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Life cycle assessments of different electricity production scenarios in France with a variable proportion of nuclear energy

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Abstract

The environmental impacts of four French scenarios of electricity production systems are compared. They propose a variable part of nuclear which is essentially replaced by wind and solar energy. The paper proposes a comparison of these scenarios based on a Life Cycle Assessments. The systems with a large part of intermittent wind and solar sources need a higher installed power. In addition, for the same installed power, renewable energies require more building materials than nuclear ones. Therefore, the environmental impacts of infrastructures increase with the part of renewable energy. During the use phase, the environmental impacts of fossil fuels, especially coal, are significant. Consequently, the best systems must use the least fossil fuels and need the lower installed power. Finally, if we exclude the risk of nuclear disaster and if we consider that nuclear wastes are well managed, the electricity production systems that achieve the lowest environmental impacts, with the same availability for the electricity to end users, are those that have a large part of nuclear power.

Keywords: Life cycle Assessment, nuclear, renewables, electricity, wind energy, solar energy, electricity production system, scenario comparison.

1. Introduction

In France, in 2019, nuclear power plants produced 70% of the electricity [1]. The “Energy Transition for Green Growth Act”, voted in 2015, aims at reducing this part to 50%. The French company RTE (“Réseau de Transport de l'Electricité”, which means Electricity Transmission Network) is the French electricity transmission system operator, member of European Network of Transmission System Operators for Electricity, ENTSO-E, that manages the power grid. RTE has studied how to achieve this objective without increasing greenhouse gas emissions. In the whole world, the main sources of energy for electricity production are coal and gas, which emit CO₂, the main greenhouse gas responsible for global warming. Therefore, it is essential to replace nuclear power sources by renewable energies and not by fossil ones. Four scenarios called Ampere, Hertz, Volt and Watt, published by RTE in 2017 [2][3][4][5], plan to reduce the part of nuclear power in the production system, using mainly wind and photovoltaic plants. More recently, RTE published the study “Futurs énergétiques 2050” which presents three scenarios with and three scenarios without new nuclear power in 2050 [6]. In all cases, no more than 50% nuclear power generation is envisaged. The scenarios published in 2017 are therefore still relevant to know which trajectory to consider.

RTE's approach is part of a more general framework defined by the European community and based on numerous scientific studies. A paper published in 2014 focuses on human health impacts of the electricity production system. It shows that nuclear and renewable sources impacts are much below those of fossil technologies [7]. Other recent paper deal with LCA of power plants [8] [9]. The first one focuses on materials and energy requirements for power plant construction and their emissions during

use phase. The second paper applies these concepts in the particular context of the United Arab Emirates. These papers show that the problem is complex and that proposed solutions depend on local contexts.

In France, the large number of installed nuclear power plants create a specific context. A recent report published by the Joint Research Centre (JRC) of the European Commission's science and knowledge service in 2021 [10] provides a deep analysis of the effects of the whole nuclear energy life-cycle in terms of existing and potential environmental impacts, including the safety of nuclear installations and the management of the radioactive waste. This detailed study can be considered as a reference for the LCA of nuclear electricity.

This paper can be part of a sustainable development approach [11]. It focuses only on the comparison of the four RTE's scenarios with the existing system, considering a variable part of renewable intermittent sources. With more intermittent sources that depend on the weather, it is necessary to increase the installed power for obtaining the same available electrical power at any time for end-users. Therefore, the question of the environmental impact of the higher installed power arises. The paper attempts to answer this question, through the analysis of the four scenarios proposed by RTE, over the whole life cycle of the French electrical power production system. The risk of a nuclear disaster is out of the scope of LCAs. Renewable sources more numerous and disseminated over a large territory can modify the structure of the transport and distribution grid, these impacts are not either considered. The study is based in part on the work of Olivier Vidal [12] who analyzed the materials needed for the various means of electricity production. It is also based on the life cycle analysis software Simapro and the Ecoinvent data base.

2. The four scenarios of electricity production in France

The four electricity production scenarios for France in 2035, proposed by RTE, are summarized in Table 1 with data of 2019 [1][2][3][4][5]. The Ampère scenario is generally the most popular because it makes it possible to reduce the part of nuclear energy and CO₂ emissions. The Hertz scenario uses less nuclear energy but keeps CO₂ emissions constant. The Volt scenario produces the lower CO₂ emissions, which makes it popular with decision-makers, but it still requires 56% nuclear energy in production. The Watt scenario, which uses the lower nuclear energy part and the higher renewables sources, leads to increase the part of fossil fuels (gas) and therefore the CO₂ emissions. Ampère and Hertz consider roughly the same electricity consumption in France as in 2019 while Volt and Watt require a decrease of 7% and 13%. However, the Ampère and Volt scenarios consider a much larger production that can be exported to European neighbors. It should be noted that since the publication of these scenarios by RTE in 2017, the French national low-carbon strategy published in 2020 now plans an increase in the consumption of electricity (it is a question of replacing part of the oil and gas by electricity). The Volt and Watt scenarios are therefore now less relevant.

| | 2019 | Ampère 2035 | Hertz 2035 | Volt 2035 | Watt 2035 |
|--------------------------|------|-------------|------------|-----------|-----------|
| French consumption (TWh) | 473 | 483 | 480 | 443 | 410 |
| French production (TWh) | 538 | 635.5 | 536 | 613 | 442 |
| Nuclear production (%) | 70.5 | 46.2 | 47 | 56 | 11 |
| Renewable production (%) | 19 | 49.5 | 45 | 40 | 71 |
| Fossil production (%) | 9 | 4.3 | 8 | 4 | 18 |
| CO2 emissions (MT) | 19 | 12 | 19 | 9 | 32 |

Table 1: overview of French power generation in 2019 and in 2035 with RTE scenarios.

Table 2 gives in detail the installed power (GW) and the annual energy production (TWh) for each scenario. All decrease the installed nuclear power, i.e., the number of nuclear reactors. Out of 58 reactors in France in 2019, there would be less than 8 in the Watt scenario. The three other scenarios stop 9 to 27 reactors. The increase in installed wind and solar power is significantly higher than the decrease in nuclear one. Consequently, the total installed power increases considerably, it is 135 GW 2019, and would reach 179 GW to 209 GW in 2035. Indeed, the wind and the sun are intermittent sources, it is necessary to increase the global installed power for providing, at any times, the electrical energy corresponding to the demand of end-users [13]. In Germany, where wind and solar power have been considerably developed, there has been a significant increase in installed electrical power over the last 20 years: it has risen from 115GW in 2002 to 220GW in 2021, while consumption has remained stable. In France, a scenario published by RTE in 2021 for 2050 [6] envisages a three-fold increase in installed power, i.e. more than 400GW, while consumption would only increase by 35%. These additional infrastructures have an environmental impact that must be considered. These scenarios also require adaptations of the end-user consumption, which are not considered in the proposed study (load shedding and deferral of consumption, savings and control of peaks, improvement of building thermal insulation ...).

| | 2019 | Ampère 2035 | Hertz 2035 | Volt 2035 | Watt 2035 |
|---|-------|----------------|---------------|--------------|--------------|
| French production (TWh) | 537.7 | 635.5 | 536 | 613 | 442 |
| French consumption (TWh) | 473 | 483.1 | 480 | 443 | 410 |
| Nuclear installed power (GW) | 63.1 | 48.5 | 39.1 | 55 | 7.6 |
| Nuclear production (TWh) | 379.5 | 293.8 | 251.9 | 346.0 | 48.2 |
| Onshore wind installed power (GW) | 16.5 | 52.3 | 40.2 | 40.2 | 52.3 |
| Onshore wind power production (TWh) | 34.1 | 115 | 88.1 | 88.1 | 115.0 |
| Offshore wind installed power (GW) | 0 | 15 | 10 | 10 | 15 |
| Offshore wind power production (TWh) | 0 | 47 | 29.1 | 29 | 47 |
| Total solar installed power capacity (GW) | 9.4 | 48.5 | 35.7 | 35.7 | 48.5 |
| Solar roof (GW) | 5.4 | 9 | 13 | 13 | 9 |
| Solar ground (GW) | 4 | 39.5 | 22.7 | 22.7 | 39.5 |
| Solar production (TWh) | 11.6 | 58 | 42.7 | 42.7 | 58 |
| Hydrolic installed power (GW) | 25.6 | 25.5 | 25.5 | 25.5 | 27.5 |
| Hydrolic production (TWh) | 60.0 | 67.8 | 64.6 | 65.5 | 68.4 |
| Biogas biomass waste installed power (GW) | 2.1 | 4.1 | 3.5 | 3.5 | 4.1 |
| Biogas biomass waste production (TWh) | 9.9 | 18 | 15.4 | 15.4 | 18 |
| Marine energies installed power (GW) | 0 | 3 | 1 | 1 | 3 |
| Marine energies production (TWh) | 0 | 8.7 | 2.9 | 2.9 | 8.7 |
| Coal-fired plant installed power (GW) | 3 | 0 | 0 | 0 | 0 |
| Coal-fired plant production (TWh) | 1.6 | 0 | 0 | 0 | 0 |
| Oil-fired plant installed power (GW) | 3.4 | 1 | 1 | 1 | 1 |
| Oil-fired plant production (TWh) | 2.3 | 0 | 0 | 0 | 0 |
| Fossil gas-fired plant installed power (GW) | 12.2 | 12.2 | 22.2 | 9.0 | 33.4 |
| Fossil gas-fired plant production (TWh) | 38.6 | 27.6 | 45.7 | 23.7 | 78.7 |
| Total installed power (GW) | 135.3 | 209 | 179 | 180.9 | 192.4 |

Table 2: installed power for electricity generation in 2019 and in 2035 with RTE scenarios.

3. Assumptions for life cycle assessment

3.1. Construction and end-of-life impacts of power generation systems

The environmental impacts of construction and end-of-life of the various electricity production systems, are computed using two complementary methods:

- The results of the research works of Oliver Vidal [12] are applied, he is a French researcher specialized in mineral resources of energy production systems. He estimated the masses of concrete, steel, copper and aluminum required for building the power generation systems. To do this, he synthesized various scientific studies. His results are of course questionable: there may be significant differences between the different studies. Olivier Vidal specifies that "*Part of this dispersion can be explained by the fact that we considered studies published between 1995 and 2014 and that technologies are evolving very rapidly. Another reason is the measurement itself, which in some cases considers the solar panel or the isolated wind turbine, while other studies integrate interconnections and/or the distribution of electricity to the grid. A final reason is the different technologies*". The values are given in tons per megawatt in Table 3, which we use with Simapro, a life cycle assessment software associated to the Ecoinvent database. This study neglects other necessary materials that masses much lower.
- We use directly Simapro associated to Ecoinvent, after having adapted the input data to the scenarios of the study. In this case we rely on the Ecoinvent database. This is also questionable, especially because of the rapid evolution of some technologies. For example, solar photovoltaic has evolved a lot in recent years and it is possible that we have overestimated some impacts. Several parameters are tuned following several hypotheses:
 - o infrastructure of "hard coal power plant construction 500MW"
 - o infrastructure of "wind power plant 2MW offshore fixed parts" and "wind power plant 2MW offshore moving parts"
 - o infrastructure of "2MW onshore wind turbine"
 - o infrastructure of "Oil power plant 500MW"
 - o infrastructure of "gas power plant 100MW" (Combined-Cycle gas turbine)
 - o infrastructure of "hydropower plant, reservoir, alpine region"
 - o infrastructure of "nuclear power plant, pressured water reactor 1000MW"
 - o infrastructure of "photovoltaic mounting system, open ground module"
 - o infrastructure of "photovoltaic face installation 3kWp single Si", which is a commonly used technology for solar power plants.

Data quality can be debated in LCA [14]. One criticism that can be made of Simapro and the Ecoinvent database is that the environmental impacts of different technologies evolve over time. For example, we know that the EROI (Energy Return On Invested) of photovoltaics has increased in recent years, which means that its environmental impacts have also decreased. It is therefore also relevant to consider the quantities of materials required for each technology. They change little over time, and are largely proportional to the environmental impacts: more materials means more mining, processing, transport, waste, etc.

The study of construction and end-of-life impacts requires to consider the expected lifetime of each installation, which are given in Table 3. These lifetimes are extracted from the study of O. Vidal. For example, this author gives 60 years as the lifespan of a nuclear reactor, which is confirmed by the

French association "Société Française d'Energie Nucléaire" [15] or a recent report by RTE and the International Energy Agency [16]. However, for wind power generators, the expected lifetime is 25 years, as announced by several manufacturers. For biomass and marine energies, which have not been studied by O. Vidal, we have considered 30 and 25 years. Biomass energies concern biogas, wood and wastes, marine energies mainly concern the exploitation of sea currents, waves and tides.

| | nuclear | gas | oil | coal | Onshore wind | offshore wind | roof PV | ground PV | hydro | bio | marine |
|------------------------|---------|------|-----|------|--------------|---------------|---------|-----------|-------|------|--------|
| Concrete (t/MW) | 427 | 68 | 157 | 229 | 422 | 814 | 35 | 564 | 5342 | ? | ? |
| Steel (t/MW) | 55 | 43 | 62 | 78 | 150 | 181 | 88 | 100 | 410 | ? | ? |
| Aluminum (t/MW) | 0.1 | 0.8 | 0.6 | 3.9 | 2 | 2.6 | 24.1 | 30.7 | 12.2 | ? | ? |
| Copper (t/MW) | 1.1 | 0.9 | 1.5 | 1.3 | 4.9 | 4.1 | 6.7 | 5 | 2.8 | ? | ? |
| Life time (years) | 60 | 30 | 30 | 30 | 25 | 25 | 30 | 30 | 80 | 30 | 25 |
| 2019 load factor (%) | 68.7 | 36.1 | 7.7 | 6.1 | 23.6 | // | 14 | 14 | 26.8 | // | // |
| Ampère load factor (%) | 69 | 25.8 | 0 | // | 25.1 | 35.8 | 13.6 | 13.6 | 30.3 | 50.1 | 33.1 |
| Hertz load factor (%) | 73.5 | 23.5 | 0 | // | 25 | 33.1 | 13.6 | 13.6 | 28.9 | 50.1 | 33.1 |
| Volt load factor (%) | 71,8 | 30.1 | 0 | // | 25 | 33.1 | 13.6 | 13.6 | 29.3 | 50.1 | 33.1 |
| Watt load factor (%) | 72.4 | 26.9 | 0 | // | 25.1 | 35.8 | 13.6 | 13.6 | 28.4 | 50.1 | 33.1 |

Table 3: masses of materials for the construction of means of electricity production, lifetime, and load factors.

Our work is based on a period of 60 years. Consequently, the impacts of the construction of power plants that have a life span of 25 years are multiplied by 2.4. For those with a life span of 30 years, the impacts are multiplied by 2. For hydroelectric powerplants, which lifespan is 80 years, the impacts are multiplied by 0.75. In the real life, the power generation system never stays the same for 60 years. However, for comparing the systems assumptions on identical basis must be made.

The last five lines of table 3 give the load factors deduced from table 2. The load factor is the ratio between the real average power and the installed power. Therefore, for wind farms and photovoltaic ones, the load factor depends essentially on wind and sun. For the other controllable production systems, it depends on maintenance shutdowns but also on the grid control system, which adjusts, at any time, the production to the actual consumption, it should be remembered that electricity is difficult to store [17].

Figure 1 is a graphical representation of O. Vidal's data providing a comparison of the quantities of basic material required for building each production systems. It appears that renewable sources require more materials per megawatt than traditional ones. Wind and photovoltaic sources require more copper while hydroelectricity requires more concrete and steel. Scale factors are used for getting a readable figure (0.1 for concrete, 1 for steel, 10 for aluminum and 100 for copper).

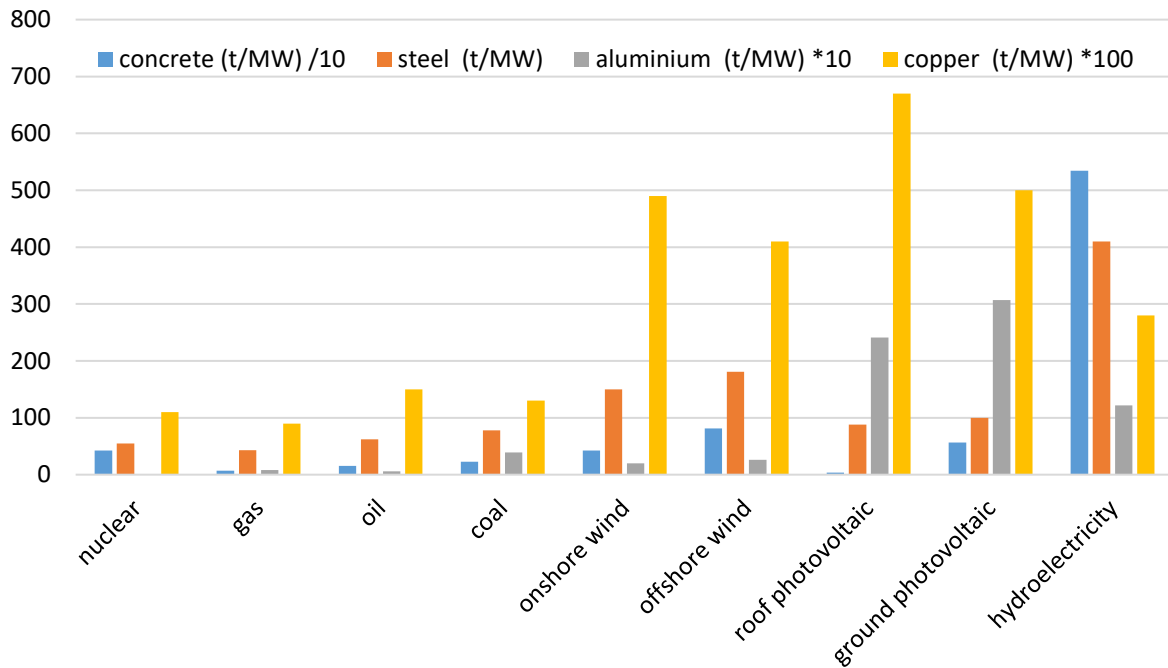


Figure 1. Comparison of the quantities of concrete, steel, aluminum and copper in relation to the installed capacity (values from Oliver Vidal [12]).

The quantities of building materials must be related to the energy production (MWh) rather than the installed power (MW). Figure 2 compares the quantities of materials required for producing 1 MWh of electricity, taking into account the load factors of the Ampere scenario and the lifetimes of table 3. Units are 10^{-1} kg /MWh for concrete, 10^{-2} kg/MWh for steel and aluminum and 10^{-3} kg/MWh for copper. The differences between renewable sources and the other ones are larger. This presentation should be taken with caution because the material demands for the fuel supply chain for nuclear and gas are not included. However, for nuclear, it is known that uranium mining represents a minor amount compared to the importance of a nuclear reactor construction.

For several production systems, data are not available; several hypotheses are made in the continuation of this study. For the production systems based on biomass, we consider that they require the same material quantities as fossil gas power plants. For marine energies, we consider the quantities of offshore wind power. These assumptions probably have a small influence on the results since these electricity sources are not widely used in RTE's scenarios, but this point remains to be verified.

Figure 3, based on Tables 2 and 3, compares the quantities of materials required for building the all power plants that correspond to the five scenarios. It appears that the Ampere and Watt scenarios require the larger amount of materials while the 2019 system requires the least. These results are not surprising since Ampere and Watt require the larger installed power.

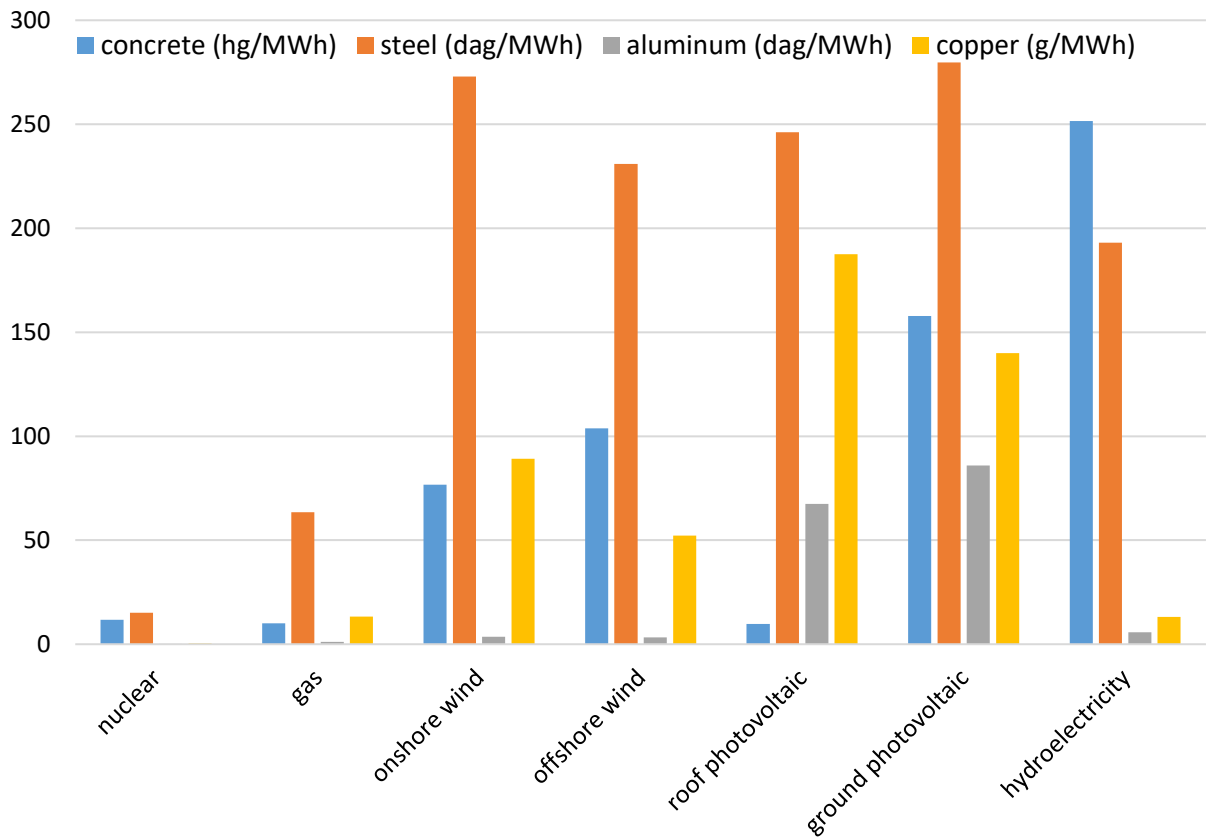


Figure 2. Comparison of the quantities of concrete, steel, aluminum and copper in relation to electricity production (power factors from Ampère and lifetimes from table 3).

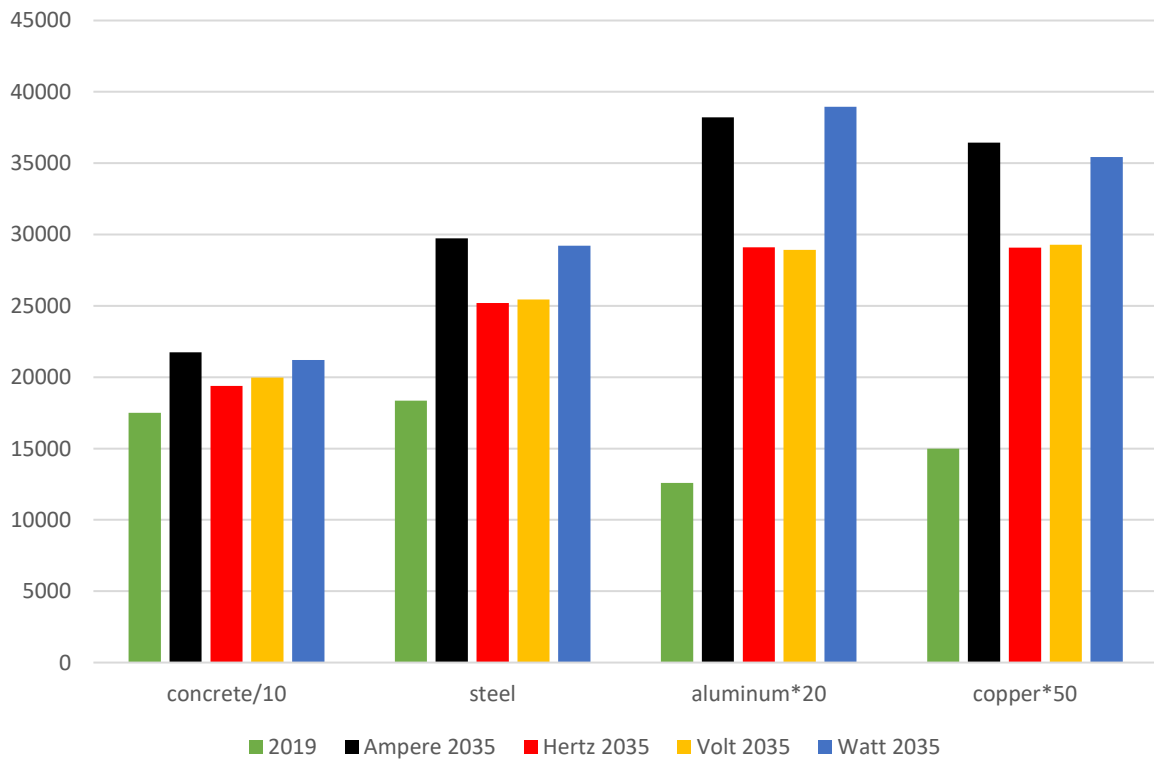


Figure 3: quantities of concrete, steel, aluminum and copper with the French electricity production system in 2019, and with RTE scenarios, in Mt.

3.2. Selected configurations for Life Cycle Assessments

The goal is to compare the environmental impacts of several ways of producing electricity, by varying the share of nuclear and renewable energies. The selected configurations for Life Cycle Assessments make it possible to estimate the environmental footprint of the system by considering the extraction of raw materials, transport, manufacture, use and end of life. Simapro software is used to perform this analysis; it uses the Eco-Invent database (version 3.5, November 2018). Many LCA methods exist, we use the "CML-IA baseline" method which is often used by specialists. The CML method is proposed by Center of Environmental Science of Leiden University. We use the attributional LCA-A method, assuming a static system [18] with allocation point of substitution, but the consequential LCA-C method give similar results. The functional unit is "produce the electricity needed in France for 60 years". The global geographical location has been chosen: the minerals and materials used in the construction of power plants can come from all over the world. The considered end of life is the classical "waste scenario in France" considered by Eco-invent (the database contains Life Cycle Inventory data on energy systems, transport systems, waste treatment systems, chemicals, building materials...).

Eleven impact categories are classically considered by the CML method:

- The abiotic depletion refers to the depletion of nonliving (abiotic) resources. Most abiotic resources are non-renewable. The first category concerns only the minerals.
- The second category of abiotic depletion concerns the fossil fuels. Fossil fuels are not only a problem because of their CO₂ emissions and pollutants, but also because of their scarcity. Experts do not all agree on the imminence of a production "peak", but it is clear that the lack of supply compared to demand has already had serious economic consequences.
- The global warming concerns the anthropogenic greenhouse gas emissions caused by the emissions of human activities. The human emissions of greenhouse gases, such as carbon dioxide (CO₂) and methane enhance the heat radiation absorption of the atmosphere, which results in the rise of the earth's surface temperature. This criterion is now of prime importance. Many countries, including France, have committed to achieving carbon neutrality by 2050.
- The ozone layer depletion is the thinning of the stratospheric ozone layer as a result of anthropogenic emissions. This causes a greater fraction of solar radiation to reach the Earth's surface, with a potential damage to human health, ecosystems, biochemical cycles and materials.
- The human toxicity covers the impacts on human health of toxic substances present in the environment. This calculated index that reflects the potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of a compound and its potential dose.
- The aquatic eco-toxicity category covers the impacts of toxic substances on aquatic ecosystems. Aquatic toxicity in general refers to the effects of a chemical on organisms living in water and is determined with organisms representing the three trophic levels: Algae or plants, Invertebrates, Vertebrates, representing "secondary consumers". The first category concerns only the fresh water.
- The second category of aquatic eco-toxicity concerns the marine eco-toxicity.
- The photochemical oxidant indicator describes the formation of reactive chemical compounds from certain air pollutants by the action of sunlight. Toxic gases may appear on sunny days.

- The acidification: the acidity of water and soil systems can be increased due to acid deposition from the atmosphere, mainly in the form of rain. Sulphur dioxide (SO₂) and nitrogen oxides (NO_x) emitted by combustion processes are responsible for most acid deposition, commonly called "acid rain". Potential consequences are forest decline, soil acidification and damage to building materials.
- Eutrophication occurs when there is an increase in the concentration of nutrients, mainly nitrogen and phosphorus in water or soil. It leads to a reduction in species diversity as well as changes in species composition.
- Terrestrial eco-toxicity refers to the impact of toxic substances emitted to terrestrial ecosystems, in air, water and earth. Terrestrial eco-toxicity chemicals can be emitted to the environment during all life cycle stages of products, services and systems. Emission inventories of different products may contain hundreds of chemicals, of which many will have the potential to cause ecotoxic impacts on aquatic and terrestrial ecosystems, leading to damages on ecosystem quality.

The choice of impact indicators is complex. What are the most important environmental criteria? The CML method is one of the most recognized, but it does not rank the impacts among themselves. This would be difficult because each impact has its own unit (CO₂ for global warming, Joules for fossil fuels, Sb for abiotic depletion, CFC for ozone...). Perhaps some criteria should be considered more important than others. Global warming, for example, is currently considered a fundamental and urgent problem and it is known that the generation of electricity in the world contributes largely to it. On the other hand, eutrophication is probably not caused significantly by electricity production.

4. Impacts of installations alone (construction and end of life).

As the Simapro software has been filled in with the previous data, we can make comparisons. Initially we are only interested in the impacts related to the installed power (namely construction and end of life), regardless of use period of the equipment during its lifetime. Figures 4 and 5 compare the five power generation systems with the 11 criteria. Figure 4 is based on the Simapro/Eco-invent infrastructure, while Figure 5 is based on the quantities of concrete, copper steel and aluminum of O. Vidal (Figure 3). Results are presented with a relative value to the higher impact which is arbitrary set to 100%. It should be noted that this presentation in percentages makes it possible to compare systems on each criterion, but may mask the relative importance of one criterion compared to another.

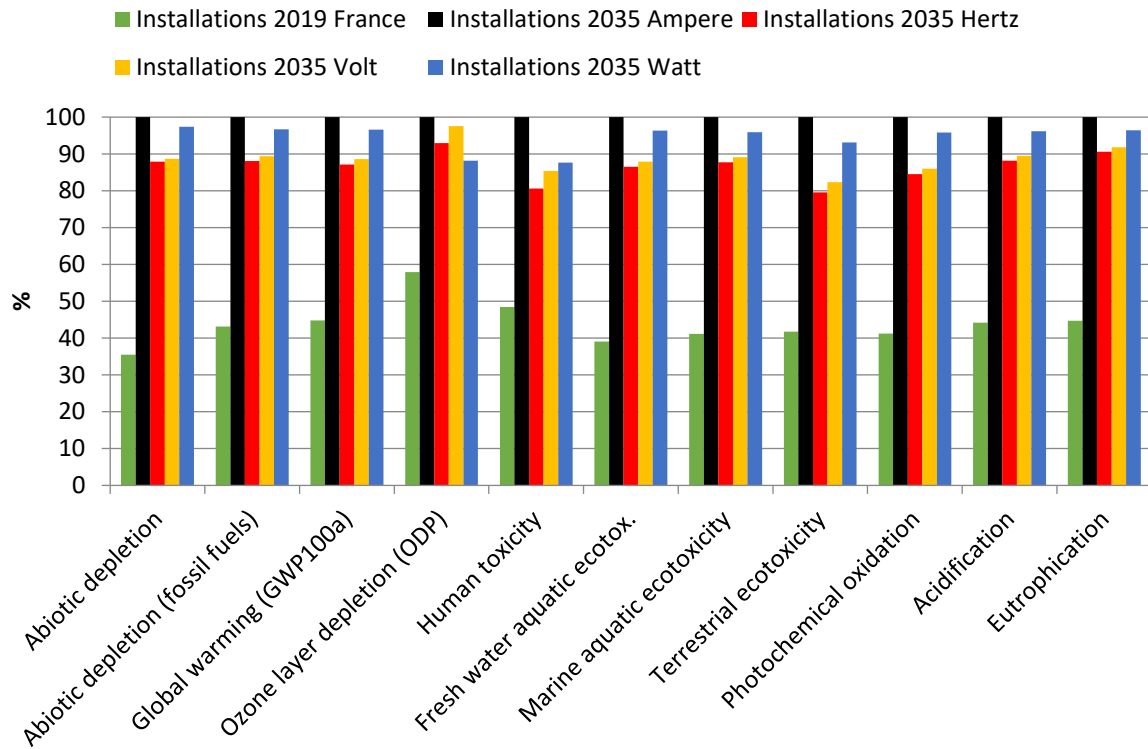


Figure 4. Impacts of system infrastructures, based on data from Simapro/Ecoinvent and CML criteria.

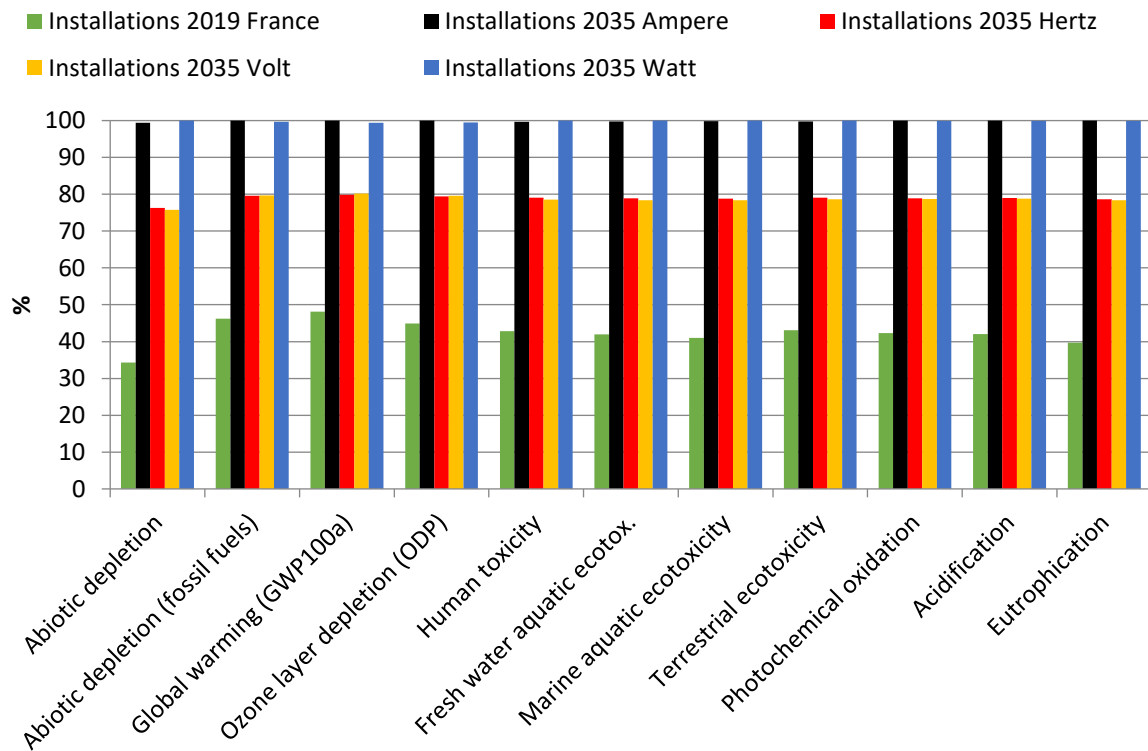


Figure 5. Impacts of system infrastructures, based on quantities of concrete, copper steel and aluminum, according to Simapro/Ecoinvent and CML criteria.

With both methods and considering only the construction and end-of-life impacts of infrastructures, the production system used in France in 2019 is the best for environment (green lines). The Ampere and Watt scenarios require more installed power, they have the largest impact. The differences would be even greater if the necessary power grid reinforcements would be included. In particular, since the Ampère and Volt scenarios require more exports, they require more transmission lines not studied here. Of course high voltage lines and associated transformers add environmental impacts, these are difficult to assess as the additional need for electricity transmission is difficult to evaluate. However, it is clear that the increase in wind and solar power production implies an increase in electricity exchanges in Europe and therefore in transmission lines. Note that the environmental footprint linked to the elimination of radioactivity during the dismantling of nuclear power plants does not appear here due to the lack of data.

5. Complete environmental balance, including infrastructure and use phase

5.1. Additional CO₂ emissions caused by use phase

The aim of this section is to verify that the CO₂ emissions due to use phase are preponderant and that the increase of installed power does not change the conclusions. The global CO₂ emissions for the 2019 electricity production system and for the four RTE scenarios are presented in table 4. The values for the infrastructures are calculated by Simapro/Eco-invent, they correspond to the “global warming” of the performed LCA. The annual emissions of the use phase are those of RTE (table 1); they are multiplied by 60, and the emissions of the infrastructure are added to have the global emissions over 60 years.

| | 2019 | Ampère 2035 | Hertz 2035 | Volt 2035 | Watt 2035 |
|---|-------------|----------------|---------------|--------------|--------------|
| Infrastructure emissions computed by Simapro (Mt of CO ₂) | 110 | 248 | 216 | 220 | 240 |
| Annual operating emissions according to RTE (Mt of CO ₂) | 19 | 12 | 19 | 9 | 32 |
| Operating emissions for 60 years (Mt of CO ₂) | 1140 | 720 | 1140 | 540 | 1920 |
| Total emissions, infrastructure + use phase (Mt of CO ₂) | 1250 | 968 | 1356 | 760 | 2160 |
| Total emissions per years (Mt of CO₂) | 20,8 | 16,1 | 22,6 | 12,7 | 36,0 |
| Relative part of emissions due to infrastructure (%) | 8,8 | 25,6 | 15,9 | 28,9 | 11,1 |

Table 4: influence of the infrastructures on the global CO₂ emissions for the 2019 electricity production system and for the four RTE scenarios.

It can be seen that the part of infrastructure is relatively high in the Ampere and Volt scenarios, which require a more installed power and use less fossil fuels. This higher part increases their total emissions but does not change the results which are still dominated by use phase. Considering the global CO₂ emissions Volt remains the best scenario and Watt the worst. Note that the French system in 2019 uses some coal, which emits a lot of CO₂, while the other scenarios do not.

This result is not surprising since Volt makes little use of fossil fuels and more use of nuclear power. This energy is low in greenhouse gas emissions [19][20]. However, this gain must be put into perspective because CO₂ equivalent emissions from the whole French energy sector (including oil and gas from transport and heating) were 299 Mt in 2019 [21], while the country's greenhouse gas emissions (including agriculture, waste and industrial processes) were over 400Mt [22].

The influence of use phase on other environmental impacts must also be considered.

5.2. Overall impacts of the power generation systems, due to infrastructure and use phase.

Simapro allows us to know the impacts of the infrastructure alone in relation to the installed power in Watts (presented Figure 4); or the impacts of the infrastructure and the use phase in relation to the energy produced in Watt-hours. Therefore, we use Simapro's data concerning the environmental impacts of the infrastructure and use phase of each electricity production mode. They are presented in Figure 6 with the CML criteria for the same amount of electricity produced.

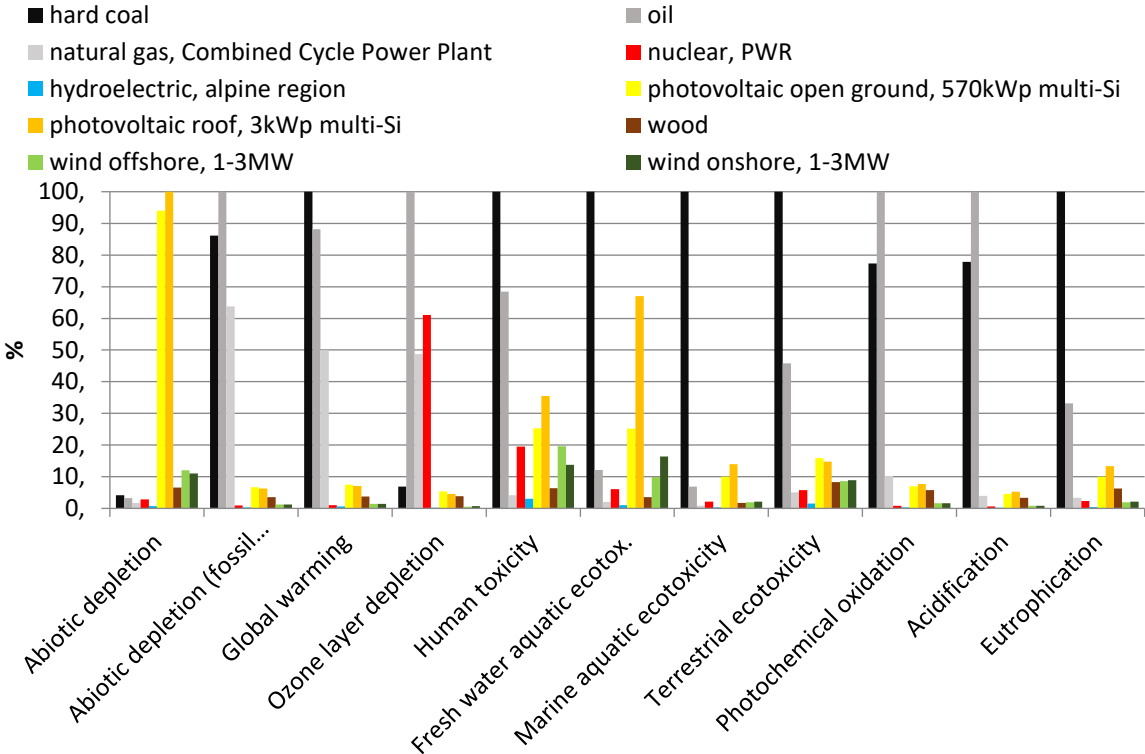


Figure 6. Comparison of CML environmental impacts of the production of the same electrical energy, computed by Simapro/Ecoinvent, for the 10 considered primary energies.

Coal and oil are unsurprisingly the most polluting primary sources (black and gray lines). Natural gas emits important greenhouse gases (global warming). Nuclear power seems quite bad concerning the ozone layer depletion. Nevertheless, it seems that these impacts were due to the use of CFCs as a coolant in uranium enrichment plants by gaseous diffusion. CFCs have now been banned and, above all, this enrichment technique is being replaced by centrifugation. This is undoubtedly why the recent report by the European Commission's Joint Research Center does not confirm these bad results concerning the impact of nuclear power on the ozone layer [10]. The impacts of photovoltaics are not

minor. This energy source seems globally the most polluting after fossil fuels because of the high environmental cost of the infrastructure for a given energy production. The least impacting energy source is hydraulic. These conclusions are globally confirmed by the recent report of the Joint Research Center of the European Community [10].

The global environmental impact (infrastructure + use phase) of each scenario can be evaluated with the 11 CML criteria using Simapro/Eco-invent and considering the produced annual energy of the scenarios (Table 2). The scenarios that have a higher production exported out of France have a small disadvantage; the proposed method favors the Watt scenario, and disadvantages slightly the Volt and Ampere ones when the European market is able to absorb the full production capabilities. Results are presented in figure 7.

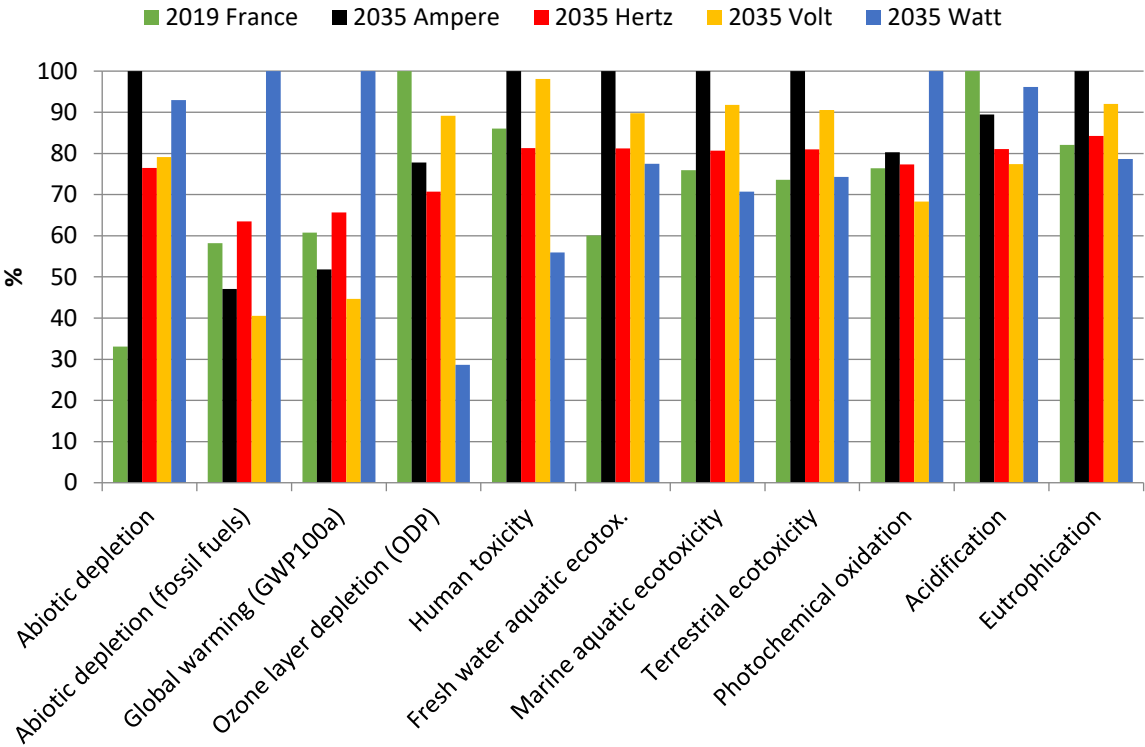


Figure 7. CML environmental impacts of use phase and infrastructures, computed by Simapro/Eco-invent.

The Ampere scenario often appears to be the worst. The 2019 system is on average the best. Hertz, Volt and Watt are close, but Watt emits more greenhouse gases because it uses more fossil gas. As coal and oil will disappear from the future electricity mix, it is interesting to replace them in the 2019 system by gas. This one allows a controllable production while polluting less than coal and fuel [7]. These results are presented in Figure 8.

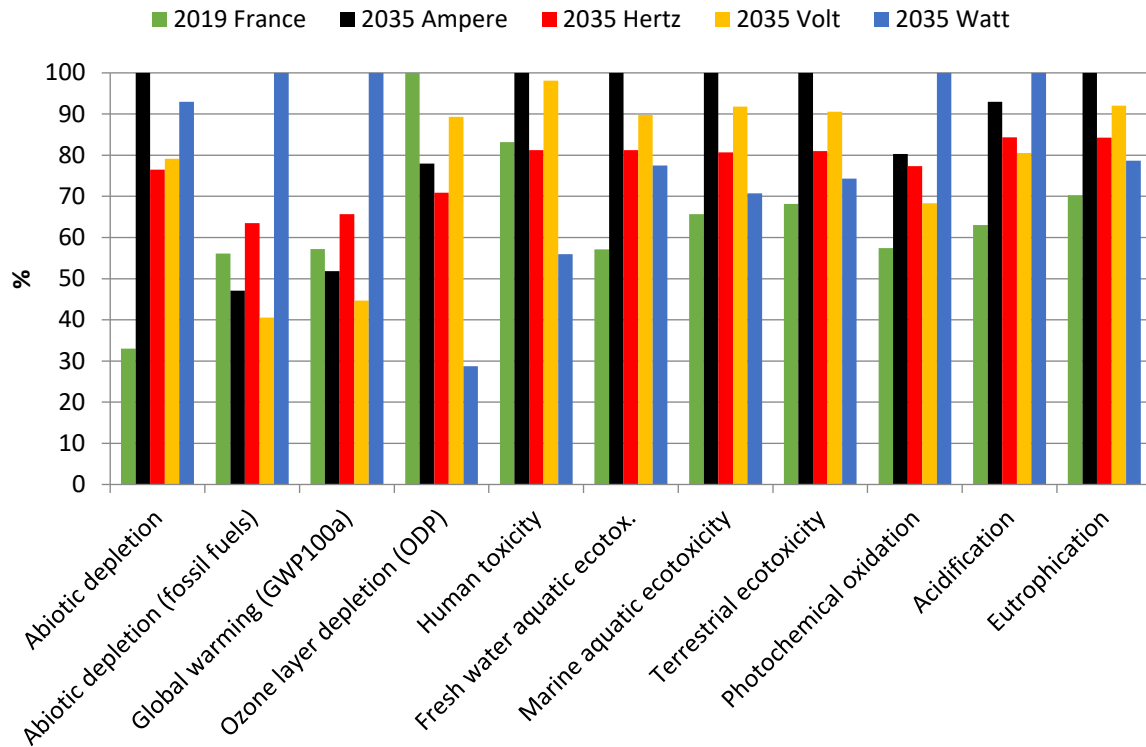


Figure 8. CML environmental impacts of use phase and infrastructures, computed by Simapro/eco-invent, when coal and oil of 2019 are replaced by gas.

With gas instead of coal and oil, the 2019 system is clearly the best for the environment: it then leads on 7 of the 11 criteria. Coal and oil are not largely used in the 2019 system, but they are so polluting that their impacts are significant. The worst performing scenario remains Ampere, which requires the highest installed power, followed by Watt, which is four times the worst although its production is lower. Regarding only greenhouse gas emissions, Volt remains the best. So the 2019 and Volt systems, which use the larger part of nuclear power, seem to be the best for the environment. However, it should be pointed out that they produce more nuclear waste that does not appear here.

In order to consider other environmental criteria, including ionizing radiation of nuclear power plants, the RECIPE criteria can be used instead of CML ones. The results presented in figure 9 are computed by Simapro/Eco-invent using RECIPE midpoint criteria [23].

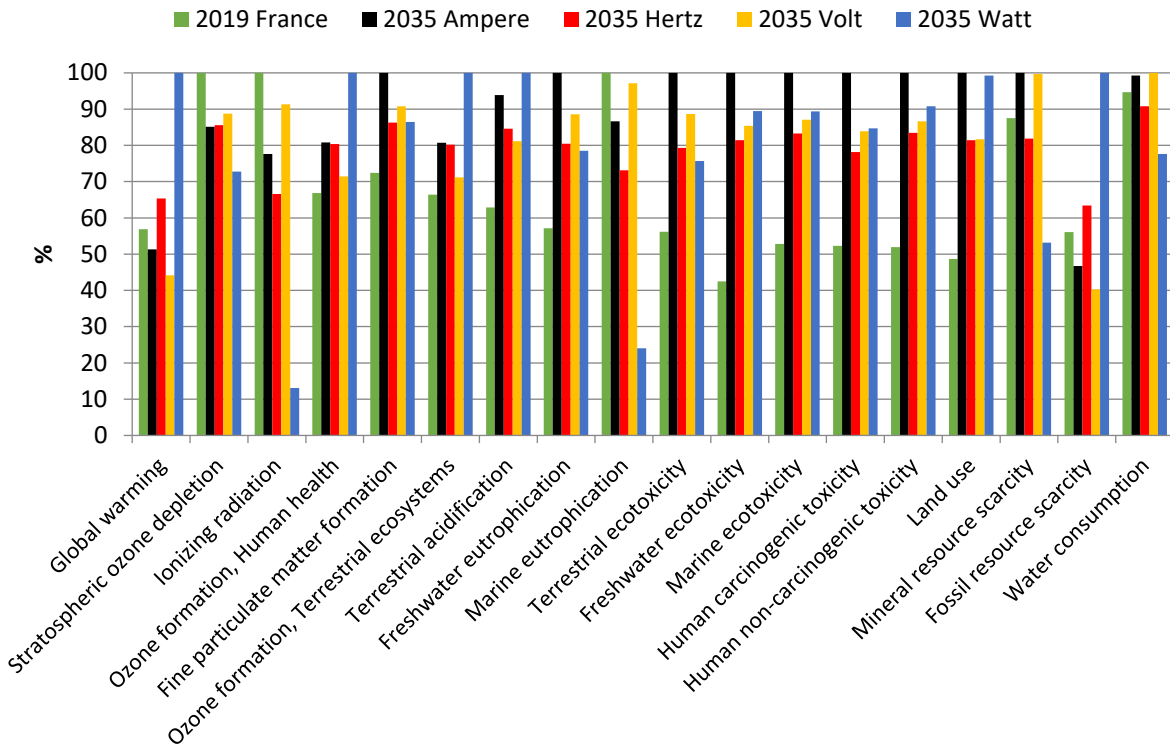


Figure 9 : RECIPE environmental impacts of use phase and system infrastructures when coal and oil of 2019 are replaced by gas.

The 2019 system is also the most advantageous: it is the best on 11 of the 18 RECIPE criteria. It is the one that uses the most nuclear energy and therefore emits the most ionizing radiation. This being said, ionizing radiation during normal nuclear use phase has little impact on living organisms. The risk of a nuclear disaster, like any other accident risk (hydraulic dam failure, gas explosion...), can hardly be taken into account by LCA.

Ampere comes in last position 10 times and remains the worst. Watt is in first position for 5 criteria and the last for 6. It is more difficult to make a difference between Hertz and Volt, but it should be remembered that Volt is at a disadvantage because of its higher production used for exportation (613 TWh compared to 536 TWh), while its installed capacities are almost the same.

6. Conclusion and Policy Implications

The Ampere scenario is, in France, the most highlighted as an objective for the electrical system in 2035. It reduces annual CO₂ emissions from electricity production by 22.5% compared to 2019 and it reduces the part of nuclear energy to 46%. However, the significant increase in installed power is leading to an increase in a lot of environmental impacts. Ampere is the worst scenario on many environmental criteria as land use, fine particulate, eutrophication and many toxicities.

The Watt scenario, which depends the least on nuclear sources, produces less ionizing radiation and nuclear waste. But it uses the largest installed and fossil gas. It is the worst according to several criteria, in particular that of global warming. Moreover, it considers a decrease in electricity consumption incompatible with the objectives of decreasing oil and gas consumption in France.

It is more difficult to distinguish between Hertz and Volt which seem similar. However, Volt's electrical production is more important and can be exported to contribute to a cleaner European production. Moreover, if the priority is the limitation of global warming, Volt emits 44% less greenhouse gas than Hertz.

Among the 4 scenarios planned by RTE for 2035, Volt seems to be the best environmental compromise. It still requires 56% nuclear power in the production of electricity and does not strictly respect the law that imposes less than 50% nuclear power in electricity production. The nuclear production decreases only by 9%. This decrease is largely due to an increase of the total electricity production.

Ultimately, the best way to limit greenhouse gas emissions and most of environmental impacts would be to keep the 2019 generation system, simply replacing coal and oil-fired plants with gas-fired plants. Volt and 2019 are the systems that rely on the largest nuclear power. Accepting the disadvantages of nuclear power, they are the best for the environment. If it is accepted that the low levels of ionizing radiation from the nuclear industry (excluding accident) have a negligible impact on life, that the risk of accident (not considered in this study) is acceptable, and that nuclear wastes are well managed, the systems relying on the larger nuclear part appear to be the best for environment. The conclusions of the RTE reports published in 2021 [6] are in the same direction because they show that systems without nuclear power require more copper, aluminum, or steel than systems with nuclear power. Similar findings were obtained, for example, for South Korea [24]. Concerning only CO₂ emissions, recent RTE reports [6] for 2050 confirm this trend: the scenarios with nuclear power emit slightly less CO₂ than the scenarios without. Note that the scenarios studied in this paper do not require battery or hydrogen storage, which would amplify the environmental impacts.

The proposed electricity production scenarios are based on several sciences: mechanical engineering for wind turbines and hydraulic production, carbon chemistry for the coal fuel and gas, microscopic scale quantic physics for the photovoltaic cells and nuclear physics based on fission for the nuclear power plants. Human knowledge about nuclear energy is recent and not well understood by the general public, chain reactions can have serious consequences. On the other hand, there is a confusion between military and civil nuclear energy. Consequently, the nuclear industry may appear as more dangerous and societal decisions are made considering more criteria than environmental impacts [25]. The reduction of the nuclear part to 50% for the French electricity production system has been taken in this wider context and not only according to environmental drawbacks.

A non-negligible part of the global environmental impact of the electricity production system depends on the intermittence of wind and solar production and on the variations of the instantaneous power required by the end-users. This problem is linked to the practical difficulty of electrical energy storage and to the difficult changes of end-user demands. At a longer time scale the context may change with deep societal changes [26]. Several international research works on resilient grids propose challenging solutions where the consumption is more flexible [27]. In particular electric cars could have a more active part [27]. These long-term solutions suppose more electric cars connected to the grid when they do not move [28], a dynamic pricing, with negative financial sanctions during the peak hours.

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