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Anticipation of potential trade-offs and synergies between energy and water in the context of the French ecological transition to 2050: A Nexus approach

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Anticipation of potential trade-offs and synergies between energy and water in the context of the French ecological transition to 2050: A nexus approach

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Abstract

Water and energy are closely linked: water is part of various energy production systems (power plants, hydroelectricity), and energy is necessary for cleaning, transporting and distributing water. However, in the context of climate change and energy transition, both sectors are to evolve quickly and deeply: energy needs to be increasingly decarbonized (energy transition), and climate change is altering the availability of water resources in time and space, leading to a profound transformation of our ecosystems. It is thus important to evaluate if these two transformations are compatible. France is particularly exposed as around 75% of the electricity mix relies on nuclear and hydropower, two technologies that use an important amount of water to produce energy. More specifically, two projections have not been sufficiently addressed in previous years: the impact of a potential water scarcity on electricity prices, and the impact of energy transition on water demand. This type of analysis of trade-offs and synergies is called Nexus, a concept developed – among others – by the Food and Agriculture Organization of the United Nations (FAO), meaning that water security, energy security and food security are very much linked to one another, and that the actions in any one particular area often can have effects in one or both of the other areas. In this work, a nexus between the water and energy sectors is studied.

From a bottom-up approach, this master thesis work evaluates the potential trade-offs and synergies between energy and water in France within the context of the ecological transition towards 2050. Two links are quantitatively explored in depth: the impact of the rise of water prices (obtained through literature review) on electricity costs (with the metric of the Levelized Cost of Electricity - LCOE and its sensitivity to changes of water prices, in €/MWh), and the impact of energy transition on water demand (with the metric of consumption, in million cubic meters (Mm³) per year in 2050).

The study reveals that the total LCOE of the French electrical transition towards 2050 is calculated at 71.6 €/MWh (in €₂₀₂₀). The sensitivity analysis indicates that the water price is the parameter with the least influence on this result, with an increase in LCOE to 72.1 €/MWh when the water price doubles for industrials (less than 1% of variation). On the other hand, demand scenarios indicate that water demand from the energy sector is to increase from a consumption of around 500 Mm³ in 2020 to 700 Mm³ in 2050. It represents 14% of the current French water consumption (~5 000 Mm³), compared to 10% today. Therefore, even if further work is needed to study the water demand of other sectors as well as the impact of water scarcity due to climate change, it is valid to say that the energy transition will increase water needs by 2050. This work thus demonstrates that overall, the main trade-off between water and energy is the increase in water demand for energy by 2050, with a potential impact on other water uses or the balance between ecosystems.

However, synergies may also exist between the two sectors. This work focuses on the links in governance (framework of processes, functions, structures, rules, laws and norms born out of the relationships, interactions, power dynamics and communication within an organized group of individuals) of the water and energy sectors. The thesis emphasizes the unique aspects of the water sector within decentralized governance and participatory democracy, highlighting its potential benefits for transition, particularly when compared to the energy sector.

Keywords: Water demand, energy costs, Nexus, trade-offs, synergies, energy transition, governance, France.

Sammanfattning

Vatten och energi är nära kopplade till varandra: vatten ingår i olika energiproduktionssystem (kraftverk, vattenkraft) och energi behövs för att rena, transportera och distribuera vatten. Men i samband med klimatförändringarna och energiomställningen kommer båda sektorerna att genomgå snabba och genomgripande förändringar: energin måste i allt högre grad bli koldioxidfri (energiomställning) och klimatförändringarna förändrar tillgången på vattenresurser i tid och rum, vilket leder till en genomgripande omvandling av våra ekosystem. Det är därför viktigt att utvärdera om dessa två omvandlingar är förenliga. Frankrike är särskilt utsatt eftersom cirka 75 % av elmixen är beroende av kärnkraft och vattenkraft, två tekniker som använder en betydande mängd vatten för att producera energi. Mer specifikt har två prognoser inte behandlats tillräckligt under tidigare år: effekterna av en potentiell vattenbrist på elpriserna och effekterna av energiomställningen på vattenbehovet. Denna typ av analys av avvägningar och synergier kallas Nexus, ett koncept som bland annat utvecklats av FN:s livsmedels- och jordbruksorganisation (FAO) och som innebär att vattensäkerhet, energisäkerhet och livsmedelssäkerhet är starkt kopplade till varandra och att åtgärder inom ett visst område ofta kan ha effekter på ett eller båda de andra områdena. I detta arbete studeras kopplingen mellan vatten- och energisektorerna.

Med ett bottom-up-perspektiv utvärderar denna masteruppsats de potentiella avvägningarna och synergier mellan energi och vatten i Frankrike inom ramen för den ekologiska omställningen fram till 2050. Två kopplingar undersöks kvantitativt på djupet: effekten av stigande vattenpriser (framkomna genom litteraturgenomgång) på elkostnaderna (med måttet Levelized Cost of Electricity – LCOE och dess känslighet för förändringar i vattenpriserna, i €/MWh), och effekten av energiomställningen på vattenbehovet (med måttet konsumtion, i miljoner kubikmeter (Mm³) per år 2050).

Studien visar att den totala LCOE för den franska elomställningen fram till 2050 beräknas till 71,6 €/MWh (i €2020). Känslighetsanalysen visar att vattenpriset är den parameter som har minst inflytande på detta resultat, med en ökning av LCOE till 72,1 €/MWh när vattenpriset fördubblas för industrin (mindre än 1 % variation). Å andra sidan indikerar efterfrågescenarierna att vattenbehovet från energisektorn kommer att öka från en förbrukning på cirka 500 Mm³ år 2020 till 700 Mm³ år 2050. Det motsvarar 14 % av den nuvarande franska vattenförbrukningen (~5 000 Mm³), jämfört med 10 % idag. Även om det krävs ytterligare arbete för att studera vattenbehovet i andra

sektorer samt effekterna av vattenbrist till följd av klimatförändringarna, är det därför rimligt att säga att energiomställningen kommer att öka vattenbehovet fram till 2050. Detta arbete visar således att den övergripande avvägningen mellan vatten och energi är den ökade efterfrågan på vatten för energi fram till 2050, med en potentiell inverkan på andra vattenanvändningar eller balansen mellan ekosystemen

Det kan dock också finnas synergier mellan de två sektorerna. Detta arbete fokuserar på kopplingarna i styrningen (ramverk för processer, funktioner, strukturer, regler, lagar och normer som uppstår ur relationer, interaktioner, maktförhållanden och kommunikation inom en organiserad grupp av individer) av vatten- och energisektorerna. Avhandlingen betonar de unika aspekterna av vattensektorn inom decentraliserad styrning och deltagardemokrati, och lyfter fram dess potentiella fördelar för omställningen, särskilt jämfört med energisektorn.

Nyckelord: Vattenbehov, energikostnader, Nexus, avvägningar, synergier, energiomställning, styrning, Frankrike.

List of abbreviations

LCOE: levelized cost of electricity

OPEX: operating expenditure

CAPEX: capital expenditure

GHG: greenhouse gas

SGPE: *Secrétariat general à la planification écologique*

PPE: *Programmation pluriannuelle de l'énergie*

WACC: Weighted average cost of capital

SNBC: *Stratégie nationale bas-carbone*

MWh: megawatt hour

Mm³: million cubic meters

EPR: European pressurized reactor

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1 Introduction

1.1 French environmental transition and ecological planning

Faced with the consequences of environmental degradation due to climate change, the collapse of biodiversity and the depletion of resources [1], public authorities worldwide are seeking to implement policies that limit or even reverse these trends, and to adapt human societies to this new situation [2].

To meet this ecological and societal challenge, public authorities must implement their "ecological transition", which involves a global transformation of society and the economy towards a decarbonized and biodiversity-rich state [3]. The aim is therefore to bring about a series of changes to the economic and social model to meet the demands of sustainable development and reduce society's ecological footprint. The scale of the changes required is massive. All sectors of economic activity, all regions of the world, and all lifestyles are concerned. The urgency to act is supported by scientific findings expressed and recognized on a planetary scale [1]). These findings are translated into precise and time-bound objectives, beyond which the collapse of biodiversity and the impact of climate change on ecosystems and humanity will no longer be controllable. Almost all nations have enshrined these objectives in international standards (Paris Climate Agreement, Kunming-Montreal Global Biodiversity Framework Agreement). At the regional level of the European Union, this corresponds to the Green Deal, which gives the objectives a normative character [2]. The ambition of achieving carbon neutrality by 2050 requires European countries to implement an ecological transition with intermediate milestones, notably 2030 (-55% greenhouse gas emissions compared with 1990 [2]).

In response to this challenge, France opted for "ecological planning". Historically, ecological planning is a planning process defined as "the use of scientific and technical information to provide alternatives for making decisions" [3], which underlines the importance of input data based on biophysical parameters and their interactions. Besides data, methodology is also a specific aspect. Literature identifies the following steps as the core of the ecological planning process [3]: 1) goal setting, 2) inventory and analysis of data, 3) suitability analysis, 4) developing alternatives, 5) implementation, 6) administration, and 7) evaluation.

By opting for "ecological planning", France is keeping with the tradition of planning by the public authorities that prevailed in France from the end of the Second World War until the neo-liberal era. In 1946, the *General Planning Commissioner* ("Commissariat Général au Plan") was created, with the aim of defining long-term State intervention to organize the economy in the face of market failures and improve its resilience to crises [4]. The rest of the twentieth century was then characterized by the integration of European and world markets, economic liberalization and a State that

was not a "strategist" but a "companion" [4]. Planning was thus multiplied into a number of objects such as "strategies" or "plans", multi-year and often sector-based but not binding.

In 2022, a specific body, the *General Secretariat for Ecological Planning* (SGPE for "Secrétariat Général à la Planification Ecologique"), was created to coordinate these various plans and lead a global strategy for the transition of all sectors of the French economy [5]. To reinforce its role as coordinator, the SGPE was placed directly under the authority of the Prime Minister, to help draw up the "collective, concrete and credible plan that should result in a comprehensive, coherent and effective strategy". The decree establishing the SGPE specifies its two priority missions [5]:

- Drawing up national strategies for climate, energy, biodiversity and the circular economy, ensuring compliance with France's European and international commitments.
- Monitoring of the implementation of these strategies by all the ministries concerned, and their translation into action plans. A *posteriori*, evaluation of the success and coherence of these action plans.

Since September 2023, France has had a transition plan [6]. Once this first step has been taken, the challenge is to ensure that the necessary resources and actions are in place to meet the trajectory. This can be achieved through regulatory and legislative means (e.g., a decree concerning passive heating systems), or through financial means (10 billion euros have been earmarked for ecological planning in 2024).

The plan is based on six sectors (Figure 1) [6, 7], each of which is divided into several sub-sectors with their own levers for ecological transformation. The six sectors are transportation, housing, production, consumption, food, and ecosystems. For each one of them, the plan aims for a fair reduction in greenhouse gases; an estimate of the resources and funding needed to achieve this objective; the actors to be mobilised to this end, at the national, regional and local levels [6, 7].



Figure 1 French ecological planning along six axis – transportation (“se déplacer”), housing (“se loger”), production (“produire”), consumption (“consommer”), food (“se nourrir”), ecosystems (“préserver”) [6]

1.2 Purpose and scope of thesis

As described in Section 1.1, the main purpose of this master thesis is to foster the French ecological planning strategy by focusing on the links between energy and water sectors.

Water and energy are closely linked: water is part of various energy production systems (power plants, hydroelectricity), and energy is necessary for cleaning, transporting and distributing water [8]. However, in the context of climate change and energy transition, both sectors are to evolve quickly and deeply: energy needs to become increasingly decarbonized (energy transition) [6], and climate change is altering the availability of water resources in time and space, leading to a profound transformation of our ecosystems [6] (refer to section 3. Literature review). It is thus important to evaluate if these two transformations are compatible. France is particularly exposed as around 75% of the electricity mix relies on nuclear and hydropower [9], two technologies that use an important amount of water to produce energy. More specifically, two projections have not been sufficiently addressed in previous years [10, 11]: the impact of a potential water scarcity on electricity prices, and the impact of energy transition on water demand. This type of analysis of trade-offs and synergies is called Nexus, a concept developed – among others – by the Food and Agriculture Organization of the United Nations (FAO) [8], meaning that water security, energy security and food security are very much linked to one another, and that the actions in

any one particular area often can have effects in one or both of the other areas. In this work, only water and energy sectors are studied.

In summary, this thesis explores three areas of research to improve the current understanding and knowledge of the water-energy nexus, with a case study in France:

- Does the current low impact of water prices on energy costs remain true in the context of climate change and the expected rise in water prices in certain regions?
- Does the current low impact of the price of water on the cost of energy remain true in an electricity system that has done its ecological transition towards low-carbon energies?
- What are the differences of governance between energy and water? How could energy sector could be inspired by water governance to reinforce its transition plan in the coming years?

This master thesis begins by recalling objectives and research questions in Section 2, explaining research gaps, scope of the study and limitations. Then Section 3 draws a literature review, delving into key studies and similar evaluation of sensitivity of energy costs. Section 4 outlines the methods and materials essential to the study, especially the models used for quantitative analysis and data sources, including expert interviews. Finally, results about the three research questions are presented in Section 5 before the study concludes in Section 6, drawing consequences for French ecological planning and further possible work.

2 Objectives and research questions

2.1 Research gaps and research questions

Today, the links between water and energy in France are increasingly documented [9, 10, 12]. With a few exceptions, the proportion of water withdrawn and consumed by the energy sector does not call into question the availability of water resources, and conversely, the price of water is low enough not to constrain energy production choices [10, 12] (also, see *Section 3*, Literature review).

However, the ecological transition will lead to a profound change in this observation: for energy, the increase in decarbonized electricity production will lead to increased water consumption, and therefore potential stress on the resource (see Section 3.1, ***Error! Reference source not found.***) [8]. For water, the investments necessary for the transition of the sector, as well as the reduction of available water resources, will automatically lead to an increase in the price of water, which could call into question current energy cost estimates (see Section 3.1, General literature review of the French ecological transition) [13]

Therefore, this thesis aims to analyze the interactions (or nexus) between the water and energy sector. From the current estimations of rises in water consumption by the energy sector in 2050 for each region, higher water prices can be anticipated in these regions and need comparisons with current water prices. Then, higher water prices may lead to higher electricity generation costs. Therefore, it justifies the need for an analysis to evaluate the impact of water prices on electricity generation costs.

There is a need for this prospective work for planning integrated sectoral plans. This study is thus dedicated to addressing the imperative of anticipating the potential trade-offs between the two sectors to eventually match the SGPE objectives for French ecological transition.

To achieve this objective, both quantitative and qualitative analysis will be developed. Indeed, quantitative metrics are required to account for the mutual impacts on water and energy driven by the ecological transition (e.g. surge in water prices for energy producers or development of renewable energies intensive in water use), especially on territorialized and seasonal levels. In this study, levelized cost of electricity (LCOE) and sensitivity analysis will be conducted to support quantitative statements. Qualitative relations are also of interest. Water and energy are two public goods, the organization of which (price, sharing of the resource, accessibility) is a societal choice. The identification of trade-offs must therefore be followed by an examination of the qualitative relationship to be favored to deal with these constraints. In particular, the modes of governance, consultation and decision-making are an essential aspect of the energy-water link, and the potentiality of trade-offs solving. In this study, interviews with experts and analysis of a case in point (French political instability in 2024-2025) will be performed to support qualitative statements.

In conclusion, in France, there is a lack of evaluation for the future interactions between energy and water in the context of ecological transition. On the one hand, two potential trade-offs need to be assessed with quantitative methods when aiming for 2050 environmental objectives:

- What will be the impact of an expected increase in the price of water on energy transition? In other words, is water an important cost parameter in France transition towards electrification? For this question, a LCOE analysis and sensitivity analysis (to evaluate the impact of a change in water prices) will be performed.
- Conversely, what will be the impact of an expected increase in decarbonized electricity generation on the availability of water? In other words, does energy transition add a stress on water resources? As explained in *1.2 Energy sector in the French ecological transition*, only electrification is considered in this Master Thesis work (see *2.3 Limitations*). Therefore, biofuels are not taken into account, but it implies that the stress

on the water resources may be even stronger than the one calculated here. Focusing on the water demand is one part of the methodology to assess water footprint and water scarcity in a changing world [14]. For this question, a projection of the water demand in 2050 is used.

On the other hand, synergies may also exist between the two sectors, or even be strengthened. In particular, the question of the adequacy of energy and water governance methods arises. In a context of ecological transition, which governance method should be favored in order to resolve these potential trade-offs, among other things? This governance question will be studied with a qualitative analysis relying on interviews with experts from both sectors.

Therefore, this study seeks to clarify the following issue: “A Nexus approach: anticipation of potential trade-offs between energy and water in the context of the French ecological transition to 2050.”

2.2 Description of the study focus area

This work is conducted with the *General Secretariat for Ecological Planning* (SGPE for “Secrétariat général à la planification écologique”), placed under the authority of the French Prime Minister [5]. After elaborating the French overall transition plan between 2022 and 2023, it now coordinates interministerial work to align decisions with the trajectories of the plan. This study therefore focuses on the effects of the ecological transition and its potential trade-offs, particularly in the eventuality of success of this French transition [6, 7].

These environmental objectives (for example, how are new electricity generation units obtained) are therefore not re-examined in the model and are considered as an external factor for this study: this work is conducted within the scope of the achievement of French environmental objectives in 2030 and 2050. This method is part of the methods used by the French administrative ecosystem for enhancing ecological planning. It consists of assuming the success of the predefined objectives and identifying the resulting contradictions. For example, in this case, the quantity of water consumed may conflict with the increase in decarbonized energy production.

The quantitative analysis (LCOE calculation, sensitivity analysis and water demand projection) will focus on two metrics to assess the potential trade-offs. On the one hand, the cost of energy production towards 2050 via the levelized cost of electricity (LCOE, in €/MWh), to isolate the part relating to water. On the other hand, water consumption (in cubic meters per year in 2050), to isolate the part relating to energy production.

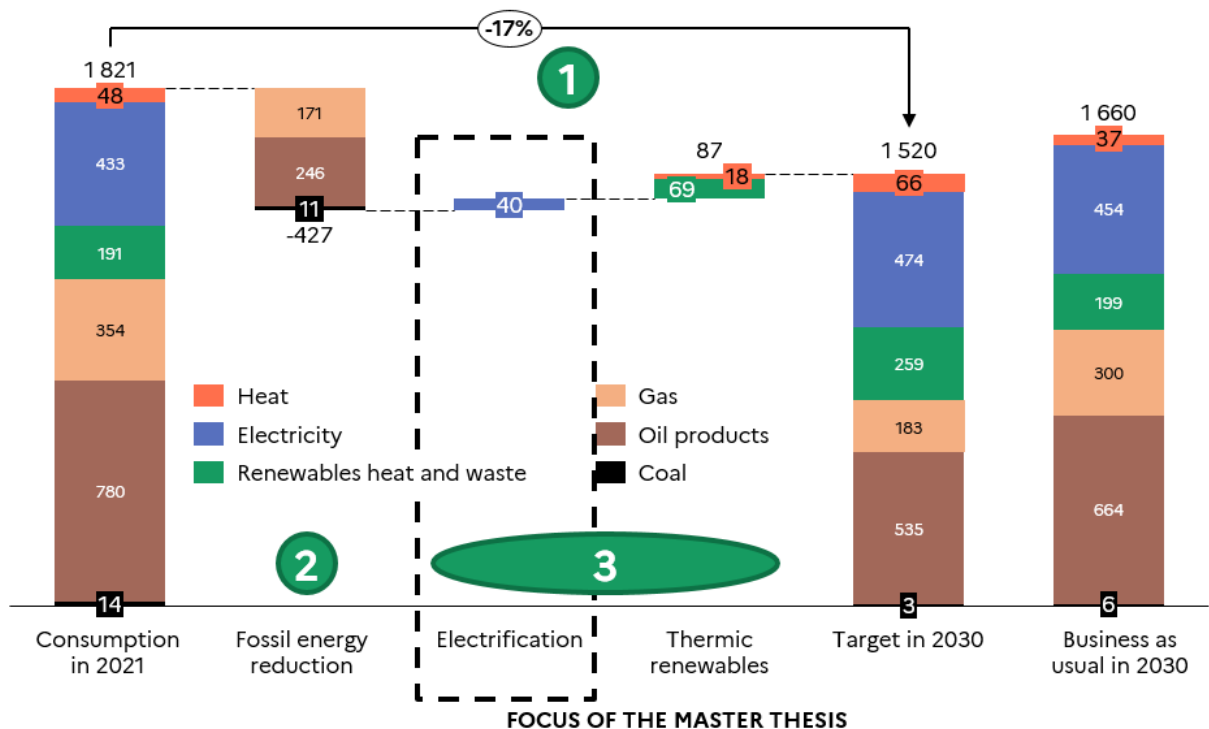


Figure 2 Focus of this Master Thesis in terms of final energy consumption (TWh) [15]

As explained in Figure 2, this study will focus on the electrification part of the energy transition (the need to develop new decarbonized energies in order to reduce the carbon intensity of the sector) [15]

The qualitative analysis (non-based on numerous metrics) will combine two approaches (section 4. Methods). The first is that of the case study: the instability of the current French political situation makes it possible to compare the respective resilience of water and energy governance. The second is that of interviews with key players in the two sectors, to identify the synergies that may also emerge and the possible adaptations.

2.3 Limitations

Despite the ambition to anticipate potential trade-offs between the water and energy sectors in the coming years in case of ecological transition, this study still suffers from four major limitations and needs to be completed with further work in the future.

The first is the fragility of the assumptions on which the trajectories of the energy and water sectors are based. Indeed, 2030 is close enough to have a good estimate of water and energy consumption at that time. On the other hand, the trajectories for 2050 are currently based on extrapolation, and several sectors such as nuclear power are still dependent on major decisions to come. For example, fourteen

nuclear power reactors are to be constructed in the coming years, but the launching phase has not started yet, and a change in the political agenda could eventually endanger this roadmap. Thus, the calculations and the resulting comparisons should be used as an aid to public policy decision-making to evaluate these hypotheses, and not as a guaranteed prediction of the French trajectory in the coming years.

The second concerns the energy sector. This study focuses solely on the evolution of decarbonized electricity production (nuclear and renewable energies). However, the evolution of the energy mix will also depend on fossil fuel consumption, for example, a use that can involve significant water consumption during production. However, this source is largely imported into France [9], and therefore represents a minor water consumption on a national scale. Restricting ourselves to a 'bouclage' on French territory therefore allows us to overcome this limitation. Moreover, French fossil fuel consumption should gradually decrease until 2050 to reach net-zero emissions, thus contributing in an increasingly weak manner. Besides, some costs linked to electrification are not taken into account in this work's evaluation. In particular, for the sake of simplicity, the cost of the networks is not addressed, although the development of renewable energies must be accompanied by the adaptation and development of the French electricity transmission networks. This can represent a significant cost (up to a third of the necessary investments in the energy sector [16]). Here again, the water consumption associated with this adaptation is marginal. If the results confirm that water represents a low cost of the French transition, this becomes even more true once the network costs are considered. This limit must therefore be reassessed once the LCOE results are in.

The third concerns the water sector. This study analyses the changes in demand for the resource up to 2050. However, this work does not consider the supply question of water, and particularly its forecasted scarcity in the context of climate change [13]. Therefore, to get a complete picture of the tensions of water stress that may result, it would also be necessary to anticipate and map the changes of local water scarcity. The amount of water available per territory and per region will not be the same in 2050 as it is today.

The last concerns qualitative analysis. Energy and water strategies will be subject to public consultation in 2025 [17]. The results of these two processes will not be known until the end of the year. It would have been interesting to compare the conclusions of these consultations with those of this master's thesis.

Further work (See Section 6.2, Future work) could address these limitations in order to make the conclusions of the master thesis more relevant.

3 Literature review

Firstly, this work is a Nexus approach. Many works have studied the interactions between energy and water in the world [8,10, 11, 12, 14], and some of them have specifically focus on the French situation [4]. These studies provide the following useful findings. Firstly, energy costs evolution is a major metric to evaluate when studying the impact of the water sector on energy [12]: “A more water-constrained future, as population and the global economy grow and climate change looms, will impact energy sector reliability and costs” [12]. Secondly, these works give insights on the general conduction of a Nexus work: objectives, data collection, methodology, scenario development [10, 11]. Thirdly, the energy sector will generally lead to high water demand [14], mainly because of energy plant cooling (nuclear energy for France) [15]. Therefore, evaluating the water demand from the energy sector is completely in the scope of a Nexus work, as it is generally studied as a major parameter of the water equilibrium in 2050.

3.1 General literature review of the French ecological transition

In Figure 1, energy is one of the sub-sectors linked to "production". Beyond its potential to reduce GHG emissions, energy is a social issue (industrial jobs, affordability), an environmental issue (resource use), and an economic issue (leading role in reindustrialization). As part of ecological planning, energy therefore has its own plan (within the Climate Plan, relating to emissions), coordinated by the SGPE and the Ministry of Ecological Transition, and updated regularly.

Published in November 2024, the third French *National Low Carbon Strategy* (SNBC for “Stratégie Nationale Bas-Carbone”) [17] describes the roadmap for France on how to steer its climate change mitigation policy. It provides guidelines to enable the transition to a low carbon economy in all sectors of activity. The overarching goal is to achieve carbon neutrality by 2050. It also sets an intermediary greenhouse gas emissions reduction target of -50% in 2030 in comparison with 1990 [17]. As shown in Figure 3, fulfilling this objective for 2030 requires reducing emissions of about 126 Mt CO₂ eq between 2022 and 2030, which is considerable, as emissions have been reduced of 144 Mt between 1990 and 2022 [15].

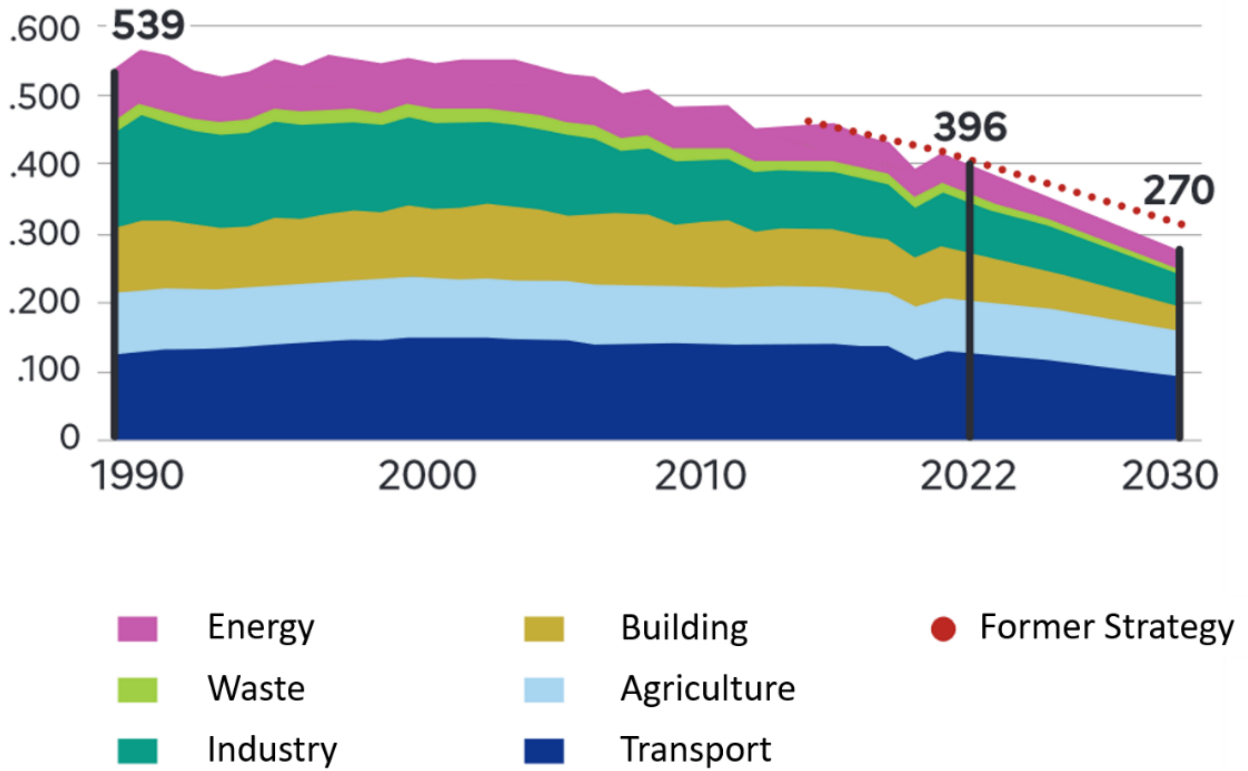


Figure 3 French greenhouse gas emissions between 1990 and 2022 (in Mt CO₂ eq for different years)

The energy sector will play an important role in achieving these objectives. It currently accounts for 11% of national GHG (43 Mt in 2022, compared to 396 Mt on national level) [6, 7]. Indeed, almost 60% of the French energy mix is still fossil based, as shown in Figure 4 [6].

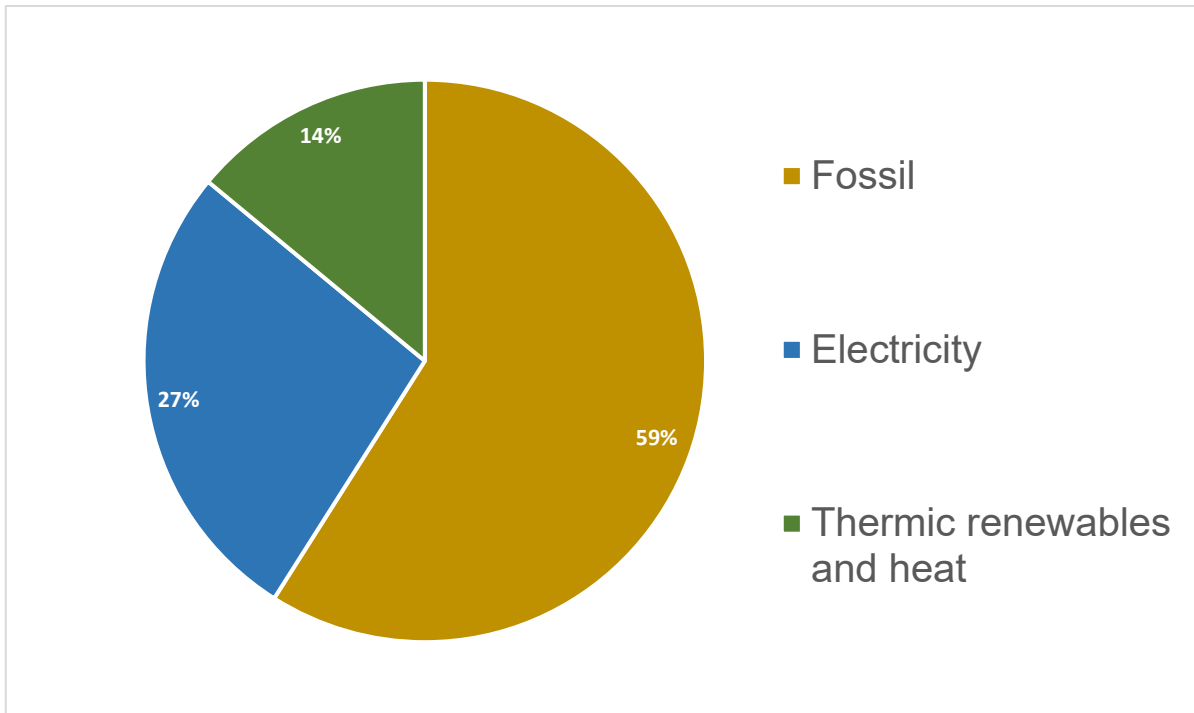


Figure 4 French final energy consumption mix in 2022 [in %] [6]

In 2030, GHG emissions for the French energy sector should reach 27 Mt, which represents a drop of emissions of almost 40% (compared to 2022) [6]. Therefore, energy benefits from its own national plan inside the National Low-Carbon Strategy, the *Multi-year Energy Plan* (PPE for “Programmation pluriannuelle de l’énergie”) [17], which lasts from 2025 to 2035 with a revision in 2030. Its main goal is to transition from a 60% fossil-based energy to a 60% non-fossil-based in 2030 [17]. This will rely on three main directions, also explained in Figure 5 [15]:

1. Reducing final energy consumption, both with energy efficiency and sobriety. The goal is to obtain a reduction of 30% between 2012 and 2030 (and 17% between 2021 and 2030).
2. Phasing out of progressively of fossil energy.
3. Developing electrification and renewables production. Considering only electrification, the additional amount of energy needed is +40 TWh in 2030 by comparison with 2021. To achieve this progress, solar photovoltaics installed capacity should for example increase from 16 GW in 2022 to 60 GW in 2030 in France.

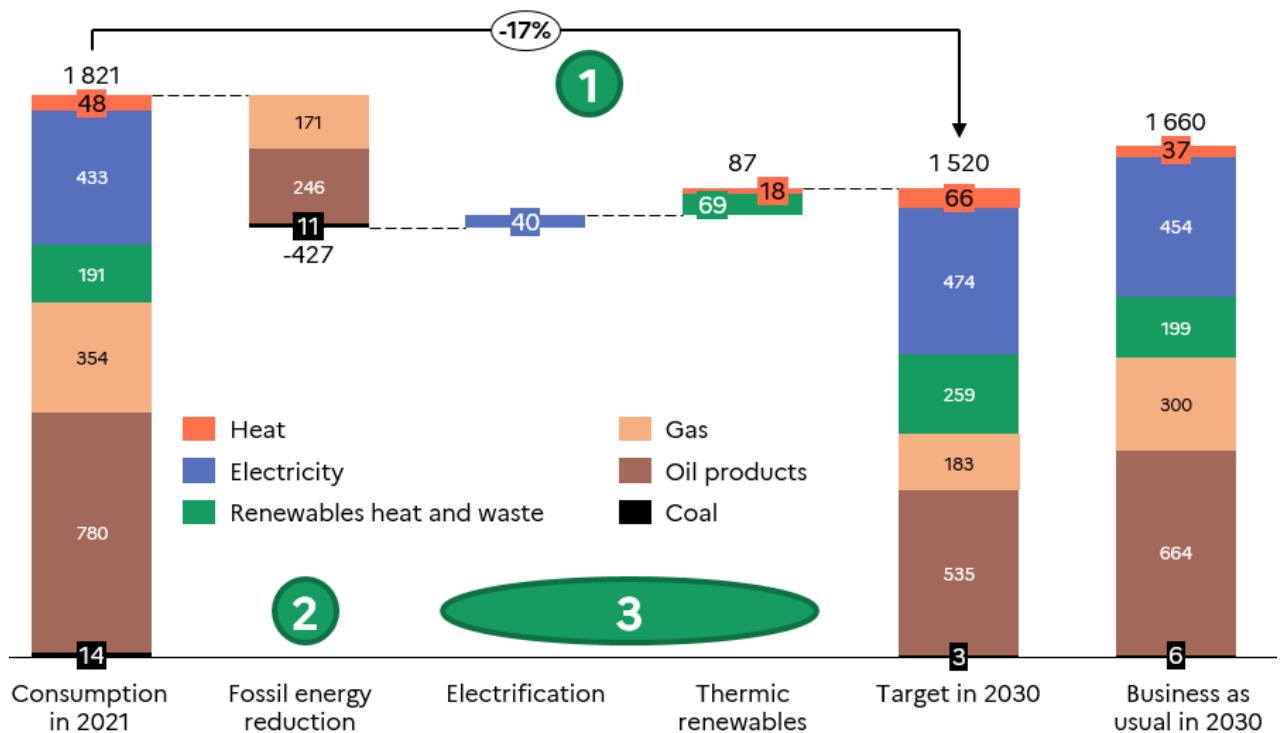


Figure 5 Summary of the three directions in terms of final energy consumption (TWh) [15]

Among these three directions of the PPE (*Programmation pluriannuelle de l'énergie*), this master thesis focuses on “electrification” (part of “developing electrification and renewables production”), which represents an increase of 40 TWh of final energy consumption in 2030 by comparison with 2021 (Figure 5) [15], by developing electrification and renewables production. Considering only electrification, the additional amount of energy needed is +40 TWh in 2030 by comparison with 2021. To achieve this progress, solar photovoltaics installed capacity should for example increase from 16 GW in 2022 to 60 GW in 2030 in France [15].

This part of energy transition is particularly important, as currently the French electricity mix is quite decarbonized (Figure 6), with only 11% relying on fossil fuels. This is mainly because of the importance of nuclear production in France, which represents more than 60% of the French electricity mix [6].

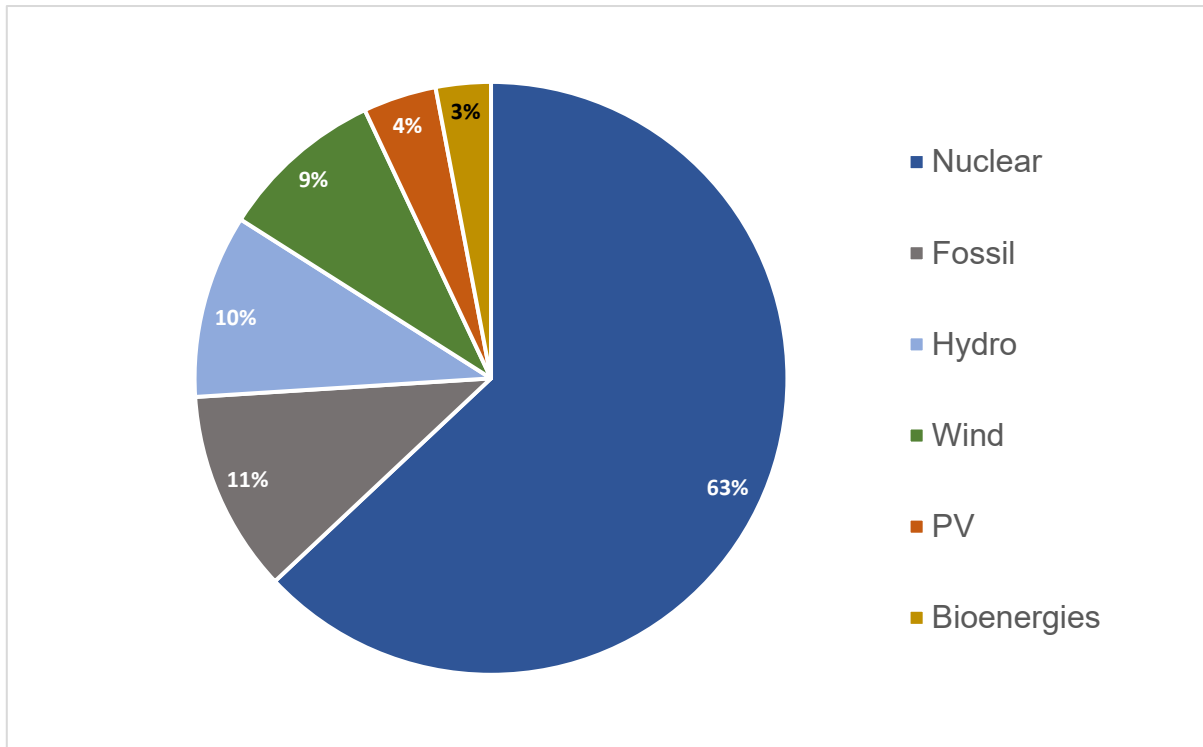


Figure 6 French electricity mix in 2022 [6]

In order to still improve this electricity mix in the context of the ecological transition, the anticipated increase of 40 TWh in consumption needs to be backed by a substantial development of low-carbon energy production (nuclear energy and renewables), to improve this electricity mix and decrease the share of fossil fuels. This will rely on the development of solar PV, wind energy (both onshore and offshore), hydropower and nuclear energy [7].

However, achieving global ecological transition requires integrating the subject of mitigation in the global framework of adaptation, resources and biodiversity [6, 18]. Water is one of the core challenges of this transition, and the link between energy and water thus deserves close interest from public decision-makers.

In Figure 1 of the French transition plan from Général Secrétariat for Ecological Planning (SGPE), water is one of the sub-sectors linked to "ecosystems" [6]. Indeed, climate change is altering the availability of water resources in time and space, leading to a profound transformation of our ecosystems [18]. For example, available water resources are set to decline by 25 to 50 billion cubic meters (i.e. 12 to 25% of annual availability), which is more than the total amount of water withdrawn in a year [18]. Added to this are water quality issues, with the chemical and ecological status of water bodies deteriorating as a result of diffuse pollution (pesticides, nitrates, PFAS, etc.), a situation that will become more problematic as water availability declines [18].

For the energy sector, water is mainly used from the river water [18], but other sectors use the same amount of both ground and river water (agriculture) and the housing sector uses more ground water than river water [18].

Similarly to the energy sector, water benefits from its own plan [18]. Announced in March 2023, the *Water Plan* has three main objectives:

- To reduce water withdrawal (not to be confused with consumption) by 10% by 2030. For example, the 55 industrial companies responsible for 25% of industrial water withdrawals are mobilized [19], and reutilization projects are highly encouraged.
- To optimize water resources and their use, and to develop alternative resources as part of a circular water economy. Agriculture is for example of major interest for this point.
- To preserve water quality.

This transition plan requires to rethink the water funding model [20]. Indeed, this model obeys to two principles [20]:

- 'Water pays for water': the costs generated to distribute drinking water and treat wastewater must be supported by the users of these public services. The money collected is thus used to finance the service.
- 'Polluter pays': the costs of pollution prevention, reduction and control should be supported by the polluter. This principle is implemented through taxes and fees on activities and uses that may generate pollution of aquatic environments, eventually redistributed to pollution reduction actions.

Therefore, the price of water is to increase in the coming years. Current estimations for necessary future investments range around 6 billion euros/year (which represents twice the current level) [21]. This amount will finance pipes replacement, stricter regulations (e.g. treatment of new pollutants) and adaptation to climate change. Major questions thus raise about the fair repartition of this financial burden, especially between different categories of users (individual, energy sector, agriculture, etc.).

Energy and water are thus two major axis of the French ecological transition plan [6]. Even if they have their own separated plan, their interactions need to be studied carefully in order to ensure that the energy trajectory is consistent with the water one. This refers to the Nexus approach, which was essentially popularized by the Stockholm Environment Institute (SEI) in an attempt to build an integrated model to address the challenges of transition towards sustainability [8].

Acknowledging that this process will put a combined pressure on resources, the Nexus aims for better understanding of the interdependence between water, land, energy, and food [8]. This approach should help governance to account for potential externalities in their models, provide a sustainable framework and ultimately harness synergies and avoid trade-offs. As explained in Figure 7, the global interactions between the two sectors are for example:

- Water for energy: Energy currently amounts to about 8% of world water withdrawals [11]. Indeed, water is required for the extraction, mining, processing, refining, and residue disposal of fossil fuels, as well as for growing biofuels and for generating electricity. Oil and gas production require about 1–10 liters of water per GJ of energy [11].
- Energy for water: energy is required to treat, distribute and clean water for end-users [11]

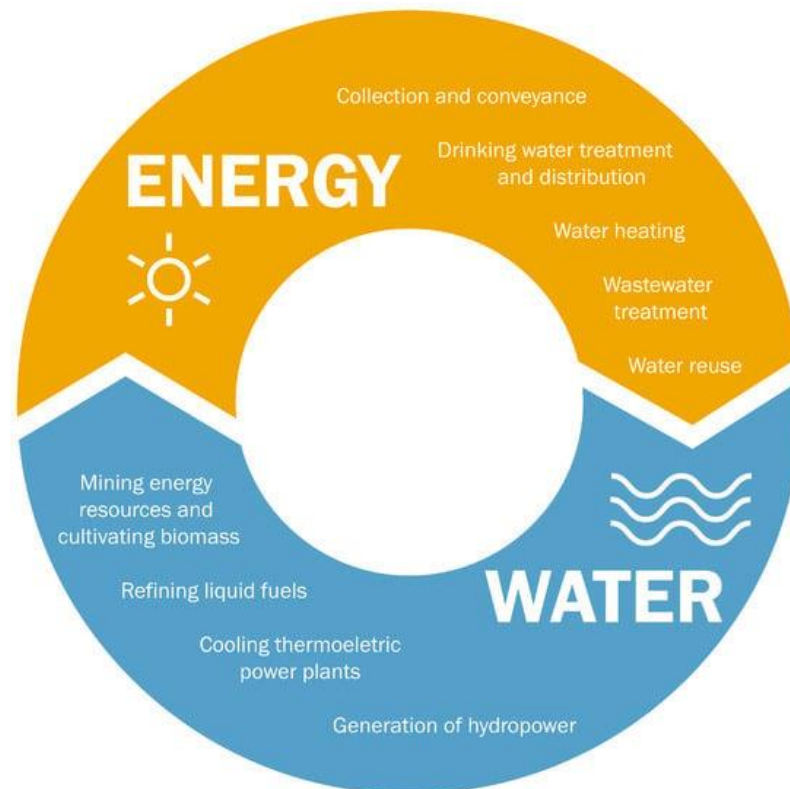


Figure 7 Key examples of interactions between water and energy systems. [11]

In France, this interaction is of particular interest. As shown in Figure 6, around 75% of the electricity mix relies on nuclear and hydropower [6], two technologies that use an important amount of water in order to produce energy. This will become even truer with the planned development of new nuclear: 14 new reactors are to be built in the country before 2050 (and four of them on river side) [15].

3.2 Impact of higher water prices on electricity generation costs

The cost of the French energy transition has been studied by several academic works since the 2015 Paris Agreement. In particular, one report has achieved relative consensus in analyzing the investments required for the transition [16]. Published in 2023 by France Stratégie, Selma Mahfouz and Jean Pisani-Ferry's report on "Assessing the Macroeconomic Impacts of the Ecological Transition" estimates the additional investment required to transition the French energy system to decarbonized production in 2050 at 8 billion euros per year [16]. Excluding the cost of networks, this amount is reduced to 6 billion euros per year (three for nuclear, three for renewables). This effort needs to be shared between the private and public sectors. Another study chooses to explore all the costs of transition, including OPEX (and not just investment). Despite the timeframe chosen (only up to 2030, which does not take into account several investments, particularly nuclear, taking place after 2030), the results also show that the cost of the transition is increasing each year, by between 5 and 10 billion euros [22], which is consistent with the former evaluation from Pisani-Ferry and Selma Mahfouz.

In total, RTE, the French electricity transmission company responsible for the electricity generation scenarios, estimates that the total cost of the electricity generation system could reach more than 60 billion euros per year by 2050 (or even 80 in some scenarios), compared to 45 today [23].

Table 1 Summary of evaluations of French energy transition costs, for different sources and scopes

Source (authors)	Energy transition costs	Scope
Pisani-Ferry and Mahfouz [16]	6 billion euros per year	Only investment, in 2030
Anna Fache [22]	5-10 billion euros per year	Investment and OPEX, in 2030
RTE [23]	15 billion euros per year	Investment, OPEX and network costs, in 2050

These estimations of costs (Table 1) are consistent, as the differences can be explained by different scopes (CAPEX, CAPEX and OPEX, all costs including network) and different time-ranges (2030 vs. 2050).

Instead of focusing on the total cost, other analyses concentrate on the cost of each technology and production choices, in a more bottom-up approach. Lebrouhi et al. analyze the trade-offs to be made according to the LCOE of each production mode (wind, nuclear, PV...) [24]. Other authors go into the details of a technology to assess

its cost structure, its determinants (CAPEX and OPEX) and its competitive potential. Alexandrou & Khatiwada investigate the potential of green hydrogen to decarbonize the aviation sector, concluding, for example, that the cost of electricity is the primary parameter to be considered for the competitiveness of this innovation. Electrolysis costs around 5 €/kg, or half the cost of LCOH (Levelized Cost of Hydrogen). By way of comparison, the use of water represents only 0.03 €/kg [25]. This methodology for highlighting the marginal contribution of water to the total cost should serve as a basis for this work. Similarly, El Kinani et al. do the same with the wind energy sector in France, calculating the LCOE and the contributions of the essential factors [26].

Two approaches are thus confronting each other: one, top-down, which focuses on the total costs required to complete the transition; the other, bottom-up, which analyzes the costs per technology (often via the LCOE) to work out the ideal mix for making this transition at the lowest cost. In France, there is a real lack of work combining the two approaches. The probable total cost is accessible via current renewable development targets, yet it is interesting to identify the contribution of micro-hypotheses to this cost, for water for example. To do this, it is necessary to calculate a global LCOE for the transition, which makes it possible to combine the two approaches.

The impact of the price of water on the cost of energy production has been studied in a number of studies. Regularly, this calculation is carried out on the scale of a particular energy, when calculating its LCOE. Thus, Alexandrou & Khatiwada calculate the LCOH of green hydrogen to decarbonize the aviation sector, concluding with a minor water cost of 0.03 €/kg [25]. Similarly, Reineh & Yousefi find water consumption costs of around 0.2 €/MWh for steam turbine power generation [27]. Therefore, most industry studies therefore conclude that the price of water has a marginal impact on the cost of energy. On a larger scale, the synthesis work of the Water-Energy Nexus does not address the question of the price of water for energy, preferring to focus on its availability [28, 29].

A project is currently underway in France on water pricing [30]. It is one of the issues to be decided at a "water conference", which is currently beginning with deliberations at French regional level [31]. Decentralized consultation makes sense, as the price of water is determined at the level of each French commune, according to the costs of subscription, treatment, distribution and sanitation. The results of this consultation and synthesis work are thus not yet available. However, there is already consensus in the academic world that the price of water is set to rise in the coming years, because of climate change [32] and the growing costs of pollution control. By 2022, the average price has already risen by 8 c€/m³, compared with an average of 4 c€/m³ over the 2010-2021 period. This increase affects regions unevenly: in some communes, water prices are rising by 10% each year [33].

3.3 Impact of the energy transition on water consumption

Unlike electricity, the water sector has long suffered from a lack of forward-looking studies to assess its future availability [34]. A study is currently underway in France to remedy this shortcoming. It is a joint effort by academics and the French administration to establish scenarios for water demand and supply in France up to 2050 [32], as a basis for all future public water policies. *It has* drawn up three scenarios for consumption in the coming years

- Trend: the dynamics of water consumption over the decade 2010-2020 are extended to 2050 to reflect an evolution at the same rate, without any change in uses.
- Public policies: French public policies announced to date and having an impact on water consumption (nuclear reactors, agricultural irrigation, demographics) are taken into account.
- Breakthrough: a major sobriety effort is considered.

The results of the three scenarios are broken down by economic sector (agriculture, industry, energy, individual consumption, etc.), by scale (40 zones in France), and by month, to establish a complete picture of French water consumption by 2050 [32].

This study confirms that water demand is becoming a major issue in French public policy. However, its scope does not allow for a detailed analysis of the link with electricity generation [32]. The aim of this Master thesis is therefore to draw in part on the preparatory work of these studies to explore in greater depth the question of potential trade-offs (for example, a development of French energy that would endanger the balance of water gestion in France) between the water and energy sectors. Kalvani et al. confirm that this Water-Energy Nexus is little covered in France compared with other European countries [34] (Figure 8), and that it deals more with subjects such as biofuels. Water consumption by energy is rarely addressed, and the price of water as a cost factor never (Figure 9) [29]. There is therefore scope for bridging this research gap by investigating these two issues in French public policy over the coming years.

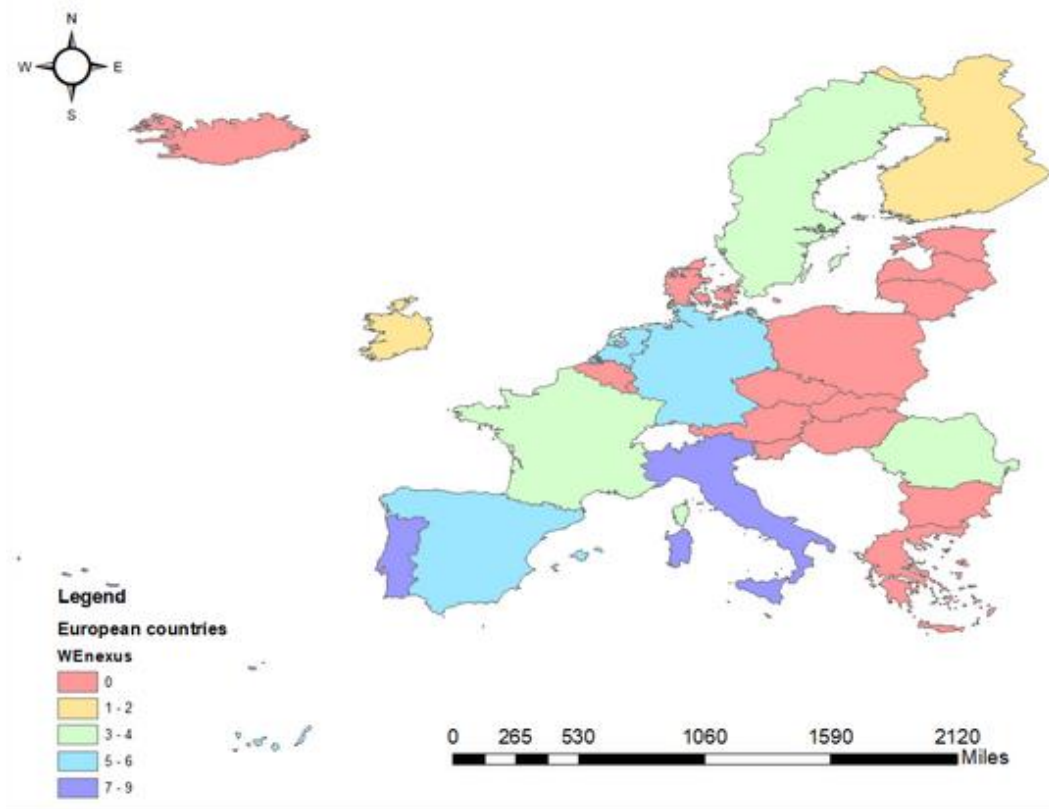


Figure 8 Number of Water-Energy Nexus studies in Europe [31]

Note: Water-Energy Nexus is the subject of between three and four studies in France, less than in Italy (seven to nine)

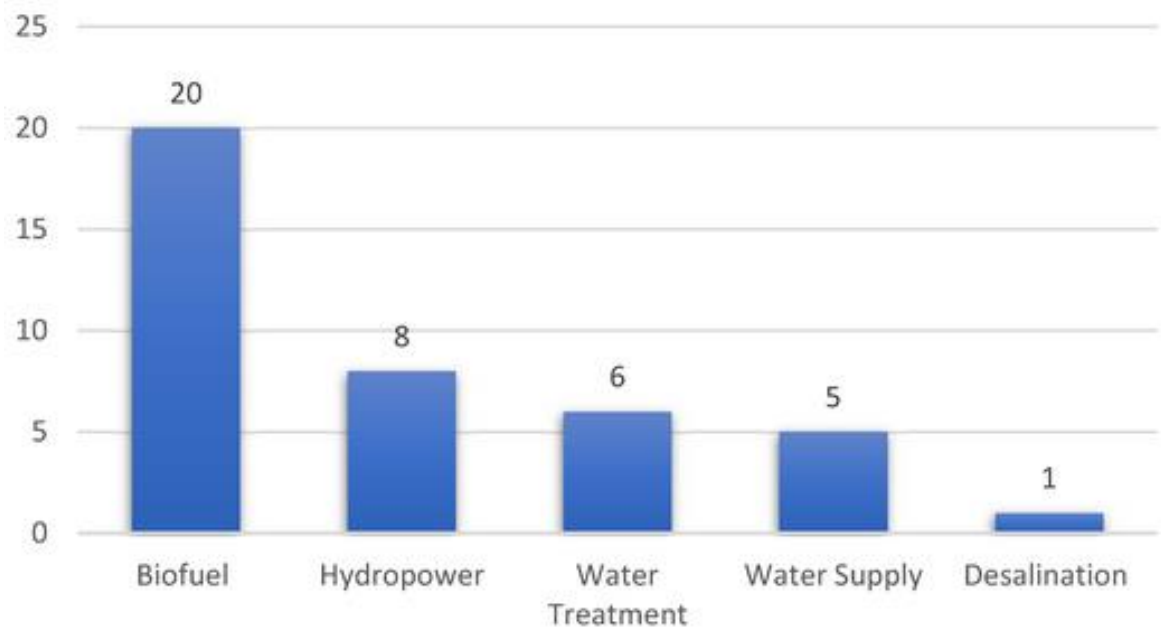


Figure 9 Subjects of Water-Energy Nexus studies in Europe [29]

The case of specific water demand from the energy sector has been studied [8, 10, 11, 12]. In its global Nexus study, the European Commission identifies the

dynamics of water abstraction by energy for France to 2050 according to different regions, as depicted in Figure 10 [8]. However, this work needs to be completed for two reasons. Firstly, it dates from 2019 and therefore does not incorporate the latest energy transition announcements, in particular the development of new nuclear power. As the SGPE transition plan was completed in 2023 [6], new work is needed to integrate the assumptions. Secondly, it only calculates water withdrawals, not consumption. Yet consumption is the best metric for assessing future water stress: it corresponds to the portion of withdrawals that is not returned to the environment. This type of work has been carried out in Spain, which gives an idea of the method to be employed, but is not applicable to France due to the differences between the energy mixes of the two countries [35, 36].

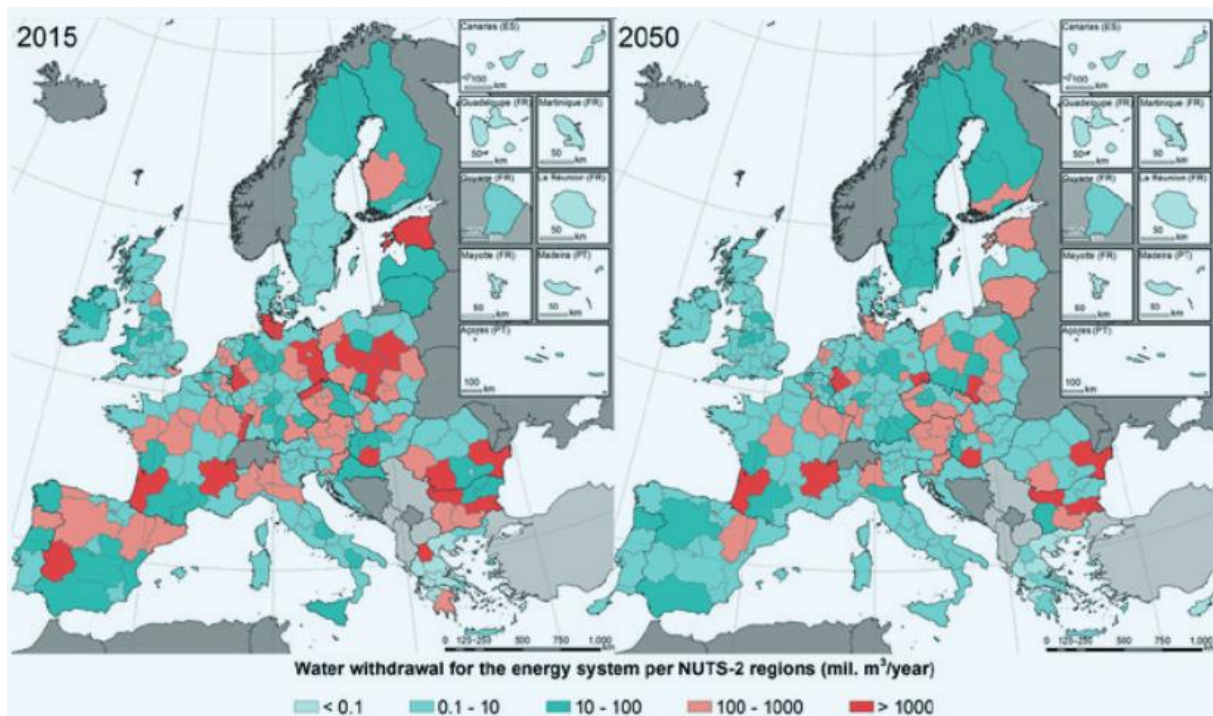


Figure 10 Water withdrawal for the energy system in Europe [34]

3.4 The synergy of water and energy governances

In France, energy mainly benefits from centralized decisions from the French government or national parliament through decrees and laws [15]. On the contrary, water governance is historically decentralized and more democratic [31], with local parliaments gathering elected representatives, public authorities, economic players and users. This difference can also be observed in the pricing and taxation system. Electricity obeys the principle of ‘tariff equalization’, which means that the fixed costs of electricity are shared equally between all consumers throughout France. Conversely, water prices vary at local level depending on the investment choices made by local authorities [30]. For taxation, energy is subject to excise duty, while water is

subject to charges, which vary according to the type of use and the quantity to reflect the public service provided.

Kalvani et al. confirm that the in-depth study of governance in the water sector compared to energy is not addressed in most scientific articles on the Nexus [34]. In order to apply this governance theme to France, it is necessary to establish the scientific corpus defining the various forms of water governance.

According to Di Vaio et al, "Water governance across the world is multilevel, where services are provided by various actors and responsibilities shared at national, regional and local levels" [37]. Consequently, there are as many governance models as there are countries in the world. Restricting ourselves to the European context, the common characteristics of "good governance" are often active citizenship, culture of dialogue and negotiation [38].

In France, governance is a mix of what Molle calls "state governance" [38] (characterized by centralized management in which the state plays a dominant role in decision-making) and "horizontal governance" (water management carried out by democratic assemblies representing the various users, as well as national and local administrations) [38]. To a lesser extent, France also relies on "market governance", with market mechanisms for allocating water resources, such as pricing and public-private partnerships. Since 1964, France has set up river basin committees, bringing together various stakeholders such as representatives of the State, local authorities, users and environmental associations. The aim of this approach is to promote integrated, participatory management of water resources on a river basin scale [39].

Yet the link with energy is understudied in governance issues, mainly because other links (in particular water with the agricultural sector) are considered politically tense and have therefore been the subject of more study [40]. So, once again, there is a research gap to be filled in order to integrate water governance into the water-energy Nexus.

4 Methods and materials

In this section, the underlying methodology and data for modelling both quantitative (impact of surge in water prices on electricity costs; impact of energy transition on water demand) and qualitative energy-water Nexus are described. Figure 11 draws an overview of the methodological steps.

Firstly, input data is collected in Section 4.1 (Data collection and model parameters). It consists of internal data from the SGPE (particularly concerning ecological transition roadmaps), external data from the literature review (costs' structure, utilization years, weighted average cost of capital - WACC...) and data from

expert interviews. Subsequently, based on this data, a model is developed for each axis of the problematic and a metric (such as LCOE or water consumption) is defined to assess potential trade-offs or synergies (Sections 4.2.1 and 4.2.2, Impact of the water price on electricity cost, Impact of energy transition on water demand (*France Stratégie*)), with different scenarios by the deadline of 2050. Depending on the scenario, with LCOE calculations and demand modelling, different levels of impacts of trade-offs and synergies are identified in relation with the three research questions.

	Quantitative		Qualitative
	Impact of the water price on electricity cost	Impact of energy transition on water demand	Links between the sectors' governances
1 Data collection and literature review	<ul style="list-style-type: none"> Costs' structure for energy technologies: CAPEX, OPEX, WACC, utilization years Electricity capacity installation schedule Planned energy production in TWh/yr per energy source Capacity factors 	<ul style="list-style-type: none"> Water withdrawal and consumption by energy source Planned addition of energy capacities with high use of water Focus on local scale: 40 zones in France 	<ul style="list-style-type: none"> Academic governance models and the case of France Interviews with administration, local representatives, private sector
2 Modelling	<ul style="list-style-type: none"> Levelized cost of electricity between 2022 and 2050 (especially considering additional production to reach environmental objectives) Sensitivity analysis: impact of a surge in water prices on LCOE 	<ul style="list-style-type: none"> Reference year in 2020 Water withdrawal and consumption by the energy sector (million cubic meters per year) Details by location and seasonality 	<ul style="list-style-type: none"> Strengths, weaknesses, opportunities, and threats (SWOT) comparison Case in point: transition of both sectors in period of political instability to evaluate resilience
3 Scenario development	<ul style="list-style-type: none"> Range of potential water prices in the coming years to produce sensitivity analysis Two different ways to deal with utilization years beyond 2050 	<ul style="list-style-type: none"> Three scenarios: trend, public policies, breakthrough For each scenario: narrative and key hypotheses 	<ul style="list-style-type: none"> Governance in the context of ecological transition and adaptation to +4 degrees Anticipation of trade-offs to assess governance's resilience
4 Key insights	<ul style="list-style-type: none"> Potential trade-off: increased LCOE due to surge in water prices Sensitivity per energy source 	<ul style="list-style-type: none"> Potential trade-off: high demand for water due to energy transition Potential hydric stress in some regions / for some months of the year 	<ul style="list-style-type: none"> Opportunities to inspire from opposite sector Inventory of opinions on optimal governance at this time
5 Future work	<ul style="list-style-type: none"> Extend to whole energy and not only electricity Confront energy costs and water price for each region (as water prices are established at local scale) 	<ul style="list-style-type: none"> Consider future water availability scenarios to confront offer and demand in specific regions / time of the year 	<ul style="list-style-type: none"> Results of both consultations for energy and water (available at the end of 2025) and comparison to current results

Figure 11 Overview of the methodological steps

This study adopts a mixed-methods approach, incorporating both quantitative and qualitative frameworks. Specifically, two quantitative models will be constructed based on data to evaluate trade-offs between energy and water in terms of price and

demand. Additionally, interviews will contribute to reflection on optimal governance, thus following a qualitative approach.

The boundaries of the study are limited to the French ecological transition between ~2020 and 2050, with the reference year being 2022 for energy and 2020 for water demand due to the absence of more recent data. The analysis encompasses all the French decarbonized electricity production on the one hand, and the water demand from energy (not only from renewables) on the other hand. The data collected will thus enable to quantify and forecast the potential trade-offs and synergies from 2020 to 2050.

4.1 Data collection and model parameters

This section provides an overview of the data sources used to derive input data for (a) LCOE computation, (b) Water demand from energy sector modelling and (c) qualitative links between governances. It can be divided into three distinct parts: input parameters from SGPE database (Section 4.1.1), literature review (Section 4.1.2) and interviews (Section 4.1.3). The combination of these data will enable the development of the models (Section 4.2), and eventually the calculation of overall trade-offs and synergies (Section 5).

4.1.1 Data from SGPE and French administrative database

The first part of the data comes from SGPE files, publications and plans in the water and energy sectors.

In fact, as the body coordinating France's ecological transition, the SGPE and associated bodies provide a number of forward-looking data needed to assess the qualitative part of this study (Table 2).

Table 2 Data from French administrative database [15]

Axis	Data
Impact of the water price on electricity cost	<ul style="list-style-type: none"> - Annual trajectories for decarbonized power generation (TWh) and capacity installation (MW/year) to meet climate targets - Water price trajectory in a context of climate change and resource pollution (€/m³)
Impact of energy transition on water demand	<ul style="list-style-type: none"> - Annual trajectories for power generation (TWh) and capacity installation (MW/year) to meet climate targets → limiting ourselves to water-consuming technologies. - France divided into forty hydrographic zones

4.1.1.1 Impact of the water price on electricity cost

Among the data needed to calculate the LCOE (Section 4.2.1, Levelized Cost of Electricity (LCOE)), the SGPE's internal plans provide decarbonized energy and

power trajectories between 2022 and 2030 (Figure 12) [9]. This close horizon ensures a low margin of error. Within this timeframe, the increased production of decarbonized electricity is divided between two trends:

- Increased production capacity: photovoltaic, onshore wind and offshore wind power need to increase their installed capacity in France to ensure additional energy production without changing the capacity factor.
- Increased production at constant installed capacity: with one exception (one new nuclear reactor out of fifty-seven), nuclear and hydroelectric energies will increase their production at constant installed capacity. In the case of nuclear power, the aim is to return to past production capacity, before the drop in 2022 due to the shutdown of certain reactors irregularities observed during safety inspections. For hydroelectricity, it is essentially a question of steering supply to increase production in line with the transition.






		Capacity and production in 2022	Major changes	Capacity and production in 2030
Wind energy		21 GW 38 TWh	Installed capacity	33-35 GW ~64 TWh
Offshore wind energy		0,6 GW 1 TWh	Installed capacity	4 GW ~14 TWh
Solar PV		16 GW 19 TWh	Installed capacity	54-60 GW ~65 TWh
Nuclear		56 reactors 279 TWh	One new reactor Improved disponibility	57 reactors 360 TWh
Hydroelectricity		26 GW 43 TWh	Improved energy production with same capacity	26 GW ~54 TWh

Figure 12 Comparison of energy production and capacity between 2022 and 2030 [5]

However, trajectories towards 2050 are much less certain. As the SGPE focuses on the 2030 target, the best data to date comes from French electricity transmission network (RTE), which provides several scenarios for the electricity mix in 2050 [23]. Using the intermediate hypothesis (mix of nuclear and renewable), the forecast generation capacities in 2050 are as follows (Table 3):

Table 3 Forecast of the electricity generation capacities in 2050 [17]

	Capacity (GW)	Energy production
Wind	52	To be derived from nominal capacity with capacity factors, assumed to be constant between 2030 and 2050
Offshore	36	
Solar PV	90	
Nuclear (old)	16	
Nuclear (new)	23	
Hydro	26	

The annual installation capacity in MW/year per energy source can therefore be extrapolated between 2030 and 2050 on the basis of available data, assuming a linear installation rate.

Nuclear power is specific to this study: from 2030 onwards, it is necessary to distinguish between new nuclear power (EPR2 reactors built from 2035 onwards) and old nuclear power (which is about to see its production reduced due to the closure of power plants at the end of their life - currently estimated at ~60 years).

This information ties in with the first limitation of this work, mentioned in Section 4.3. Numerous assumptions are required to evaluate decarbonized electricity production in 2050, and sometimes force us to extrapolate to assume missing data. One of the challenges of the results will therefore be to provide a sufficiently well-argued sensitivity analysis to transcribe the probabilities of deviating from these central assumptions.

4.1.2 Data from literature review

4.1.2.1 *Impact of the water price on electricity generation costs*

In order to calculate the LCOE and carry out the sensitivity analysis, data on the cost structure of the different energy sources are required. As explained in Section 3 Literature review, the literature review provides the following values for CAPEX and OPEX, in particular to highlight the role of water (Table 4 Costs hypotheses for energy sector: CAPEX & OPEX).

Table 4 Costs hypotheses for energy sector: CAPEX & OPEX

	CAPEX (€/MW)		Learning rate for CAPEX per year	OPEX		
Wind	1.47 [41]		1,4% [41, 43]	43.0 €/kW/yr [44]		
Offshore wind	3.12 [41]		2,2% [41, 43]	110 €/kW/yr [44]		
Solar PV	0.671 [41]		4,6% [41, 43]	9 €/kW/yr [45].		
Nuclear	<u>Flamanville (2023):</u>	<u>EPR2 (post-2035):</u>	/	O&M:	Fuel:	Water:
	8,2 [42]	4,35 [42]		30 €/MWh [42]	7 €/MWh [42]	1 €/m ³ , so 1,5 €/MWh [42]
Hydroelectricity	Undefined (no new capacity)		/	67.6 €/kW/yr [46]		

These figures are based on several assumptions:

- Wind, offshore wind and solar PV: CAPEX are expressed in €₂₀₂₀ in the source. Two corrections must therefore be applied to return to current €: the corresponding inflation rate, but also the progression factor (corresponding to the drop in cost associated with increased productivity over time), available from the data in the article cited [41]. OPEX correspond to O&M costs, and are therefore expressed in €/kW, since they depend on installed capacity and not on the energy produced.
- Nuclear: CAPEX are calculated on the basis of actual or estimated overnight costs for French nuclear power plants. It is therefore necessary to distinguish between the Flamanville EPR, for which the bill has risen in line with launch delays, and the EPR2s due to be built from 2035 onwards, for which the cost is currently considered to be under control [42].
- Hydroelectricity: There are no forecasts for the construction of new French dams, hence the absence of CAPEX. However, OPEX are necessary to evaluate the cost of increased production due to an improved capacity factor.

Final needed data is the discount rate for France in the coming years. In accordance with the method proposed by Christian Gollier [47], the rate used will be 5% as an average value. For the sensitivity analysis, this rate will vary between 3% (low value) and 7% (high value).

4.1.2.2 Impact of energy transition on water demand

Dealing with the issue of water demand requires defining the difference between abstraction and consumption. For the energy sector, water is withdrawn from rivers [18], but other sectors use the same amount of both ground and river water (agriculture) and the housing sector uses more ground water than river water [18]. Withdrawals refer to the quantity of water removed from the natural environment (and eventually discharged after use, thus becoming available again), while consumption corresponds to a quantity of water that is not returned and is therefore non-renewable.

Water consumption in the energy sector is mainly driven by nuclear power plants (96% of the sector's total consumption [32]). A simplifying assumption is therefore to consider that water demand in the energy sector depends solely on nuclear power. Next, two types of data are required to calculate water demand: the energy output of each power plant, and the unit water demand per energy output (in m³/MWh) of each nuclear power plant.

Therefore, the necessary data are given in [32] for each nuclear power plant in France, for the years 2020 and 2050, as available in the figures (Figure 13, Figure 14) and tables below (Table 5, Table 6).

Nuclear reactors in operation (Year 2020)

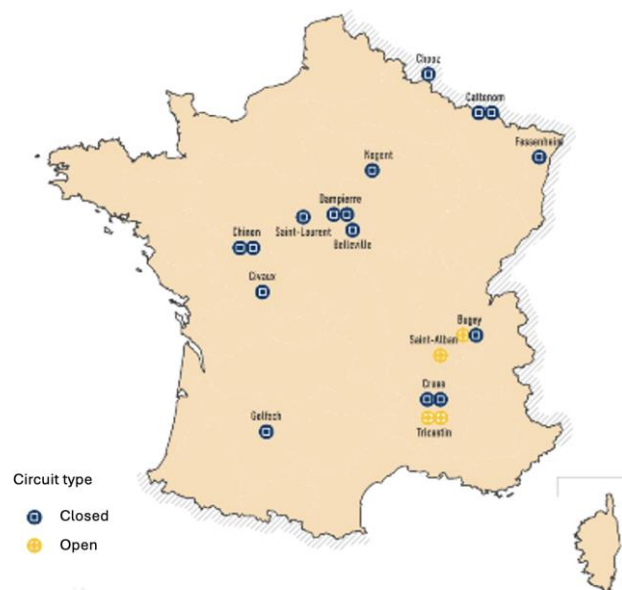


Figure 13 Location of riverside nuclear reactors in operation in 2020 and type of cooling system [32]

The first needed data is the production of each nuclear plant per year. Table 5 provides the catchment areas and electricity production (*France Stratégie* [32])

Table 5 Annual production in 2020 by nuclear power plant [32]

Central	Catchment area	Production (MWh)
Belleville	Middle Loire	14 791 761
Bugey 2&3	Rhône upstream	2 677 432
Bugey 4&5	Rhône upstream	12 150 171
Cattenom	Moselle	30 314 234
Chinon	Middle Loire	19 459 050
Chooz	Meuse	12 531 653
Civaux	Vienne-Loire	15 033 441
Cruas	Downstream Rhône	21 213 558
Dampierre	Middle Loire	19 587 680
Fessenheim	Rhine	4 696 876
Golfech	Garonne upstream	16 183 820
Nogent	Rivers Île-de-France	14 819 136
Saint-Alban	Rhône upstream	17 301 282
Saint-Laurent	Middle Loire	11 677 259
Tricastin	Downstream Rhône	23 543 937

Then, the consumption ratio of each nuclear plant is needed. Unit demands differ greatly depending on the type of cooling circuit (open or closed circuit, which refers to the type of cooling – open circuit withdraws and rejects water for a one-time use, while closed circuit reuse water several times in the same boucle): closed circuit consumes higher quantities (but withdraws less water, what is not considered in this work) (refer to Table 6).

Table 6 Unit demand in withdrawals and consumption (m³/MWh) for nuclear power plants [32]

Central	Circuit	Consumption (m ³ /MWh)
Belleville	Closed	3
Bugey 2&3	Open	1
Bugey 4&5	Closed	6
Cattenom	Closed	2
Chinon	Closed	2
Chooz	Closed	2
Civaux	Closed	1
Cruas	Closed	4
Dampierre	Closed	2
Fessenheim	Open	1
Golfech	Closed	2
Nogent	Closed	2
Saint-Alban	Open	1
Saint-Laurent	Closed	2
Tricastin	Open	1

Nuclear reactors in operation (year 2050)

Thanks to simplifying assumptions (only water consumption from nuclear energy is considered), the major change between 2020 and 2050 is the end of life or creation of new nuclear plants. According to recent announcements [48], it is considered that 14 new-generation nuclear power plants (EPR) are constructed between 2035 and 2050 – but only four of which are located on riverbanks. At the same time, some nuclear power plants are reaching the end of their service life and are being shut down. Figure 14 summarizes these changes: four reactors are constructed on two sites (Nogent and Bugey), and some reactors are stopped because of aging.

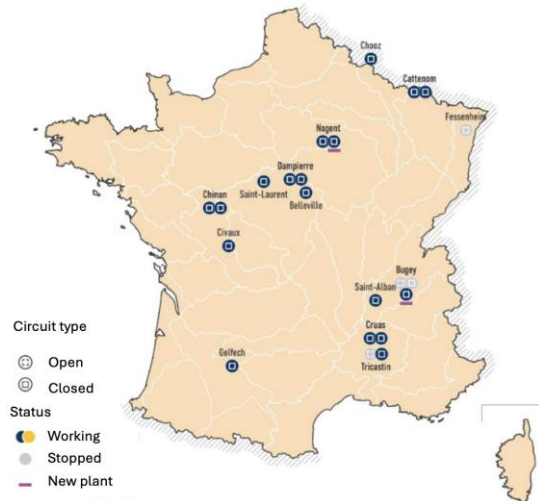


Figure 14 Location of riverside nuclear reactors in operation in 2050 and type of cooling system [32]

Besides, the four new reactors are constructed in close fuel cycle and their water consumption ratios are provided in Table 7.

Table 7 New nuclear power reactors (riverside) before 2050

Central	Circuit	Consumption (m ³ /MWh)
Nogent (2 reactors)	Closed	2
Bugey 5&6 (two reactors)	Closed	2

In terms of additional energy, it represents around +55 TWh/year in 2050 for these four reactors (necessary to compute the water consumption with the consumption ratio).

4.2 Metrics used to evaluate the water and energy nexus

Two quantitative metrics (LCOE and demand projection) and one qualitative analysis (expert interviews) are used to evaluate the water and energy nexus. First, levelized cost of electricity (LCOE) helps analyze the impact of water prices on electricity transition costs (refer to Section 4.2.1, Impact of the water price on electricity cost). Second, water demand (i.e., increased water consumption) is estimated due to the impact of the energy transition between 2020 and 2050 (refer to Section 4.2.2, Impact of energy transition on water demand (*France Stratégie*)). Third, expert interviews help to analyze the dynamics and synergies of water and energy

governances (refer to Section 4.2.3, The synergy of water and energy governances – expert interviews for a qualitative analysis).

4.2.1 Impact of the water price on electricity cost

This subsection presents the model used in order to answer research question 1 about the impact of higher water prices on electricity generation costs.

4.2.1.1 *Levelized Cost of Electricity (LCOE)*

These collected datasets on energy technologies trajectories (such as costs hypotheses, capacities, inflation rates., etc.) from the French administrative database, the literature review and interviews are then combined to compute the Levelized cost of electricity (LCOE) for transition to 2050. This model is slightly different from LCOE uses in literature review [25]. Usually, LCOE is computed for one energy source on a certain location and period of time, to eventually compare the result with benchmarks for the sector and determine if an energy project is competitive or not by comparison with other possibilities.

Here, LCOE is used as a metric of the cost of French electricity transition towards 2050. To fulfill its climate objectives, France needs an increase in decarbonized production (nuclear and renewables), both in terms of capacities and amount of energy produced. This will require major investments, as well as increased operation & maintenance costs aligned with new objectives. Total additional costs for French electricity generation costs will be computed, as well as the costs by individual (to evaluate an approximation of the financial impact of transition on households, even if the burden should be divided into different financial instruments such as taxes or debt). Adding LCOE to the vision in total costs is useful for two reasons:

- By integrating the total of electricity produced, with a result in €/MWh, it allows to compare to other renewables development projects that have a different quantity of electricity produced (for example, a smaller country than France engaging its transition). Therefore, it indicates whether French transition projects are average (considering the costs) or suffer from a significant cost premium. If this is the case, it should lead to an in-depth investigation to determine the reason for this difference.
- Including the variable of energy produced (leading to a result in €/MWh - LCOE) also makes it possible to introduce the concept of sobriety: the result per MWh makes it possible to conceptualize the costs that could be saved if we produce less because consumption has fallen, or on the contrary the additional costs required if consumption increases significantly.

Besides, by using LCOE, these costs are aggregated in a single metric and accessible base value, which will be eventually compared to rise or decrease of LCOE in sensitivity analysis due to parameters' variations. This will eventually allow to evaluate the impact of water costs on LCOE and thus cost of the French electricity generation transition. LCOE computation is performed as follows:

$$LCOE = \frac{I_0 + \sum_{t=1}^T \frac{\sum_{energy\ sources} (I_t + C_t)}{(1+r)^t}}{\sum_{t=1}^T \frac{\sum_{energy\ sources} E_t}{(1+r)^t}}$$

Where:

- T is the project lifetime (in years, here 28 years from 2023 to 2050)
- I_0 the initial investment (in €)
- I_t the investments of year t (in €)
- C_t the operation & maintenance costs of year t (in €)
- E_t the electricity production of year t (in MWh)
- r the discount rate.

Water costs are therefore considered as C_t (operation costs in year t), as it corresponds to a cost linked with energy production each year: the more the plant produces, the more water is consumed and the water cost rises.

Therefore, LCOE unit will be €/MWh, in €₂₀₂₂ as costs and energy are discounted to correspond to year 0 of the model (2022). This precision is essential for example to evaluate the impact on public finances: costs of year 2022 are not equivalent to costs of year 2050 because of inflation.

All decarbonized energy projects happening between 2022 and 2050 are taken into account.

TO begin with, CAPEX occurring during this period of time are considered. An important assumption of this model is that, as the 2050 objective is binding, I will equal the full CAPEX invested for each energy project, even if the life-time of new technologies exceeds the year 2050. Indeed, the point of interest is to describe the full costs consented before 2050 to achieve transition, even if new technologies are still used after 2050.

Example: a 25-years solar project launched in 2045 will have full CAPEX costs accounted, and its energy only until 2050 (even if it should produce until 2070). The

objective is to transcribe the financial effort needed before 2050 to respect the norms. The counterpart of this choice of model is that after 2050, French public and private investors will recover the costs invested before 2050 by selling their energy, without CAPEX to be amortized (all considered before 2050 in this accounting choice).

OPEX for additional energy: this means that only energy produced from new capacities or from improvement of capacity factors is considered in the LCOE calculation. As before, the point of interest is to describe the additional effort needed to achieve electricity transition before 2050. Only newly produced energy enters the model.

All this data is explained in Section 4.1 Data collection and model parameters.

4.2.1.2 Sensitivity analysis

In order to map the impact of higher water prices on electricity generation costs (through LCOE), a sensitivity analysis is conducted. The process of sensitivity analysis allows to show how different values of an independent variable affect a dependent variable (here, LCOE) under the standard set of assumptions.

As explained in Table 8, in this work’s model, the objective is to compare the impact on LCOE of water prices variations with other parameters fluctuations. If the percentage of change of LCOE led by a variation of water prices is low by comparison to other possibilities of changes (discount rate, capacity factors, fuel costs...), the impact of water prices can be considered marginal and should not endanger the global capacity to achieve electricity generation transition even in the case of risks occurrences.

Table 8 Parameters for sensitivity analysis

Parameter	Base value	Lower value	Higher value	Commentary
Discount rate	5%	3%	7%	A variation of ~2% is conceivable, in particular due to inflation variation [47]
Capacity factor: Wind	Onshore: 21% Offshore: 40%	Onshore: 15% Offshore: 35%	Onshore: 25% Offshore: 45%	Capacity factor variations are fluctuating because of energy availability. For wind, this fluctuation is quite reduced, around ~5% → mainly to account for late investments in electrical connections [44]

CAPEX: all energy technologies	See Table 4	95% of CAPEX	105% of CAPEX	/
Nuclear fuel costs	7 €/MWh	5 €/MWh	9 €/MWh	[42]
Capacity factor: solar	12%	10%	14%	Capacity factor variations are fluctuating because of energy availability. For solar, this fluctuation is quite reduced, around ~2% → mainly to account for late investments in electrical connections [23,45]
Capacity factor: nuclear	75%	65%	90%	Capacity factor variations are fluctuating because of energy availability. For nuclear, this variation is important. 65% to 90% correspond to past availability of the French reactors → likely to happen again [23]
Water costs	1 €/m ³	0.5 €/m ³	2 €/m ³	Water prices are expected to increase quickly in the coming years. The important value is 2 €/m ³ , which corresponds to a rise of 100% in water prices [18] → conservative hypothesis.

4.2.2 Impact of energy transition on water demand (*France Stratégie*)

This subsection presents the model used in order to answer the research question 2 about the impact of the energy transition on water consumption.

The model seeks to calculate the increase in consumption of water from the energy sector in France, between 2020 and 2050. Built by the French agency *France Stratégie*, it anticipates the public policies announcements that will have an impact on demand, mainly about nuclear development in France (see 4.1.2.2 *Impact of energy transition on water demand*). This is therefore considered as an energy transition scenario, as it integrates current political decisions about new nuclear reactors to match requirements of reduction of greenhouse gas emissions towards 2030 and 2050. Indeed, it is considered that 14 new-generation nuclear power plants (EPR) are constructed between 2035 and 2050 – but only four of which are located on riverbanks. At the same time, some nuclear power plants are reaching the end of their service life and are being shut down [32].

As explained in 4.1.2.2, water consumption in the energy sector is mainly driven by nuclear power plants (96% of the sector's total consumption [32]), and thus only nuclear sector is considered here. The error associated with this assumption is less than 4% (since nuclear power accounts for 96% of water withdrawals).

Next, thanks to the two types of data given in 4.1.2.2, it is possible to calculate water demand: the energy output of each power plant, and the unit water demand per energy output (in m³/MWh) of each nuclear power plant. At the end, the quantity of water consumed is:

$$Water_{consumption} = \sum_{nuclear\ plants} Energy_{production} \times Consumption\ ratio_{water/energy}$$

Where:

$$Consumption\ ratio_{water/energy} = \frac{Water\ consumed\ by\ the\ plant}{Energy\ produced\ by\ the\ plant} \text{ in } \left[\frac{m^3}{MWh} \right]$$

This model is developed by France Stratégie in [32]. An addition to their work is to compare the results of water consumption by the energy sector for each region, to the price of water for each region. It will allow to **complete the Nexus loop** with the previous part: **higher water consumption from energy sector leads to higher prices, and higher water prices leads to higher electricity generation costs**. Therefore, it justifies the sensitivity analysis conducted in order to evaluate the impact of water prices.

4.2.3 The synergy of water and energy governances – expert interviews for a qualitative analysis

In order to answer “Research question 3: the synergy of water and energy governances, a qualitative analysis”, this work is also based on interviews with various players in the water and energy sectors. The global objective is to answer the research

question about the governance of both sectors, and potential synergies from a qualitative point of view. The other advantages of these interviews are threefold:

- Check the consistency of the assumptions and data on which the quantitative part of this work is based. These are crucial, but may vary from one source to another
- Draw concrete conclusions from quantitative analysis, moving from numerical results to tangible deductions and avenues for improvement.
- Exploring potential synergies between water and energy in terms of governance. By definition, this theme requires a qualitative analysis, as it concerns the unquantifiable contribution - positive or negative - of the links that exist between the players in these sectors to foster democratic, technical, ecologically and socially just decision-making.

The water sector, by definition decentralized and more democratic, offers a multitude of players to meet in comparison with the energy sector. Meeting with a wide range of experts is crucial to transcribe the different strata of water governance: local level (distribution and sanitation), regional level (management of the large water cycle, quantitative and qualitative protection of the resource), and national level (elaboration of national strategies and budgets).

In addition to public players (elected representatives and public authorities), other stakeholders need to be mobilized to gain an in-depth understanding of the governance of both sectors, like non-governmental organizations.

These meetings took place over two rounds between September and January. The first was devoted to comparing the hypotheses of the quantitative analysis (data and models) and the expected results, while the second was devoted to questions of governance of the two sectors and the potential synergies to be exploited, particularly in the context of the political instability currently affecting France.

Each time, the interviews were conducted on a private basis: one person interviewed, and one or two persons from the *Secretariat general à la planification écologique* on the interviewer side.

In order to answer research question 3 about both sectors' governances, typical actors are to be interviewed about their understanding of challenges and basis of governances. Therefore, the interviews were conducted with six actors, whose description is available in Table 9.

Table 9 Summary of conducted interviews with sectoral experts

Actor type	Number in this work	Round 1	Date and duration	Round 2	Date and duration
Local elected official (commune)	1			X	21/12/2025 1h
Water agency (region)	2	X	05/09/2024 2h	X	21/11/2024 1h
Central government - Water issues	3	X	11/09/2025 1h	X	16/12/2024 1h
Central government - Energy topics	4	X	11/09/2025 1h	X	16/12/2024 1h
Employee for private energy producer	5			X	09/12/2024 1h
NGO: preserving water resources	6			X	19/11/2024 1h

The interviews followed a specific scheme, available below:

Scheme of the interviews (not all questions were systemically asked, but no questions out of this scheme were considered relevant).

Water sector

- How would you describe the governance of water sector?
- What are the strengths/weaknesses of the governance of the water sector?
- What are the main challenges for the water sector in the coming years?
- How ready do you think the water sector is to take over these challenges? Rate it on 10.

Energy sector

- How would you describe the governance of water sector?
- What are the strengths/weaknesses of the governance of the water sector?

- What are the main challenges for the water sector in the coming years?
- How ready do you think the water sector is to take over these challenges? Rate it on 10.

Nexus

- What links do you see between water and energy governances? Now and in the future. Do you identify synergies or trade-offs?
- Which sector is doing the best with the current political instability?

In conclusion, Figure 15 provides how data is collected from different sources.

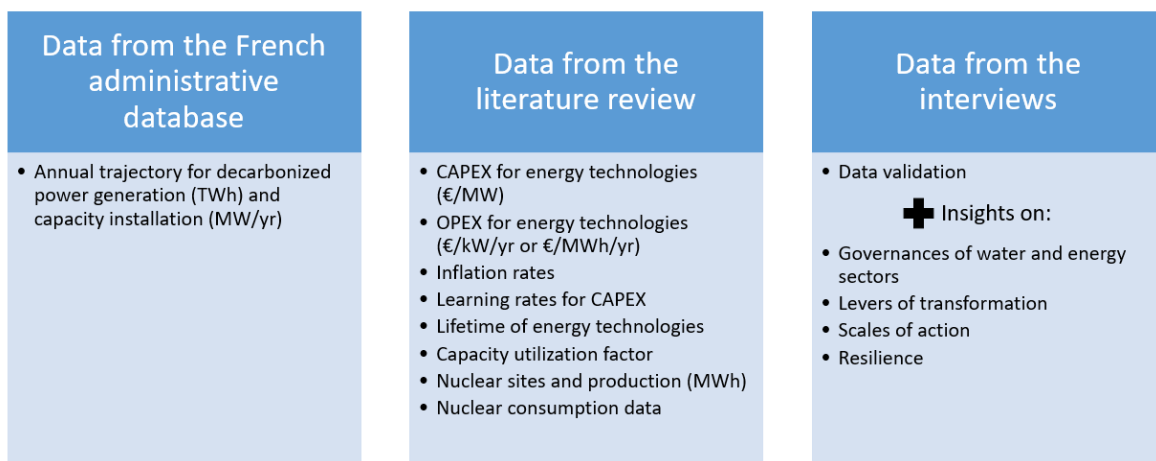


Figure 15 Summary of collected data

5 Results and discussions

5.1 Impact of higher water prices on electricity generation costs (potential trade-off assessment)

This section presents the results of the research question 1 about the impact of higher water prices on electricity generation costs.

5.1.1 Total costs, average costs per French inhabitant and LCOE

5.1.1.1 Costs distribution between 2022 and 2050

To begin with, electricity generation development rhythm and costs hypotheses (See Section 4.1.2, Data from literature review) lead to the following distribution of costs (both CAPEX and OPEX) in the coming years (Figure 16). This

CAPEX curve is consistent with four different periods in the French electricity generation strategy between 2022 and 2050:

- 2023: High CAPEX costs occur in 2023 for the commissioning of the French nuclear reactor of Flamanville, known to have greatly exceeded the original cost assumptions.
- 2023-2030: CAPEX costs are unevenly distributed and rather follow the government planning up to date. More specifically, offshore parks are entering into service by accordance to a specific calendar already publicly disclosed.
- 2030-2035: government schedule planning for renewables is not yet finalized. Therefore, a steady rate of installation is assumed, in line with the targets set for 2050, which explains the constant curve of CAPEX costs. There are no new nuclear power stations yet.
- 2035-2050: as during 2030-2035, a steady state is retained because of lack of precise schedule. From 2035, new nuclear reactors are constructed, which explains the step between 2034 and 2035. After this date, all nuclear investments are distributed evenly because of lack on further information.

OPEX costs follow these assumptions, especially depending on nuclear production (because of energy related OPEX in €/MWh, such as fuel costs) and renewables installations (because of capacity related OPEX in €/kW, such as maintenance costs).

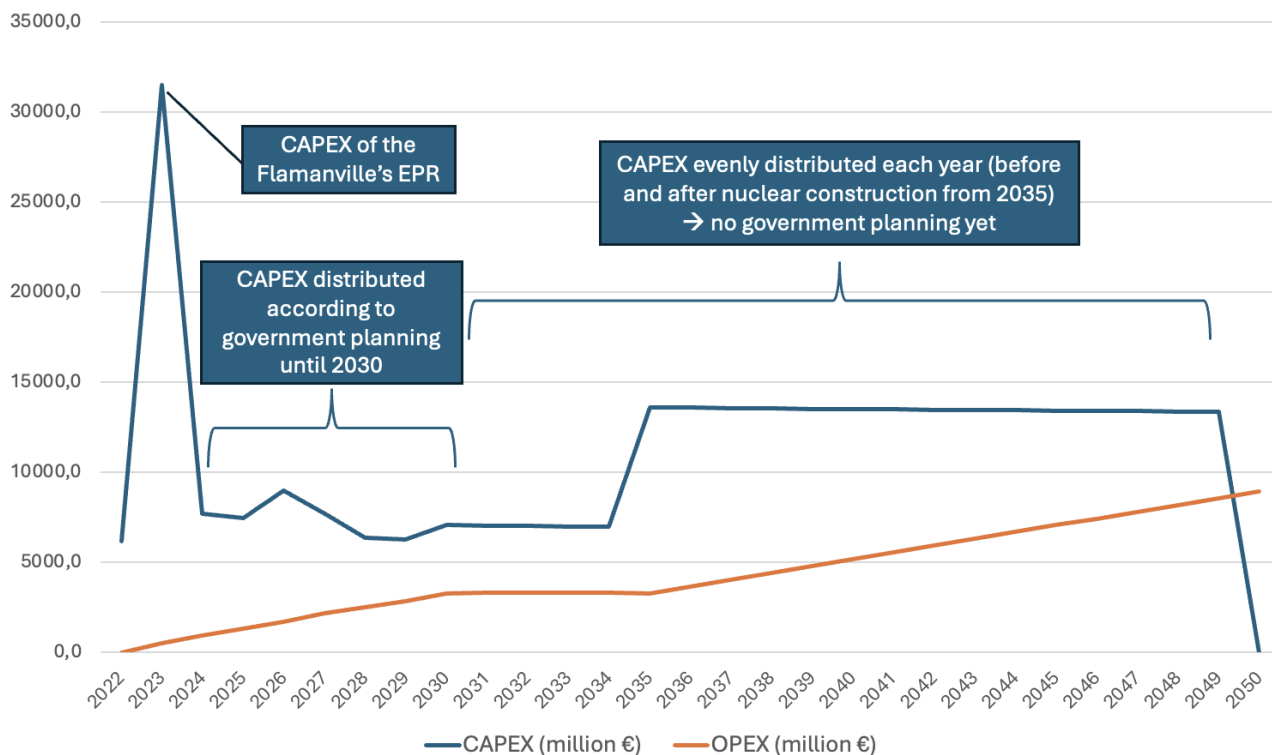


Figure 16 Costs distribution between 2020 and 2050

5.1.1.2 Total transition costs and distribution per inhabitant

Firstly, total costs are computed for the additional effort required to match objectives of electricity generation transition (without considering produced electricity for now, i.e. LCOE). The two main hypotheses of this result are first the discount rate (5%, similarly to the LCOE analysis, to obtain euros of year 2022) and then the French population (68,6 million inhabitants [49]). The results are given in Table 10.

Table 10 Electricity generation costs for transition towards 2050

Costs	Period 2022-2050	By year
Total costs	215.7 billion € ₂₀₂₂	7.4 billion € ₂₀₂₂
Per French inhabitant	3144.4 € ₂₀₂₂	108.4 € ₂₀₂₂

The results for Total costs are particularly consistent with literature review estimations of investments for French electricity generation transition. In 2023, Pisani-Ferry and Mahfouz calculated a supplementary investment cost of 6 billion euros per year in France between 2023 and 2030, for renewables and nuclear [16], close to this work estimation of 7.4 billion euros per year.

This is all the more true that Pisani-Ferry and Mahfouz model only considers years before 2030, and thus does not integrate new nuclear plants which are to be constructed after 2035. This may explain the higher annual cost in the model used here. In all cases, the results are close enough to validate the cost model used. Table 10 also provides two lessons of interest to public authorities.

- The transition of the electricity generation system requires major investments each year (around 0.25% of French GDP each year [50], only for electricity generation transition). The total costs of transition will be significantly higher. These costs must be anticipated and the distribution of the burden must be the subject of a political choice.
- More specifically, these electricity generation transition costs represent an annual effort per inhabitant of around 108 euros. This must guide political choices, so that this cost is not borne uniformly by the people of France, at the risk of damaging the purchasing power of the most vulnerable.

5.1.1.3 Levelized Cost of Electricity

Now considering the total additional electricity produced to reach climate objectives in France, total costs can be levelized to obtain LCOE. This work model gives a LCOE of 71.6 €/MWh.

As before, this result validates the model as this LCOE ranges in the common values for renewables projects in the world [32]. Besides, as explained in *4.2.1.1 Levelized Cost of Electricity*, this result can be analysed as follows: each supplementary MWh (for example for consumption demand higher than anticipated) will cost 71.6 €. This indicates the necessity of sobriety to avoid additional costs in the context of constrained public finances.

5.1.2 Sensitivity analysis

The sensitivity analysis aims at exploring the impact of parameters' variations on LCOE, especially variation of water prices in this Nexus work. The different variations of parameters explained in *4.2.1.2 Sensitivity analysis* range as follows in terms of LCOE modifications (Figure 17).

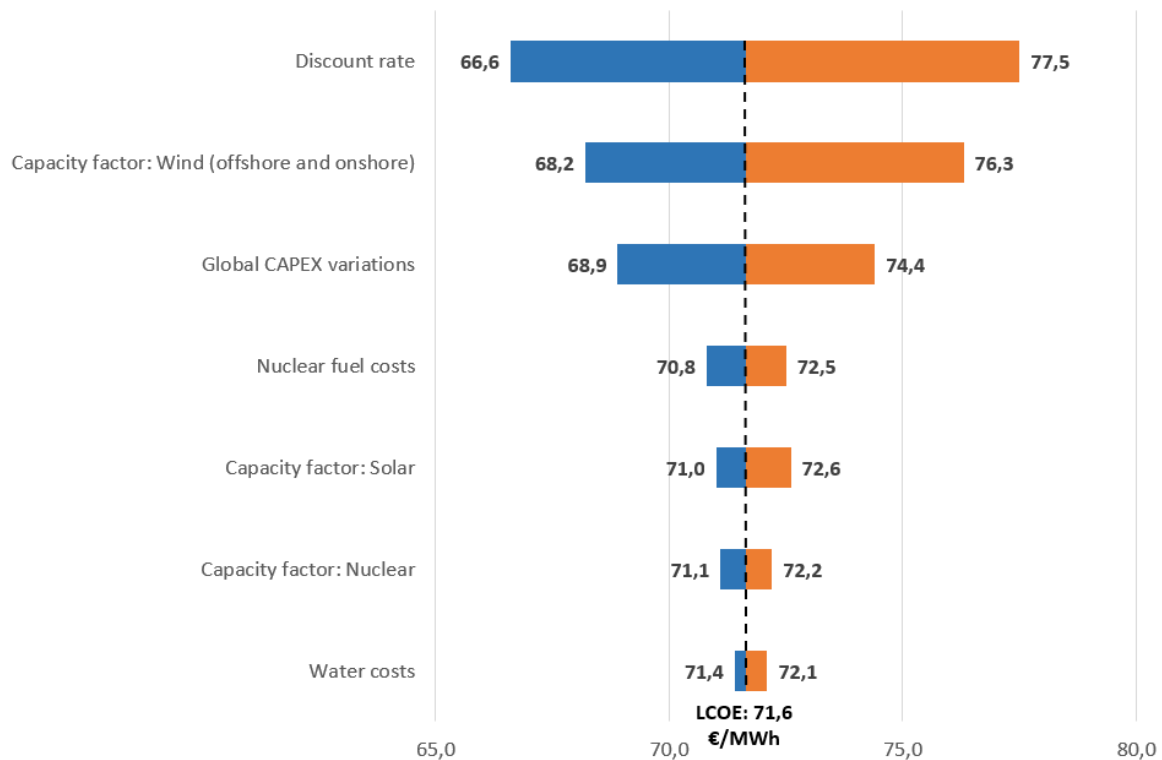


Figure 17 Results of sensitivity analysis

The main potential differences with the base LCOE (71.6 €/MWh) come from the discount rate variations, the capacity factor variations for wind energy, and the global CAPEX variations. This should incite public authorities to focus on these three uncertainties to maintain costs at an acceptable level. Here are examples of potential actions of prevention for each one of these uncertainties:

- Discount rate: the discount rate mainly depends on capital and debt costs (nominal rate), as well as inflation rate (real rate). Therefore, public authorities should be attentive to maintain:
 - Affordable capital and debt costs (for example through debt containment and risks mitigation with projects gathering).
 - Sufficient inflation (to lower real rate, as $r_{real} \approx r_{nominal} - inflation$).
- Capacity factor for wind energy: this capacity factor can be ameliorated by focusing on better prevision of wind characteristics and high availability of wind turbines:
 - Prevision of winds characteristics, for example with data management methods, should allow to adjust the wind turbines parameters to optimize production at instant t.
 - Availability of wind turbines is related to proper natural conditions, as well as performant maintenance. Therefore, the location of the

wind plant should be carefully studied before the project, and maintenance designed for maximizing the production.

- Global CAPEX variations: in order to obtain low investment costs, public authorities can foster grouped purchases, public guarantees on private investments, or foreign trade support for low-cost supplies.

On the contrary, some of the costs parameters have a marginal impact on LCOE and can thus be considered of low interest for public authorities. Among them, water prices range last on the scale of impact on LCOE. Even a multiplication by two of the water prices leads to an increase in LCOE to only 72.1 €/MWh (less than 1% of change). Therefore, with a Nexus point of view, it is safe to state that water prices have a minor impact of the global costs of electricity generation transition towards 2050.

Still, the impact of water prices can be significantly higher for other sectors (industry, agriculture or households). This means that public authorities should focus on these categories when considering the rise in prices and maybe prioritise them in relation to the energy sector.

5.2 Impact of the energy transition on water consumption (assessment of a potential trade-off)

This section presents the results of the research question 2 about the impact of the energy transition on water consumption.

5.2.1 Water consumption from the energy sector in 2020 and 2050

Water consumption demand from the energy sector is available in Figure 18. It shows that it greatly increases in 30 years, from a consumption of around 527 million cubic meters in 2020 to 687 million cubic meters in 2050 (increase of +160 million cubic meters). This consumption in 2050 represents 14% of the current French water consumption (~5 000 million cubic meters [10]), compared to 10% today for energy sector.

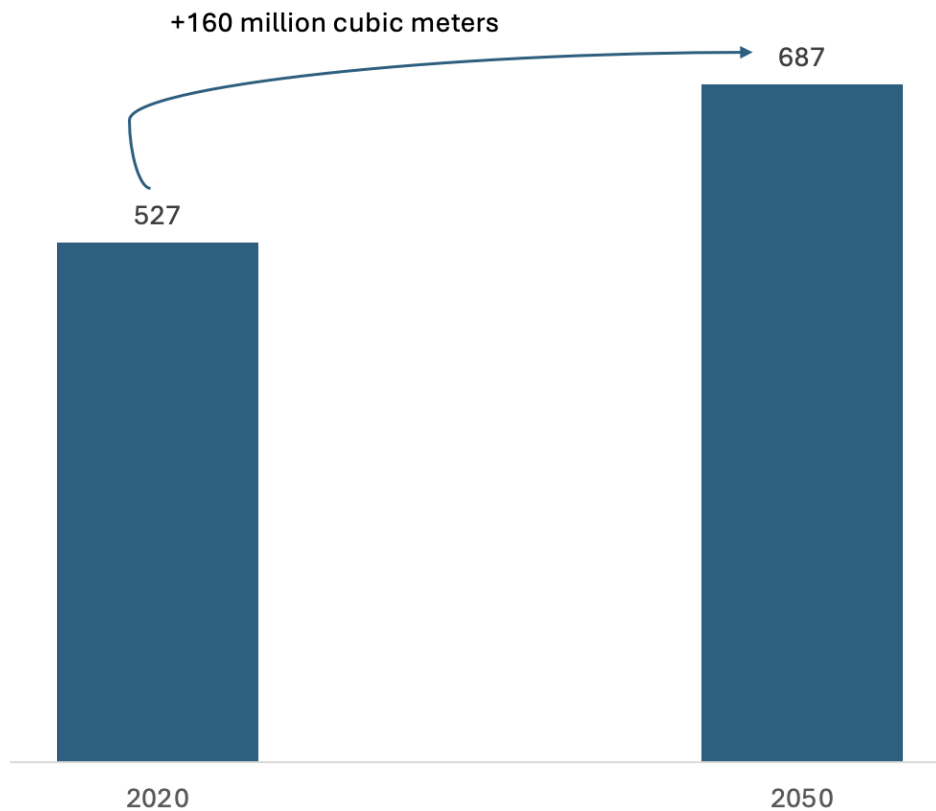


Figure 18 Increase in water consumption due to energy transition (data from [32])

Therefore, unlike price of water for energy costs', water consumption from the energy sector is a potential trade-off to anticipate from now. More specifically, as water availability and quality are largely territorialized (it depends on the studied zone), there is an urge for public authority to map these changes in water availability for different French regions. It is part of the work realized by *France Stratégie* to reflect on the future of water for French prospective, under the authority of the Prime Minister [32].

In this work, as the energy-water nexus is particularly studied from a price and costs point of view, it is interesting to give a first insight into the impact of increase in water demand on water costs. Therefore, it allows to conclude the “loop” initiated in part “Impact of higher water prices on electricity generation costs”. As explained Figure 19, the main objective of this work is to avoid a vicious circle, where electricity transition requires increased amount of water (higher demand in water consumption); in reaction, water prices increase, and thus electricity generation costs increase as well. This vicious circle is mainly unrealistic (see Figure 21), as shown in this work. It is therefore one of the main results obtained through this master thesis development.

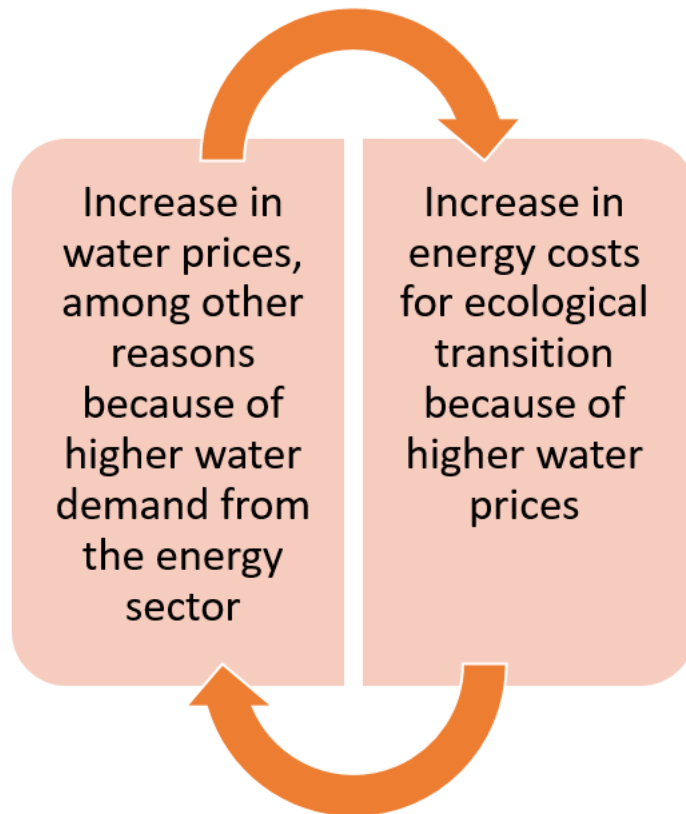


Figure 19 Potential trade-offs to avoid between energy and water

A first and very general evaluation of the potential increase in water prices due to higher consumption demand is to compare the future location of nuclear reactors in 2050 (which represent 96% of the energy water consumption in France, see 4.1.2.2, Impact of energy transition on water demand) with current regionalized water prices. This comparison is available in Figure 20 Comparison of water demand from nuclear reactors and current water prices. The result is quite reassuring: future nuclear reactors are mostly located in regions where water prices are below the current mean (around 4,5 €/m³ on 1st January 2023 [51], so around 4,8 €/m³ on 1st January 2025 under standard inflation [43]). This suggests that even under the influence of nuclear reactor consumption, the price of water in these regions is likely to reach the same price as water in other regions where it is already expensive. The risk of a general price surge due to this factor is therefore limited, and the vicious circle is unlikely to happen (Figure 21 Resolution of trade-offs and avoidance of potential vicious circle).

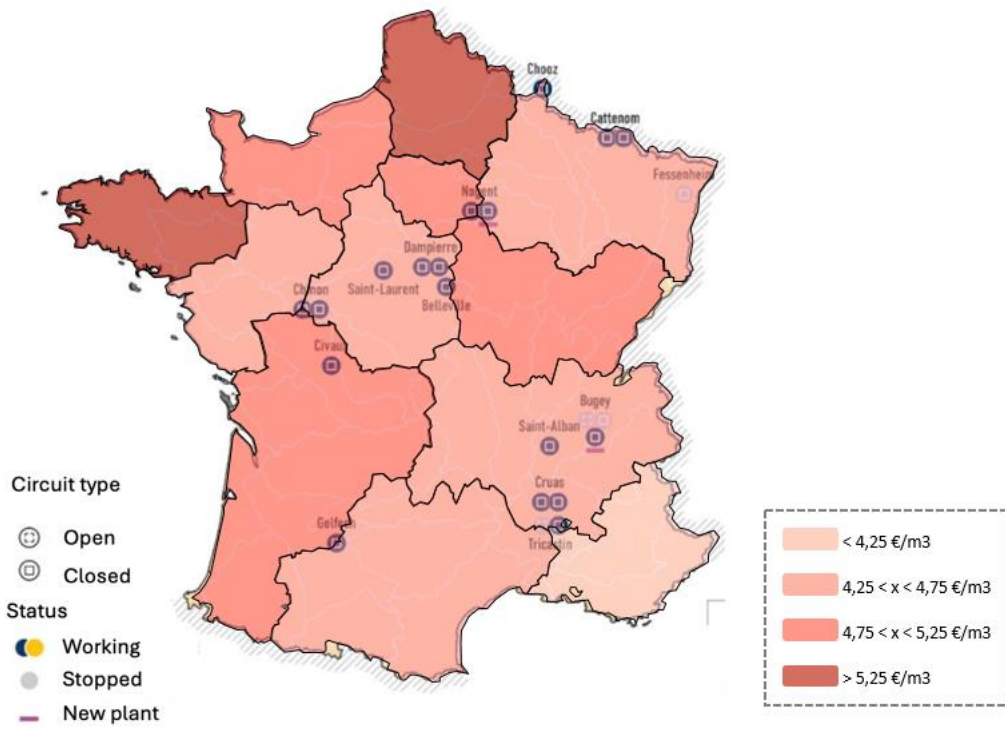
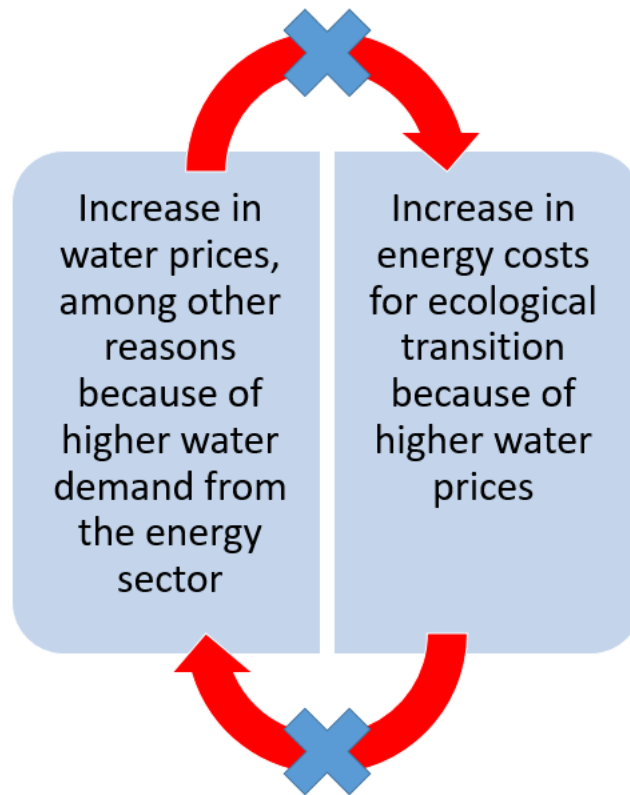


Figure 20 Comparison of water demand from nuclear reactors and current water prices

Sensitivity analysis shows that the impact of increase in water prices has a small impact on electricity generation costs



Regionalized comparison of nuclear reactors and water prices shows that the risk of a sudden rise above the current levels is quite unlikely

Figure 21 Resolution of trade-offs and avoidance of potential vicious circle

5.3 The synergy of water and energy governances – results from a qualitative analysis

This question presents the results of the research question 3 about governances of both sectors.

5.3.1 Expert interviews: the inspiration of the democratic water governance

Apart from data validation (for example for hypotheses on French electricity transition), the expert interviews were used to answer questions about the governances of energy and water sectors. The scheme of interviews is available in part 7 *Appendix*. The objective of the questions is to complete the picture of water and energy governances thanks to the perception of various and representative actors. The answers of the interviews were prioritized into two lessons of interest for governances.

5.3.1.1 Lesson 1: the advantages and disadvantages decentralized versus concentrated governance

As explained in the introduction (Section 1) and the literature review (Section 3), the two sectors have radically different governance structures. The French central government drives energy governance, whereas water governance has several layers of power. The six major French river basins have a “comité de bassin” (basin committee) bringing together local water stakeholders, and have real leeway in terms of tax and financing guidelines.

Water: All four (Actors 1, 2, 3, 6) experts relevant for the water sector mention “decentralization” as a specificity of the water sector, and three on four refer to this local activity as a “strength” of the sector. One of the main reason is due to the challenges faced by the sector in the coming years. In terms of frequency of appearance in the interviews, the identified challenges are “water availability and sharing” (Actors 1, 2, 3, 6); “quality” (Actors 1, 2, 3, 6); “adaptation to climate change” (Actors 2, 3, 6). All these three issues are local driven problematics. It is therefore consistent that democratic local water level is identified as a strength to cope with the coming challenges. On the contrary, “water price and financing” appears only in two interviews (2 and 3). This indicates that it may be underestimated and should thus be more part of the public communication and work of prospective, in order to install this challenge at the core of public policies – both at national and regional levels – in the coming years. The main identified weakness is the “lack of political support”, which is consistent with a decentralized governance: national government especially has few incentives to intervene in a sector without major power to act, but still with risks in public opinion.

Energy: On the contrary, energy sectors is rarely described immediately as a “centralized” or “concentrated” governance. After the specific question, all three (Actors 1, 4, 5) experts relevant for the energy sector recognize that energy governance is concentrated, especially in comparison with other sectors. Among the strengths mentioned, “clear objectives”, “interconnection of major actors” and “government support” appear regularly (actors 4 and 5), even if they all (actors 1, 4 and 5) remark a step backwards recently. All these strengths can be encompassed in the term of *planning*, which is consistent with the centralized form of governance, as it allows setting an objective and sticking to it, without a multitude of actors with diverse interests. On the contrary, they all identify the “dependence to public policy” as a weakness of the sector: a lot of private and local development – especially of renewables – is linked to public support, decided at national level.

5.3.1.2 Lesson 2: Identified synergies and trade-offs between the energy and water sectors

The expert interviews also allow to reflect on the links between the energy and water sectors, especially in terms of synergies and trade-offs.

Trade-offs: The main identified trade-off is “water demand” (Actors 2, 3, 4, 5, and 6), and several experts refer to the summer 2022, when the nuclear production doctrine had to be adapted because river temperature levels exceeded the limit set by law, and water discharges from French power stations increased the temperature. Although this case did not involve a shortage of water, but rather a restriction on use to preserve ecosystems, it highlighted the dependence of nuclear production on water resources. However, the water experts (Actors 2, 3, and 6) remind that energy is only one of the sectors that drive water consumption demand. Especially, agriculture is identified as a potential more important impact in the future. On the contrary, the question of water price for energy costs is not raised. As shown in this work, the contribution of water to electricity generation costs is marginal in the coming year (even in the case of an increase), which validates the fact that actors do not focus on this issue.

Synergies: The main identified synergy identified is territorialisation (Actors 1, 2, 3, and 4), especially in the public sector actors. That is consistent with the scale of action of public policy, which seeks to launch measures at the optimal level. For example, energy is to benefit from a repartition by department of the objectives of deployment of renewable energies, as it is always the case for water policy (Actors 3 and 4). Globally, this refers to a potential weakness of the energy sector: as it is very centralized, it may not adapt to the specificity of each territory and region.

5.3.2 Case in point: the French political instability in 2024-2025

To complete this qualitative analysis, the French political instability of this year provides a case in point. Indeed, energy and water sectors have dealt differently with this instability, which gives a potential insight on resilience of both governances when facing crisis.

5.3.2.1 Energy sector: a national cause

As explained in 5.3.1.1 *Lesson 1: the advantages and disadvantages decentralized versus concentrated governance*, energy policy is often decided at the national level, whether through the government or the parliament. As the current political instability in France is national (lack of stable majority in the Parliament), energy strategy appeared to suffer from this crisis. Two examples illustrate the vulnerability of the energy sector to national crises:

- The price of a tax on electricity, which was due to increase in 2025, was one of the reasons for the rejection of the budget by the far-right opposition and the fall of the government [52]. It confirms the fact that the energy pricing strategy depends on national guidelines and thus suffer to adapt in crisis times.
- The government has announced its intention to pass the energy and network development strategy without a vote in Parliament, i.e. by decree. Here again, the far-right opposition has voiced its discontent, threatening to overturn the government's plans [53]. The energy is becoming a political object, which could lead to a lack of action towards the transformation needed.

Overall, the energy governance deeply suffered from the political crisis, which indicates that energy may be insufficiently resilient to crisis, especially at national level.

5.3.2.2 Water sector: a local cause

On the contrary, the water sector seems to benefit from its local governance in these times of political instability. An example of this is the case of the “Water Conference”. Announced by the Prime Minister Michel Barnier in October 2024, it was to be decentralized in the French river basins, with consultations and debates of the local actors of water, with themes such as water financing, protection against diffuse pollution, repartition of water depending on available resource [54]. This Conference was unable to be held because of the fall of Michel Barnier in December 2024.

Still, his replacement as Prime Minister, François Bayrou, decided to maintain this Conference and its format, even with a change of government. One of the explanations could be that water is sufficiently a local debate not to suffer from the national political changes. As using the Parliament way – through laws for example – is currently complicated, displacing the debate at the local level allows to bypass this limitation.

This supposition is consistent with the conclusions of a recent report on French adaptation to climate change governance. It is stated that water could gain from its decentralization in the current situation of polarization, as “the space for dialogue [in the water sector] then appears broader at the local level, where the politicization of issues is often less” [55].

6 Conclusion and future work

6.1 Concluding remarks

The potential trade-offs between French water and energy strategies could eventually endanger their consistence and their respect of environmental objectives in 2050. The objective of this work was therefore to conduct a proper evaluation of these trade-offs in France, and to objectivize them with quantitative analysis. Narrowing the focus on the economic point of view, two quantitative links are developed. Firstly, the impact of the rise of water prices on electricity costs (with the metric of the Levelized Cost of Electricity - LCOE and its water sensitivity, in €/MWh). Secondly, the impact of energy transition on water demand and thus water price, which completes the trade-off circle of retro-action (energy transition could increase the water demand, and thus water prices, which could eventually increase energy costs because of water requirements to produce energy).

Besides, interviews are performed to evaluate the potential lessons from governance from energy and water sectors, which are very different (centralized vs. decentralized).

The LCOE of the French electrical transition towards 2050 is calculated at 71,6 €/MWh. The sensitivity analysis indicates that water price is the parameter with the least influence on this result, with an increase of LCOE to 72.1 €/MWh when water price doubles for industrials (less than 1% of variation). Demand scenarios from the literature review show that water demand from the energy sector is to increase from a consumption of around 500 million cubic meters (Mm³) in 2020 to 700 Mm³ in 2050. It represents 14% of the current French water consumption (~5 000 Mm³), compared to 10% today. However, this should mainly happen in regions where water prices are quite low. Therefore, there is low risk of vicious circle between the latter trade-offs. Still, water demand is to evolve and will question the repartition of the resource in the context of low availability because of climate change.

The equitable distribution of water resources requires effective governance and decision-making, along with meaningful public involvement. This thesis therefore reveals the exploitation of the specificities of the water sector in decentralized governance, with participatory democracy, and its potential advantages for transition, especially in comparison with the energy sector. The current French political instability is also used to demonstrate the resilience of the water sector, which could be especially useful in the coming years to ensure a fair transition even with different political strategies at the national level.

6.2 Future work

Future work could be further developed in the following three areas:

As availability of water is to evolve because of climate change, the demand part of the water side is incomplete and would need to be accompanied by a prospective work of resource evaluation. It should for example focus on the hypothesis of water scarcity in nuclear plants zones, to evaluate if this may endanger the development of this energy source in France in the coming years, with less water to rely on. Besides, other uses (such as, in housing, leisure, industry) or environmental needs should be used in order to obtain a comprehensive vision of the potential water tensions to come in 2050.

This thesis is carried out at the national level, with average results. Similar quantitative analysis could be performed at the scale of a region or a department, to evaluate if results are still valid, and to evaluate the role of various strategies (e.g., changes in the electricity consumption or production, modification of the agricultural model) to reduce water demand.

This thesis presents an analysis of the strengths and weaknesses of the energy and water sectors, without offering any solutions or proposals. A detailed analysis could be part of future work, considering both quantitative and qualitative analyses in several case studies.

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