Impact of Climate Change on Thermal Power Plants

Case Study of Thermal Power Plants in France

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Case Study of France

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30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Environment and Natural Resources

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Abstract

The theoretical efficiency of thermodynamic cycles and therefore of thermal reactors is intimately linked to external factors such as atmospheric temperature, flow rate and temperature of the coolant. The modification of these factors, particularly due to climate change, is expected to negatively impact the electrical output of thermal power plants.
This study quantifies this phenomena and forecast the potential electricity loss in France due to Climate Change alone.

To achieve this, the electrical output of French nuclear, coal and oil-fueled power plant was compared to actual atmospheric temperatures, water flow and temperature.
Landlocked power plants were found to show a decrease of 0.04-0.8% output per degree increase in air temperature. Reactors using sea water as a coolant showed a relative independence on air temperature. No analysis of the water temperature dependency could be done for landlocked reactors due to lack of data. This was counterbalanced by the high correlation between air and river temperature. For reactors located close to seas, a decreased output was found for temperatures of the water over 14-16 degrees. This result is believed to be due to the limited pumping capacity of cooling systems as well as the temperature of the coolant. No dependence of the electrical output of thermal power plants on current river flows was found. By 2050 however severe draughts could lead to the shut down of several reactors, similarly to droughts observed in 2003.

To my father, climato-skeptical to the core.

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Glossary

Coolant: the fluid which cools down the working fluid of a reactor.

Ecological flow: the minimum agreed flow under which the ecosystems of a water body can prosper.

Electrical output: quantity of electricity generated.

Power plant: a site where electricity is generated. May contain several reactors.

Reactor: the electricity generating part of a power plant.

Thermal efficiency: the ratio of work generated to the heat consumed. Sometimes defined as the ratio of electricity produced to the combustible burnt.

Thermal reactor: any reactor which operates according using a cyclic succession of thermodynamic transformation of a working fluid.

Water body: any significant accumulation of water, transitional (rivers) or static (lakes).

Water consumed: the portion of water extracted from a water body to cool down a reactor and evaporated.

Working fluid: the fluid inside the reactor which undergo all the thermal transformations.

Acknowledgements

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1 Introduction

1.1 Background

In 2009, over 80% of the electricity in the world was generated using thermal power plants (IEA, 2011 ; Linnerund et al., 2011). Although technologies might change and we could see a switching to cleaner electricity, the proportion of thermal power plants in the global mix (exclusive of solar and geothermal) is still expected to be at least 75% by 2035 (IEA, 2011).

The efficiency and eventually the upper limit for electricity generation of this type of power plant is directly linked with the characteristics of the coolant (historically water), namely (chemical) quality, quantity and temperature (Aquaprox, 2009). In turn, these parameters are dependent of the local climate conditions, weather and seasonal fluctuations.

With the observation of increased water and air temperatures worldwide over the last decades, and the projected acceleration of this trend for the next century (IPCC, 2007), thermal electricity generation could be negatively affected. Until recently this impact has been neglected. The International Energy Agency for instance does not mention the links between water scarcity, its temperature and energy production before its 2012 outlook.

However, with the 2011 global electricity generation estimated at 5 429 GW and expected to increase to 9 340 GW by 2035 (IEA, 2012), the impact of climate change on production, however small, should not be neglected.

In France, 87% of the electricity generation comes from thermal power plants (IEA, 2013). Nuclear energy is particularly developed, 58 nuclear units spread over 19 power stations located around the main rivers and on the coastal areas representing 76% of the national electricity production. They operate 365 days a year to provide with the base of the electricity demand.

Gas, coal, oil and combined cycle gas turbine (CCGT) are mostly used to insure that the peak demand for electricity is met. None of these power stations operate continuously.

In recent years, draught events have forced the reduced activity of a few power stations. The combination of technical and regulatory limitations due to water shortage has, in some extreme cases, forced power plant to shut down (Linnerund, 2011).

1.2 State of the art.

Following the 2003 droughts in France, Arnell et al. (2005) reflected on the potential reduced availability of cooling water during drought but also during winter time in northern Europe, without any calculation of generation loss. This remark is cited in the 4th IPCC assessment report (IPCC, 2007), which refers to a potential electricity generation loss of 0.2-0.4% per degree increase for thermal power plants and up to 2% for nuclear.

The effect of the change in temperature of the coolant on the efficiency of energy production is a well known phenomenon. In late 19th century, Carnot linked the application of thermodynamics law to the hot and cold reservoir of an engine and

calculated theoretical efficiency. Few major studies however are found that quantitatively analyse the actual impact of increased water temperature on the efficiency using actual production data. Durmayaz and Sogut (2006) estimated that up to 0.45% can be lost in electrical power output in a nuclear reactor per degree increase in coolant temperature. Studies by Daycock et al. (2004) and Chuang and Sue (2005) found respectively a 0.60–0.72% and 0.6% reduction in electricity output in a gas turbine.
These 3 studies have in common the use of data from a single power plant (real or conceptualized) and the focus on theoretical temperature. They do not take into account future change in water availability or climate change to add to the loss of efficiency. Similarly the difference between cooling systems and their relative efficiency is not taken into account. Although a good base to work from and allowing comparison of the theoretical model, these studies lack a link to real data and might not be generalisable.

Mima and Criqui (2009) take on the results by Durmayaz and Sogut (2006) to analyse the impact of climate change on energy systems. Their model extensively covers the demand, supply and energy price variations due to increased air temperature. They however acknowledge not taking into account water availability. Only theoretical models and "rough estimates", in particular results from Durmayaz and Sogut's models, were used in this study.

Recent studies have started to compare water availability, climate change and legal framework to determine the total efficiency loss that faces the thermal power industry. Linnerund et al. (2011) follow a step by step approach, calculating the loss of efficiency due to increased temperatures in a power plant, then applying climate change scenario temperatures to the results. This study then attempts to generalise the results to a prediction for European countries by using panel data. Its analysis of the efficiency reduction of a power plant due to climate change is fairly extensive. However the generalisation method is cryptic. In particular, the study recognises that the uniqueness of each power plant with regards to technology, design and cooling requires for careful use of the findings.
Koch & Vogele (2009) uses system dynamics to forecast the production behaviour over the next 50 years, but altogether focuses on change in water demand and lacks reference to change in efficiency.

Hoffman et al. (2010) present perhaps the most exhaustive study in this field, applying both efficiency variation, climate change and legal framework to calculate future energy losses. However, this study is limited to one power plant, with a once through cooling system, and therefore its conclusion toward the need to invest in better technologies and adaptation is not supported by any comparison with different technologies.

Recent studies seem to be limited to the study of single nuclear power plants in Germany and France. A comprehensive model is currently being developed with EDF (Electricte de France, French main electricity producer), but results are not accessible yet (Anderhalt, 2011).

1.3 Goal and hypothesises.

With regard to these studies, more research is required to understand the impact of climate variation on thermal power generation. In particular, there is a need to compare different technologies to obtain significant data at the scale of a country. Models need to leave the theoretical approach and tackle real data and observables to determine the actual effect of climate on the electricity generation of a country.

This thesis aims at studying the impact of climate change on electricity generation.
2 main hypothesises will be tested:

- Increased air and water temperature due to climate change will negatively impact the electrical output of thermal reactors.
- Water scarcity due to climate change will lead to limitations on the potential water intakes of thermal reactors, thus limiting their output.

These hypothesises will be tested against different types of reactors, with various fuel, cooling systems and design output.
In a first time, this thesis will look at past electricity production data fr each reactor and compare it to air and water temperature and water flow. It will determine if a link exists between fluctuation of the latter and variation of the former. In the occurrence of a link between the electricity output and one or more parameters, this link will be quantified.
This correlation (or lack of thereof) will be applied to local climate change model to determine the impact of climate change on the electricity output of thermal reactors.
From there, conclusion and suggestions will be made concerning the choice of thermal power plants in the electricity mix.

2 Theory

2.1 Thermal power plant

A thermal power plant is a power plant which produces electricity using a heat source. A working fluid, usually water (liquid and vapour) or natural gas, is heated and pressurized. Its expansion in a turbine will create work which will be used to power an electricity generator.
Traditionally, the definition of thermal power plants encompasses only nuclear, oil, gas, coal and biomass-fuelled power plants. Other technologies enter the category “thermal” in the strictly speaking sense, such as concentrated solar and geothermal, but are rarely included, as their respective share in the global electricity mix is currently under 1% (IEA, 2011).

The operating principles are in reality very close to those of theoretical heat engines and their thermodynamic cycles:

*Rankine (Hirn)-type cycle (*figure 1*).* In most thermal power plants, the turbine is actioned by steam. The latter can either be produced in a boiler, directly (fossil/organic fuels or concentrated solar type) and indirectly (nuclear type) or extracted from the ground (geothermal). The working fluid is generally water, although pressurized gases and liquid salts are sometimes used because of their higher thermal conductivity.

The thermal efficiency of a theoretical Rankine cycle η_{Rankine} is given by

$$\eta_{\text{Rankine}} = 1 - \frac{h_4 - h_1}{h_3 - h_2} \quad (1)$$

Where $h_{1,2,3,4}$ are the specific enthaply of the working fluid at the different steps of its transformation (figure 1). The specific enthalpies are by definition dependent on the temperature and pressure at the different steps of the cycle. The efficiency of a Rankine cycle is generally low, 15-20%

In real conditions, condensation and compression are non-isentropic. It also would be very inefficient to use a only partially vaporized water as working fluid, as it would increase erosion of the turbine and decrease efficiency. After the boiler, the water is therefore super-heated past the critical temperature and fully vaporized.
Such modified operating principles are referred as Hirn cycle. Because of the superheating, the overall efficiency of a Hirn cycle will be be higher than those of a Rankine cycle, typically 30-40%

At full load (optimum burning of combustible) enthalpy can be shown to be constant and fixed by technology, except in the condenser, where it depends upon various parameters, mostly temperature, heat capacity (itself temperature dependent) and flow of the coolant.

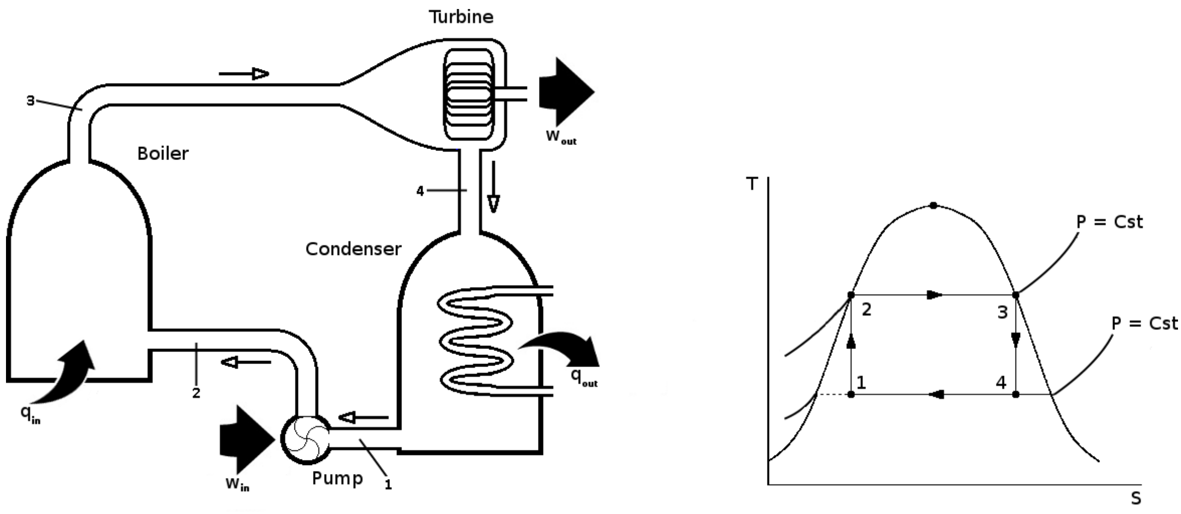

Figure 1 Rankine cycle (left) and its associated TS diagram (right). A perfect Rankine cycle (figure 1) consists of 4 main transformations of the working fluid: 1-2: Isentropic compression. The pressure of the liquid rises in the pump. 2-3: Isobaric heat transfer (vaporisation) . Pressured liquid is pumped in the boiler (2), and heated to saturation temperature. Further heating leads to the liquid being partially vaporized (3). 3-4: Isentropic expansion. The wet steam is expanded in the turbine, creating work, which will be used for electricity production. 4-1: Isobaric heat transfer (condensation). The mix steam-liquid coming from the turbine is condensed to liquid state.

Brayton-type cycle. Gas fuelled boiler-type power plant are rare, as their thermal efficiency is low. Most are used only to satisfy peak demand of electricity, except in countries whose gas resources are important. In order to use the combustible more efficiency, gas fuelled reactors operate a turbine under the Brayton cycle (figure 2).

The thermal efficiency of an ideal Brayton cycle is given by

$$\eta_{\text{Brayton}} = 1 - \frac{T_{air}}{T_{\text{comp.}}} \quad (2)$$

Where T_{air} is the atmospheric temperature and $T_{\text{comp.}}$ the temperature at the exit of the compressor.
In reality, the processes are neither perfectly adiabatic nor isobaric, leading to an actual efficiency lower than (2), typically 30%.

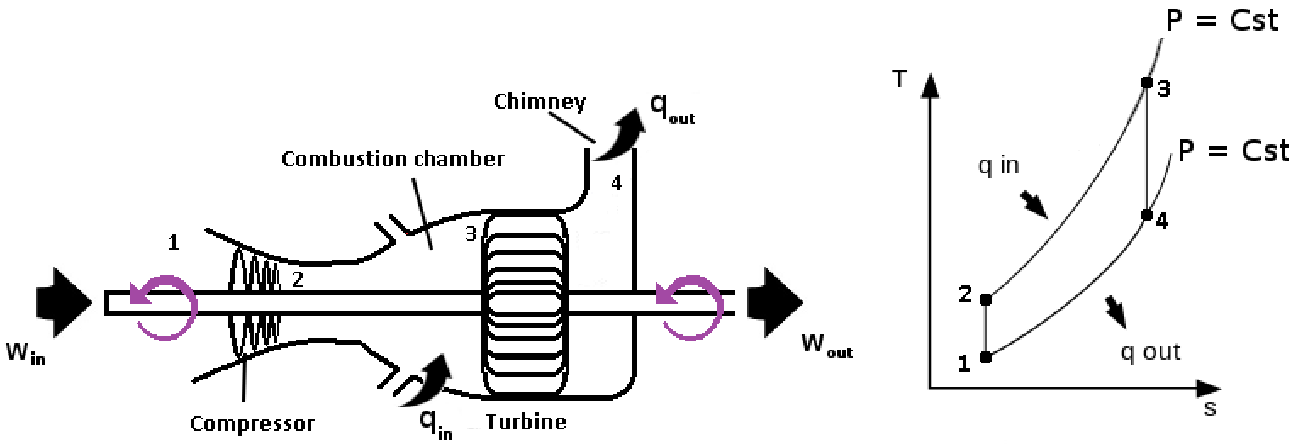

Figure 2. Brayton cycle (left) and its associated TS diagram (right). As for the Rankine cycle, an Ideal Brayton cycle can be decomposed in 4 transformations: 1-2: Adiabatic compression. Air is injected and compressed into the cycle in the combustion chamber.
2-3: Isobaric heat transfer. The air-gas mix is burned, increasing its temperature and pressure. 3-4: Adiabatic expansion. The burned gases expand in the turbine, creating work (wout), which will be used for electricity production. Some of the work is used to drive the compressor (win). 4-1: Isobaric heat transfer. Waste heat from the hott fumes is transferred to the atmosphere.

Combined Cycle: Hirn +Brayton. In many cases the gas turbine of a Brayton cycle is combined with a heat recovery scheme or a secondary (boiler-type) cycle to increase efficiency.
The hot fumes can be collected and used for electricity production through a Rankine cycle. Such reactors are called combined cycle gas turbines, or CCGT.
Their overall efficiency can reach 60% and more.
They also present the advantage to allow for the recycling of the evacuated fumes to avoid dispersion of harmful gases in the atmosphere and increase overall efficiency.

2.2 Technical sensitivity of thermal reactors to external temperature

As seen in equation 1 and 1, the efficiency of these cycles, and therefore of the reactor operating according to them, is dependent on the air temperature (Brayton cycle) or the specific enthalpy (Hirn). The latter can be linked to the temperature of the different components of the reactor, in particular the condenser.

The minimum temperature of a condenser, the efficiency of the heat exchange and the removal of the waste heat are *de facto* dictated by the temperature of the cooling fluid. This cooling fluid can either be air (dry cooling) or water (wet cooling).
This implies that any thermal reactor is dependent on climate: an increase in air temperature would lead to reduced efficiency of a gas turbine and boiler type reactor with dry cooling, while an increase in water temperature would reduce the efficiency of a reactor with wet cooling.

These weaknesses are particularly stressed in CCGT, since it combines the dependencies of both Hirn and Brayton cycles on air and water temperature.

2.3 Cooling systems

As the thermal efficiency of a boiler type and CCGT reactors are linked with the temperature of the condenser, the latter needs to be cooled down continuously in order to maintain best performance and maximum electrical output of the reactors.

3 major cooling systems are currently in use, 2 of them dependent on water.

2.3.1 Open system

In a once through cooling system, or open system, the water is extracted from the water body, and run through the condenser, where the heat from the working fluid is transferred to it. The heated water is then dumped back into the water body.

The heat transfer per unit of time $\frac{dq}{dt}$ in the condenser is dependent of the heat capacity C_p and flow Q of cooling water, according to

$$\frac{dq}{dt} \leqslant C_p \cdot \rho \cdot Q \cdot \Delta T \quad (3)$$

Where ρ is the density of water and ΔT the difference in temperature between the coolant and the working fluid.

With the density of water fixed, the heat transfer rate is limited by the flow rate of the coolant, the specific heat of the coolant (itself dependent on its temperature) and the difference in temperature between the coolant and the working fluid. As the temperature of the water body source increase, higher water extraction rates are required in order to keep the efficiency of the condenser at a maximum.

The water quantity which can be extracted from the water body source is limited, both by the actual physical debit of the body (or height in case of static sources such as lakes and reservoirs) and legal and ecological limitations.

In locations where the water supply is adequate, this does not present any issue. In warmer areas, where water restrictions and quotas are often in place, the efficiency of thermodynamic cycles can decrease drastically. This problem is especially pronounced during summer, when both the temperature of the water and the risk of draught are higher.

Another important drawback of open system is the rejection of hot effluents in the water body. As the cooling water absorbs the biggest part of the heat of the working fluid, its temperature greatly increases. The dumping of over heated effluents impacts negatively the water body, as it changes its physical properties. Eutrophication and destruction of ecosystems have been observed as direct results of this phenomenon.

2.3.2 Closed system

To insure an adequate supply of cooling water, and limit the rejection of hot effluents in the water bodies, many thermal power plants are equipped with cooling towers. In such devices, a part of the cooling water coming from the condenser is evaporated and evacuated from the chimney into the atmosphere. The heat from the cooling water is transferred to the air during the evaporation (figure 3). A large portion of the cooling water will be reintroduced in the cooling circuit, at a lower temperature.

This has the advantage of limiting the amount of water which needs to be withdrawn from the water body source. As some of the cooling water is evaporated (consumed) in the process, this however means the water extracted from the body is not given back to it. As extraction is generally low (typical of 0.5-0.8 m^3/s instead of 20-60 m^3/s for once through), this does not present a major issue in many cases. However again, in areas where flow restrictions are in place, this can lead to shut-down of the site.

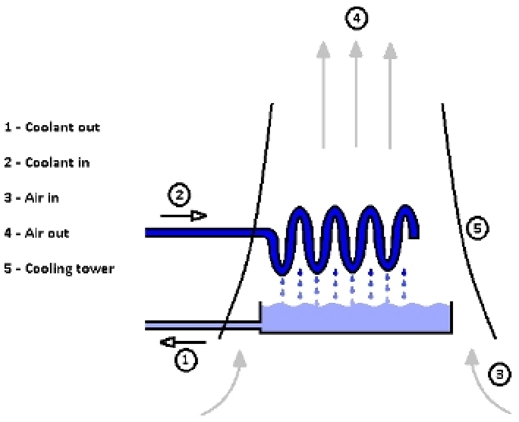

Figure 3. Operating principle of a cooling tower (left) and cooling towers from the nuclear power station of Chooz (right). Image source www.edf.fr.

Another disadvantage of cooling tower is that the water reintroduced in the cooling circuit after the passage through the cooling tower is usually warmer than the water extracted from the source. Referring to equation 1 this means decreased efficiency of the heat transfer in the condenser and therefore diminished production.

2.3.3 Reactors cooled by air

In areas where water availability is limited, reactors can be connected to a air cooling system, or dry cooling. In these systems, the working fluid is cooled down by an air flow before being reinjected in the cycle.

This cooling method presents the double advantage of being independent of water reserves and adaptable to any working fluid. The heat capacity of air being far lower than that of water, the heat exchange between the working fluid and the environment is lower.

There is so far no major power plant which use air as its main coolant, although Eskom is currently commissioning a reactor of installed capacity 800MW (WNA, 2013). In most cases, dry cooling is combined with wet cooling to obtain maximum efficiency.

2.4 Climate change

11 out of 12 years in the period 1995-2006 were amongst the warmest ever recorded (IPCC, 2007). Greenhouse gases (GHG) due to human activities are suspected to be the cause of this increase in temperatures. Unfortunately, projection show the atmospheric levels of GHG could double by 2050, if the current trends in anthropogenic emissions are not reduced.

Models, most notably the UN Special Report on Emission Scenarios (SRES), focus on forecasting the emissions of GHGover the coming century, depending on demographic and socio-economic developments as well as technological changes. Based on these models, various simulations are made to forecast climate variations.
Differences are seen between these results, depending mostly upon the scenario chosen for such predictions, but also because of the complexity of such calculations.
However global trends can be observed: in most models, global temperatures are expected to rise, extreme meteorological events to become more frequent. The hydrocycles will be affected at regional and global levels, notably with decreased precipitation in summer and increased in winter.

The energy production sector and climate change are intimately linked to each other. Electricity produtcion represents over 40% of the total emissions of GHG, mostly due to the share of fossil fuel in the global energy mix (figure 4).

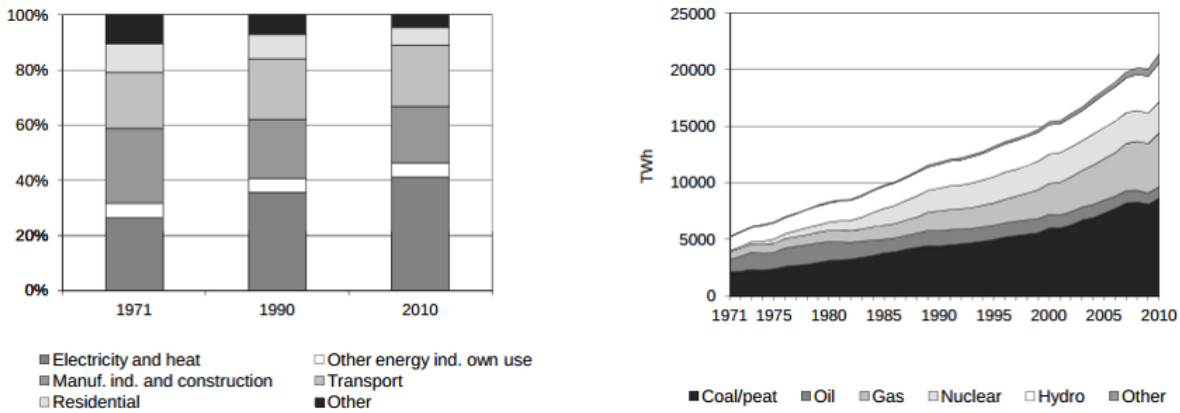

Figure 4. Relative share of GHG emission by sector (left) and total electricity production by energy source (right). Source IEA, 2012a.

As population and energy need increase, so does the electricity sector. Most scenario of climate change are based on the speed at which this growth occurs and the evolution of the energy mix.
With climate change, the temperature variability is expected to increase, leading to unknown changes in the efficiency of thermal power plants.

In a business as usual scenario, the share of fossil fuel (nuclear excluded) in the energy mix similar would be comparable to current levels. Climate, energetic and thermal factors coupled together would become a vicious circle: with increased temperatures, the efficiency of thermal reactors would diminish, requiring additional power to be installed, which in turn would lead to an increase of the levels of atmospheric CO2, accelerating and deepening climate change.

Forecasting this change is becoming paramount, as anything susceptible to impediment the efficiency of the thermal sector is an added argument in the discussion of phasing them out.

3 Methods

3.1 Power plants and data set

3.1.1 Choice of the sites

12 sites were chosen in France, accounting for 31 reactors. The following parameters were considered:

- Types of power plants.
  24 nuclear reactors, spread over 12 sites, were chosen to account for the importance of nuclear energy in the French electricity mix.
  4 coal reactors located in Cordemais, Bouchain and Le Havre.
  3 oil reactors located in Martigues and Cordemais.
  No gas reactor was chosen, to reflect the politics of France of phasing them out and replacing them with CCGT. This phasing out being undergone at the time of writing this study, no relevant data could be found.

- Location (figure 5). The reactors are evenly split on each side of a virtual division line, with 16 reactors in North and West of the country and 15 South and East.
  4 sites (Tricastin, Bugey, Cruas, St Alban, totalling 14 reactors) are located in the Rhone valley and 3 sites (Chinon, Cordemais, Civaux, totalling 10 reactors) on the Loire river and its Tributaries, representing 2 of the main river basins.
  The 2 reactors of Penly and the reactor of Le Havre border the English Channel, Martigues' is located on the Mediterranean Sea.
  The 2 reactors of Chooz border the Meuse river and the reactor of Bouchain the Escaut canal.

- Output. The electricity output form each reactor ranges from 250, 600 and 700 MW for the coal and oil reactors, 900, 1350 and up to 1450 MW for the nuclear reactors.

- Cooling system.
  The nuclear reactors are evenly split between once through and recirculating cooling systems.
  The power station of Bouchain is the only non nuclear thermal power station to be equipped with a cooling tower.
  The remaining reactors are once through.

Figure 5. Location of the chosen power plants (red) and water intake source (blue).

– Relative importance. 2 sites were chosen for their strategic role in the French electricity market.
  The reactors of Cordemais account for 25% of the electricity consumption of the region they are located in. The site is the biggest non nuclear thermal in France.
  The reactors of Tricastin power the French Uranium enrichment facilities.

3.1.2 Data Type and source

The hourly production of each considered reactor for 2012 were provided by the French Elctricity Transport Network (RTE, data publicly accessible on their website http://www.rte-france.com).

The French meteorological entity (Meteo France) provided hourly air temperature for the city closest to the reactors (data available on request). Each meteorological station was chosen as to be located within a 10 km radius from the power station, on the same riverbank when applicable.

Daily river flows, average flows and draught minimum, were provided by the 2 main French water data base: OSUR (publicly accessible on http://osur.eau-loire-bretagne.fr/exportosur/Accueil) and “la Banque Hydro” (on request).
The hydrological station chosen was the closest to the power station. Upstream and downstream was not considered, as long as the power station and the hydrological station were on the same section (i.e. no tributary between the power plant and the hydrological station).
Partial data on river temperature coud also be found on the OSUR data base.
The daily water temperature for the Mediterranean and English Channel were extracted from the French Research Institute for Sea exploitation (IFREMER).
The temperature if the Loire river at the Estuary (power station of Cordemais) was obtained through the Loire Estuary association (http://www.loire-estuaire.org/)

3.1.3 Data quality

The OSUR data base provided only partial information (biweekly at best) for the temperature of rivers. The only hydrological stations recording daily and instantaneous measurements of the water temperature in land belong to the French electricity supplier, EDF, who refused to communicate them based on confidentiality basis. Only the daily temperatures in the Loire Estuary could be found, with an error of +/- 0.5 degree Celsius.
Flow of the Rhone river in the section relative to the stations of St Alban and Bugey for 2012 could not be found but could be deduced from a regression of past flows and 2012 flows at different locations (Appendix D).
No river flow could be found for the sites of Tricastin and Cruas, due to lack of historical data for the hydrological stations considered and of flow records for important tributaries.

3.1.4 Assumptions and removal of data

Each set of electricity output contained anomalies, from computer or measuring glitches. different methods were used to remove faulty data.
Any output data punctually over 100% of the design output was removed as being a probable glitch. In some cases a vast majority of the production data were over the design production. This was attributed to a scaling or converting issue and scaled down (no data removed, but the overall values were scaled down).
Any production data corresponding to a technical or fuel supply issue of the reactor leading to a partial load was removed. Punctual data (singularities) under 80% of the production design were thus removed.
When data were in sufficient number (all but Cordemais 2 and 3), punctual extremes were removed.

Electrical output and air temperature could directly be compared as being recorded hourly. Flow and water temperature were measured daily, a rule had to be established to

compare with production data: following the rule on removal of bad data, the remaining output points of a same day were averaged in a daily production average (per reactor).
In the case of Cordemais, validated data was not sufficient for proper analysis. The output of the reactors 2 and 3 in one hand and 4 and 5 in the other were averaged as follow: no data if data from both reactors were faulty (under 80%). Validated data of one reactor if the second one is faulty. Averaged value of the production of each reactor if both were validated. These data are referred as Cordemais 23 and Cordemais 45 respectively for the averaged values of the reactors 2 and 3 combined and 4 and 5 combined.

Table 1. Data found for each power plant/reactor.

Site	Type of fuel	Reactors	Cooling water source	Hourly air temperature	Water temperature	Water flow
Bouchain	Coal	250MW	River (Escaut Canal)	√		
Le Bugey	Nuclear	4x900MW	River (Rhone)	√		Daily average
Chinon	Nuclear	4x900MW	River (Loire)	√		Daily average
Chooz	Nuclear	2x1450MW	River (Meuse)	√		Daily average
Civaux	Nuclear	2x1450MW	River (Rhone)	√		Daily average
Cordemais 2 and 3	Oil	2x700MW	River (Loire Estuary)	√	Daily average	
Cordemais 4 and 5	Coal	2x600MW	River (Loire Estuary)	√	Daily average	
Cruas-Meysse	Nuclear	4x900MW	River (Rhone)	√		
Martigues-Ponteau 1	Oil	400MW	Sea (Mediterranean)		Daily average	
Le Havre 1	Coal	250MW	Sea (English Channel)	√	Daily average	
Penly	Nuclear	2x1300MW	Sea (English Channel)	√	Daily average	
St Alban	Nuclear	2x1300MW	River (Rhone)	√		Daily average
Tricasin	Nuclear	4x900MW	River (Donzere-Mondragon Canal)	√		

3.2 Temperature dependency

As seen in equation 2, the efficiency of a gas turbine theoretically varies linearly with the atmospheric temperature.
As no data was found for gas and CCGT, the efficiency of reactors studied were based on the efficiency of Hirn cycles, i.e. dependent of the temperature of the condenser (equation 1) and thus of the coolant.

3.2.1 Open systems: water temperature dependency

The temperature of the condenser was in a first time assumed to be the water temperature (or proportional to it). Air temperature and river flow were assumed to be uncorrelated to the electrical output.
The hourly output *P* of a each reactor was decomposed in series according to

$$P(T_{\text{water}}) = \sum_i \alpha_i \cdot P_D \cdot T^i_{\text{water}} \quad (4) \quad ,$$

With α_i coefficient representing the dependence of the production on the air temperature T_{water} to the order i.

Following Rankine theoretical efficiency, the dependency beyond the 2nd order is assumed low with regard to the first 2 orders. As background noise and lack of accuracy in data would drown these dependencies this reduces (4) to

$$P(T_{water}) = \alpha_0 \cdot P_D + \alpha_1 \cdot P_D \cdot T_{water} + \alpha_2 \cdot P_D \cdot T^2_{water} + \delta \quad (5) \quad .$$

P_D is the design production, α_0 a coefficient representing intrinsic production loss i.e. the inefficiency of thermodynamic cycle independently of climate conditions or fuel.
The coefficients α_1 and α_2 represent a first and second degree dependence of the production on the air temperature T_{water}.
δ is an error term expressing the inaccuracies of the decomposition in series, as well as noise.

For each reactor (or averaged twin reactors values according to rules above) equipped with a one through cooling system, the daily electrical output was plotted against the daily water temperature. Two outputs could be obtained from this: either the obtained curve had a distinct shape or none.
In the first case (output data clustered), the curve was directly fitted against the quadratic regression (equation 5). In the second (output data spread), only the upper values (general profile of the curve) were fitted.

3.2.3 Closed systems: air temperature dependency

Having a relationship between water temperature only and electrical output is risqué at best. In the case of a power plant equipped with cooling tower, it can be argued that the condenser temperature is at least partially regulated by the air temperature.

In real conditions, equation 5 can be corrected by replacing T_{water} with the temperature of the condenser T_C, itself the sum of weighted temperatures of water coming from the tower (T_{tower}) and the water source (T_{water}) used to top up the condenser (water lost by evaporation):

$$T_C = \beta_0 \cdot T_{\text{tower}} + \gamma_0 \cdot T_{\text{water}} \quad (6)$$

The weight coefficients β_0 and γ_0, expressed as percentages of the design flow of cooling water, are linked: $\beta_0 = 1 - \gamma_0$. γ_0 corresponds to the water used to top up the condenser, i.e. the water loss by evaporation in the tower.

Technical data from EDF suggest an evaporation rate of 0.75m^3/s for a 1450 MW power plant (Civaux), compared to a 43.5m^3/s flow in the cooling circuit. This gives a ratio $\frac{\gamma_0}{\beta_0} = 0.0173$. In the case of a power plant equipped of cooling tower, the dependency to water temperature can be neglected. As the temperature in the tower can be assumed to be close to air temperature, equation 5 becomes

$$P(T_{air}) = \alpha_0' \cdot P_D + \alpha_1' \cdot P_D \cdot T_{air} + \alpha_2' \cdot P_D \cdot T^2_{air} + \delta' \quad (7)$$

The analysis between the air temperature and the electrical output in power plants equipped with cooling towers is therefore similar to those of a open system and water temperature. However the availability of data allows for plotting hourly air temperature against hourly output, compared to daily data for water temperature. The fitting was undergone similarly, water flow was not taken into consideration.

3.3 Water flow dependency

For each river and each reactor, a minimum flow Q_m is defined. Under this flow, which can be determined by ecological, legal or technical reasons, the thermal efficiency of the power plant is nul and the electrical output equals 0.
Above this flow, a power plant with cooling tower is assumed to work at full capacity, independent of the flow, as the water extracted to replace the water evaporated in the tower is minimal ($1m^3/s$ or less).
In the case of an open cooling circuit, the power station has a design flow. Above this flow the output is maximal. We assumed the correlation between river flow and efficiency is proportional to the ratio $\frac{Q}{Q_{base}}$, where Q_{base} is the base flow (or design flow), i.e. the minimum necessary flow to have full efficiency of the condenser.
Daily electrical output were plotted against daily flow of all power plants on a river.

3.4 Climate change

3.4.1 Choice of scenario

Climate change is hard to predict and various model exist. Most are based on the scenarios A1, A2, B1 and B2 of the IPCC, which represent the different assumptions regarding technological, behavioural, demographic and economical changes.
This part follows the assumptions of the scenarios A2 and B2.
Scenario A2 represent the “pessimistic” model. In this scenario, demographic transition is slow and population still continues to rise at levels similar to the current ones. Energy efficiency and improvements in technologies are reduced, the use of renewables in the global energy mix is unchanged. Nuclear power and fossil fuels are not phased out.
Economically, there is little change in the rift North/South and the GDP per capita slowly progress toward convergence (IPCC, 2007).

In the scenario B2, changes are more optimistic while still being realistic and achievable. Although a smaller proportion of fossil fuels is present in the energy mix, we will assume this does not affect the share of nuclear. The general evolution of economics and behaviours is less extreme than scenario A2, and changes toward convergence (less difference between richer and poorer countries) are seen, as well as a general effort to use renewables.
Both scenarios show increasing levels of atmospheric CO2, with concentration growth similar to current one in the scenario B2, and higher in the scenario A2.

3.4.2 Temperature variation

Various models have been constructed to forecast the evolution of climate in France. This paper uses conclusions from the ARPEGE model (www.meteofrance.fr). This model has been developed by the French Meteorological Services (Meteo France) in the 90s, to describe at local scale (20km grid) the evolution of climate.

It foresees a increase of 0.5 to 1.5 Celsius over France by Year 2050. This rise would be slightly more stressed in summer (temperature rising by 1.5-2 degrees) and winter (rising by 1-2 degrees) than autumn and spring.

This rise in temperature per season can be directly associated with the results of the temperature-efficiency correlation in order to forecast a range of efficiency loss (if any) for each power station, by 2050. In the scope of this paper, the temperature rise after 2050 will not be used, as most power plants studied, if no all, will decommissioned and dismantled (or in the process of being so).

3.4.3 Impact on hydrology (flow)

The impact of climate change on the hydrology of the studied rivers for this paper is twofold:

- Change in average flow (Base flow).
- Change in the intensity and frequency of draughts.

According to the National Office for Water and Aquatic Environment (ONEMA), the average flow for French rivers is expected to be reduced by 15-30% by 2050, with great regional differences. It has also established a map forecasting the potential increase of the levels of draughts (i.e. the reduction of the yearly minimal flow).

These data are grouped in Table 2. Data for the station of Tricastin (on the Donzere-Mondragon Canal) and Bouchain (Escaut canal) could not be found, as canals flow is usually regulated and dependent of the river(s) the canals are tributaries of.

These data were used to forecast average and minimal flow for each river by 2050. The ecological flow (defined in France as 1/10 of the average flow) was then compared to the minimal flow requirement (base flow) of each power station.

Table 2. *Current and estimated flows and draughts for chosen French rivers. Data source Banque HYDRO, 2013 (1), ONEMA, 2012 (2), Ducharne, 2010 (3), EAURMC, 2012 (4), AMICE, 2012 (5) & SIEGES, 2013 (6)*

Power Station	**River**	**Average flow (m^3/s) (1)**	**Forecast decrease in average flow (%)**	**Average drought flow (m^3/s) (1)**	**Forecast decrease of the drought flow (%) (2)**
Chinon	Loire	393	15-45 (3)	90	20-30
Cordemais	Loire (Estuary)	865	15-45 (3)	200	10-20
Bugey	Rhone	455	'9-36 (4)	210	20-50
Cruas	Rhone	1480	'9-36 (4)	590	30-70
St Alban	Rhone	1030	'9-36 (4)	380	40-50
Chooz	Meuse	143	'10-40 (5)	31	30-50
Civaux	Vienne	80	'10-20 (6)	17	50-80

4 Results

4.1 Dependency of the electrical output on air temperature

The electrical output of all reactors, with the exception of Bouchain, Chooz 2 and the 4 reactors of Cordemais, show a clear plateau at lower temperatures (Appendix A).
In the case of St Alban, this plateau is preceded by an increasing output with increasing air temperatures (lower than -6 for the reactor St Alban 1 and -8 for the reactor 2).

With the exception of Bouchain, a clear decrease in electrical output with higher air temperature is shown.

The loss of output occurs for air temperatures over 10 Celsius in 14 out of 30 studied reactors. An additional 6 reactors show this decrease in output for air temperature above 15 Celsius.

This loss is regular and present features similar to Bugey 4 (3rd graph in figure 6) for 12 reactors. A further 11 reactors show a neat regular decrease of higher values of the output with increased temperatures, but with various thresholds.

In the case of Penly (2nd graph in figure 6), this decrease of output can be seen when the air temperature rises above 20 degrees for the reactor 1 and 24 degrees for the reactor 2. The reactor of Tricastin 4 presents this decrease for temperature higher than 25 Celsius.

The quadratic fit for the various reactors showing a decrease in output with increased air temperature is presented in the Appendix B, along the first and second order coefficients found for every reactor (except Martigues, Penly and Bouchain).
The regression coefficient R^2 for the reactors of Chinon (except Chinon 4), Bugey and Cruas (except Cruas 2) are calculated superior to 0.6.
This coefficients are comprised between 0.23 and 0.47 for the reactors of Chooz, Civaux 2, Cruas 1 and Chinon 4.
Civaux 1 present the worst fit (R^2<0.1).

No direct fit could be found for the power plants without cooling towers. The maximums (profile of the plot) was fitted against a quadratic curve.
These coefficients were used to calculate the decrease of electrical output per degree increase in air temperature (figure 6). The reactors of Penly 1 & 2 and Tricastin 4 could not be calculated due to the high uncertainties (lack of output data for high air temperatures)

16 out of 30 reactors show diminished efficiency of 0.18-0.40% per degree increase (figure 7). There is no noticeable difference between reactors equipped of cooling towers and once through circuits.

The average loss in electrical output is 0.32% per increase of one degree in air temperature, with a wide differences between reactors. This average is of 0.27% for the 16 median reactors.

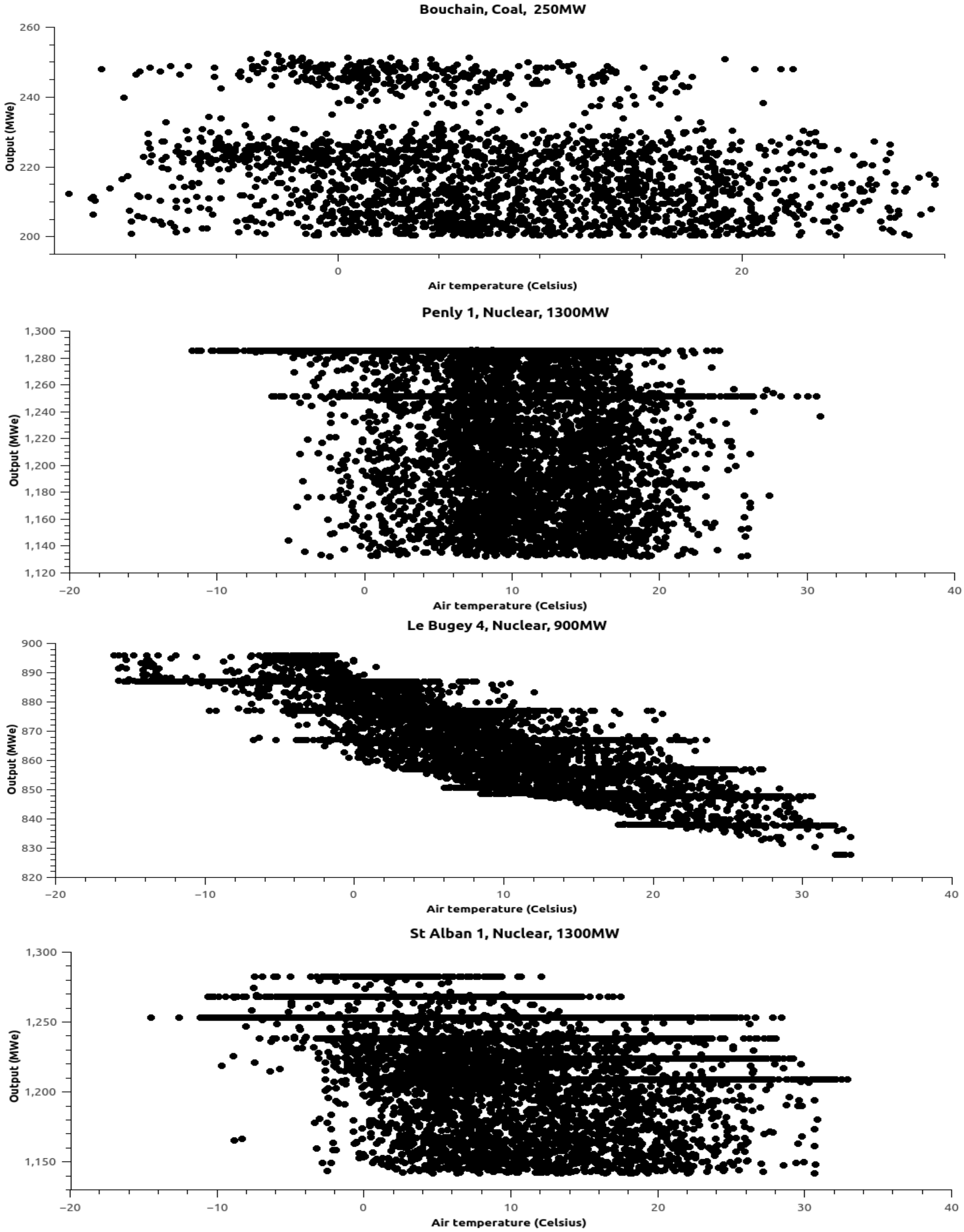

Figure 6. Graph examples representative of the observed electrical output of a reactor compared to air temperature. From top to bottom: 1 – No correlation: no observed link between output and air temperature (ex. Bouchain). 2 – Little correlation: output independent of low air temperatures and loss of output at high air temperature (ex. Penly 1). 3 – Strong correlation: regular loss of output with increasing temperature (ex. Bugey 4). 4 – Decreased output at lower temperatures (ex. St Alban 1). In the 3 lower cases, the plateau corresponding to maximum output is clearly seen. All graphs can be found in Appendix A.

The change in electrical output for the reactor Tricastin 4 was found equal to 33% (increase of electrical output by 33% for each degree rise in air temperature). Lack of data for the electrical output of the reactors of Penly 1 & 2 with atmospheric temperatures above 20 Celsius did not allow to calculate the change in output.

Martigues has been removed as air temperature data is missing.

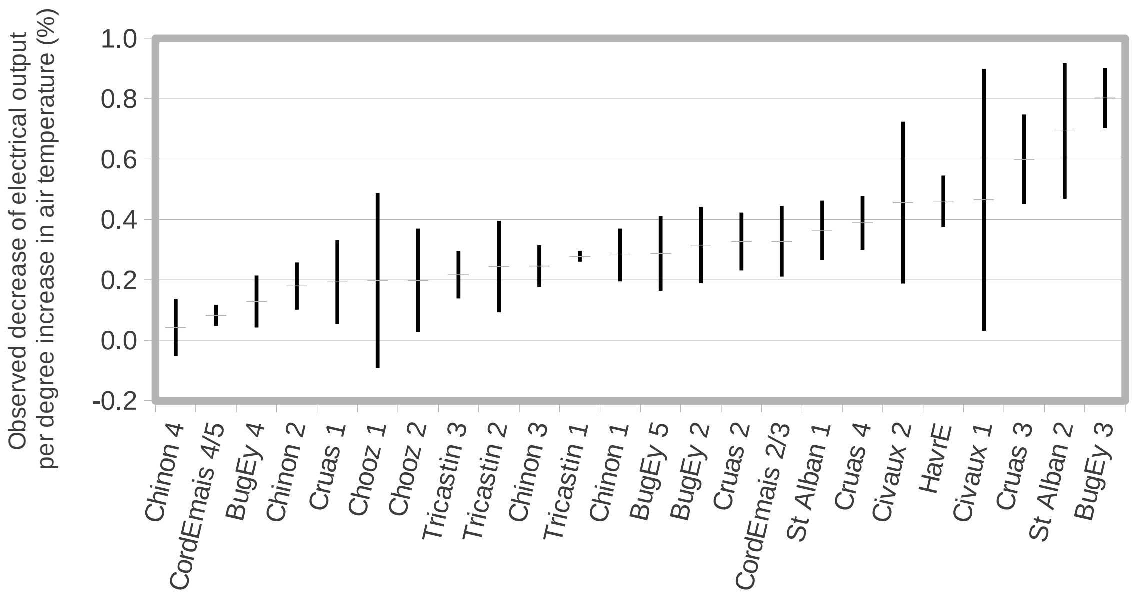

Figure 7. Observed relative decrease of electrical output of studied reactors with a one Celsius increase in air temperature.

4.2 Water temperature dependency

Limited data allows for the comparison only with reactors located on the Mediterranean Sea (Martigues) and the English Channel (Penly and Le Havre) .

Le Havre and Martigues show a decreased electricity outptut for water temperature over 14 Celsius (figure 8). There is no data for the temperature of the Mediterranean Sea under 14 degrees in association with any output from the reactor of Martigues.
Penly 1 and 2 show a diminished electrical output with water temperature above 13 and 16 Celsius respectively.

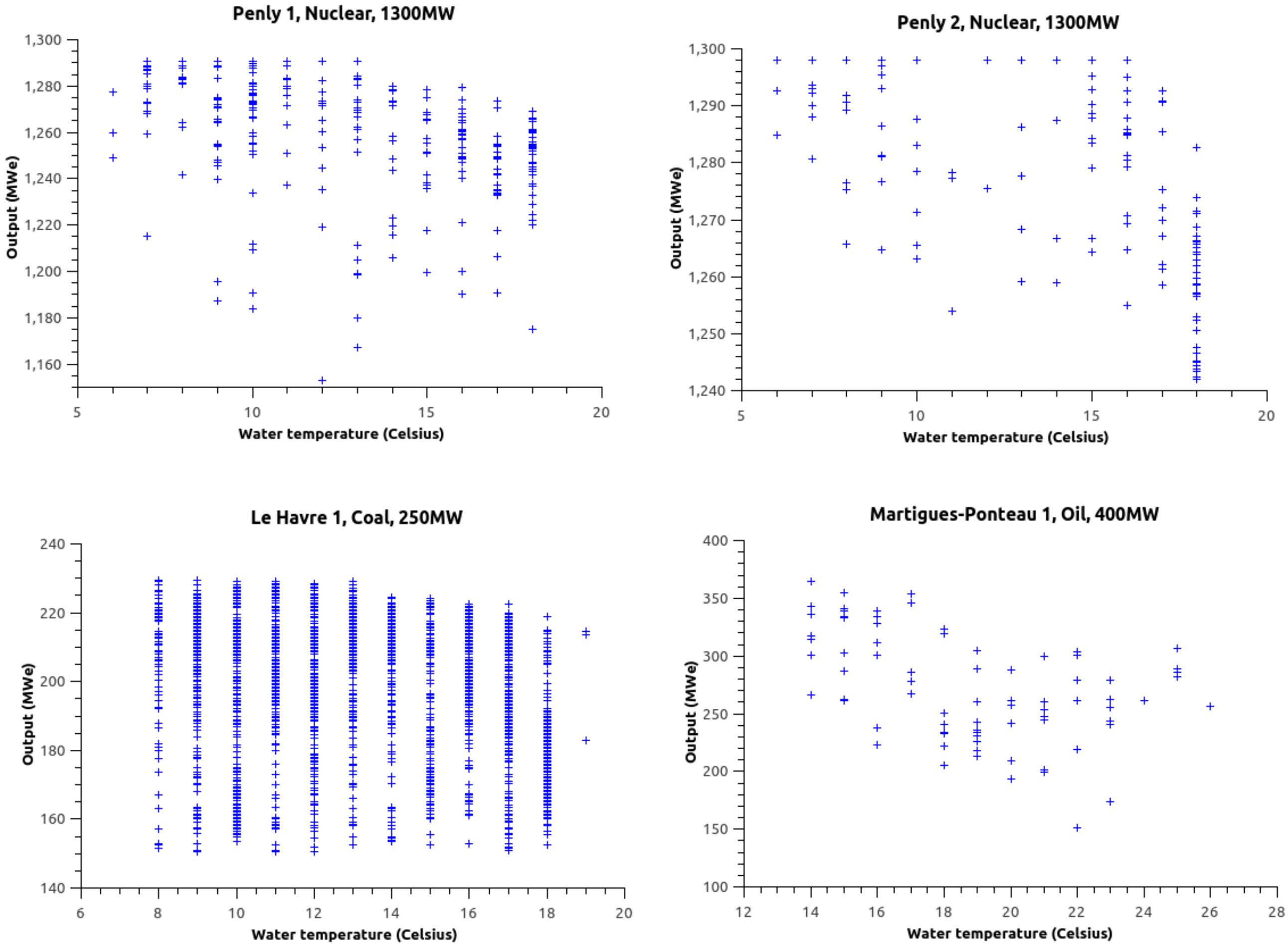

Figure 8. Observed electrical output of the reactors of Le Havre, Martigues and the 2 reactors of Penly compared to the temperature of the coolant.

4.3 Flow dependency

No visible decrease in output could be found with reduced river flow of any of the studied reactors. As seen in figure 8, the maximum output at a any given flow remain constant, with slight fluctuations at low and high values of the flow.

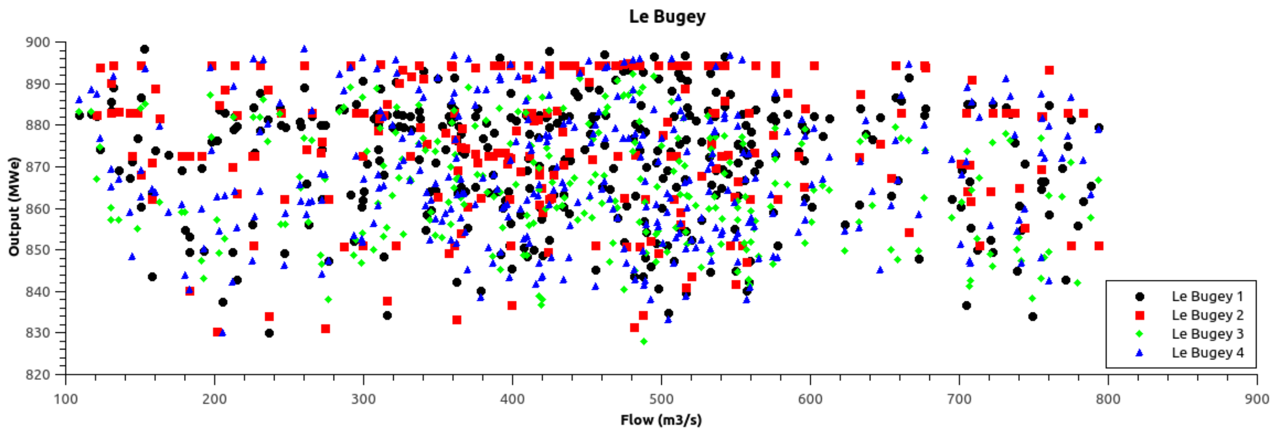

Figure 9. Observed electrical output of the 4 reactors of Le Bugey compared to the flow of the river Rhone.

4.4 Climate change predictions

4.4.1 Temperatures

With the first and second order coefficient found previously, the loss in electrical output for each power plant by the year 2050 can be deduced (figure 9).
In over 80% of reactors the loss in electrical output is under 200 MWh/day, with the exception of Bugey 3 (280 MWh/day), Civaux 1 and 2 (300 MWh/day) and St Alban 2 (360 MWh/day).

The difference between winter and summer losses compared to current output is not particularly visible, as the upper values are the same in both seasons (increase in 2 degrees in temperature in average).

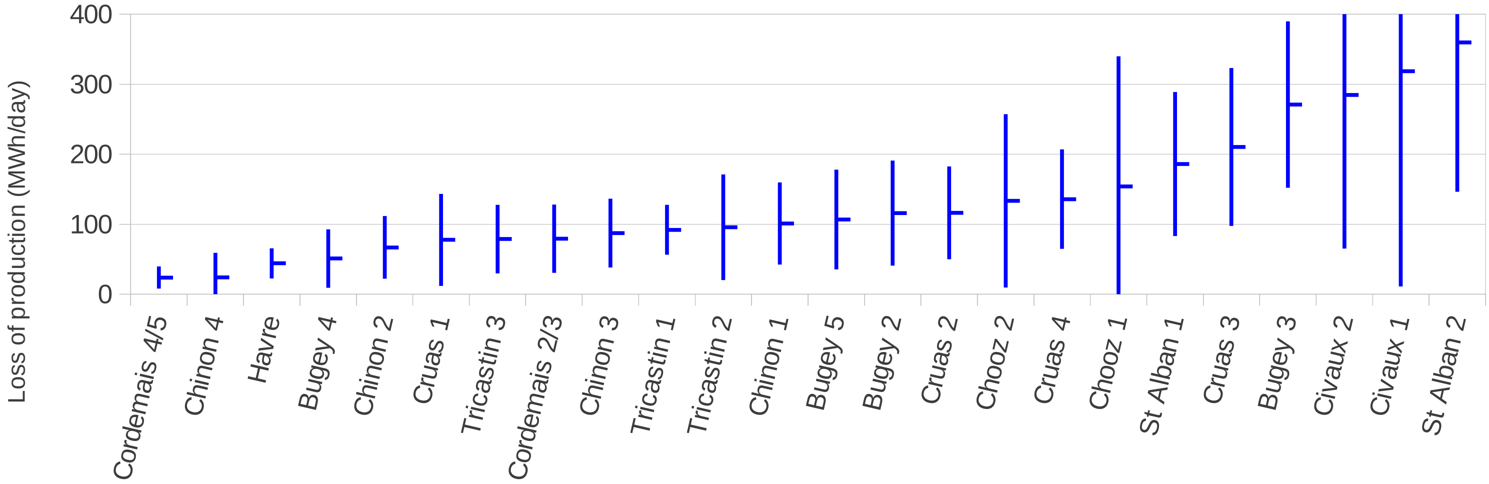

Figure 10. Average daily electrical output loss per reactor in the year 2050. Error bars for the reactors of Chooz 1, Bugey 3, Civaux 1 and 2 and St Alban 1 are off the scale.

The total average yearly loss in output calculated over the 26 reactors is over 830 GWh. The daily average loss ranges varies greatly with each reactor, ranging from 7 MWh/day (winter minimum of Cordemais 45) to 625 MWh/day (summer maximum of Civaux 1), with an average value of a loss of 21-169 MWh/day/reactor. This loss is slightly more pronounced in summer (62-226 MWh/day/reactor) than winter (42-226 MWh/day/reactor)

4.4.2 Water flow

Based on ONEMA's model, the average river flow at some stations can be forecast, both the yearly average and draught. It can be seen from table 3 that in case of draught, the power station of Civaux will not meet the ecological flow (8 m^3/s plus 0.75m^3/s of evaporation of the cooling tower).
Similarly, in case of draught the Rhone in Ternay (St Alban) would fall to an estimated

190m^3/s, of which 103m^3/s of ecological requirement (that is 87m^3/s water that can be extracted).
Each reactor of St Alban requiring and estimated 45m^3/s of water to cool down, both reactors operating conjointly with a draught would lead to the ecological requirements of the Rhone river barely met.

During droughts, particularly during dry years, the flow of the Meuse river near Chooz and of the Rhone near Cruas would be close to ecological limits.

Table 3. Forecast average flow and draught flow range for chosen French rivers by 2050 compared with current values of the ecological flow. Values highlighted in yellow indicate that a reactor operating at full load would reduce the river flow close to its ecological flow. Values highlighted in red indicate a river flow naturally under the ecological flow or that a reactor operating at full load would reduce it under its ecological value.

Power station	Forecast maximal average flow (m^3/s)	Forecast minimum average flow (m^3/s)	Forecast drought flow (wet year) (m^3/s)	Forecast drought flow (dry year)(m^3/s)	Current ecological flow (m^3/s)
Bugey	414	291	168	105	45.5
Chinon	334	216	72	63	39.3
Chooz	128	85	22	16	14.3
Civaux	72	64	8.5	3.4	8
Cordemais	735	476	180	160	86.5
Cruas	1347	947	413	177	148
St Alban	937	659	228	190	103

5 Discussion

5.1 General air temperature dependency of production

There is high confidence that an increase of air temperature will decrease the efficiency of a thermal power plant with cooling tower. In every reactor studied, this decrease in output was shown even at low temperatures (figure 6 and Appendix A).

In the case of Bouchain, we can see the graph can be separated in 2 main clouds of point. The lower one stabilizes at 230 MW and is shown not to vary with change of air temperature, while the upper cloud peaks under 250 MW and shows a decreasing slope in the output. Although this result is far from perfect, it does show that the maximum output at any given time does not exceed the design output minus a function of the temperature. Bouchain is therefore considered validated under the hypothesis of inverse correlation between air temperature and production. Its value was however not included in the tables of values and graphs, as the uncertainty on this is high.

Similarly, the correlation for the reactors Cordemais 2 and 3 is doubtful. The graph does show the decrease in output, but the little quantity of data for these reactors is too low to be significant.

The presence of a plateau in all but a few reactors is puzzling, so is the fact it does not arise at the same temperatures, even on the same site and/or with the same technology (design output and type of fuel). Our guess is that it shows the dependency on the water temperature that was neglected in equation 7. As air temperature gets colder, so does the temperature of the river. However water has the particularity of having its highest density at 4 degrees. As the intake of a power plant is usually located under the surface of the water body, it is likely the temperature of this intake will stabilize around 4 Celsius when air temperatures decrease. This would explain why the maximum production is reached in some power plants even with air temperature higher than 0. However this hypothesis cannot be verified with the current data, as this phenomenon could be a simple flaw or saturation effect in the measurements .

We can see on many of the graphs from nuclear reactors the decrease in temperature is not regular or the presence of multiple plateaus (see Appendix A). It could be that in order not to waste fuel on production that would be lost in heat exchange, the load is purposely reduced. Without knowing the exact daily or hourly load intended by the operators of the reactor, this explanation cannot be validated.

There is little difference observed between the loss of efficiency with increase temperature with regards to the type of fuel used. Cordemais 2&3 (oil) and Cordemais 4&5 (coal) show a correlation of the same order of magnitude as most other reactors. Le Havre seems a bit higher, but not significantly so.

In the case of reactors equipped with once through, this relation is uncertain. Both the sites of Penly, and Tricastin present a plateau at the maximum output for a wide range of temperatures. The decrease in output is not shown till the air temperature reaches 20 degrees ad more. This could be due either to the fact both sites have an access to water ample enough to compensate the loss due to increased air temperature. St Alban pushes toward the second explanation, as it shows the efficiency of the site decreases at negative temperatures. This would not be likely linked to water scarcity in winter, as flows are sufficient and the other sites on the same river (Tricastin, Bugey, Cruas) do not show anything similar.

Overall, the findings for the correlation of air temperature-efficiency/output are in agreement with previous studies. In particular, the study by Linerrund showed a decrease of 0.37-0.72% in efficiency with each degree rise in air temperature (Linerrund, 2011). Durmayaz (2006) found this loss to be close to 0.45%. With typical temperature in the turbine of 300K, this loss of output following Carnot's efficiency is of 0.55-0.75%. Our finding are a bit lower than that of these studies. Carnot's efficiency can be disregarded as being purely theoretical and therefore inaccurate. Linerrund and Durmayaz studies, on the other hand, were based on a very limited selection of power plants. Difference in technologies could explain the gap between the findings.

5.2 Water temperature dependency

Data was lacking to study the effect of river temperature on output. There are very few hydrological stations that measure the temperature of rivers with a frequency hight enough for this type of study, and their data was not accessible.

The link between electricity output and water temperature for once through reactors located on the sea is however satisfactory (figure 9) .

Both reactors of Martigues and le Havre show a steady decrease in output with increasing water temperature over 14 Celsius.
Penly shows a decrease in efficiency with water temperature higher than 13 (16) degrees for reactor 1 (reactor 2).
This is however in agreement with the theory put forward: as water temperature increase, the flow pumped in the cooling circuit increases so to maintain the thermal efficiency of the cycle (as depicted in equation 3). When the upper limit of the pump capacity is reached the increase in of water temperature is not balanced by increased flow anymore and the efficiency decreases.
The slightly higher temperature threshold for Penly 2 could be due to higher pumping capacity, or uneven split of the cooling water between the 2 reactors of Penly (which would explain the lower threshold for Penly 1).

The results from the reactors Cordemais 4 and 5 seem to agree with the expected results (higher water temperature decreases the efficiency) but the lack of data, particularly in the range of temperature 5-15%, advises cautious when interpreting this observation.

5.3 Forecast impact of climate change

This study shows with a high confidence that the increased air temperature will

affect the overall production of electricity in France.
The total installed power of the reactors considered in this paper represent a little over 28 GW, that is 32% of the total installed thermal power stations of the country. If we assume the results we found can be transposed directly to the scale of the country, this means that by 2050 the increase in air temperature due to climate change would be responsible for the loss of 0.5- 4.6TWh per year, with an average of 2.6TWh. To put things in perspective this is the yearly production of a 300MW reactor.

Concerning water flow, it is shown that the predicted increase in draughts combined with the high water requirement for nuclear power plants will adversely affect the state of some reactors in the near future. On rivers whose flow is normally sufficient (Rhone) to provide sites with cooling water, episodes of draught would lead to water intake restrictions (in order to keep the river over the ecological flow) incompatible with the necessary water intake for once though. When this occurs, power plants on the segment of the river will be forced to shut down. We based our analysis on yearly minimal flow, it is therefore expected that this draught of the Rhone river will occur every year.

ONEMA forecast that the length of the draught will increase compared to actual levels by 1.5-6%, it is however difficult to predict how many times per year the draught levels will lead to flow restrictions. The combined results from table 2 and the flow measured suggest that the Rhone is currently on state of draught 10-15 days per year, which would mean this draught would last for an average of 10-16 days per year by 2050.
During that periode, if the shut down of at least one reactor of St Alban is demanded by regulations, the subsequent loss of production from this reactor would be of 310000-500000MWh per year.

A similar if more dramatic analysis can be made for the reactors of Civaux. By 2050, the level of the Vienne river would permanently be under the ecological flow during summer draught. Even with limited water intake (cooling towers), this could mean the forced shut down of both reactors. Once again it is difficult to forecast the length of summer draught, but based on a averaged 15-30 days of draught for the Vienne river, this means a yearly loss of production of 0.52-1.04TWh/year/reactor.

5.4 Possible mitigation

Little, if anything, can be done in terms of decreasing the loss of efficiency due to increase air temperature. Unless technology evolves greatly to reduce the impact of air temperature on the efficiency of thermal power stations, this loss is unavoidable.
It could be suggested to relocate the power plants close to the sea, as we analysed the output of thermal stations on the shore was relatively independent of the air temperature. This suggestion is however highly unrealistic, as nuclear power stations cannot be relocated easily. This however gives the policy maker a good idea about the choice of location of future power plants. Although it involves higher construction costs, a study by EDF shows the overall efficiency of a sea side reactor is 0.9% higher than a landlocked site (WNA, 2013). This finding is 3 times higher than the results of this thesis, but compatible: the reactors of Penly, le Havre and Martigues do not show any loss in efficiency and output for sea temperatures lower than 14 degrees.

It also suggests the establishment of a reactor on the North Sea/English Channel is preferable to the Mediterranean sea, as the count of daily water temperatures higher or equal to 16 degrees is lower (97 counted for 2012 close to Penly VS. 185 close to Martigues).

As the loss of output is negligible at lower temperatures, we concluded the loss of efficiency does not come from elevated water temperature but from reaching the limits of the pumping capacity for cooling water. If this proves true, loss of output could be counterbalanced by higher pumping rates, and the installation of pumps with a bigger flow could represent a fairly cheap solution.

As for the nuclear reactors of St Alban, one solution to avoid the loss of output due to reduced river flows would be the switching from open cooling systems to closed one. However the price of retrofitting a nuclear power plant with a cooling tower is of the order of 0.5 billion €. Considering the highest cost of electricity in France (0.12 €/kWh for individuals), it would take 8-13 years of intense draughts to cover the investment. Although regulations might force the site to undergo a retrofitting, it is unlikely EDF would carry it out by itself, if only on economical arguments.

It is however important to note that most reactors undergo phases of planned shut down for maintenance, cleaningof the water intake, repairs and other. Scheduling these shut downs so that they happen during the dry season would help prevent any loss of electrical output. These scheduled shut down are currently planned so that the loss of electricity supplies does not affect the demand. A modification of this schedule might however be necessary in order to satisfy new climate conditions.

5.5 Quality of data / interdependence of parameters

Plotting water temperature against air temperature in the Loire Estuary shows a linear relation which is not as clear in seas (figure 10). In the case of Cordemais (and by extrapolation of power plants located on river side) it can be hypothesized that water and air temperature can be used interchangeably. This means that any result obtained from air temperature and loss of electrical output could be generalized to the temperature of rivers.
As far as sea and air temperatures also seem to vary together, this relation is not as linear. This implies that if both water and air temperature play a role in the efficiency of the thermal reactors located on sea side, they must be weighted. This has been ignored in this study, where we concluded the electrical output of a reactor located on a sea side to be entirely dependent of water temperature.

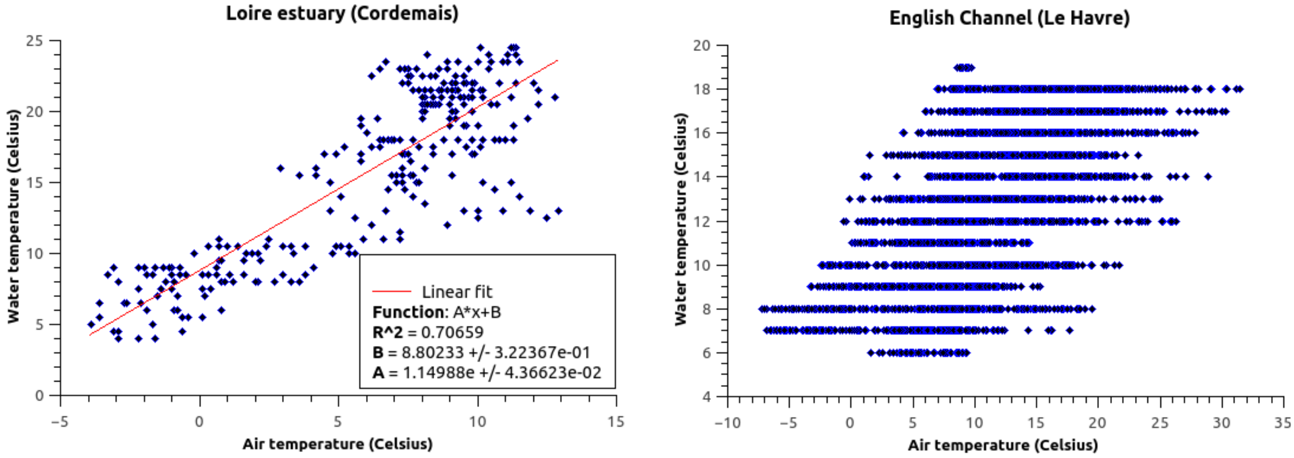

Figure 11. Relationship between water and air temperature in the Estuary of the Loire (left) and the English Channel (right).

Contrary to most research that have been published in this field, the noise levels is extremely high. With the exception of the reactors of Chinon and Bugey, the noise level is way past 1%, up to 15% in Cordemais.
This explains the high variation of values at any given temperature and/or flow, but makes the interpretation of data a tedious task.
This is particularly true for the flows: at lower flows, a decreasing trend is observed, which take in many instance the shape of an exponential function $1-e^{(1-\frac{Q}{a})}$ (Q is the flow and a a constant), as seen on figure 12.

This phenomenon was seen on many data sets but, in the absence of any theoretical explanation, has been dismissed as being a glitch.

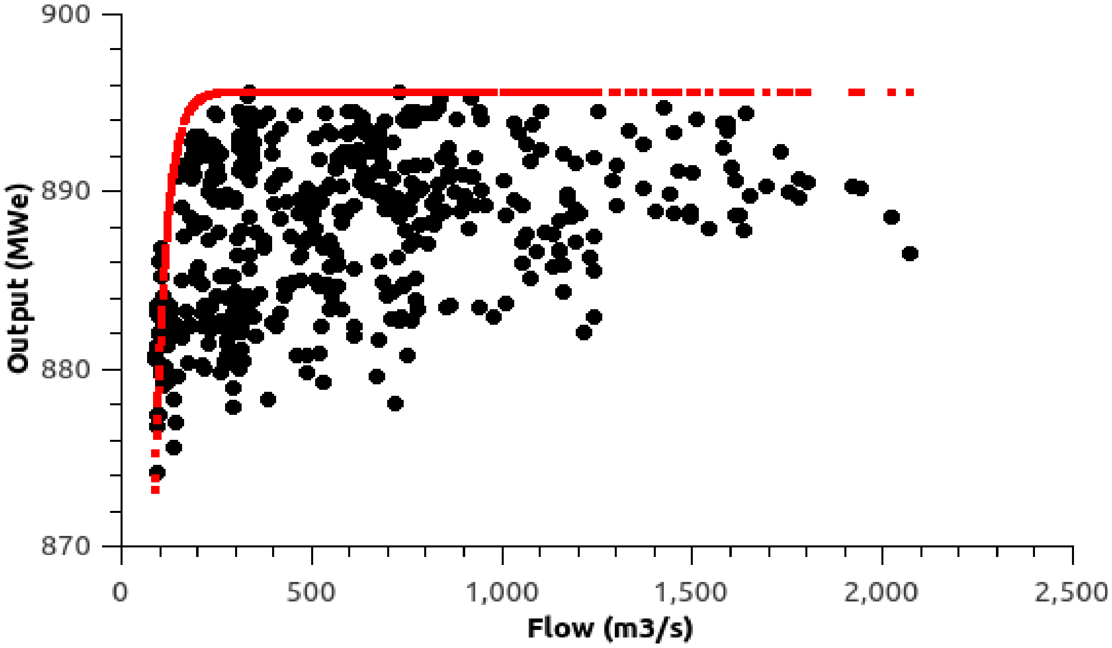

Figure 12. Relation between the electrical output of the reactor Chinon 3 and the flow or the Loire river. The red plot corresponds to a supposed exponential link correlation.

6 Conclusion

Most reactors not connected to the sea were found to present a correlation between air temperature and electrical output. This link has bee estimated to represent a loss of production of 0.04-0.8% per degree rise in air temperature. This finding is in agreement with previous research done in this field.
The lack of quality data however poses a problem of accuracy. In particular, the output loss at higher temperature is at best uncertain (Rhone valley) or unknown (Loire Valley).
When connected to climate change data and the suspected rise in temperature in the next half century, this thesis indicates a loss of electrical output of 0.5 – 4.6TWh per year. This correspond to the loss of the full production of a unit of an installed capacity of 57MW (lower limit) up to 525MW (higher limit).

Analysis of the water temperature dependency was unconvincing. The lack of data for the temperature in rivers did not allow for any conclusion. For reactors located close to seas, a decreased output was found for temperatures of the water over 14-16 degrees. This results indicate the loss of electrical output could be linked to the flow of coolant pumped as well as the temperature of the water. Higher pumping capacity could decrease the loss in the near future.

The flow dependency was inconclusive. In all studied cases, the river flow at the lowest point of the draught was still sufficient to allow the extraction of 100% of the water needed for cooling in each reactor.
Forecast draughts in the next 50 years however show the sites of St Alban (Rhone river, 2 reactors, no cooling tower), Cruas (Rhone river, 4 reactors, cooling towers) and Civaux (Vienne river, 2 reactors, cooling towers) are at at high risk. This is particularly true for Civaux and St Alban (the latter during episodes of extreme draught) which could face forced shutdown for ecological reasons (no extraction of water from the river and no dumping in warmer effluents downstream).
The potential shut down of these sites would cause the loss of 34800 MWh (Civaux) and 31200 MWh (St Alban) per reactor of the power station for each day.
This loss can be prevented in St Alban with the installation of cooling towers, but the prohibitive cost of retrofitting a nuclear power plant with a cooling tower represent a major counter argument.

These findings did not take into consideration the potential decommissioning of any power station nor the construction of any new one.
Although not included in this study, there is a strong belief that the loss of efficiency applies for both gas (compressed) and CCG turbines. Unfortunately, as the former is currently being phased out and replaced by the latter, no data should be available for a few years in this matter.

6.1 Issues encountered

The main issue encountered during the writing of this thesis was the lack of data. Unfortunately, very little is collected regarding the temperature of in land rivers, and the

data are not publicly available.
For those data which are accessible, finding them presented a real challenge, as each parameter was the exclusivity of one organisation (RTE for data on production for instance).
The accuracy of the data however represented a major barrier as very little was known about the conditions of measurement or extraction, accuracy, error, … Sorting through required a lot of time even before the thesis could actually begin.

Many fake patterns and coincidences were found (for instance the exponential growth of production with reduced flows) that mislead the direction of the thesis.

Another major issue was the lack of cooperation of the various organisations that did have data. With the exception of the HYDRO and IFREMER data base, for which access was granted quickly, the back and forth negotiations between each actor took month, without any success for most case.
Many French company do not like to communicate through email and phone and demand letters or face to face contact before judging of the legitimacy of the request.

6.2 Further research

So far there has been little to no interest in studies on the composition of cooling water (ions, sediments, …) and how climate change will affect this state of affair. An attempt to link chemical composition of water and fooling with electrical output failed entirely due to lack of accurate data. From a technological perspective, the impact of climate change on open and closed cooling systems is developing, but limited information is available for dry cooling, and the limitations induced by climate variations. In particular, a cost benefit analysis of the impact of climate change on the price of thermal electricity with regards to various cooling systems could be integrated in different models.
Research in these fields is highly necessary. As we suggested higher pumping rates could counterbalance the loss of output in reactors located on the sea side, research is needed on the technical feasibility of retrofitting condensers with larger pipes and increased coolant flow. This might or not present itself as an economical solution to the loss of output.

Studies (this one included) have been up to now limited to regional scale. Very little globalisation of the results or the methods was found, and only at the approximation level. Although climate change impacts are extremely region dependent, it could be possible to establish a methodology to determine the global trend.
Besides technical and physical aspects, the legal and behavioural (acceptance) environment around this subject is ever changing. It could be extremely interesting to analyse the effect of climate change on thermal power associated with changes in legal framework and public opinion.

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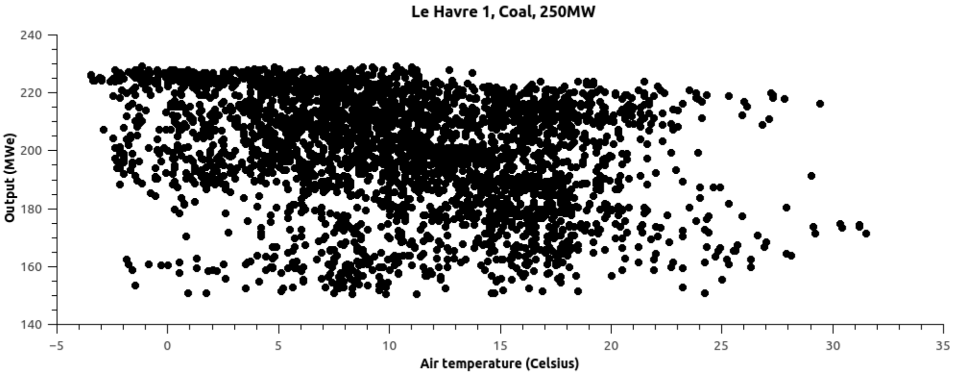
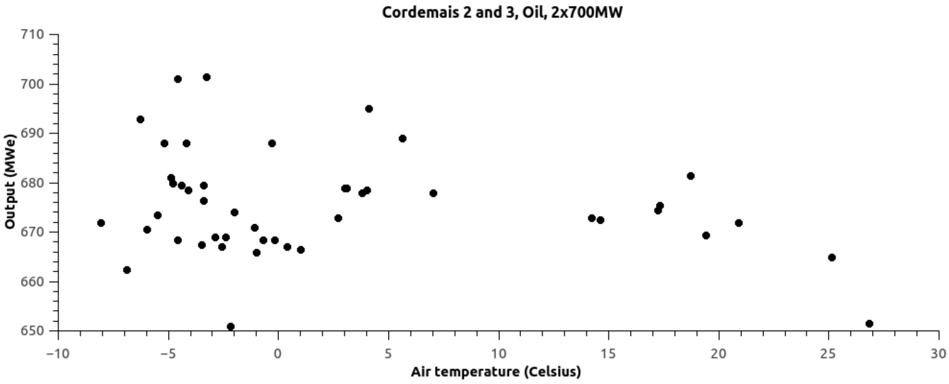
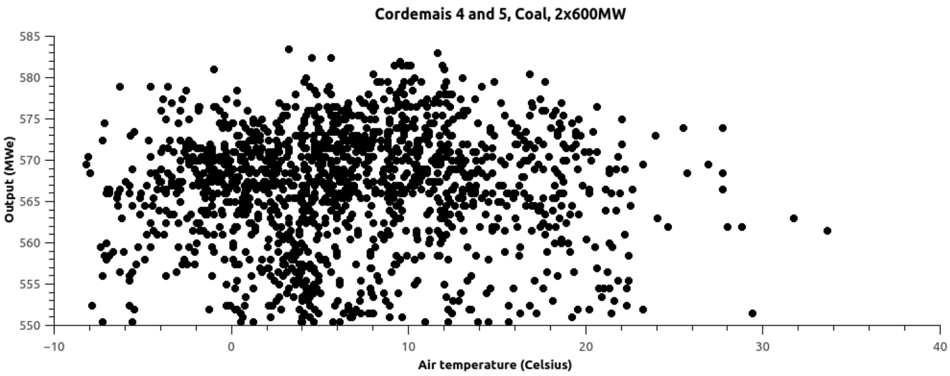
Appendix A

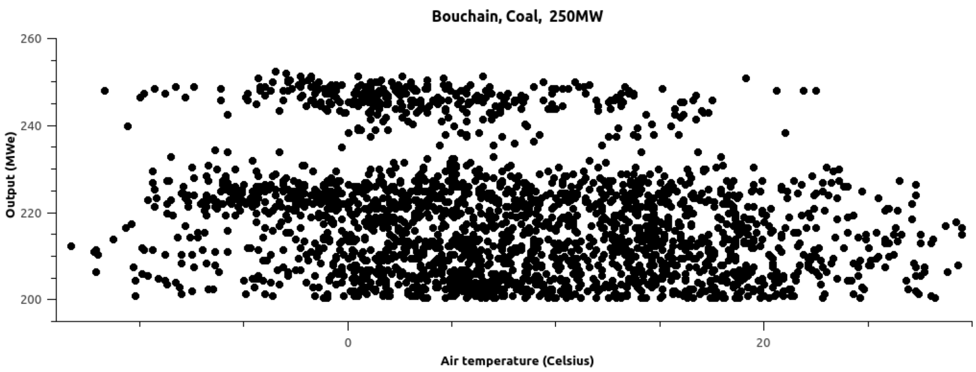
Electrical output of reactors studied vs. air temperature.

1 Coal and oil

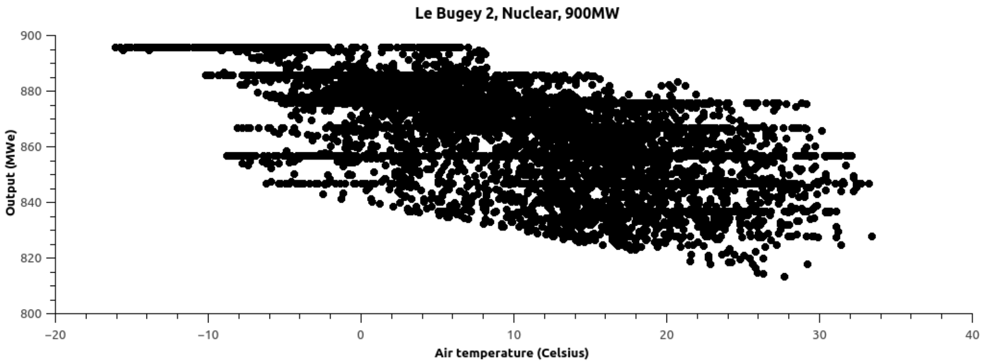




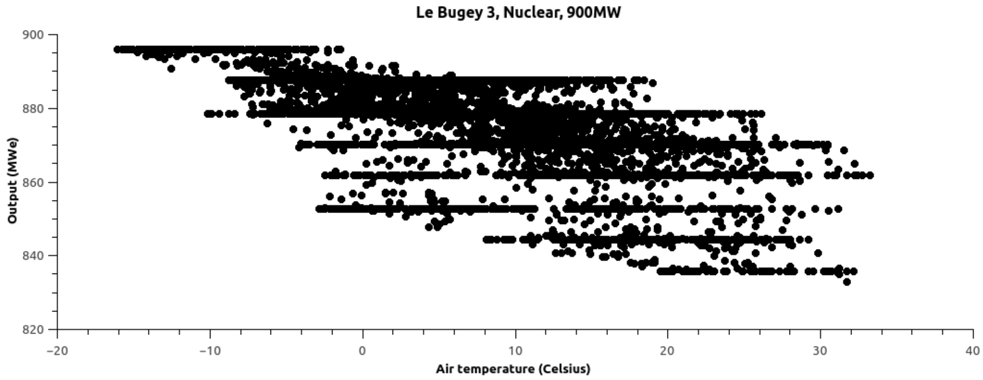




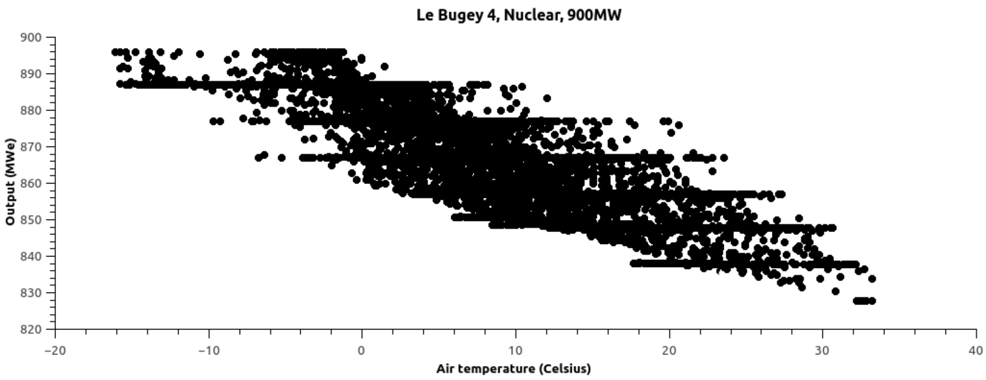
2 Nuclear



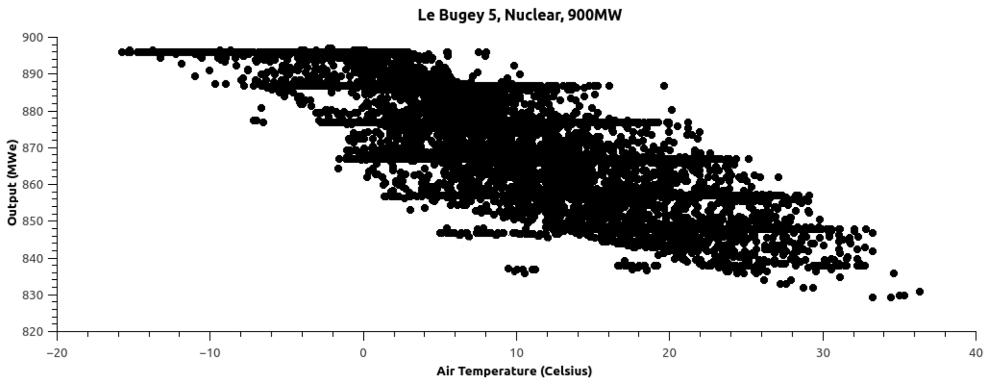
Le Bugey 2, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)



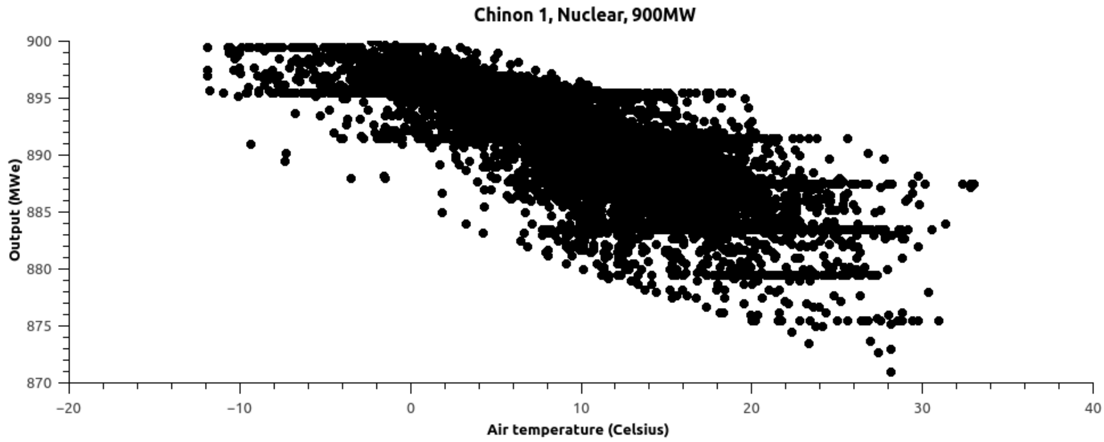
Le Bugey 3, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)

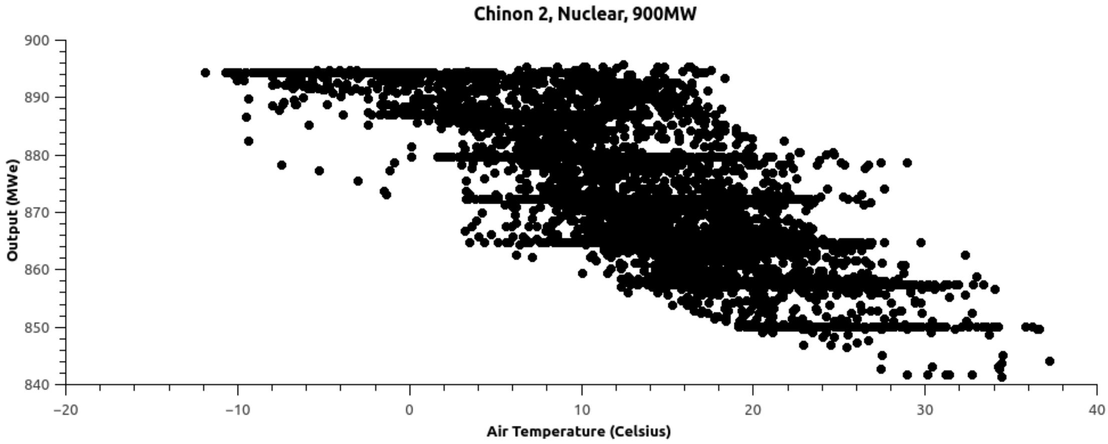


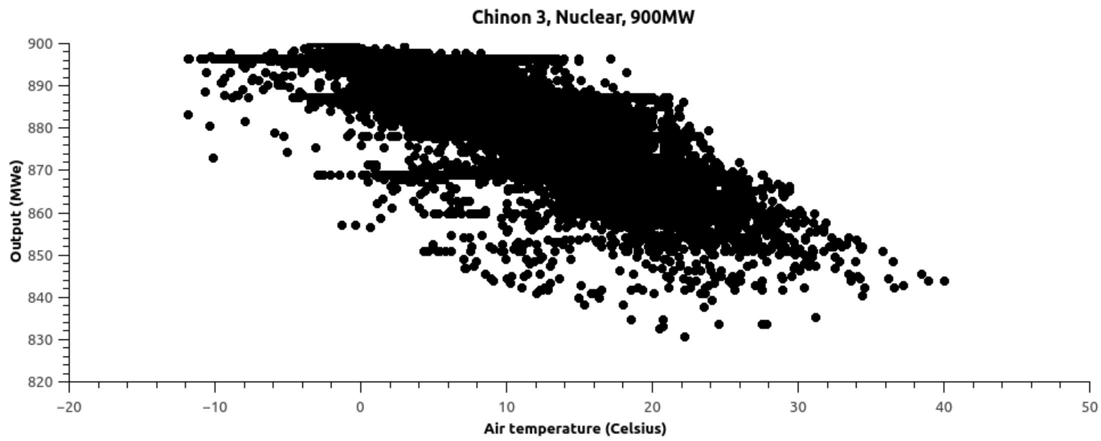
Le Bugey 4, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)

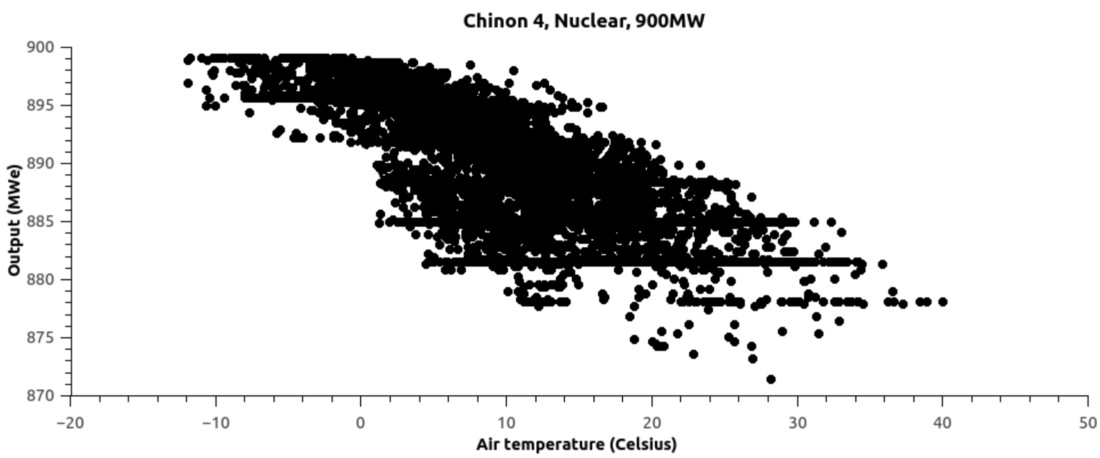


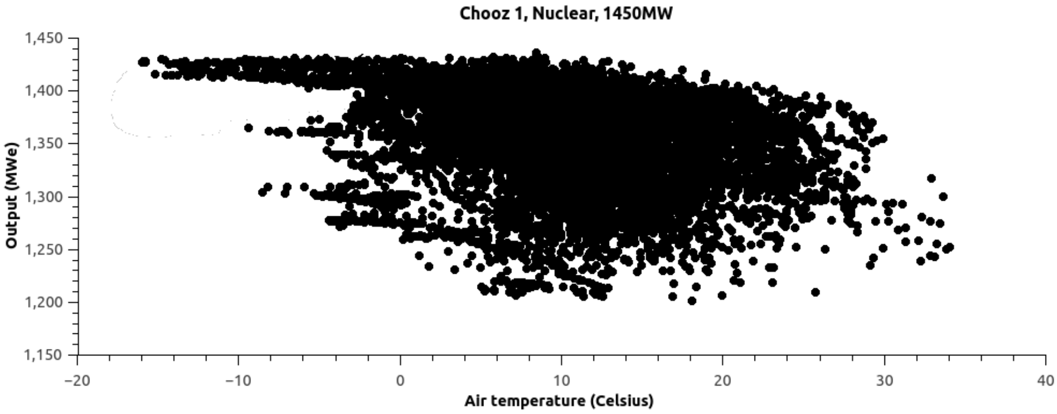
Le Bugey 5, Nuclear, 900MW
Output (MWe)
Air Temperature (Celsius)

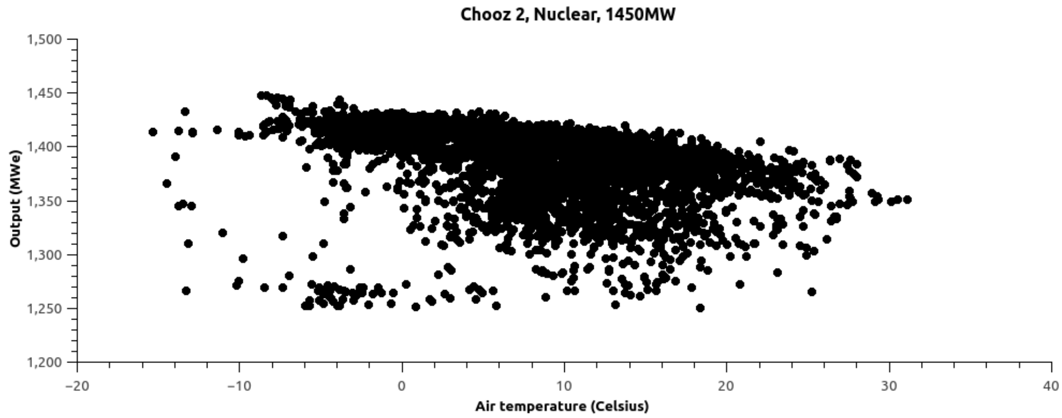

Chinon 1, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)

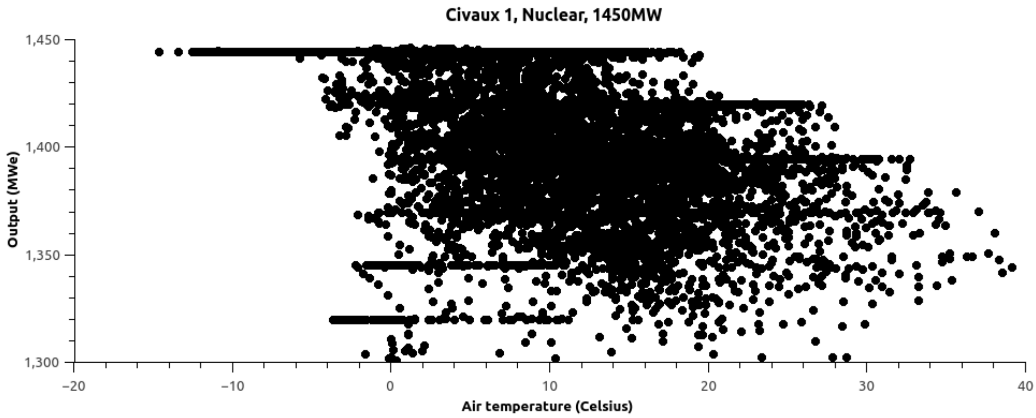

Chinon 2, Nuclear, 900MW
Output (MWe)
Air Temperature (Celsius)

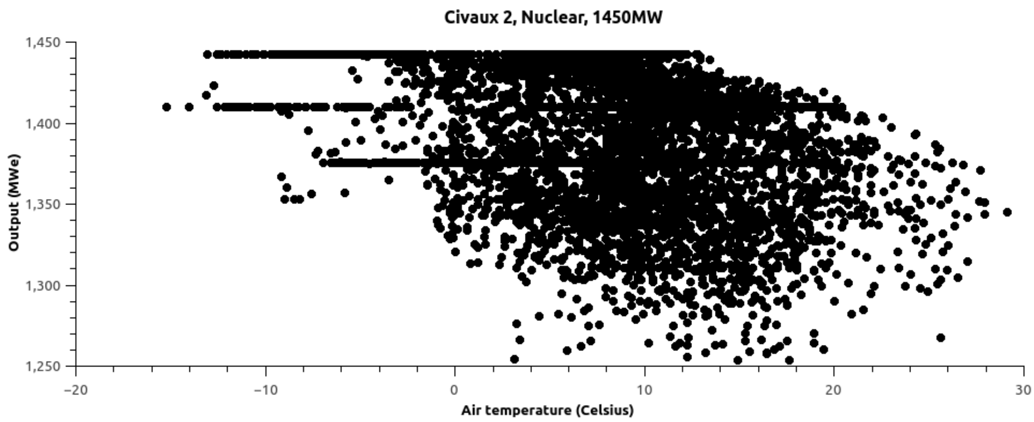

Chinon 3, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)

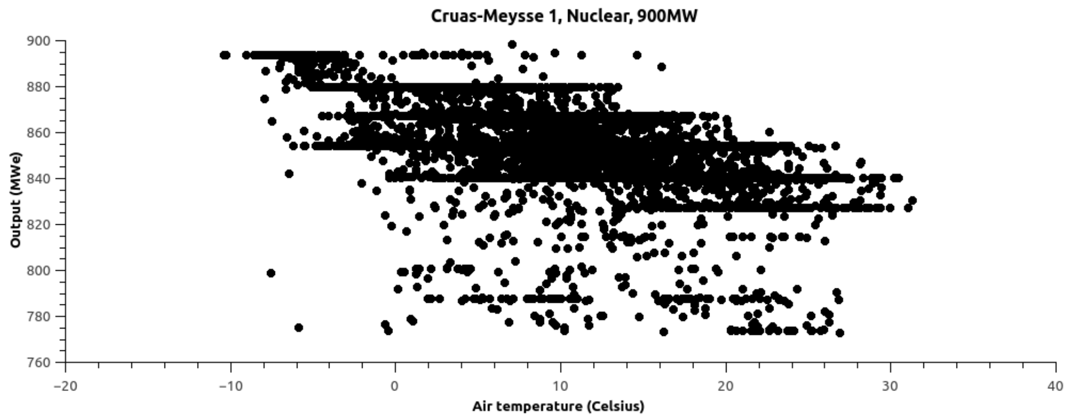

Chinon 4, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)

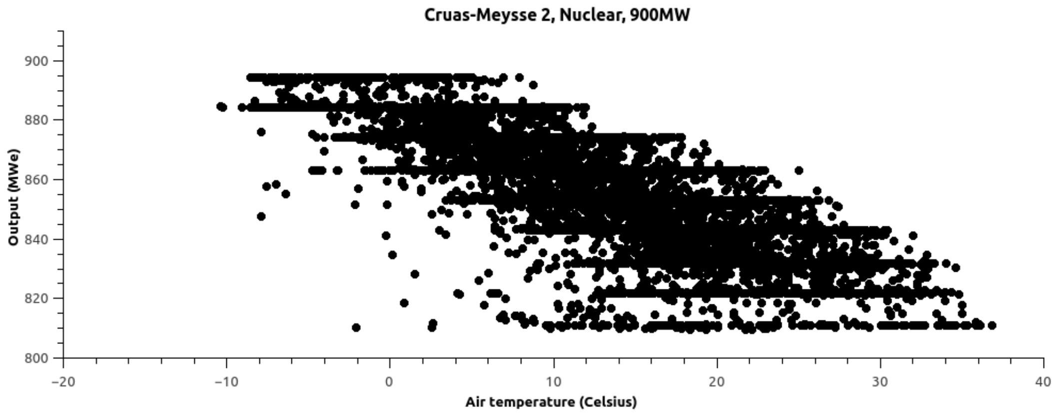

Chooz 1, Nuclear, 1450MW
Output (MWe)
1,450
1,400
1,350
1,300
1,250
1,200
1,150
−20
−10
0
10
20
30
40
Air temperature (Celsius)

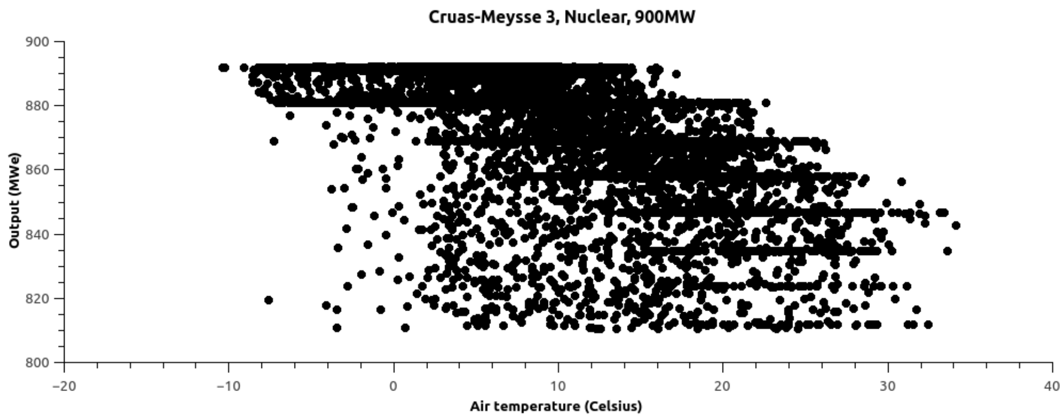

Chooz 2, Nuclear, 1450MW
Output (MWe)
1,500
1,450
1,400
1,350
1,300
1,250
1,200
−20
−10
0
10
20
30
40
Air temperature (Celsius)

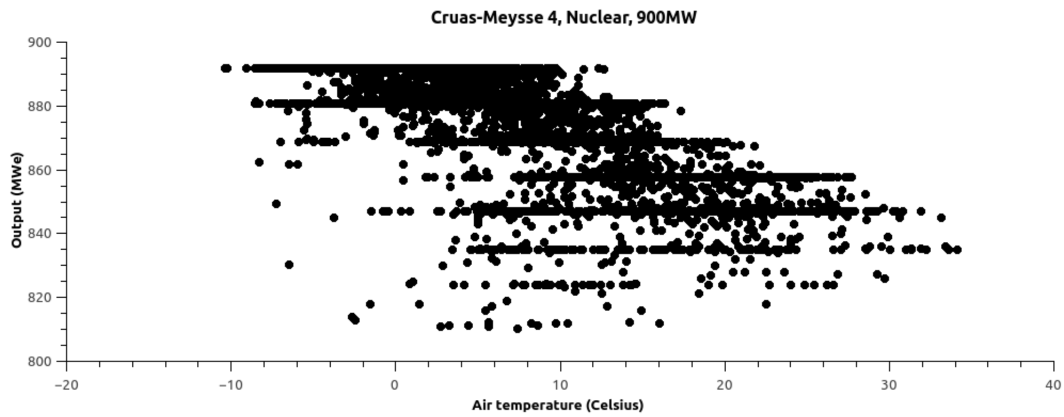

Civaux 1, Nuclear, 1450MW
Output (MWe)
1,450
1,400
1,350
1,300
−20
−10
0
10
20
30
40
Air temperature (Celsius)

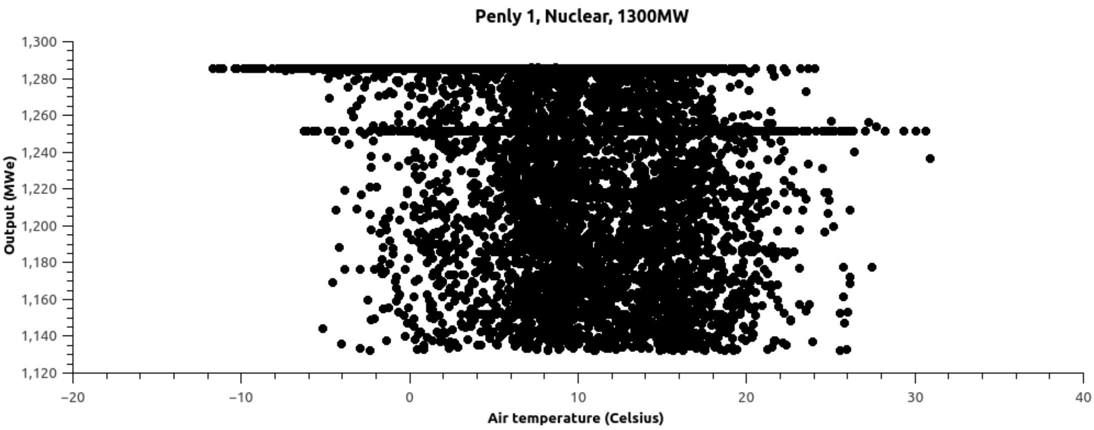

Civaux 2, Nuclear, 1450MW
Output (MWe)
1,450
1,400
1,350
1,300
1,250
−20
−10
0
10
20
30
Air temperature (Celsius)

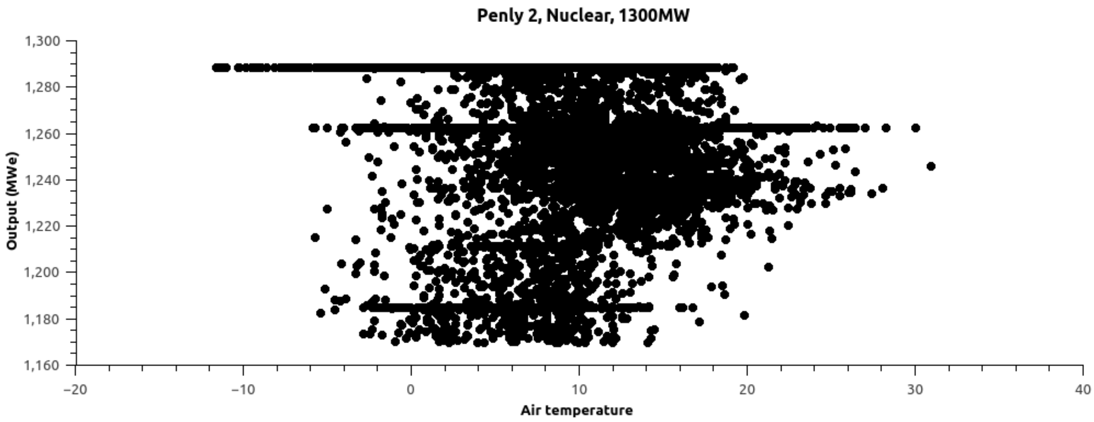

Cruas-Meysse 1, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)
760
780
800
820
840
860
880
900
−20
−10
0
10
20
30
40

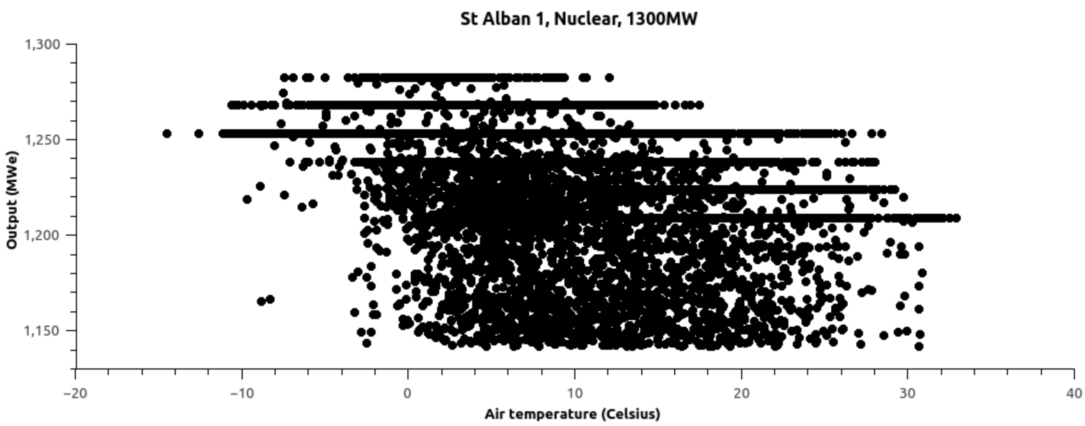

Cruas-Meysse 2, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)
800
820
840
860
880
900
−20
−10
0
10
20
30
40

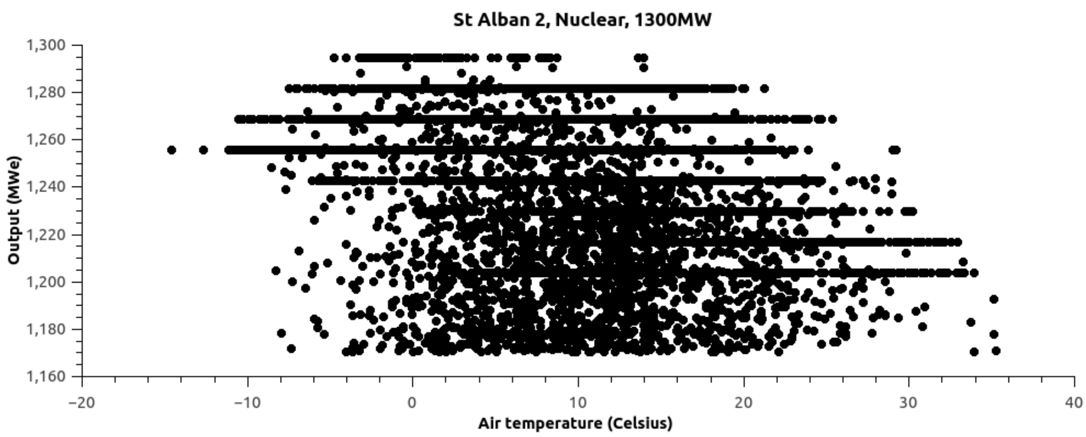

Cruas-Meysse 3, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)
800
820
840
860
880
900
−20
−10
0
10
20
30
40

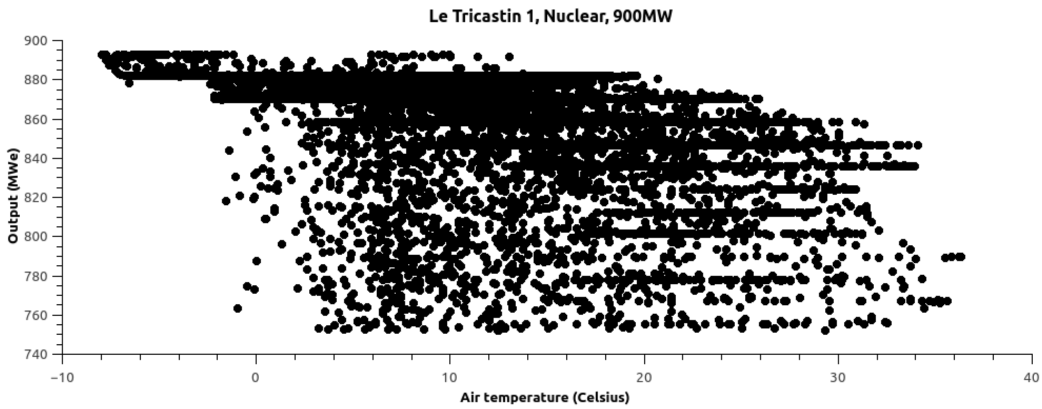

Cruas-Meysse 4, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)
800
820
840
860
880
900
−20
−10
0
10
20
30
40

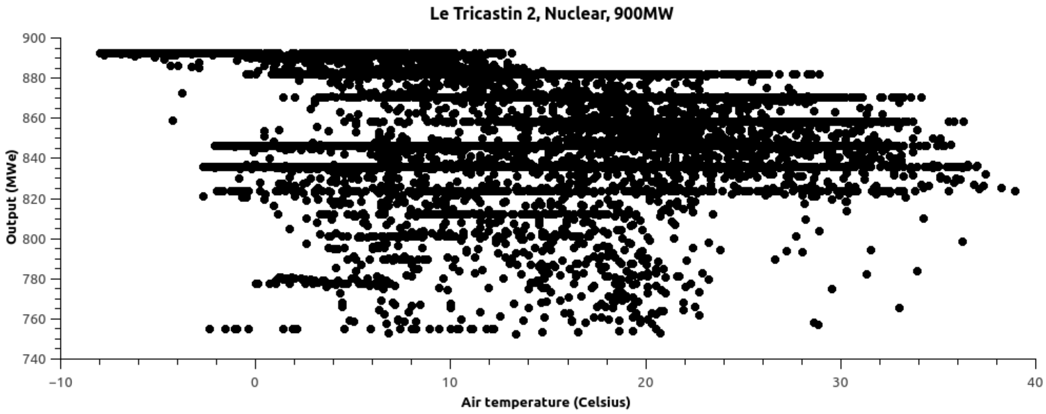

Penly 1, Nuclear, 1300MW
Output (MWe)
1,300
1,280
1,260
1,240
1,220
1,200
1,180
1,160
1,140
1,120
−20
−10
0
10
20
30
40
Air temperature (Celsius)

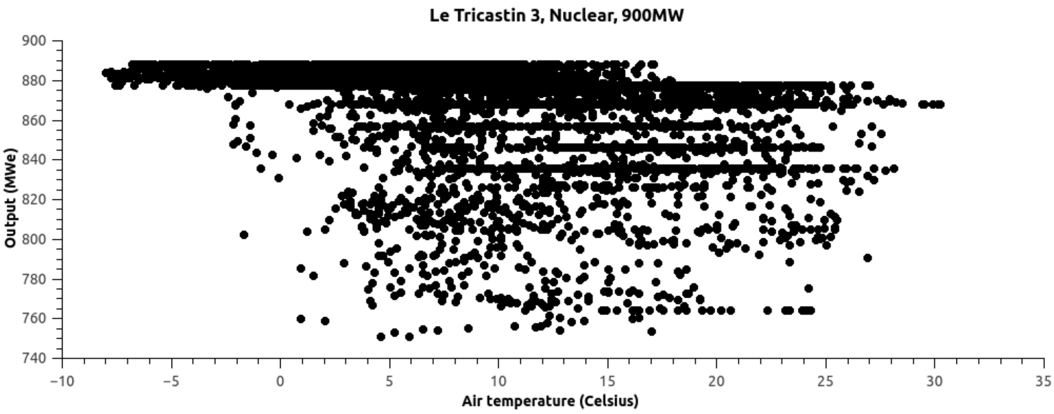

Penly 2, Nuclear, 1300MW
Output (MWe)
1,300
1,280
1,260
1,240
1,220
1,200
1,180
1,160
−20
−10
0
10
20
30
40
Air temperature

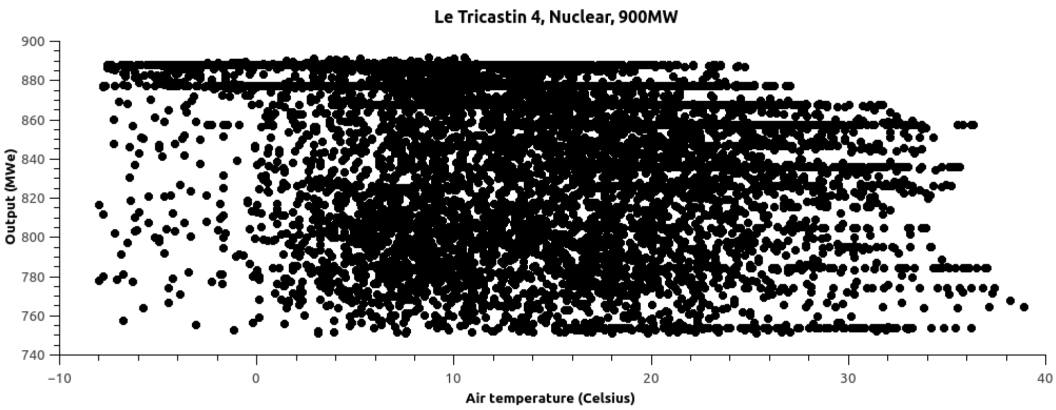

St Alban 1, Nuclear, 1300MW
Output (MWe)
1,300
1,250
1,200
1,150
−20
−10
0
10
20
30
40
Air temperature (Celsius)


St Alban 2, Nuclear, 1300MW
Output (MWe)
1,300
1,280
1,260
1,240
1,220
1,200
1,180
1,160
−20
−10
0
10
20
30
40
Air temperature (Celsius)


Le Tricastin 1, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)


Le Tricastin 2, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)


Le Tricastin 3, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)


Le Tricastin 4, Nuclear, 900MW
Output (MWe)
Air temperature (Celsius)

Appendix B

Quadratic fit and regression coefficients, electrical output loss per degree increase in air temperature.

	quadratic fit $y = P0.(\alpha_2.x^2 + \alpha_1.x + \alpha_0)$						
Power plant	r^2	α_2	Error α_2	α_1	Error α_1	Loss in electrical output per one degree increase (%)	Error
Chinon 1	5.90E-01	4.31E-06	2.94E-06	-6.98E-04	7.32E-04	-0.10	0.01
Chinon 2	5.43E-01	8.34E-06	6.19E-06	-9.81E-04	1.05E-03	-0.12	0.02
Chinon 3	5.41E-01	-3.81E-06	-5.30E-06	-5.27E-04	5.68E-04	-0.16	0.01
Chinon 4	4.41E-01	1.38E-05	1.20E-05	-9.30E-04	9.79E-04	-0.04	0.02
Bouchain	NA	NA	NA	NA	NA		
Bugey 2	3.85E-01	9.71E-06	7.16E-06	-9.01E-04	9.69E-04	-0.09	0.02
Bugey 3	2.95E-01	-1.85E-05	-2.14E-05	-1.13E-04	1.86E-04	-0.28	0.02
Bugey 4	6.45E-01	1.06E-05	8.86E-06	-9.82E-04	1.03E-03	-0.08	0.01
Bugey 5	5.72E-01	4.61E-06	2.58E-06	-8.68E-04	9.25E-04	-0.14	0.02
Chooz 1	1.52E-01	-4.65E-06	-9.87E-06	-4.71E-04	6.10E-04	-0.20	0.05
Chooz 2	1.64E-01	-2.96E-05	6.82E-006	-1.01E-03	1.38E-04	0.04	-0.19
Civaux 1	1.34E-01	-5.88E-06	-8.81E-06	-3.78E-04	4.52E-04	-0.17	0.02
Civaux 2	1.40E-01	-6.21E-05	-6.70E-05	6.01E-04	-5.12E-04	-0.66	0.04
Cordemais 4/5	NA	-8.74E-06	-1.32E-05	2.87E-04	-2.04E-04	-0.08	0.04
Cordemais 2/3	NA	-3.31E-05	-4.85E-05	9.36E-04	-6.87E-04	-0.33	0.12
Cruas 1	7.14E-01	2.10E-06	6.07E-07	-7.75E-04	8.08E-04	-0.14	0.01
Cruas 2	7.86E-01	-7.44E-06	-8.91E-06	-7.36E-04	7.71E-04	-0.25	0.01
Cruas 3	5.49E-01	-2.97E-05	-3.20E-05	-7.76E-05	1.24E-04	-0.39	0.02
Cruas 4	7.12E-01	-1.75E-05	-1.99E-05	-4.25E-04	4.65E-04	-0.31	0.02
HavrE	NA	-4.67E-05	-5.53E-05	9.23E-04	-5.92E-04	-0.46	0.08
Penly	NA	NA	NA	NA	NA		
St Alban 1	NA	-1.69E-05	-2.82E-05	-3.15E-04	6.19E-04	-0.36	0.10
St Alban 2	NA	-5.90E-05	-8.28E-05	1.20E-03	-3.77E-04	-0.69	0.22
Tricastin 1	NA	-2.90E-05	-3.08E-05	4.38E-04	-3.69E-04	-0.28	0.02
Tricastin 2	NA	-2.47E-05	-3.96E-05	1.02E-03	-4.01E-04	-0.24	0.15
Tricastin 3	NA	-2.23E-05	-3.07E-05	6.48E-04	-3.62E-04	-0.22	0.08
Tricastin 4	NA	2.69E-03	2.60E-03	1.00E-02	-1.04E-02	33.75	0.48
Martigues	NA	NA	NA	NA	NA		

Appendix C

Forecast loss of electrical output (winter daily, summer daily and yearly average) in studied reactors by the year 2050

Power plant	loss production (Mwh/year)			Summer loss production (Mwh/day)			Winter loss production (Mwh/day)		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
Cordemais 4/5	1453.04	10813.73	6133.38	11.94	39.50	25.72	7.96	39.50	23.73
Chinon 4	-2051.15	16191.40	7070.13	-16.86	59.15	21.14	-11.24	59.15	23.95
Havre	4112.58	17921.31	11016.95	33.80	65.47	49.63	22.53	65.47	44.00
Bugey 4	1676.39	25389.67	13533.03	13.78	92.75	53.26	9.19	92.75	50.97
Chinon 2	4002.60	30528.65	17265.63	32.90	111.52	72.21	21.93	111.52	66.73
Tricastin 3	5440.80	34964.99	20202.89	44.72	127.73	86.22	29.81	127.73	78.77
Cordemais 2/3	5531.16	35047.14	20289.15	45.46	128.03	86.74	30.31	128.03	79.17
Cruas 1	2162.23	39253.65	20707.94	17.77	143.39	80.58	11.85	143.39	77.62
Chinon 3	6953.28	37299.00	22126.14	57.15	136.25	96.70	38.10	136.25	87.18
Tricastin 1	10270.31	34929.56	22599.93	84.41	127.60	106.01	56.28	127.60	91.94
Tricastin 2	3657.06	46770.77	25213.91	30.06	170.85	100.46	20.04	170.85	95.45
Chinon 1	7694.09	43710.49	25702.29	63.24	159.67	111.46	42.16	159.67	100.92
Bugey 5	6467.32	48713.38	27590.35	53.16	177.95	115.55	35.44	177.95	106.69
Cruas 2	9111.65	49976.50	29544.07	74.89	182.56	128.73	49.93	182.56	116.24
Bugey 2	7425.25	52196.63	29810.94	61.03	190.67	125.85	40.69	190.67	115.68
Cruas 4	11799.41	56605.15	34202.28	96.98	206.78	151.88	64.65	206.78	135.72
Chooz 2	1742.05	70424.41	36083.23	14.32	257.26	135.79	9.55	257.26	133.40
Chooz 1	-5846.90	92993.33	43573.21	-48.06	339.70	145.82	-32.04	339.70	153.83
St Alban 1	15158.21	79024.77	47091.49	124.59	288.67	206.63	83.06	288.67	185.87
Cruas 3	17828.78	88387.50	53108.14	146.54	322.88	234.71	97.69	322.88	210.28
Bugey 3	27718.13	106705.83	67211.98	227.82	389.79	308.81	151.88	389.79	270.84
Civaux 2	11923.05	137891.17	74907.11	98.00	503.71	300.85	65.33	503.71	284.52
Civaux 1	1995.53	171293.46	86644.50	16.40	625.73	321.07	10.93	625.73	318.33
St Alban 2	26691.83	156759.86	91725.85	219.38	572.64	396.01	146.26	572.64	359.45
Total	182916.71	1483792.34	833354.52	1503.42	5420.25	3461.84	1002.28	5420.25	3211.26
Average per reactor	7621.53	61824.68	34723.11	62.64	225.84	144.24	41.76	225.84	133.80
Daily average per reactor	20.88	169.38	95.13	62.64	225.84	144.24	41.76	225.84	133.80

Appendix D

Determination of the flow of the Rhone river at the hydrological stations of Ternay and Lagnieu

The measurement of flows is not regular in the Rhone valley. For the year 2012 (year of data collected) no record of flows is available for the stations of Ternay, Lagnieu and Voulte sur Rhone (the closest hydrological stations to the power plants of St Alban, Le Bugey and Cruas respectively).
No Hydrological station altogether record the flow in the canal of Donzere-Mondragon (the canal connected to the Rhone in which the plant of Tricastin extract its cooling water).

Based on previous year, it was however possible to model the flow of the Rhone river in the stations of Ternay and Lagnieu.

The closest hydrological station upstream of Lagnieu with 2012 data is located in Surjoux. Between these 2 stations the Rhone is connected to 2 main tributaries with measured flow: the Fier (upstream) in Dingy-St-Clair and the Guiers in St-Pierre-d'Entremont/St-Christophe-sur-Guiers. Some minor tributaries (flow < 5%) were ignored.

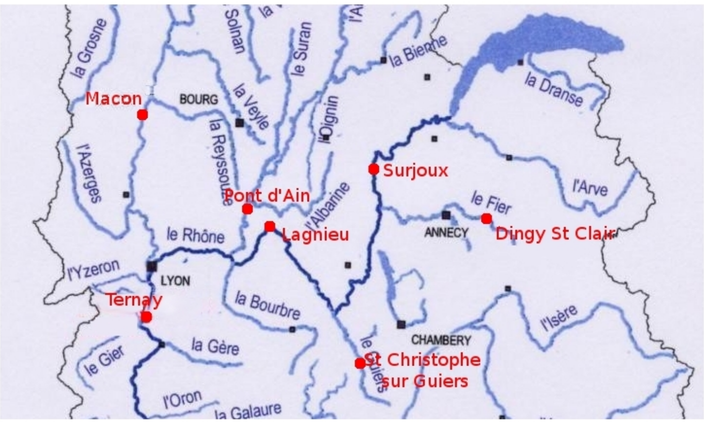


Figure D.1. The upper Rhone and its tributaries

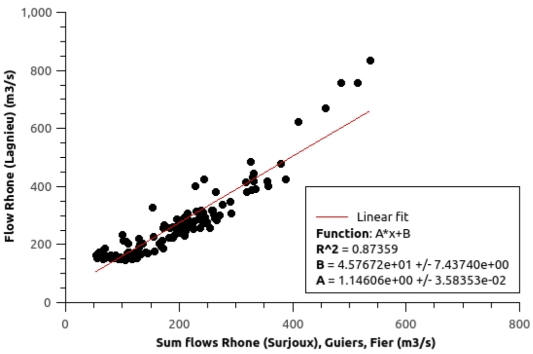


Figure D.2. The Rhone in Lagnieu, plotted against the sum of its tributaries.

The flow measured in Ternay in the first 150 days of 2011 was plotted against the sum of the flows of the Rhone in Surjoux and tributaries (figure D.2).
Both the the error and the presence of an intersect can be explained by minor tributaries not used in the calculation (due to lack of data and/or minor impact on the overall flow).
The accuracy of the fit was checked by plotting the flow modelled against the flow measured in Lagnieu for the whole year of 2011 (figure D.3).

Similar method was used to model the flow of the Rhone in Ternay, with the flow of the

Saone (Macon) and the Ain (Pont d'Ain).

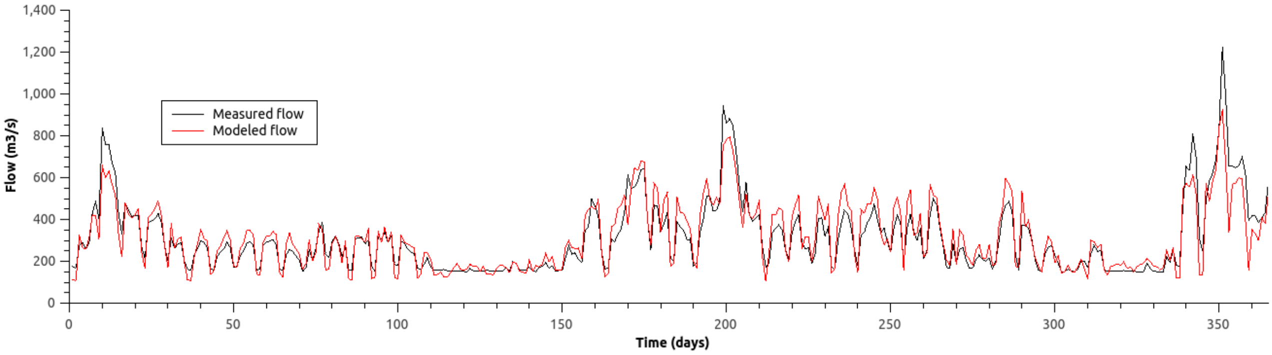


Figure D.3. Measured flow in Lagnieu (black) against modelled flow (red) for the year 2011

It was however impossible to use this method to determine the flow in Voulte sur Rhone: the sum of unknown streams flow got important enough to significantly impact the overall flow.