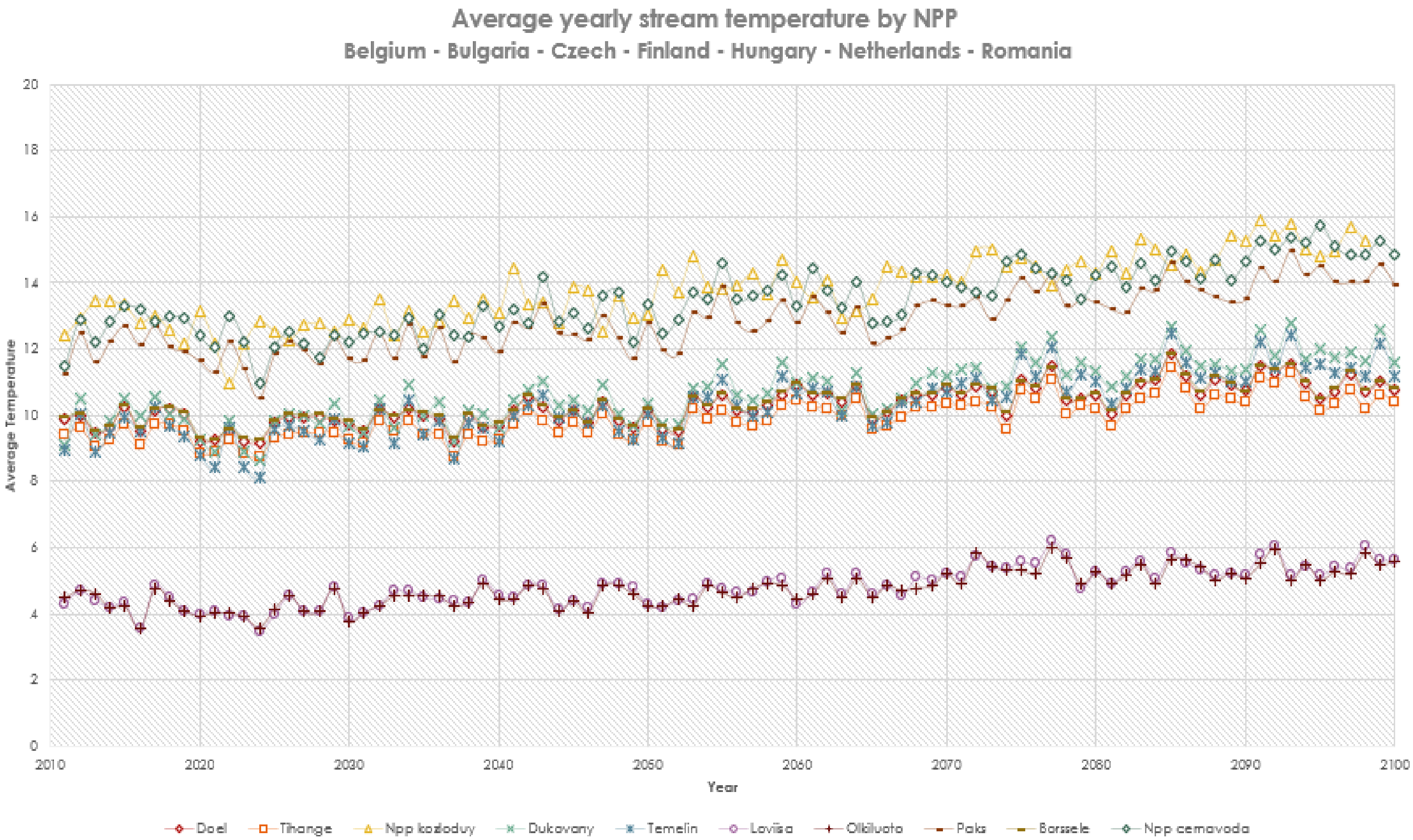

Figure 11 Average yearly stream temperature of following set of countries (a). RCP 8.5.

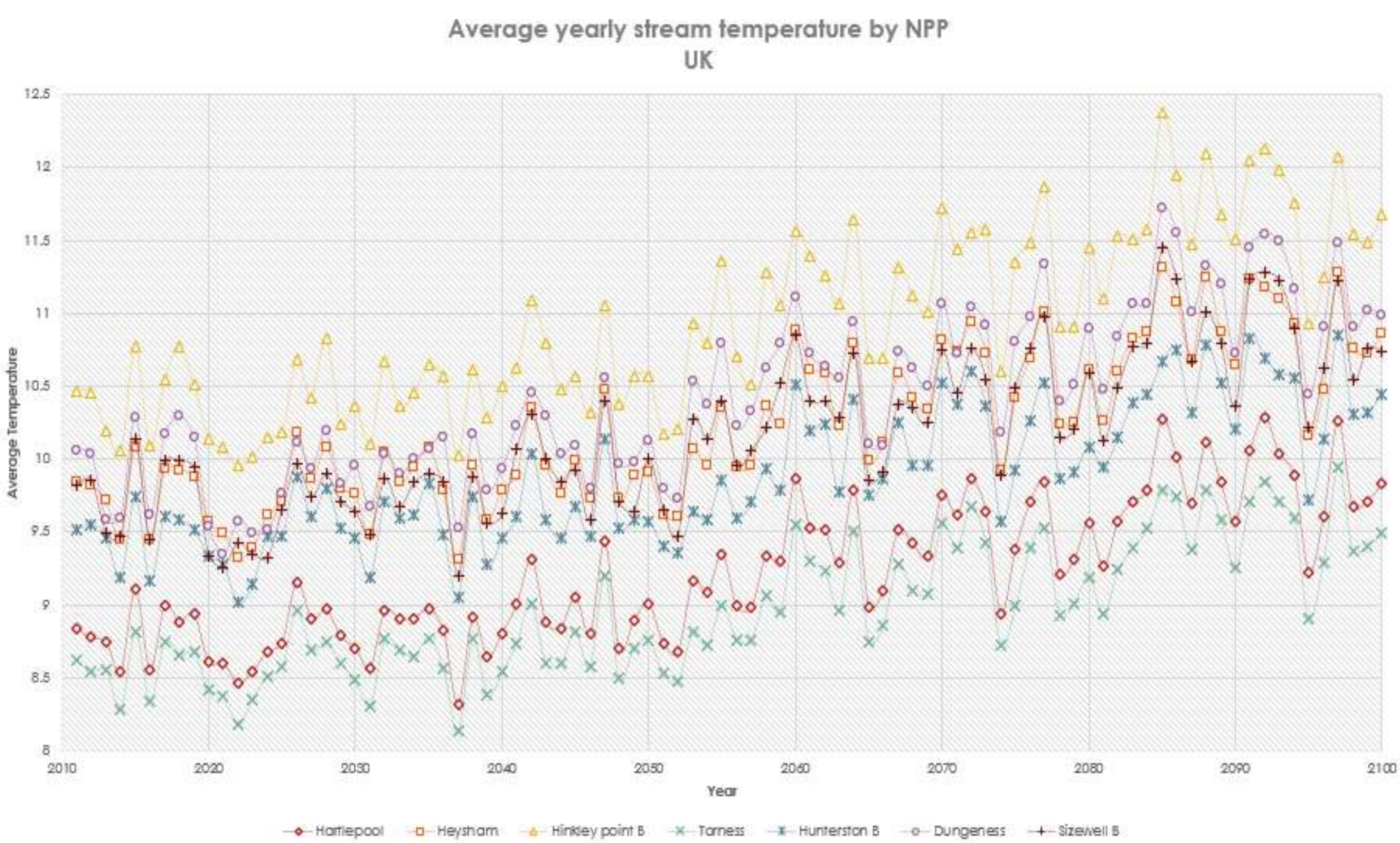

Figure 12 Average yearly stream temperature of following set of countries (b). RCP 8.5.

4.1.2.2 Analysis

The previous figures cover a specific set of reactors within Europe, while the rest can be found in the Appendix, which includes France and most of the southern European region. It is observed that the stream temperature is following a similar trend to that of the air temperature with an increasing general trend along to the fluctuating yearly values. We can observe as well the difference in temperatures in Olkiluoto power plant, located in Finland, is lower than the rest of the plants, and relatively a little lower than the air temperatures projected. This is due to the fact that the weather is relatively colder, resulting in a lower temperature climate, this will in turn result in a lower water temperature. This can be visualized on a linear regression curve, where when the tail has lower air temperatures, the stream temperatures tend to stabilize.

4.1.3 Power Output

4.1.3.1 Results

To find the power output the equations used were equations 1 and 2 for closed and open cooling systems, respectively. To achieve the desired output, the power plants across the European region were all assessed to whether they implemented open or closed cooing systems, the results of the assessment is found in Table 9 in the Appendix. After collecting the data, and with in depth analysis of the required parameters, to verify that all the values chosen are coherent with the practical experience, engineering logic, and bounds of acceptance, the study was implemented using a set of constraints. These constraints were focusing on the critical non-constant values in this study which were the maximum permissible water intake, the maximum permissible temperature increase of the return water, and finally on the total efficiency of the plant, that decreases in response to the decrease of the permissible temperature increase of the water return. With these constraints, and after simple manipulation with equations 1 and 2 we get

$$KW_{max} = \frac{AS_{max} * c * \nu * Q_{max}^{F}}{h * 3.6 * \left(\frac{1-\eta_{total}}{\eta_{electrical}}\right) * (1-\alpha) * (1-\beta) * \omega * EZ} \; ; Closed\ Cooling\ Systems\ (Eq.4)$$

$$KW_{max} = \frac{AS_{max} * c * \nu * Q_{max}^{F}}{h * 3.6 * \left(\frac{1-\eta_{total}}{\eta_{electrical}}\right) * (1-\alpha) *} \; ; Open\ Cooling\ Systems\ (Eq.5)$$

These equations will be used to find the final desired values of the maximum power generated, given the following constraints.

Open Cooling Systems		Closed Cooling Systems	
Energy > 2000 MW	65 m^3/s	**Energy > 2000 MW**	1.00 m^3/s
1500 < Energy ≤ 2000 MW	60 m^3/s	**1500 < Energy ≤ 2000 MW**	0.95 m^3/s
1200 ≤ Energy ≤ 1500 MW	55 m^3/s	**1000 ≤ Energy ≤ 1500 MW**	0.90 m^3/s
700 ≤ Energy < 1200 MW	50 m^3/s	**700 ≤ Energy < 1000 MW**	0.85 m^3/s
Energy < 700 MW	45 m^3/s	**Energy < 700 MW**	0.80 m^3/s

Table 7 Power and water intake constraints for open and closed cooling systems. Obtained from (IAEA, 2012)

The reduction of water intake was an assumption taken into this study, due to knowing that with higher water intake the efficiency is better and that results in better heat withdrawal, but as a conservative approach, in addition to lack of specific details this assumption was used in this study. With the power and water intake constraints dictated, we now move to the following two constraints, which are the maximum permissible temperature increase of the return water and the total efficiency.

Open Cooling Systems		Closed Cooling Systems	
AS ≥ 10 K	0.771	**AS ≥ 18 K**	0.83
8 ≤ AS < 10 K	0.65	**13.5 ≤ AS < 18 K**	0.77
6 ≤ AS < 8 K	0.6	**10.5 ≤ AS < 13.5 K**	0.72
AS < 6 K	0.55	**AS < 10.5 K**	0.67

Table 8 Maximum permissible water return temperature and total efficiency constraints for open and closed cooling systems.

These values were all obtained from a previous study that has been performed (Rubbelke & Vogele, 2011), where they related the open cooling systems directly with water temperature as water is the main source of heat dissipation. On the other hand, they related the closed cooling systems with the air temperature, as it is the main source of heat dissipation, also part of the reason a cooling tower is used. Rather, in this study, the relation of closed cooling systems will be done with water temperature, that is obtained from equation 3.

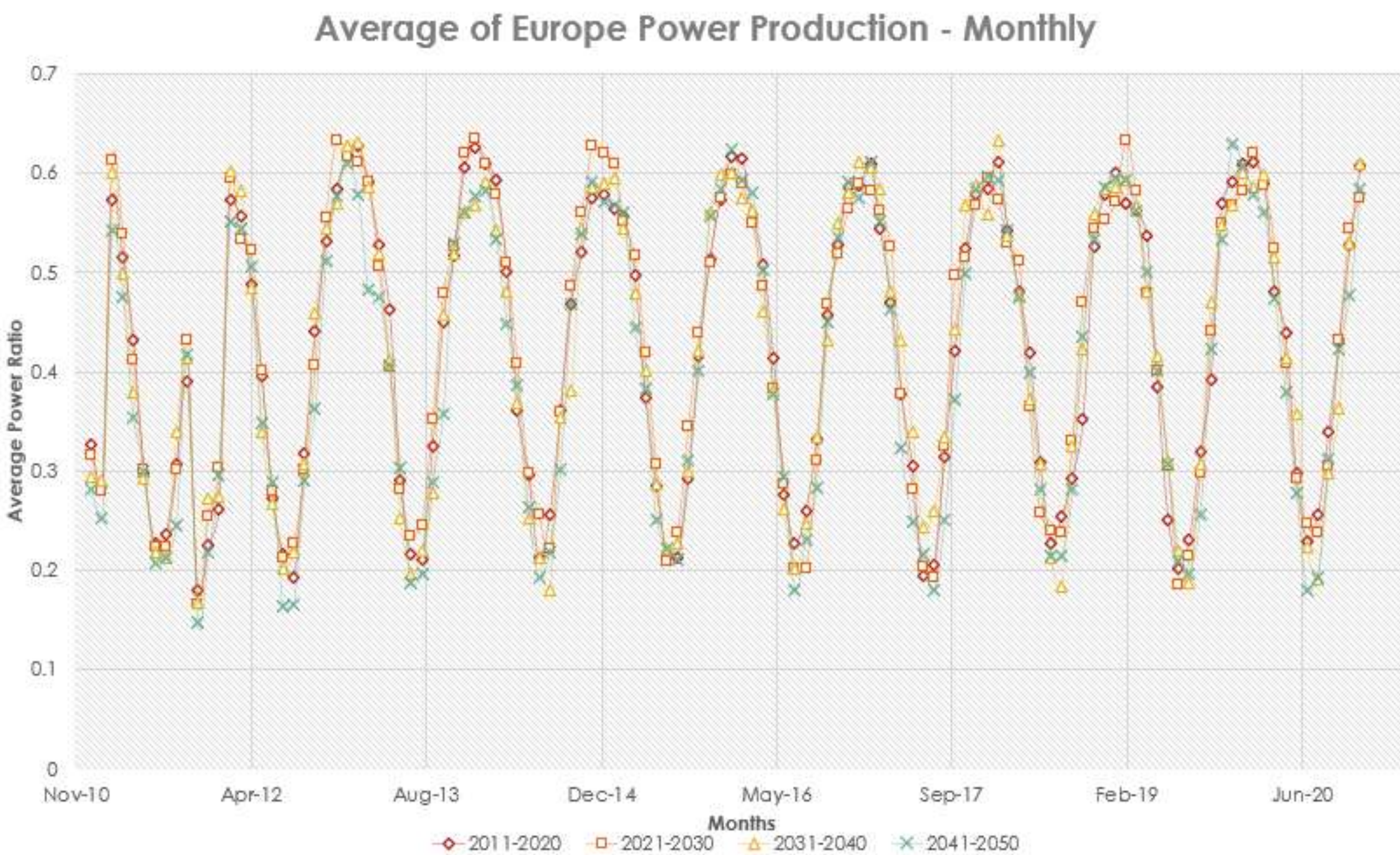

Figure 13 Average European nuclear power production per month compared by the decades (a). RCP 8.5.

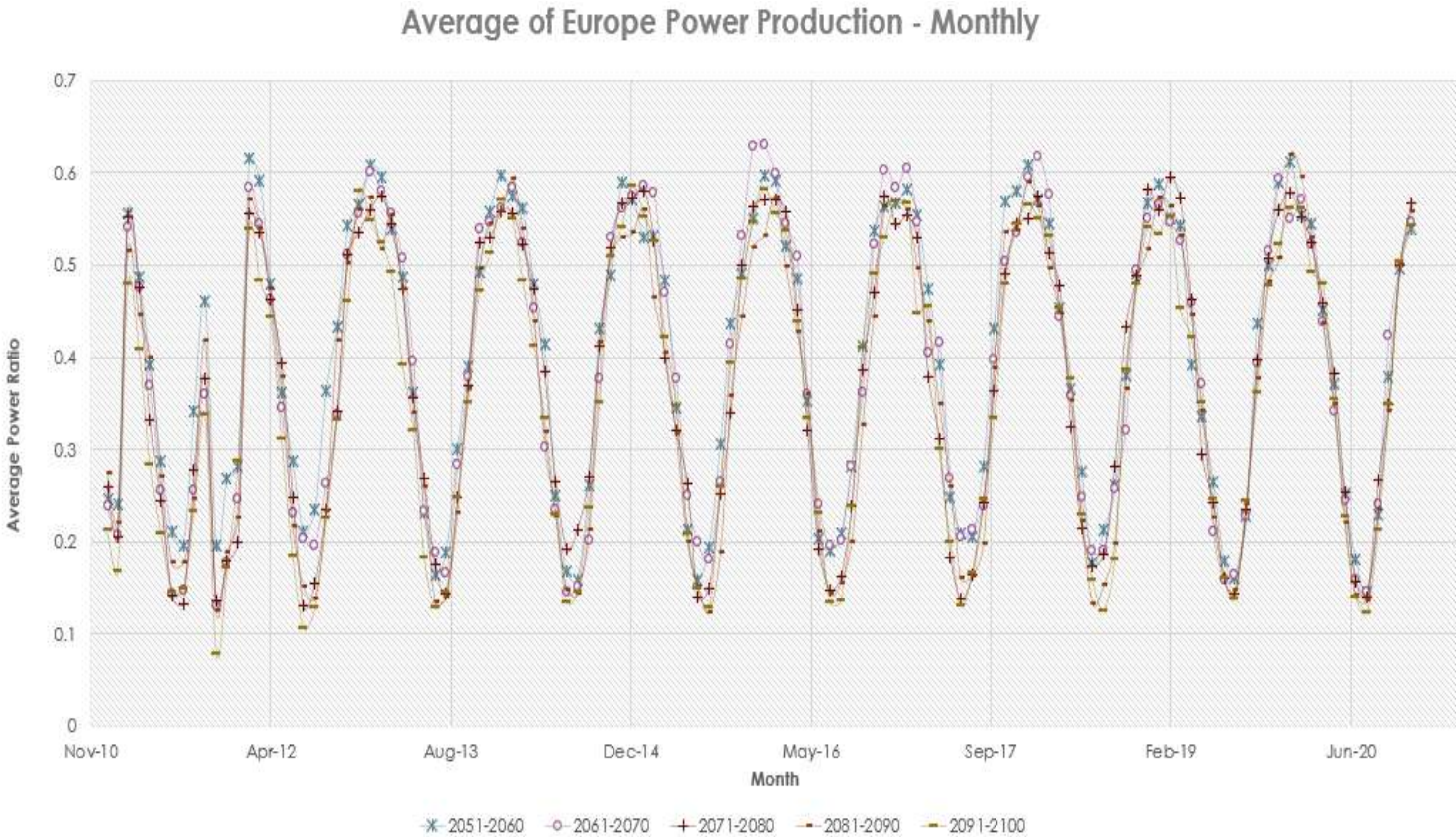

Figure 14 Average European nuclear power production per month compared by the decades (b). RCP 8.5.

4.1.3.2 Analysis

The previous figures illustrate the power generation trend within the European nuclear sector over the decades. These values are based on an average of the total monthly power generated ratio by every reactor, after finding the energy produced by each reactor. The total values obtained from equations 4 and 5 of each reactor were used to get the ratio of full power production, i.e. the final value is a ratio of the power generated to the total power that can be generated. With comparison of the two figures, we can observe that within every decade the values of the total power output ratio decreases, which is a logical trend since the RCP 8.5 scenario tends to be a worst-case scenario. Two more observations were identified, first, the general trend of the graph is on a decreasing behavior, which also correlates to the total expected outcomes from the using of this scenario. Second, the periodic behavior of the trend with the spikes and valleys of the trend, this is due to it being a monthly value, thus the values tend to be seasonal. This implies that the peaks appear during winter where the temperatures are low and, consequently, the power production is higher, and valleys appear during summer, where temperatures are high and, consequently, the power production is lower.

In this study, winter is considered to be during November, December, January, and February to compromise for the maximum permissible water return temperature. In this study, the AS_{max} was obtained using the difference between values of the water temperature from equation 3 and the maximum water temperature during the season, where during winter it was taken as 12ºC for all water bodies considered except the Mediterranean where the temperature was 14ºC due to the naturally higher temperatures in that water body. These values were obtained from the analysis performed in section 3.8.2 by determination of maximum temperatures during winter for every region. During the rest of the year, AS_{max} was taken as the difference between the maximum estimated stream temperatures (α) obtained from section 3.8.2 and the values obtained from equation 3, therefore this will result with different values for every specified region.

4.2 RCP 4.5

4.2.1 Air Temperature

4.2.1.1 Results

After the analysis of the RCP 8.5 scenario, further investigation was required to understand and to be able to assess the final results. This scenario is a moderate assumption scenario where the projections are not over-estimated yet it is not an optimistic projection with a good outcome and lower anthropogenic damage. It focuses more on the similarity of current conditions on the climate, alongside to a slight increase over the long term, which can also be viewed as stable to some extent. The same exact approach was taken and the same procedure was repeated to ensure the compatibility of results and to be able to compare the final results with each other.

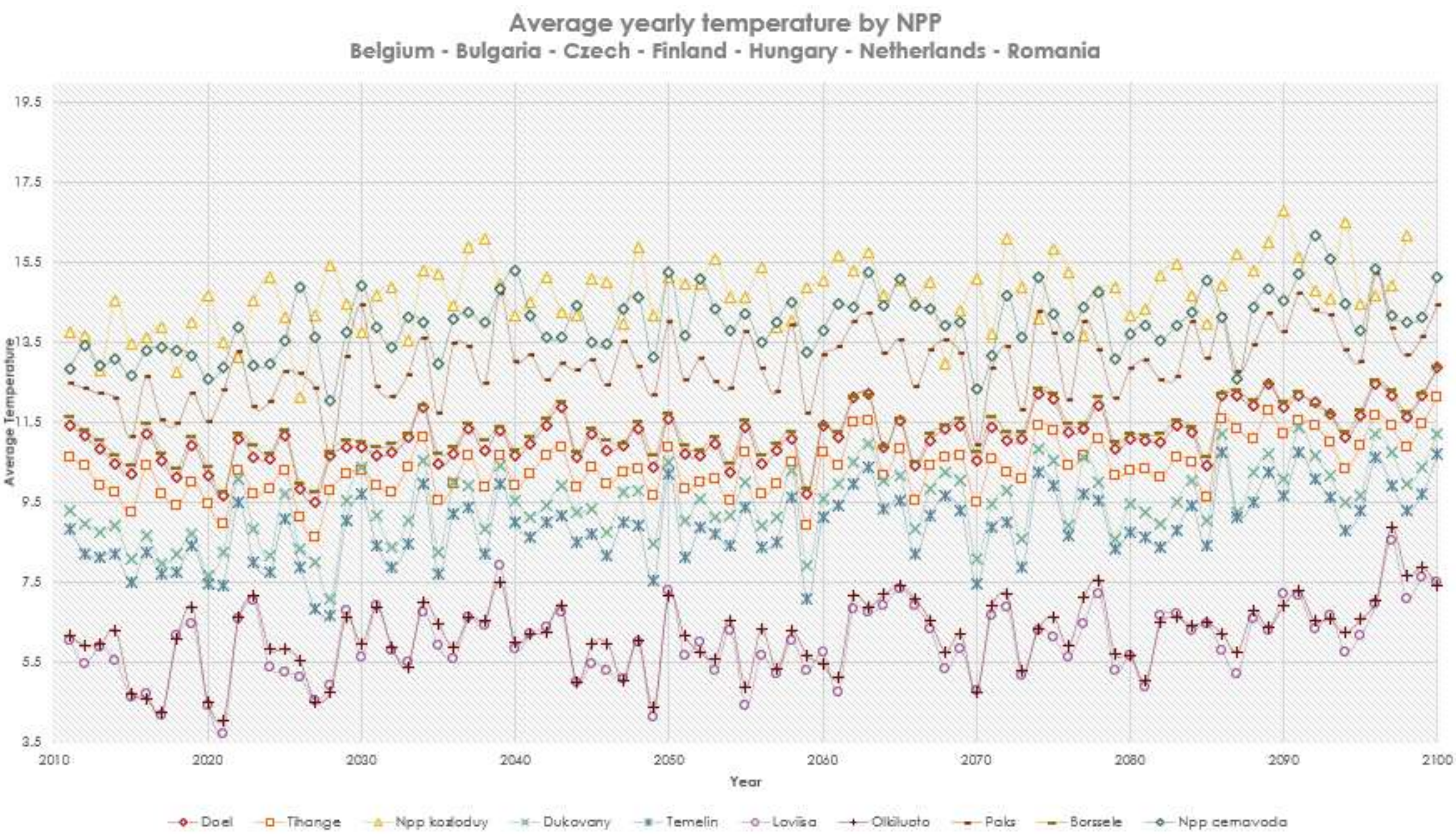

Figure 15 Average yearly near surface air temperature by NPP for following set of countries (a). RCP 4.5.

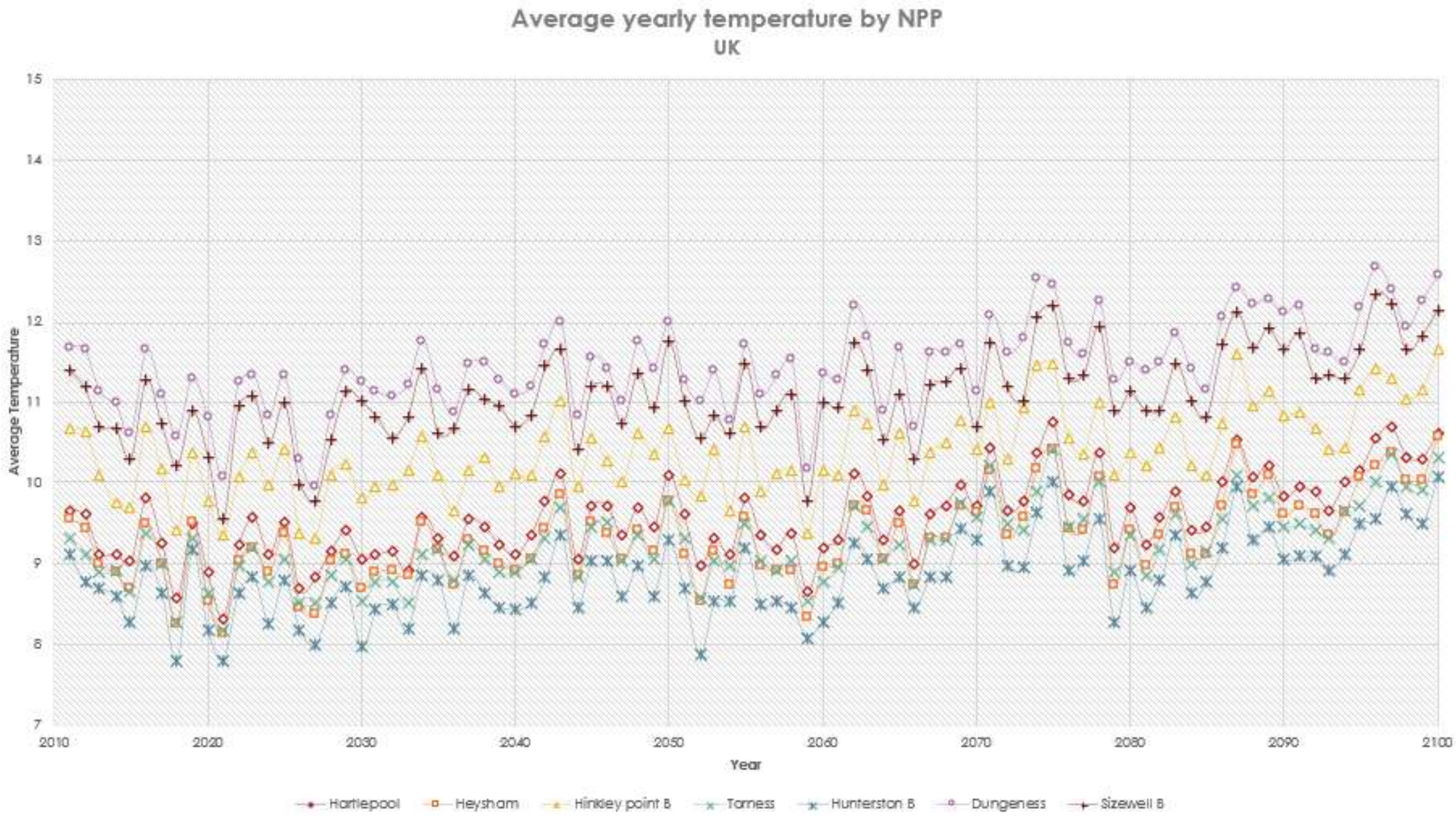

Figure 16 Average yearly near surface air temperature by NPP for following set of countries (b). RCP 4.5.

4.2.1.2 Analysis

The previous figures illustrate the near surface air temperatures obtained using the RCP 4.5 scenario across European set of countries, the rest could be found in the appendix. We can observe the results of the temperatures that they tend to have a similar behavior of non-consistency with time and on the long term. The trend tends to be inclining, with an increase in temperature that is clear for yet it is not very significant, unlike the results obtained from RCP 8.5 scenario. The results from RCP 8.5 clearly show an increasing temperature that reaches up to around 19.5ºC in Bulgaria and Romania, while they lower than 17.5ºC in the RCP 4.5 scenario. Focusing also on the general trend with all other regions we can also observe the similarity in behavior with all locations except the difference of the magnitude due to the location whether north or south.

4.2.2 Water Temperature

4.2.2.1 Results

Similarly, after obtaining the air temperatures the next main target is to obtain the stream temperature using equation 3, previously described, alongside to all the obtained parameters in section 3.8.2. Similarly, the stream temperatures were obtained using the same approach of the previous scenario, with same conditions. The following figures illustrate the average of every reactor stream temperature per year on the course of 100 years after obtaining the monthly values and averaging them on a yearly frequency.

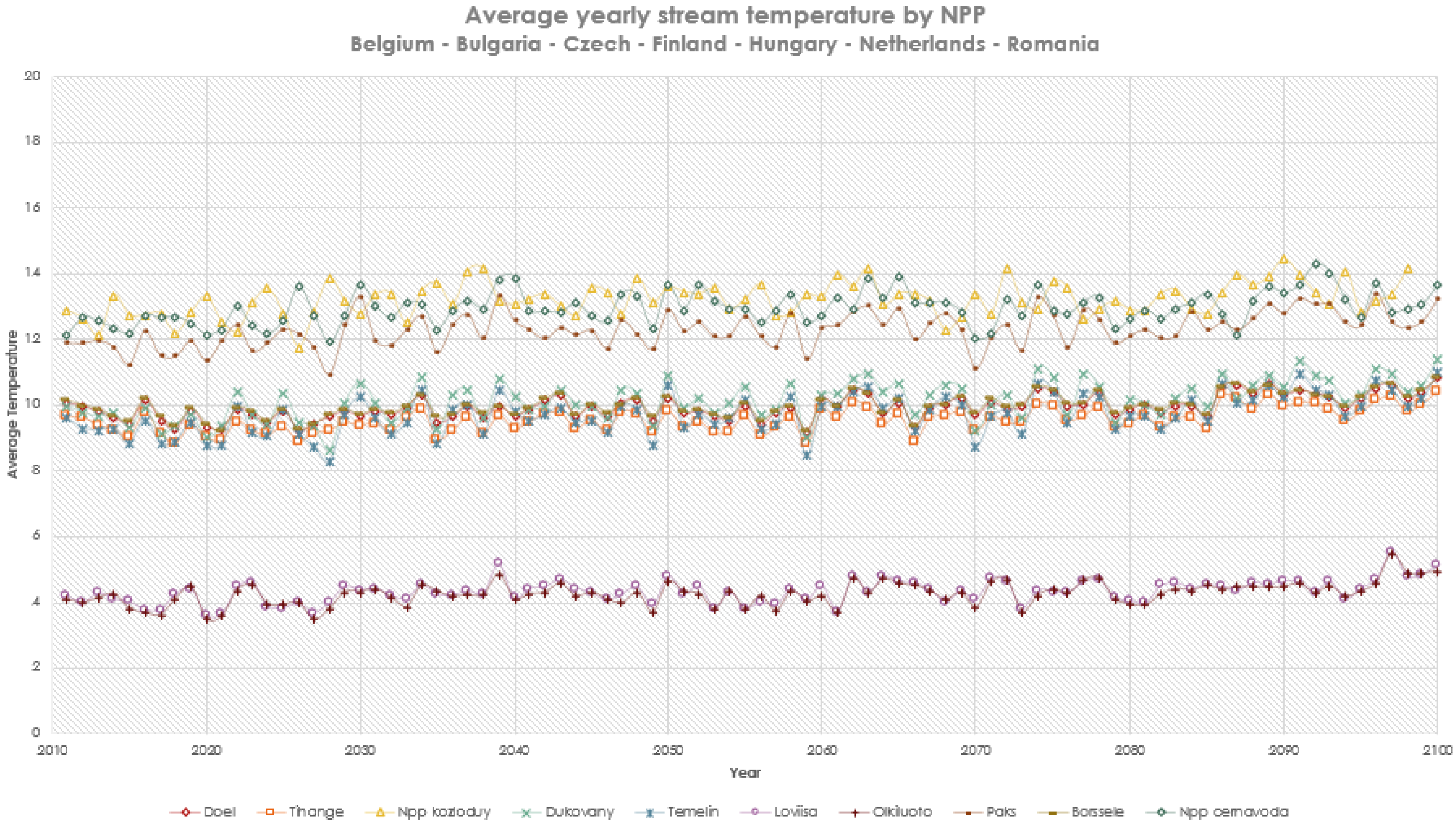

Figure 17 Average yearly stream temperature of following set of countries (a). RCP 4.5.

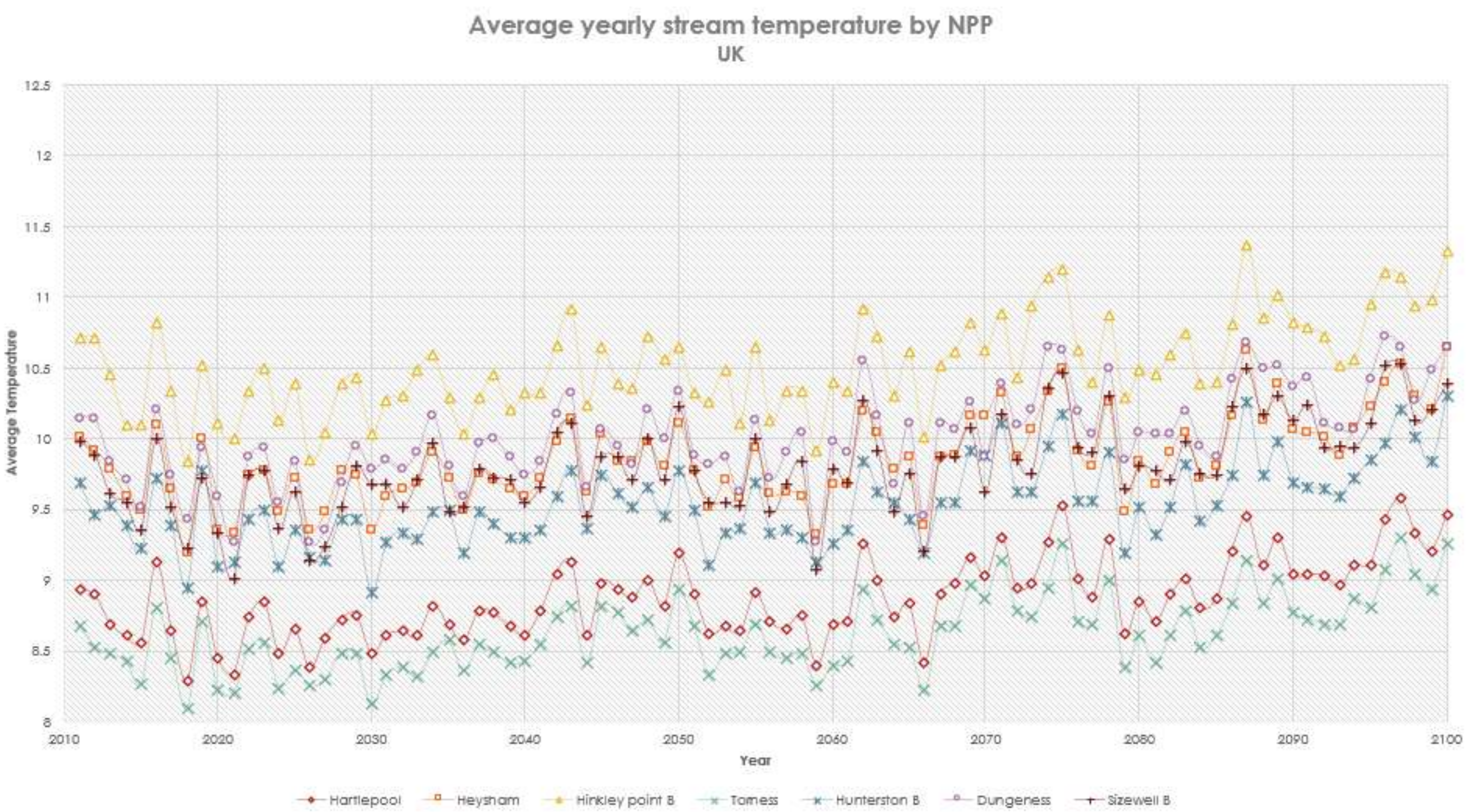

Figure 18 Average yearly stream temperature of following set of countries (b). RCP 4.5.

4.2.2.2 Analysis

From the illustrations above we can identify that the stream temperatures do not really have the same trend of quasi-stability as the air temperature, specially towards the ends of the results around the last decade. This is understandable due to how the water will tend to react and adapt with the air temperature according to equation 3. The linear regression relation between air and water temperature faces two stabilities with further increasing or decreasing temperatures at the head and tail of the graph, yet at the middle part the it is quite in an increase manner. This implies that when the temperature tends to reach this stability region at the head or tail, the water temperature will be very slightly affected, if not affected at all, which is the contrary to what happens in the middle part of the graph. The middle region imposes that water will adapt promptly to the air temperature change, and therefore the difference between two changes in air temperatures would result in a visible, if not significant change. The graphs also show the general values that lie within a smaller value of temperatures to almost all regions and locations, due to the RCP 4.5 scenario, except for Olkiluoto and Loviisa, which are the Finnish reactors, and that is due to the relatively lower temperatures found in the north of Europe where these reactors area located, yet it is similar to that of the RCP 8.5 scenario due to the adaptivity of water temperature and stability in low temperature region.

4.2.3 Power Output

4.2.3.1 Results

To obtain the final results in this section the same exact constraints were imposed on the simulation with equations 4 and 5 used to find the maximum power output, alongside to Table 7 and Table 8 being the reference for the values and parameters required. Also, same phenomenological concepts of the cooling system will be implemented in this scenario study. The following illustrations view the power output ratio of the upcoming decades and within the European nuclear energy sector.

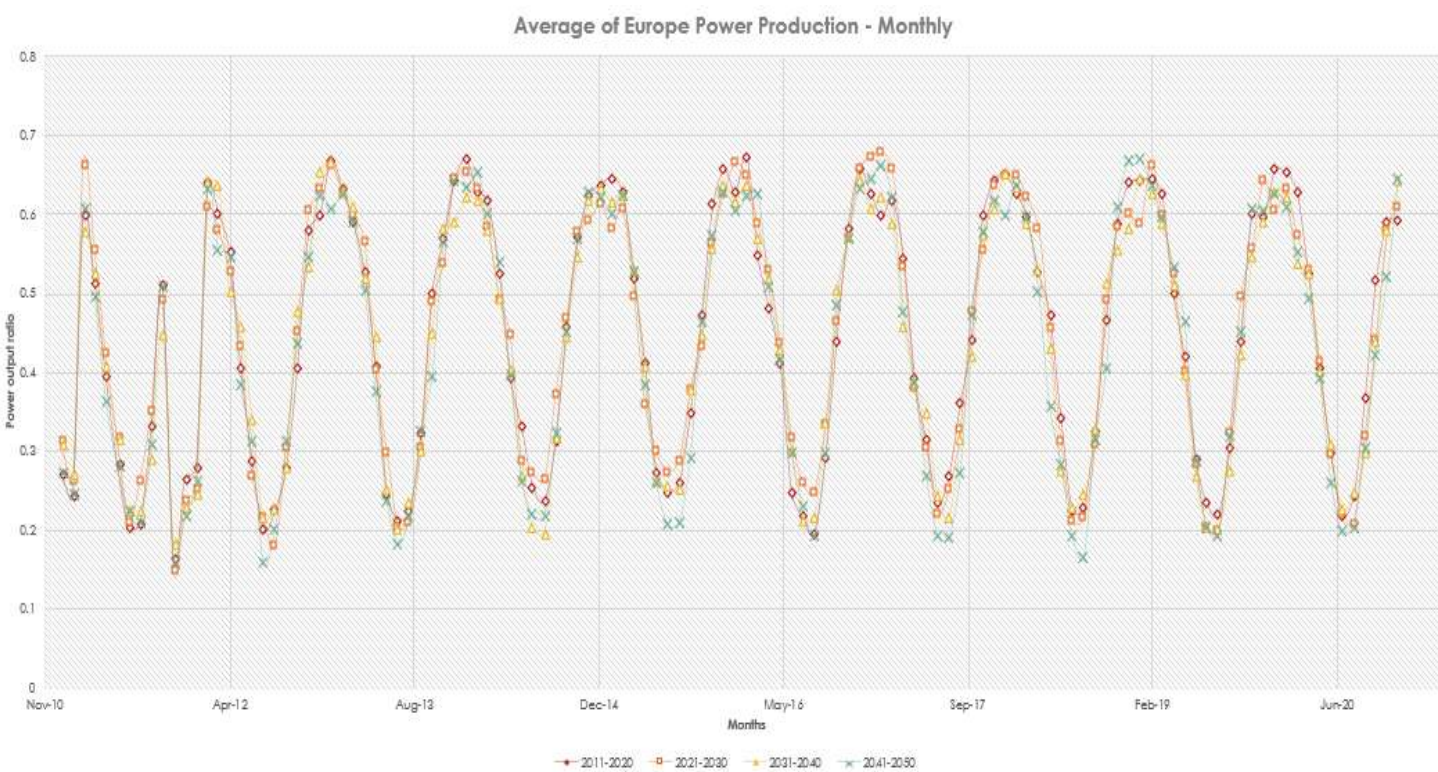

Figure 19 Average European nuclear power production per month compared by the decades (a). RCP 4.5.

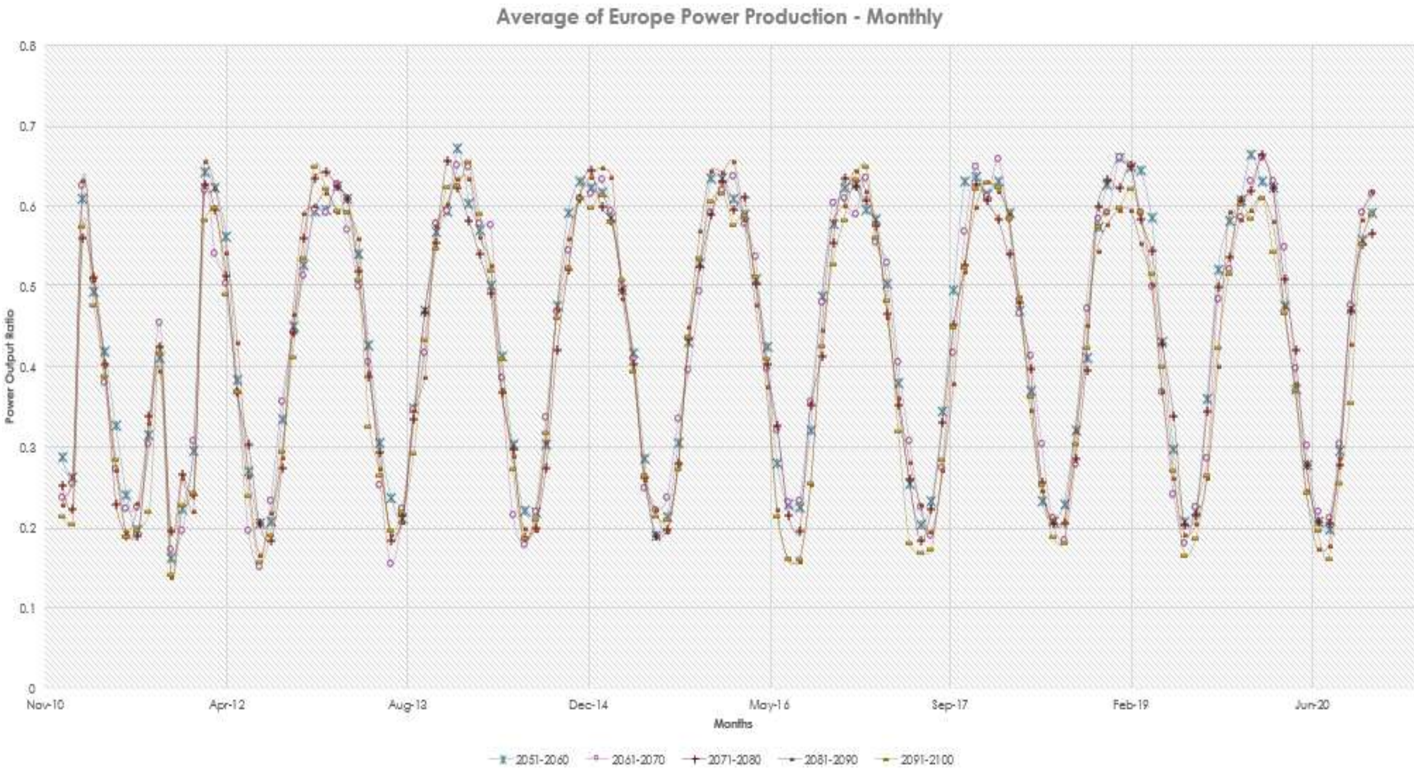

Figure 20 Average European nuclear power production per month compared by the decades (b). RCP 4.5

4.2.3.2 Analysis

We can see from the previous graphs that the average power output ratio over the long term, using the RCP 4.5 scenario, does not significantly fluctuate in values between every decade the following one. When carefully observed, the average power output is almost stable over the following 90 years, and that is coherent with the previous results of air and water temperatures. Moreover, the trend tends to be stable and not increasing nor is it decreasing as average of Europe self-stabilize with several producing lower energy yet compensated by others that produce on a higher rate consecutively. On the contrary, the values from the RCP 8.5 scenario are all on a decreasing behavior with lower average power output observed with each decade and producing an overall decreasing trend.

4.3 RCP 2.6

To further elaborate on the variability of the scenario results and to understand how it can be significantly variant, this study will also perform a simulation using the most optimistic projections. RCP 2.6 is the scenario that projects the most optimistic projections, with a possibility of a better anthropogenic response, and with the mitigation of climate change. In addition to the comparison of results that will be made between the several different scenarios available, the analysis using this scenario will also allow us to assess how the mitigation of global warming will result on the European nuclear energy market. Thus, allowing the understanding how on a larger scale the decrease of climate change is a crucial aspect of consideration and a necessity to be achieved. The following figures illustrate the results on this scenario.

4.3.1 Air Temperature

4.3.1.1 Results

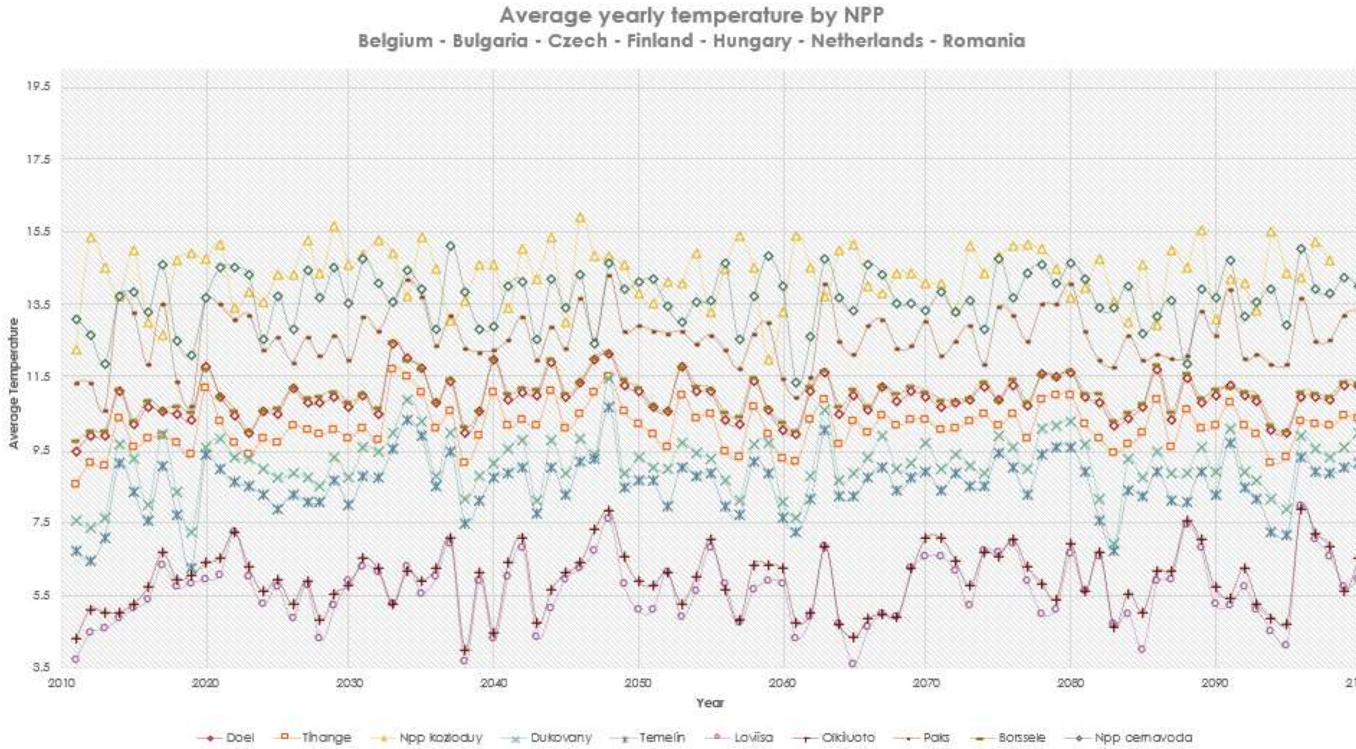

Figure 21 Average yearly near surface air temperature by NPP for following set of countries (a). RCP 2.6.

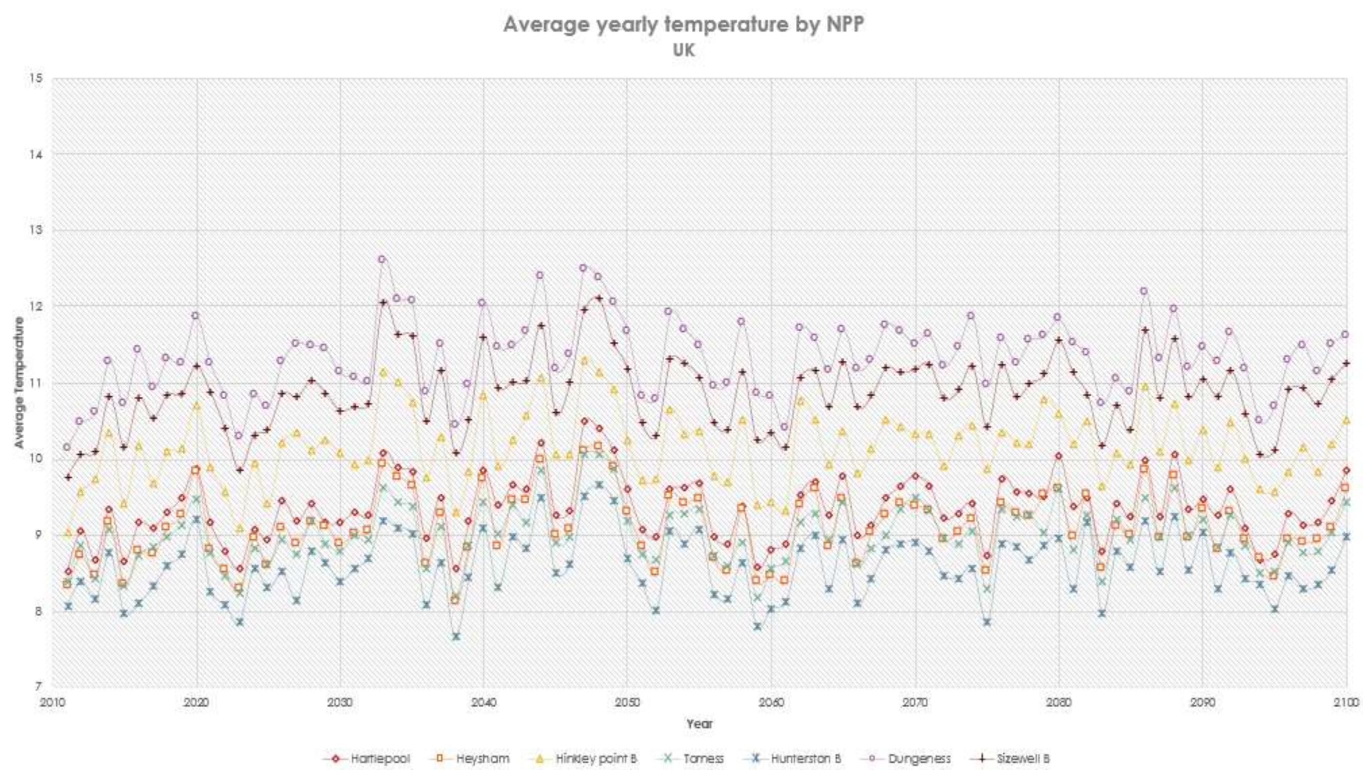

Figure 22 Average yearly near surface air temperature by NPP for following set of countries (b). RCP 2.6.

4.3.1.2 Analysis

We can observe that the temperature trend is stable and is not increasing, though fluctuations are present, yet the scenario does not impose the worsening behavior, instead it imposes stability over the long term. The values observed are also lower than that of the RCP 4.5 scenario, where the highest here are Bulgaria and Romania with a temperature under 15.5ºC unlike in the previous scenario where they are around the 17.5ºC region.

4.3.2 Water Temperature

4.3.2.1 Results

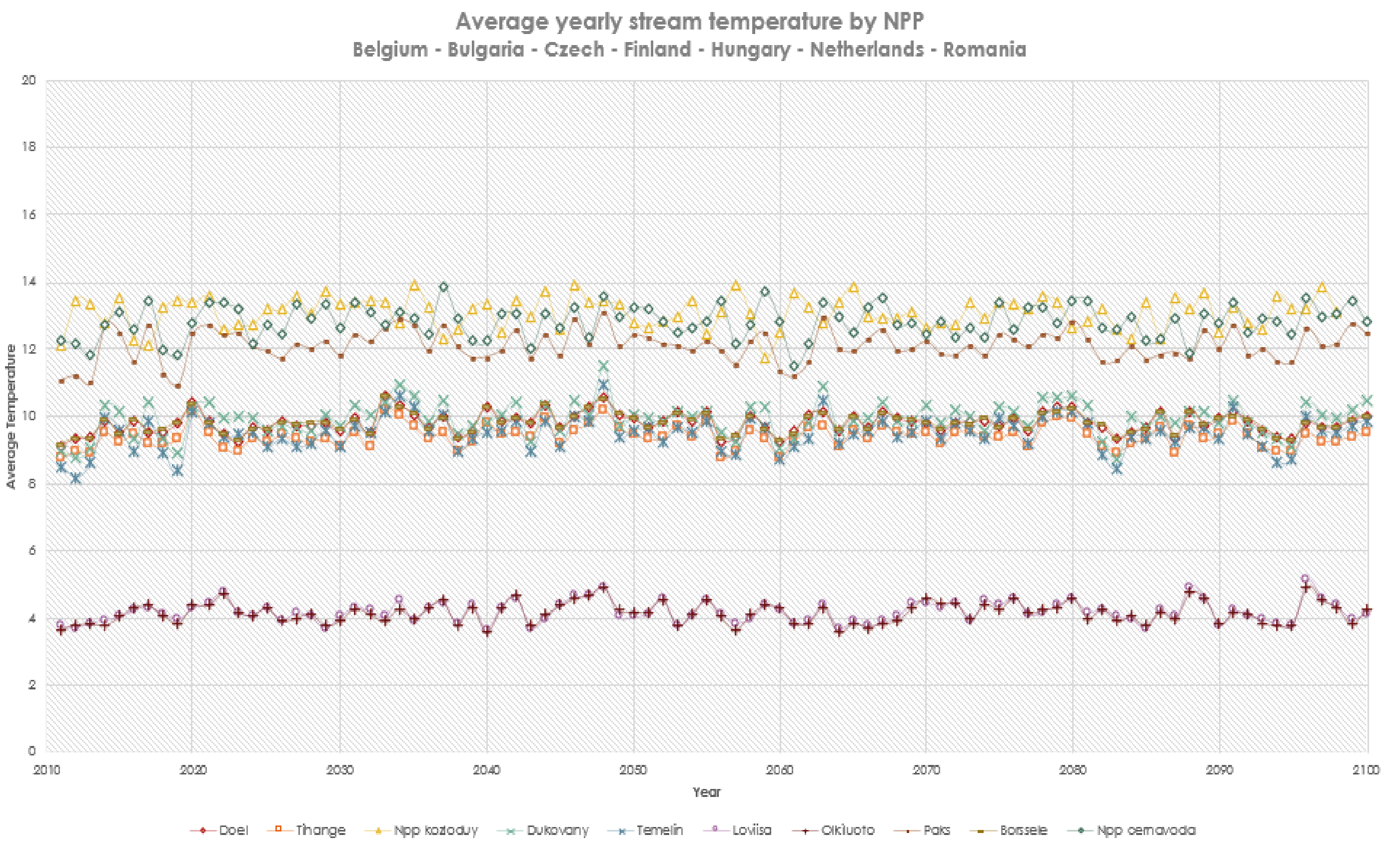

Figure 23 Average yearly stream temperature of following set of countries (a). RCP 2.6.

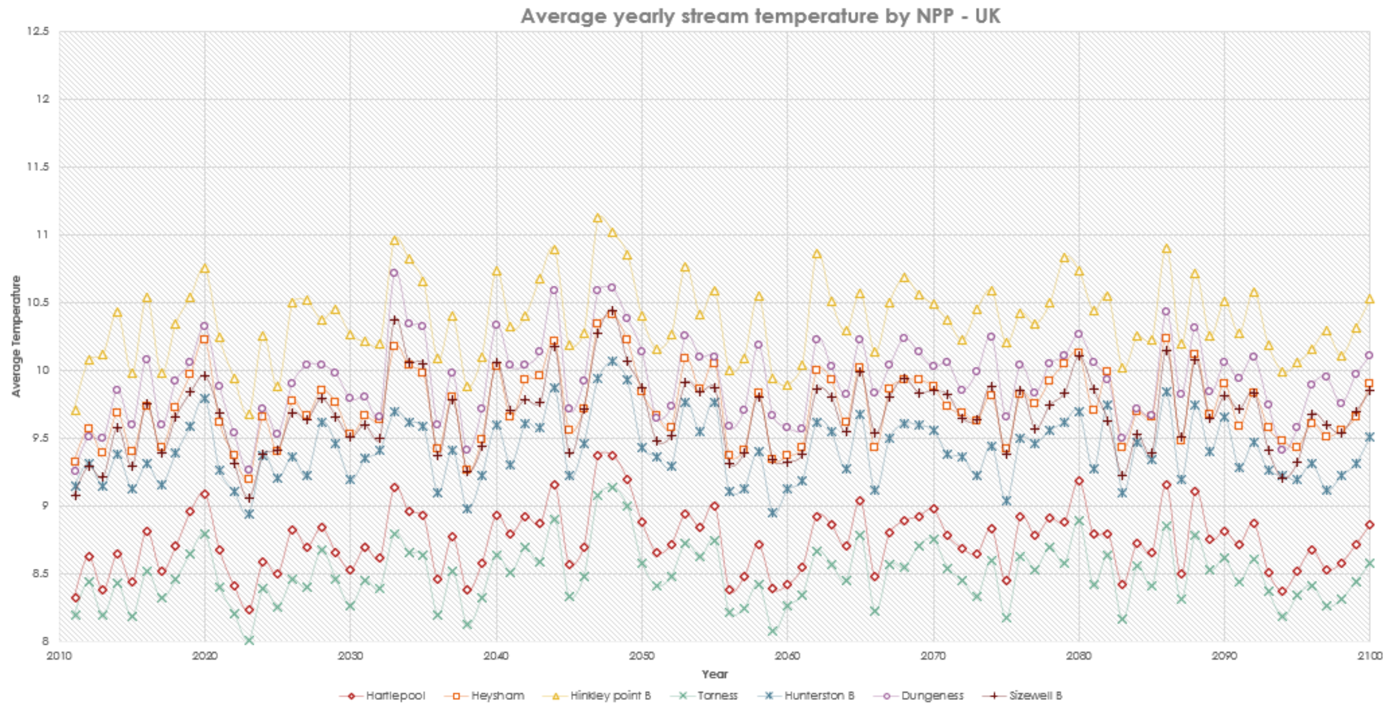

Figure 24 Average yearly stream temperature of following set of countries (b). RCP 2.6.

4.3.2.2 Analysis

We can observe from the previous illustrations that the stream temperature observes in a similar manner to that of the previous scenario due to the same physical processes, the linear regression relations, and water adaptability with the air temperature. The temperature values are slightly lower than that of the previous scenarios, yet the difference is not significant, as it is between RCP 4.5 and RCP 8.5. Clearly, if this scenario was to be compared with RCP 8.5 scenario the results will be significantly different in favor of RCP 2.6.

4.3.3 Power Output

4.3.3.1 Results

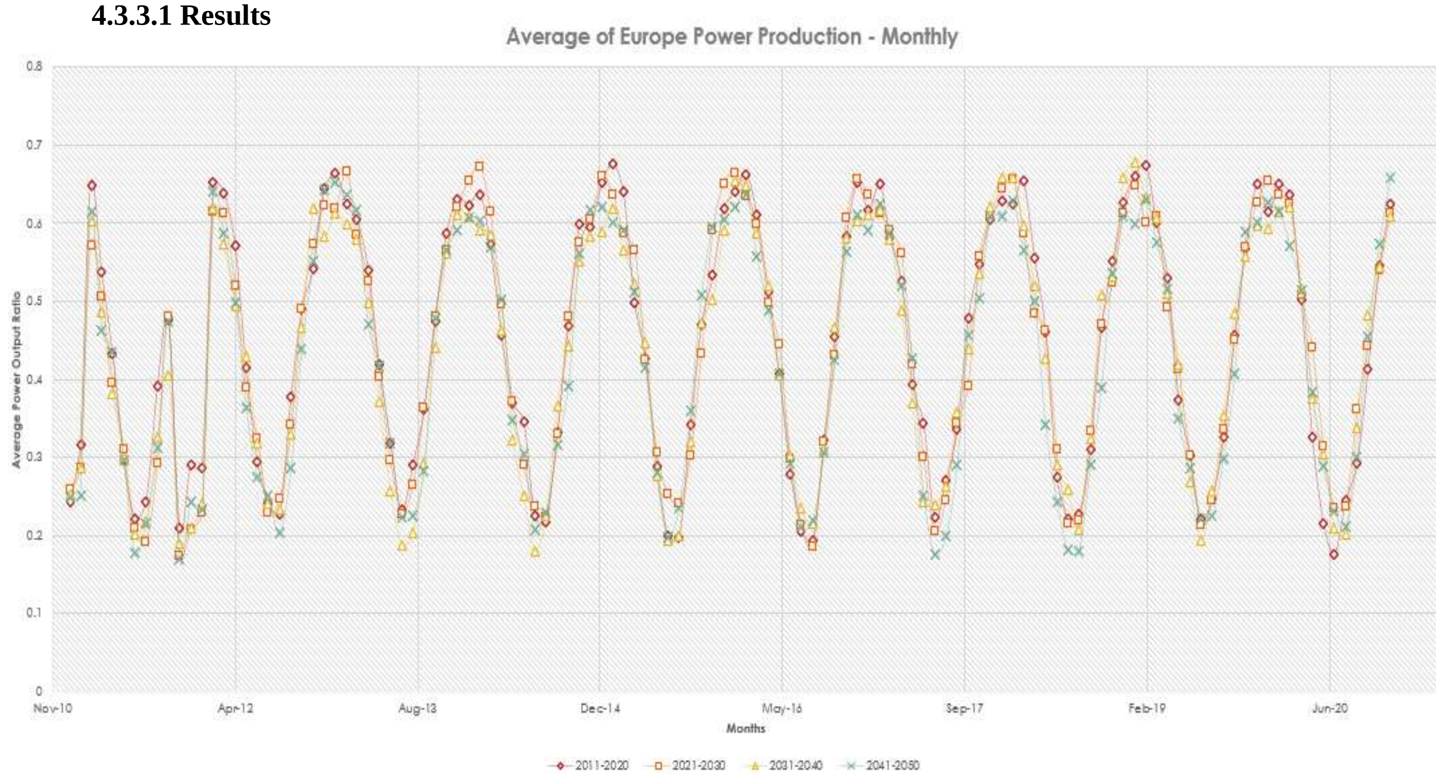

Figure 25 Average European nuclear power production per month compared by the decades (a). RCP 2.6.

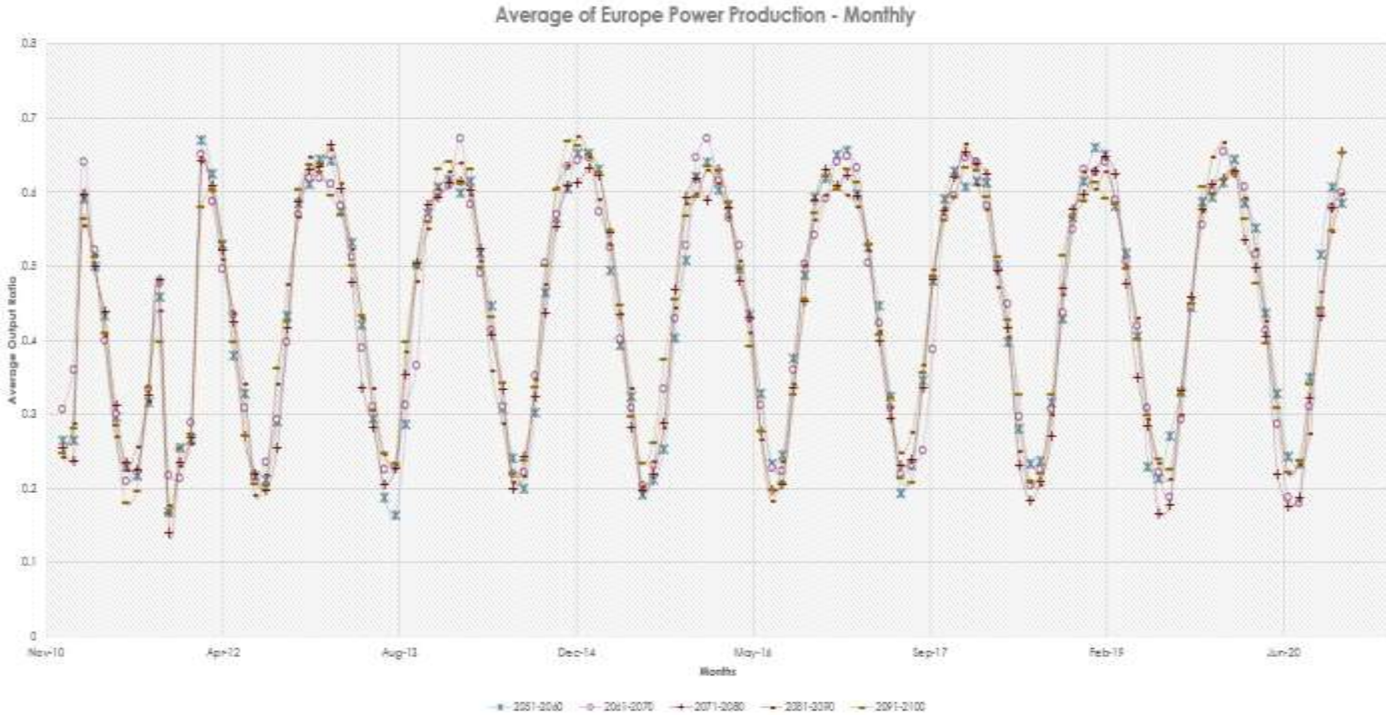

Figure 26 Average European nuclear power production per month compared by the decades (b). RCP 2.6.

4.3.3.2 Analysis

We can observe from the previous illustrations that the power over the decades is in a constant behavior with some decades achieving a higher average power output over the preceding decade. This scenario imposed less projections, which in turn resulted in the quasi-stable trend. The values obtained from these trends are higher than that of the RCP 4.5 scenario, yet not significantly higher, due to the comparability of the water temperatures obtained from the two scenarios. Nevertheless, this scenario is significantly better than RCP 8.5, as it results in peaking average output ratios around 0.7 and minimally around 0.2, while RCP 8.5 gives 0.6 and 0.15 peaking and minimal values, respectively.

Chapter 5: Conclusion

In conclusion, climate change and global warming are threats that have risen from anthropogenic activities in the near past. The consequences are severe as we are in a developing world, with increasing population, and increasing electrical demand. This must be supported by enough supply to keep the balance in a respective manner, taking consideration the mitigation of climate change. Hence, decisions are taken now to shift towards the clean energy sector using renewables, including solar, wind, and hydro, and nuclear. Knowing that more than two-thirds of the electricity produced in Europe is from hydro and thermoelectric plants along with the increasing water demand, imposes a challenge as the consequences of climate change will limit the availability of water.

Nuclear power plants require quite a large amount of water due to the cooling process needed for waste heat dissipation. The efficiency of the plant, and in turn the power output, is dependent on water availability and water temperature. Droughts and high air temperatures are threats to the availability, and result in the increase in water temperature, and therefore affecting the power production. The results of three different scenarios were taken and with the worst-case scenario, where the temperature was in a highly increasing trend, it was identifiable how the power will be reduced in the upcoming decades to up to around 0.1 of the total output of the EU, which is not a positive indicator.

Comparably, the second scenario, where the imposed assumptions were at a slower rate temperature increase, the situation was a relatively better resulting in the increase in the output ratio to around 0.2 during the lowest summer time. Nevertheless, this is still considered to be a low value as the highest power output ratio would be around 0.65 during winter, which implies that two-thirds of the energy will not be produced. In the final scenario, where the assumptions were most optimistic, relatively, implementing a stable behavior and trend on the long term with the same current conditions, the values were also getting better. The values were close to that of the second scenario, understandably due to the slower rate of increase in the second scenario. Once again, although results were comparably better, it is still not enough and specially during summer times, as the demand is quite high. This implies that even with a stable condition, without the increase in severity, it will not be enough to compensate for the power production alone, considering the rapid population growth, and the increasing water demand, and thus alternatives must be considered.

Future Perspectives

Currently, the progress on this study is still ongoing as it is necessary to understand how different regions react to the climate change, and to what extent will the corresponding power plants be affected. The study on the three scenarios on every power plant individually is in progress, along with the preparation for a paper proposal to be submitted, to be published in a journal.

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Appendix

Acronyms	
AR	Assessment Report
CI	Critical Infrastructure
CIP	Critical Infrastructure Protection
CNRM	Centre National de Recherches Météorologiques
CRS	Coordinate Reference System
CWI	Centrum Wiskunde & Informatica
EC	European Commission
EU	European Union
GCM	General Circulation Model
GW	Giga-Watt
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MATLAB	Matrix Laboratory
RCP	Representative Concentration Pathway
SMHI	Swedish Meteorological and Hydrological Institute
SRES	Special Report on Emissions Scenarios
TWh	Terra-Watt hour
UK	United Kingdom
UNFCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Program
WMO	World Meteorological Organization

Table 9 Table of Acronyms.

Power Plant Name	Country	Capacity (MW)	Latitude	Longitude	Cooling System
Doel	Belgium	2910	51.3105976	4.2649749	Closed
Tihange	Belgium	3015.8	50.5296991	5.2614551	Closed
Npp kozloduy	Bulgaria	2000	43.7438119	23.7723634	Open
Dukovany	Czech Republic	500	49.08495	16.15006	Closed
Temelin	Czech Republic	2160	49.18109	14.38641	Closed
Loviisa	Finland	992	60.4578742	26.2278098	Open
Olkiluoto	Finland	3360	61.2359295	21.4347339	Open
St laurent	France	1830	47.72006	1.58009	Closed
Nogent	France	2620	48.5153	3.51776	Closed

Golfech	France	2620	44.10479	0.84606	Closed
Gravelines	France	5460	51.01267	2.13956	Open
Penly	France	2660	49.97599	1.21025	Open
Paluel	France	5320	49.85838	0.63449	Open
Tricastin	France	3660	44.32906	4.72605	Closed
Flamanville	France	2660	49.53671	-1.88229	Open
Chinon	France	3620	47.22856	0.16824	Closed
Chooz	France	3000	50.09136	4.79242	Closed
Civaux	France	2990	46.45614	0.6524	Closed
Cruas	France	3660	44.63251	4.75105	Closed
Dampierre	France	3560	47.73252	2.51772	Closed
Cattenom	France	5200	49.41579	6.2181	Open
St alban	France	2670	45.40523	4.75527	Closed
Belleville	France	2620	47.50879	2.87574	Closed
Blayais	France	3640	45.25742	-0.69065	Open
Bugey	France	3580	45.80141	5.26614	Closed
Paks	Hungary	1886.8	46.5743687	18.8494116	Open
Borssele	Netherlands	492	51.43148	3.71871	Open
Npp cernavoda	Romania	1298	44.3175539	28.0577087	Open
Mochovce	Slovakia	940	48.26409	18.45326	Closed
Bohunice	Slovakia	1000	48.4914	17.67734	Closed
Krsko	Slovenia	727	45.93833	15.51554	Open
Vandellos	Spain	1045.31	40.950367	0.865747	Open
Trillo	Spain	1003.41	40.699986	-2.62482	Closed
Cofrentes	Spain	1063.94	39.214969	-1.052563	Closed
Almaraz	Spain	2017.13	39.807631	-5.696131	Open
Asco	Spain	1987.5	41.202217	0.571561	Closed
Ringhals	Sweden	2288	57.258987	12.110433	Open
Oskarshamn	Sweden	1400	57.417124	16.673074	Open
Forsmark	Sweden	3291	60.403993	18.174347	Open
Gosgen	Switzerland	1035	47.36552	7.96779	Closed
Leibstadt	Switzerland	1245	47.60109	8.18259	Closed
Beznau	Switzerland	760	47.55198	8.22825	Open
Hartlepool	UK	1207	54.635479	-1.181119	Open
Heysham	UK	2380	54.029263	-2.915381	Open
Hinkley point	UK	1061	51.207959	-3.130173	Open
Torness	UK	1250	55.967523	-2.407059	Open
Hunterston	UK	1074	55.722772	-4.891078	Open
Dungeness	UK	1120	50.913842	0.959699	Open
Sizewell	UK	1216	52.21511	1.62013	Open

Table 10 European nuclear power plants data considered in this study.

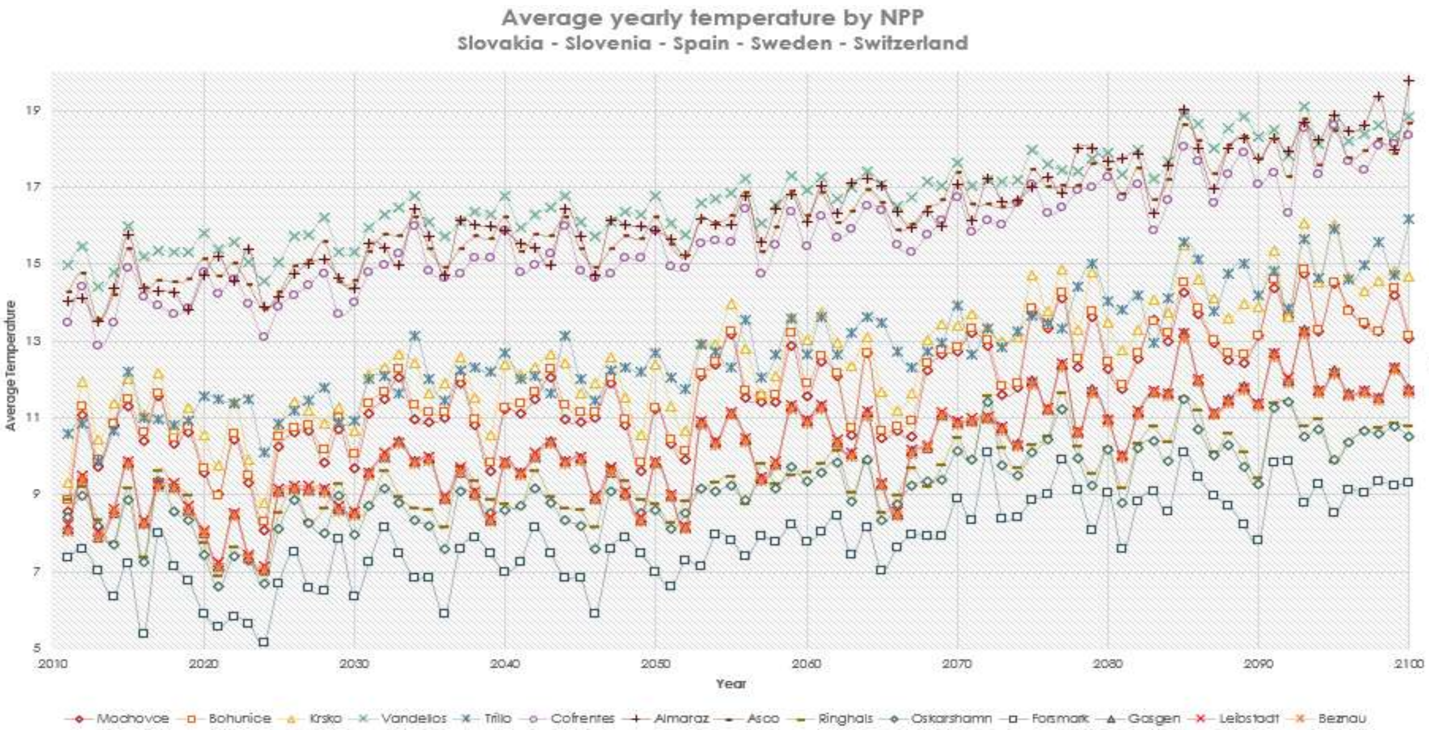


Figure 27 Average yearly near surface air temperature by NPP for following set of countries (c). RCP 8.5.

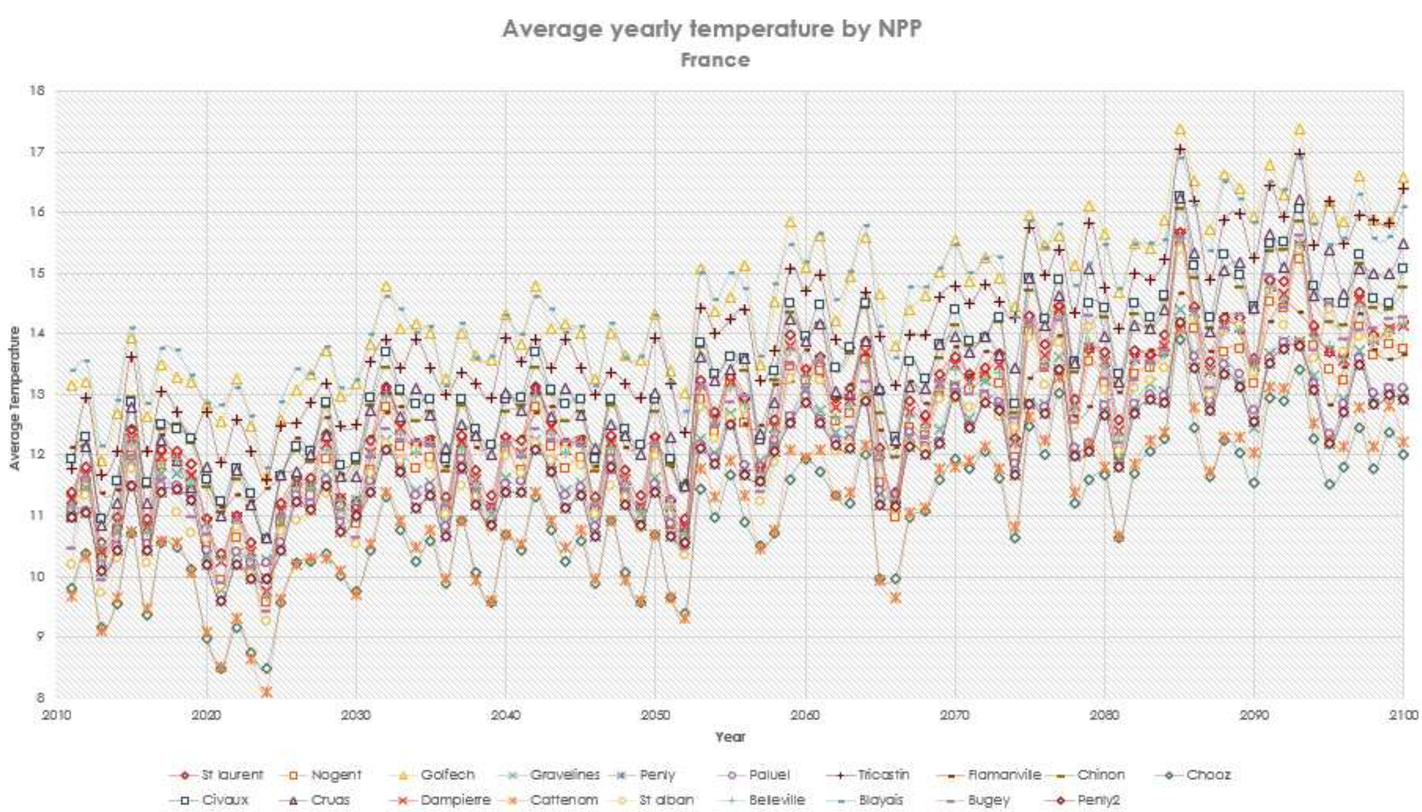


Figure 28 Average yearly near surface air temperature by NPP for following set of countries (d). RCP 8.5.

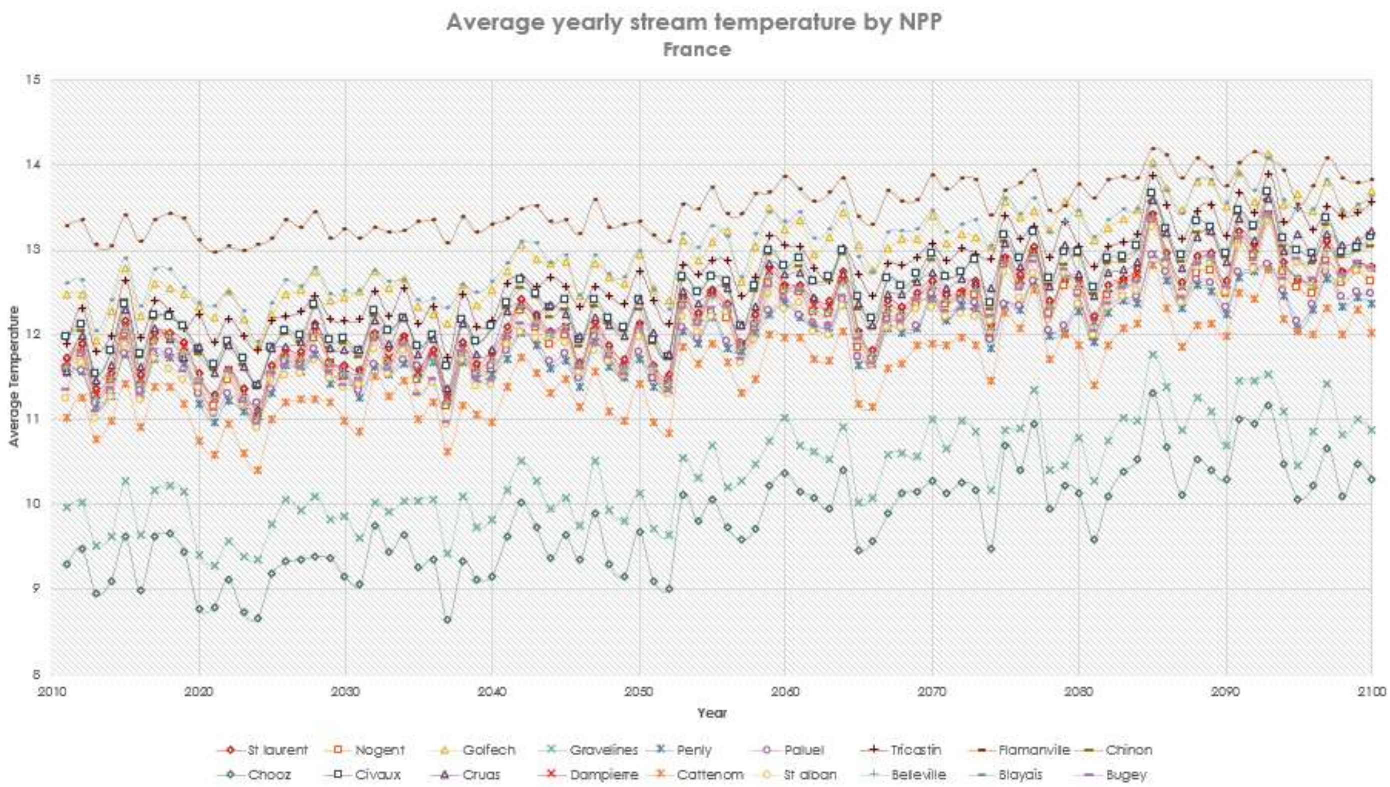
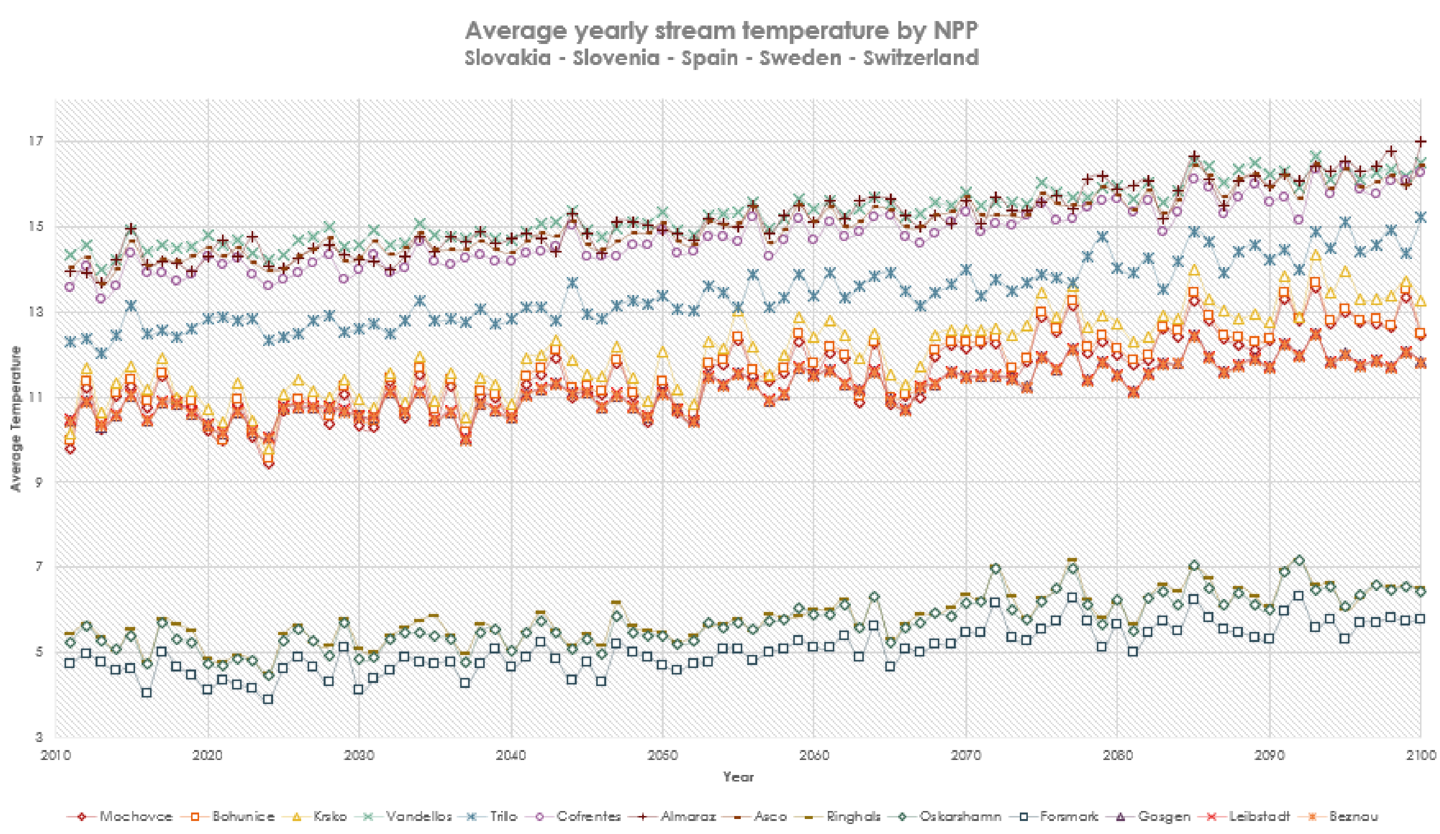


Figure 29 Average yearly stream temperature by NPP for following set of countries (c). RCP 8.5.



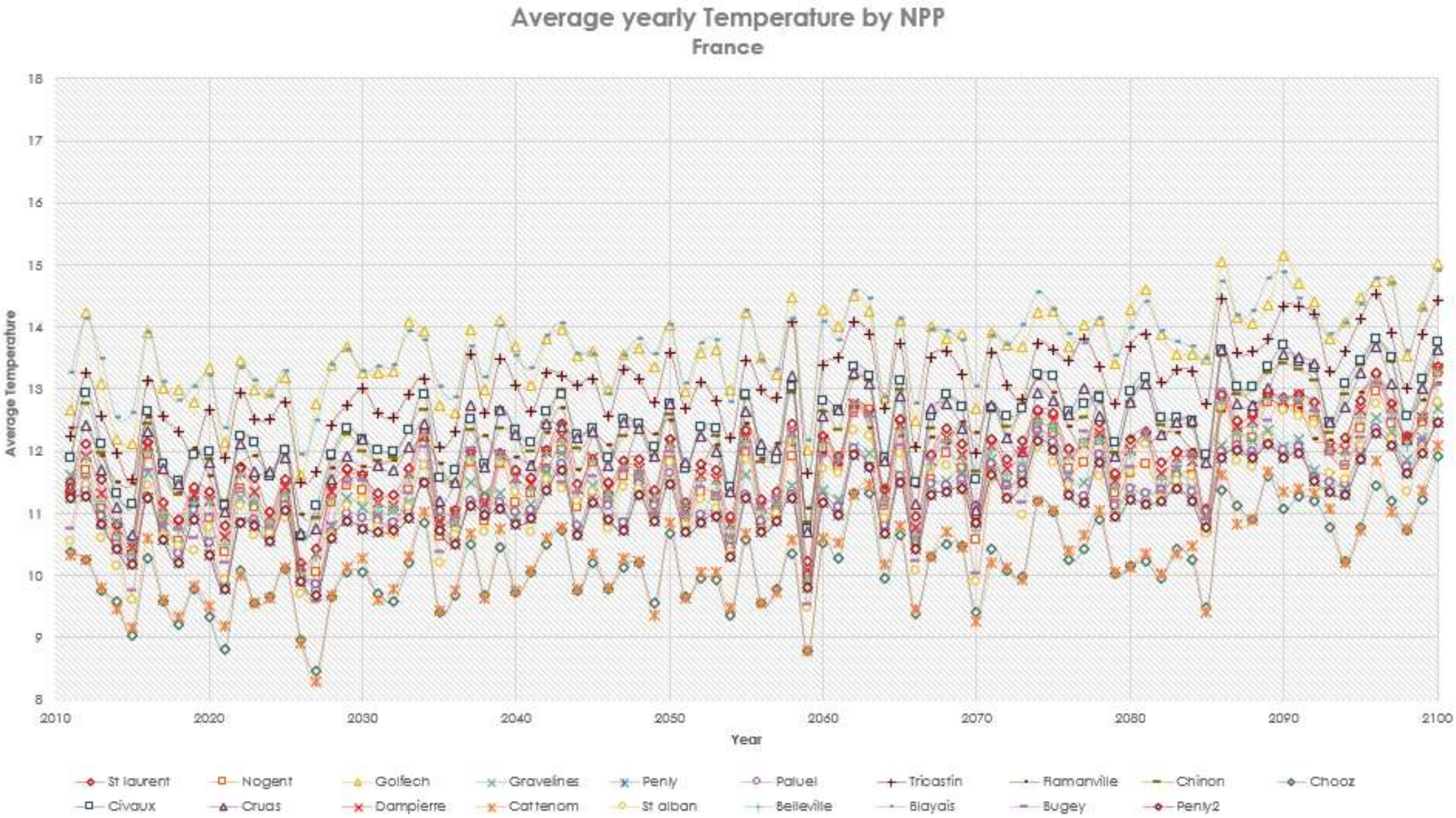


Figure 31 Average yearly near surface air temperature by NPP for following set of countries (c). RCP 4.5.

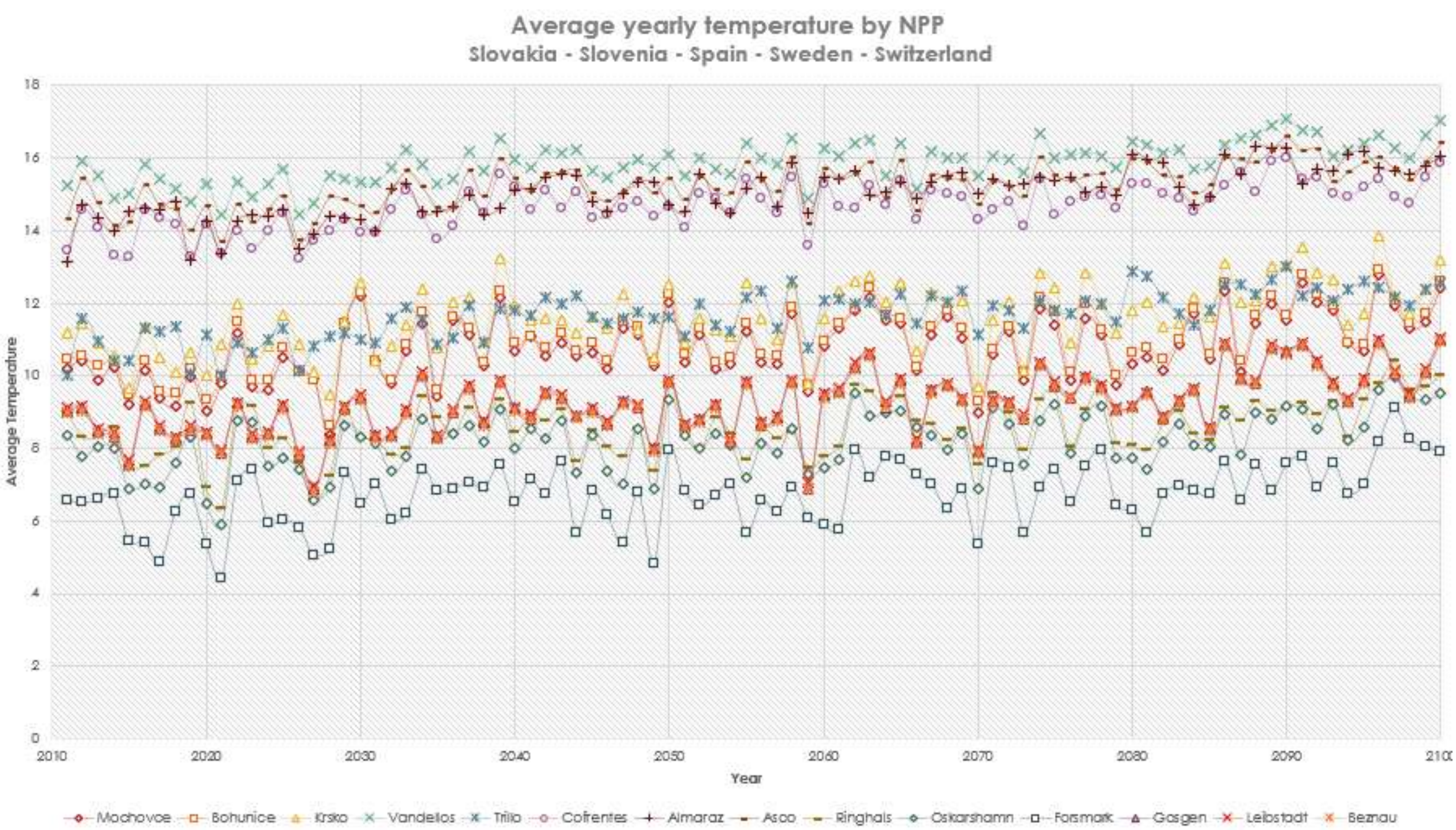


Figure 32 Average yearly near surface air temperature by NPP for following set of countries (d). RCP 4.5.

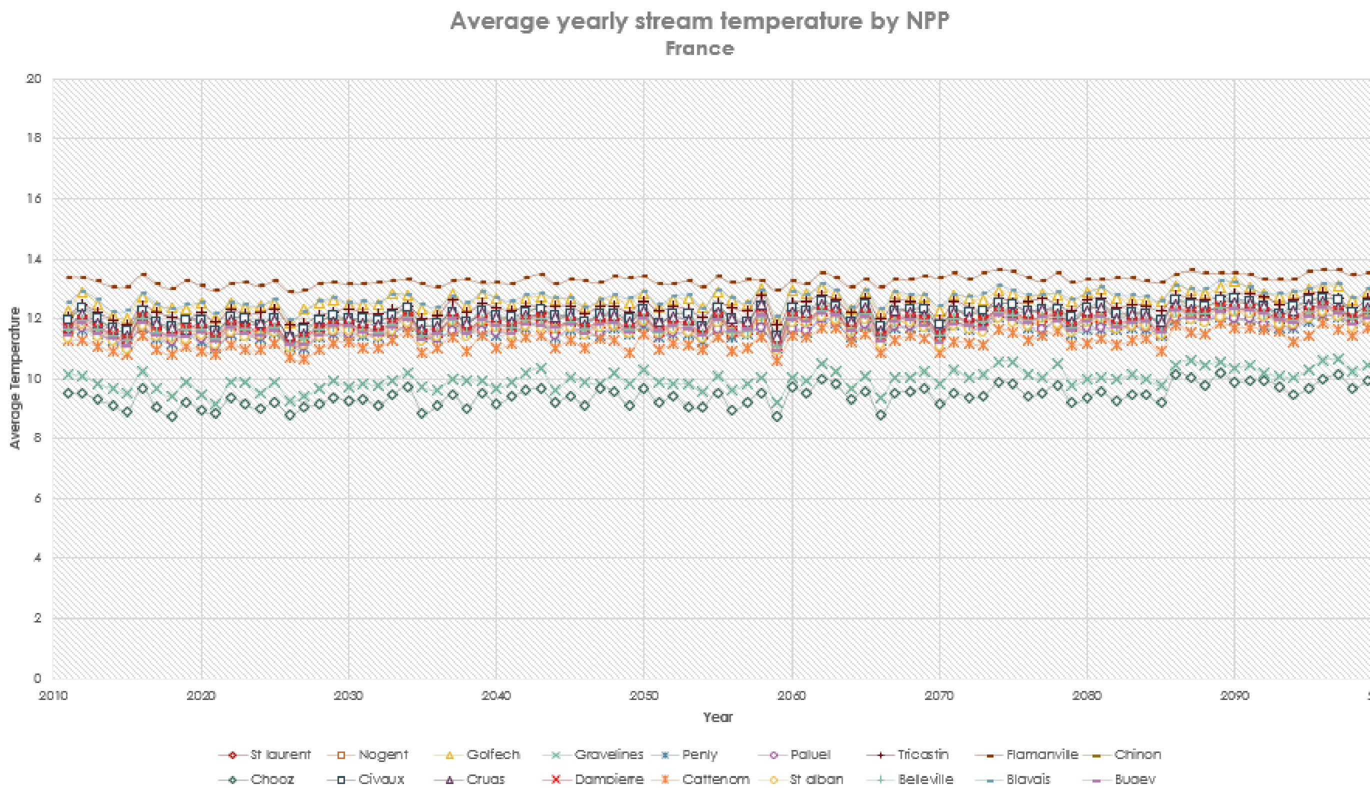


Figure 33 Average yearly stream temperature by NPP for following set of countries (c). RCP 4.5.

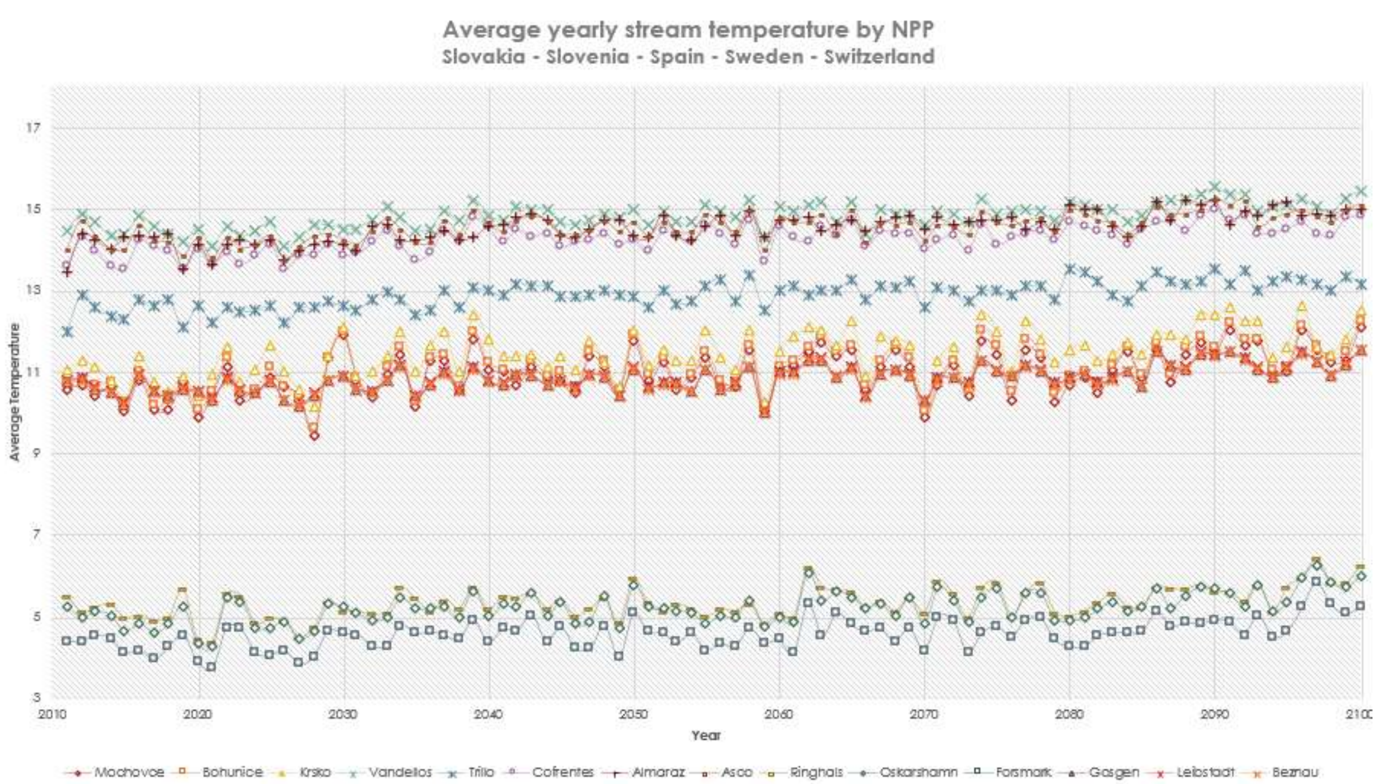


Figure 34 Average yearly stream temperature by NPP for following set of countries (d). RCP 4.5.

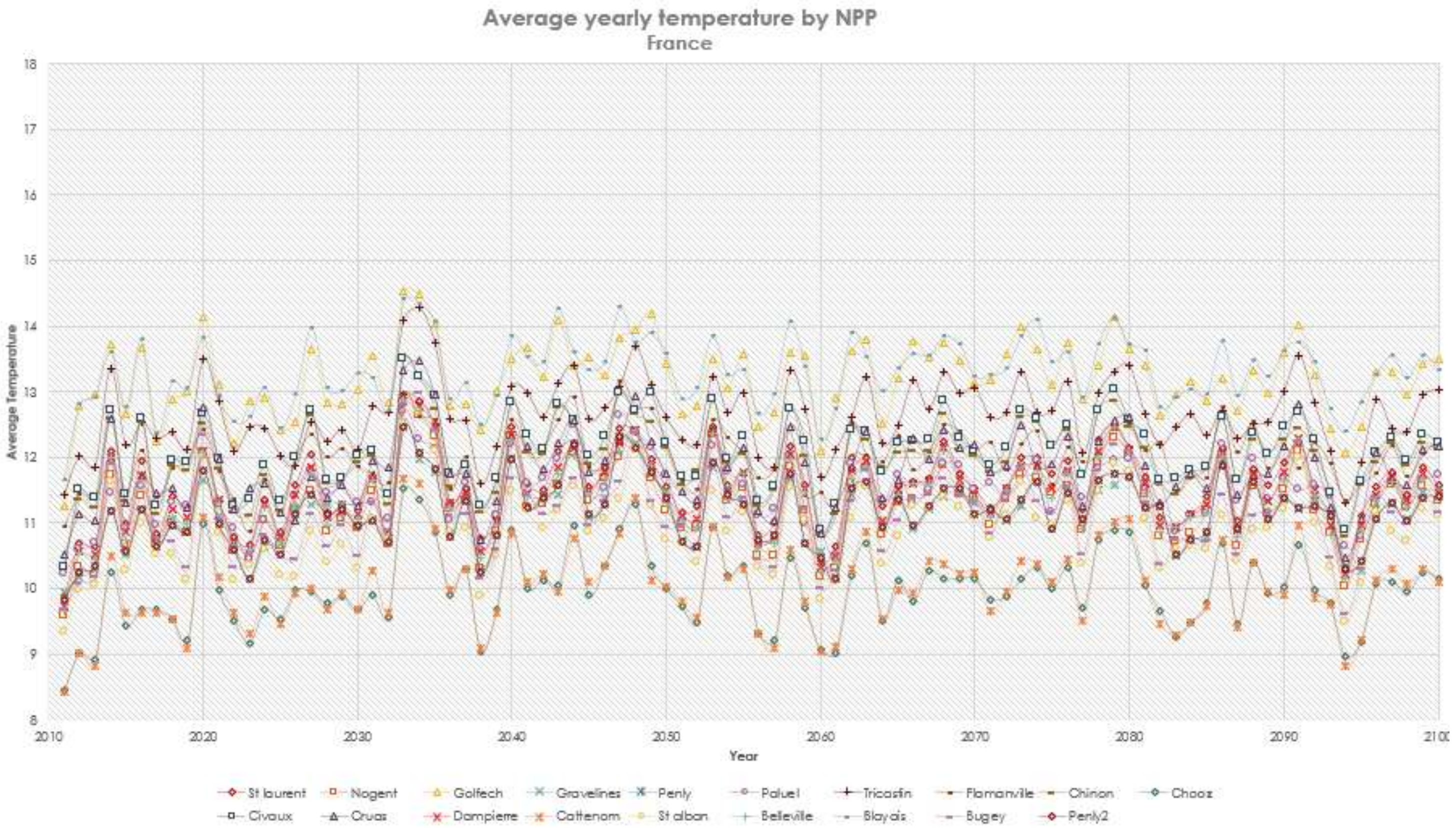


Figure 35 Average yearly near surface air temperature by NPP for following set of countries (c). RCP 2.6.

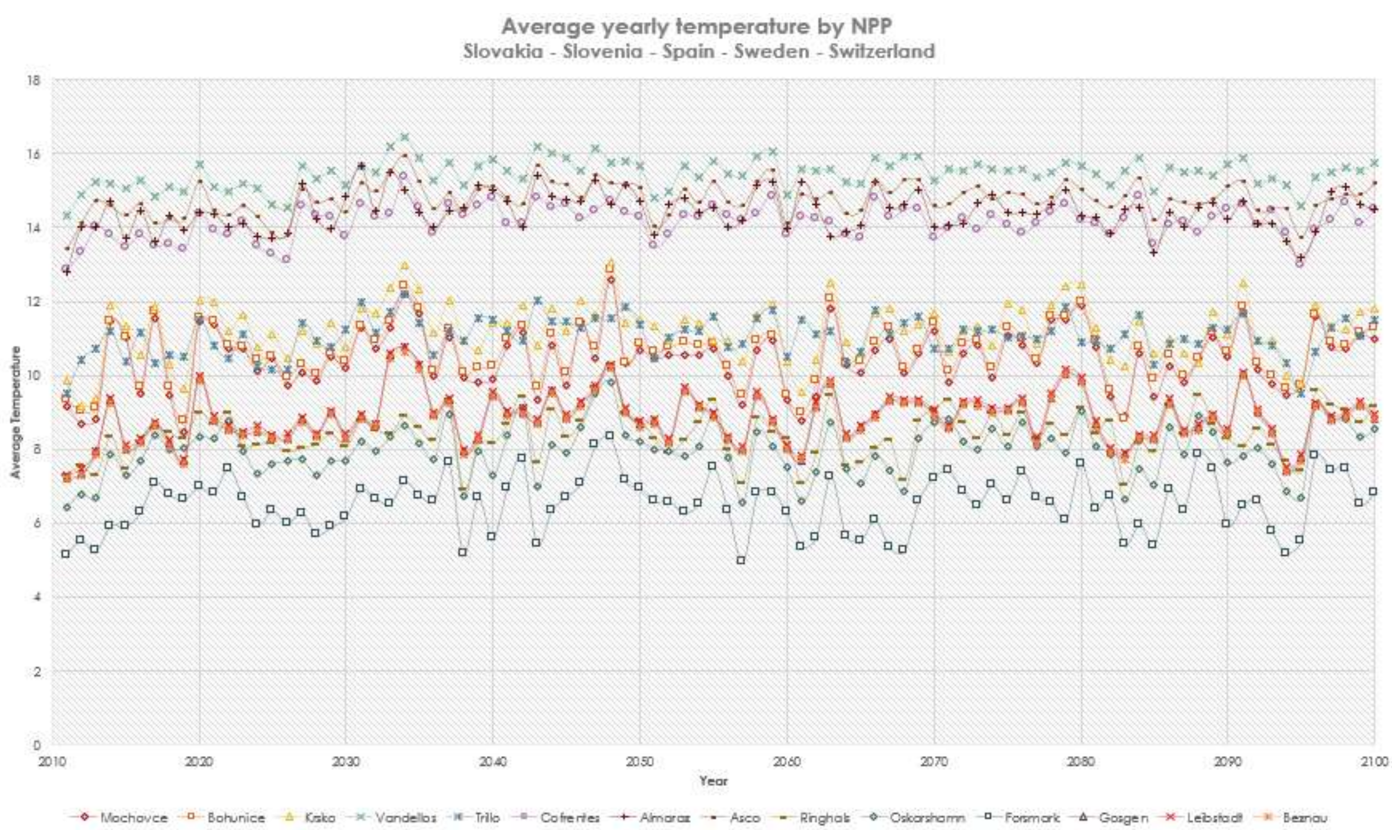


Figure 36 Average yearly near surface air temperature by NPP for following set of countries (d). RCP 2.6.

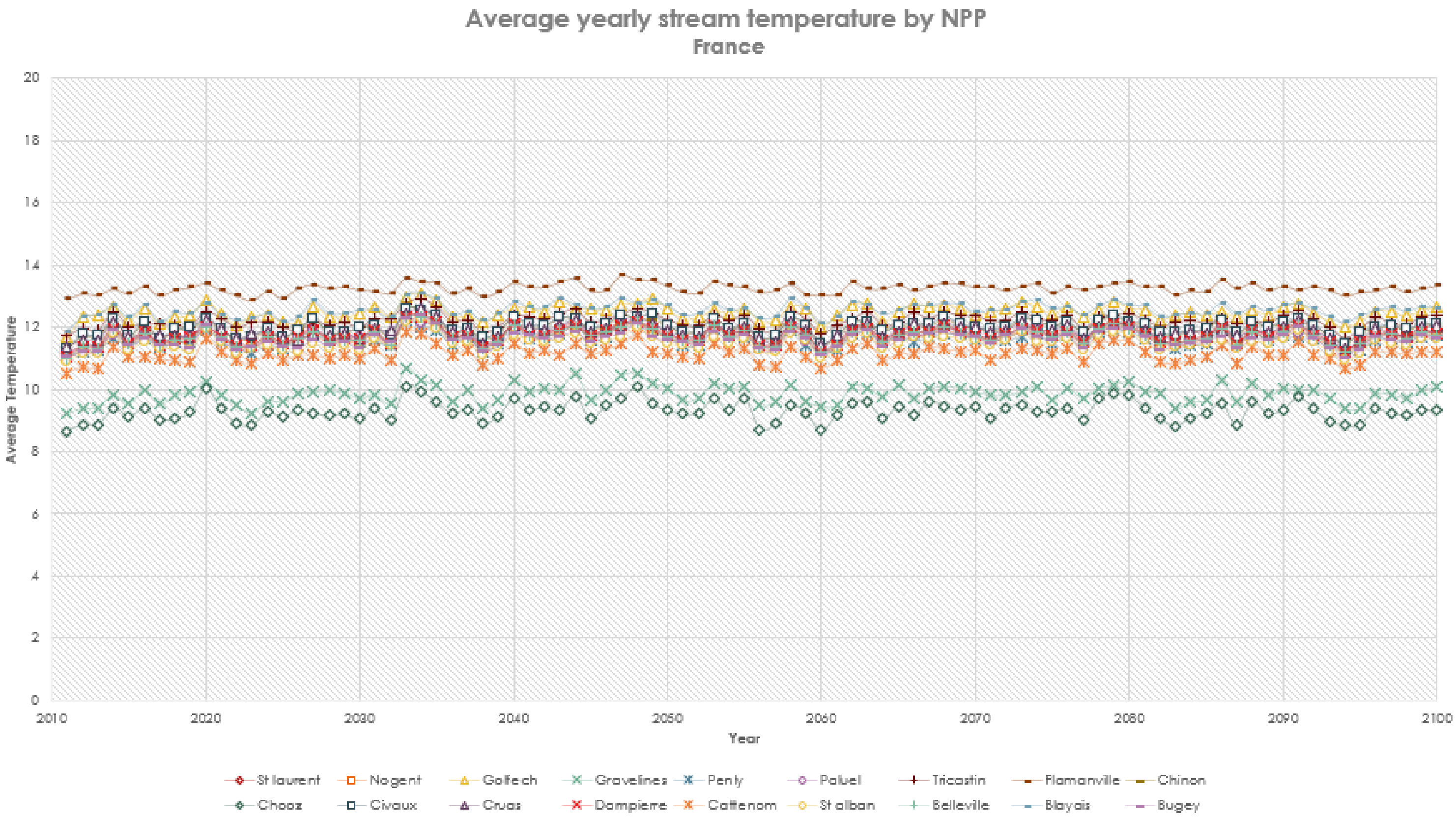


Figure 37 Average yearly stream temperature by NPP for following set of countries (c). RCP 2.6.

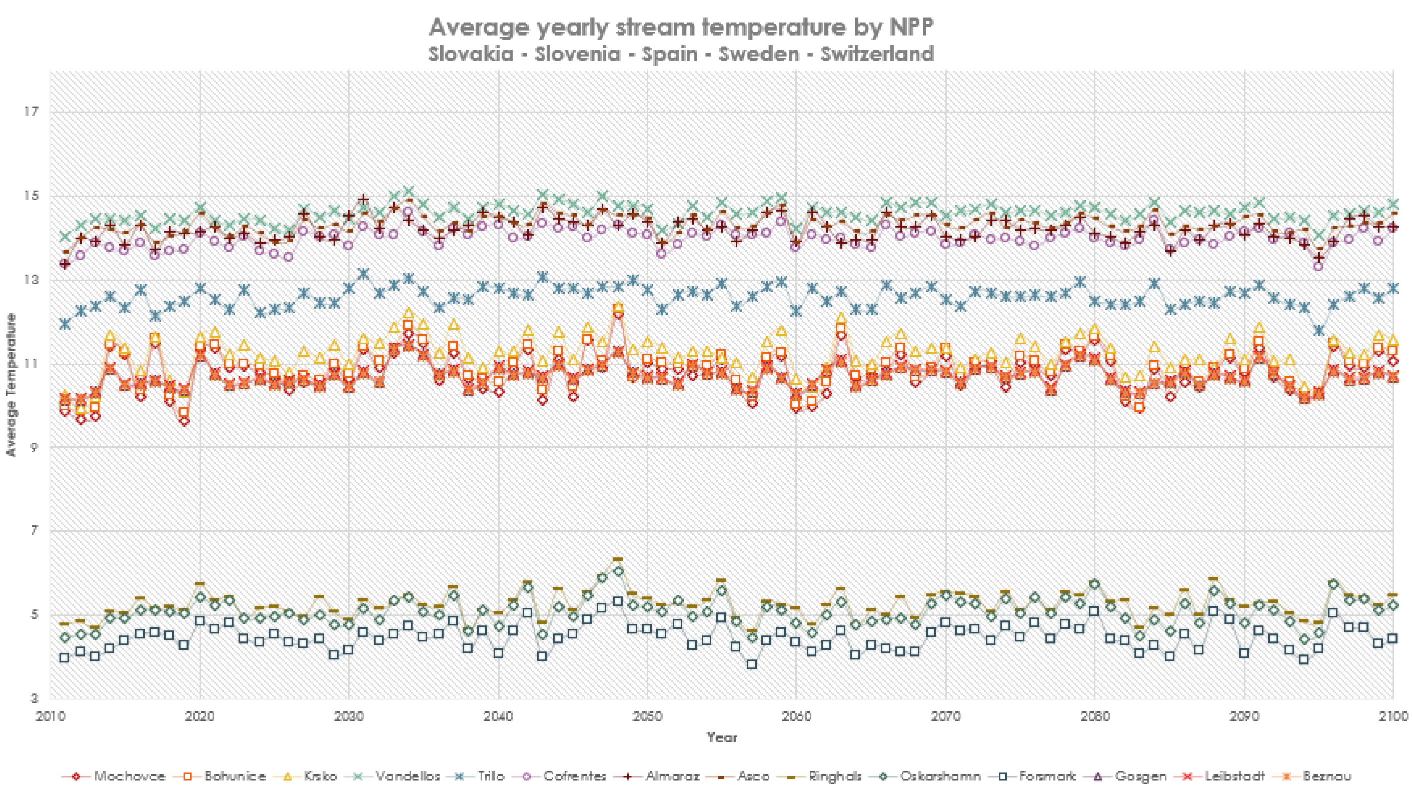


Figure 38 Average yearly stream temperature by NPP for following set of countries (d). RCP 2.6.