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Environmental Impacts of Different Electricity Production Scenarios in France

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Abstract

This study focuses on the environmental impacts of the electricity production scenarios proposed for France for 2060 by the French electricity network manager, RTE. They consider an increasing electricity consumption and a production without fossil fuels, essentially based on wind, photovoltaic, hydraulic, and, for some, nuclear power. The total power to install is significantly higher than the current one; it is higher in the scenarios that rely more on photovoltaic and less on nuclear. Renewable energies require more materials than nuclear, especially photovoltaics. The Simapro Life Cycle Assessment software is used, associated with the Ecoinvent database and CML criteria. Generally, photovoltaic electricity production, which needs more installed capacity, has a more significant impact on the environment, while hydraulic power has less effect. Based on the energy produced as well as on the installed capacity, neglecting the risk of nuclear accidents and nuclear waste management, fossil fuels being excluded from the comparisons, the scenarios that require nuclear power have less environmental impact; those that rely more on photovoltaic power have more environmental impact. For example, CO_2 emissions would range from 6.8 to 10.4 g per kWh from one scenario to another. This study can be helpful for policy-makers who have to choose future ways of generating electricity.

Keywords
Life cycle assessment; nuclear; renewables; electricity; electricity production system; scenario comparison; environmental impacts

1. Introduction

This study compares the environmental impacts of different electricity generation systems in France with varying proportions of wind, photovoltaic, and nuclear power. The French electricity mix is currently primarily based on atomic energy. By 2060, most electricity production installations will have been replaced because they are too old. On the other hand, within the context of the French National Low Carbon Strategy [1], electricity will have to replace a part of gas and oil used for transport and heating, leading to an increase in its consumption. This strategy of electrification to decarbonize can be found in many countries: the International Energy Agency predicts that global electricity consumption will more than double by 2050.

Several authors and organizations are considering future electricity mixes in different countries [2]. The French company RTE ("Réseau de Transport de l'Electricité", which means “Electricity Transmission Network”) is the French electricity transmission system operator, a member of the European Network of Transmission System Operators for Electricity, ENTSO-E, that manages the power grid. RTE published a significant report in 2021 and 2022 entitled "Futurs énergétiques 2050" [3, 4], in accordance with the French national low-carbon strategy, which considers several scenarios for electricity consumption and production in France in 2050 and 2060. This report is in accordance with the French Nationally Determined Contributions from the Paris climate agreements [5]. This study is based on this report. In its reference scenario, RTE expects a 35% increase in French electricity consumption compared to 2019. This projection is modest: at the European level, ENTSO-E is forecasting a more than doubling electricity demand. According to RTE [3], taking into account electricity requirements for hydrogen production by electrolysis, the increase in electricity consumption could reach 100% in Germany, 200% in the UK, and even more than 300% in the Netherlands, for France, RTE announced in 2023 that the increase would probably be faster than expected.

It will therefore be necessary to rebuild a production system that is able to produce more electricity. RTE has studied six production scenarios [3], which are essentially based on wind power, photovoltaic, hydraulic, and nuclear power, with varying shares. The objective of this study is to compare the environmental impacts of the different scenarios using Life Cycle Assessment (LCA). This study is based on RTE values in its scenarios and the Simapro software associated with the Ecoinvent database. It is known that environmental impacts are often related to the quantity of materials used. Renewable energies have limited impacts during their operation phase, but they have impacts related to the construction and end of life of the infrastructure.

Many studies examine the environmental impact of electricity generation methods [6], but few attempt to consider a country's entire generation system over a long period [7-10]. That's what this study attempts to do. RTE has studied some environmental impacts of the transition from the current system to the future and has looked at the required materials. The approach here is different: a fixed system is considered over a long period to determine the best system in the long term, and some environmental impacts are compared.

First, the assumptions and the context of the RTE scenarios will be presented. Then the environmental impacts in relation to the energy produced, or in relation to the installed power, will be compared. This study contributes to estimating the best choices for future electricity generation.

2. Assumptions and Context

2.1 The RTE Scenarios

RTE's scenarios aim at an electricity system that will enable France to move away from fossil fuels and become carbon neutral by 2050 as part of the fight against global warming. They were published in 2021 and 2022 following several years of work and consultations with numerous partners.

French electricity production, primarily based on nuclear energy, emits relatively little CO_2, but electricity represents only 25% of the final energy consumed. In 2050, within the framework of an energy efficiency policy largely based on the electrification of transport, heating, industrial processes, and hydrogen production, electricity would represent 55% of the final energy consumed. Annual electricity consumption would increase from 475 TWh in 2019 to 645 TWh in the consumption reference scenario. In 2024, French electricity consumption had not yet begun to grow, at 449 TWh. This projected increase of 35% is relatively small. On average, other European countries expect electricity consumption to double [3], but the share of electricity energy consumption is already higher in France than in different European countries (25% versus 20%).

French nuclear power plants were mainly opened in the 1980s and 1990s and will probably be closed after 60 years. They must, therefore, be replaced by a system that can produce more electricity. As there is no intention to use fossil fuels in the future, the question is whether a 100% renewable system is feasible and preferable, or whether new nuclear reactors should be built. In the 6 considered scenarios, renewable energies represent at least 50% of the electricity production: RTE has estimated that the French nuclear industry would not be able to build enough reactors for the atomic production to represent more than 50%. Indeed, the RTE report states, *"this share is the result of technical analyses and is not limited by a political constraint linked to the diversification of the mix*." [3].

RTE has specified that technological challenges are essential for a 100% renewable system (very high development rates of renewables, grid stability, space occupation, consumption flexibility, storage facilities using batteries, hydrogen, or synthetic gas). The aim of this work is not to judge the feasibility of the scenarios but to compare their environmental impacts. RTE has published its results for 2050 and 2060. In 2050, the transition will not yet be complete, so the scenarios in 2060 are compared. On a different side, to compare with the current situation, the year 2019 was chosen: it was not impacted by the changes in consumption linked to the Covid-19 crisis which started in 2020, the two Fessenheim nuclear reactors closed in 2020 were still in operation, the stress corrosion problems that disrupted operation from 2021 to 2024 had not yet appeared. French electricity production in 2024 was very close to 2019 (the reduction in national consumption was balanced by increased exports). Between 2019 and 2024, nuclear and fossil-fired generation decreased slightly, and renewable generation increased somewhat, but the mix was not fundamentally different.

Two prominent families of scenarios were presented by RTE: 3 "M" scenarios do not plan to build new nuclear reactors, and 3 "N" scenarios do. The M0 scenario plans an atomic phase-out as early as 2050, while the M1 and M23 scenarios plan a phase-out around 2060; M1 relies more on photovoltaic, M23 on wind power. The N1 and N2 scenarios depend on the construction of new nuclear reactors, at different rates, while N03 relies, in addition, on Small Modular Reactors.

Figure 1 compares, in percentage terms, the means of supplying the electricity demand. This includes exports and storage in the form of batteries or hydrogen. Wind energy is vital: it is the first source of electricity production in the three scenarios without new nuclear power (M) and in the N1; photovoltaic is in 2nd place. The share of hydroelectricity, which is closely linked to geographical potential, is close to 10% in all scenarios. In comparison, the share of nuclear power reaches a maximum of 49.5% in 2060, compared to 70% in 2019. The share of nuclear power is declining as overall production increases, as is the share of renewable energies. Other means exist but represent a much lower production: bioenergy does not represent more than 1.4%; the "other" category, which does not exceed 1.9%, includes the marine energies, the combustion of non-renewable waste, and "vehicle to grid" (discharge of batteries from electric vehicles). Hydrogen storage and stationary batteries have a more critical role (up to 1.7 and 5.3%).

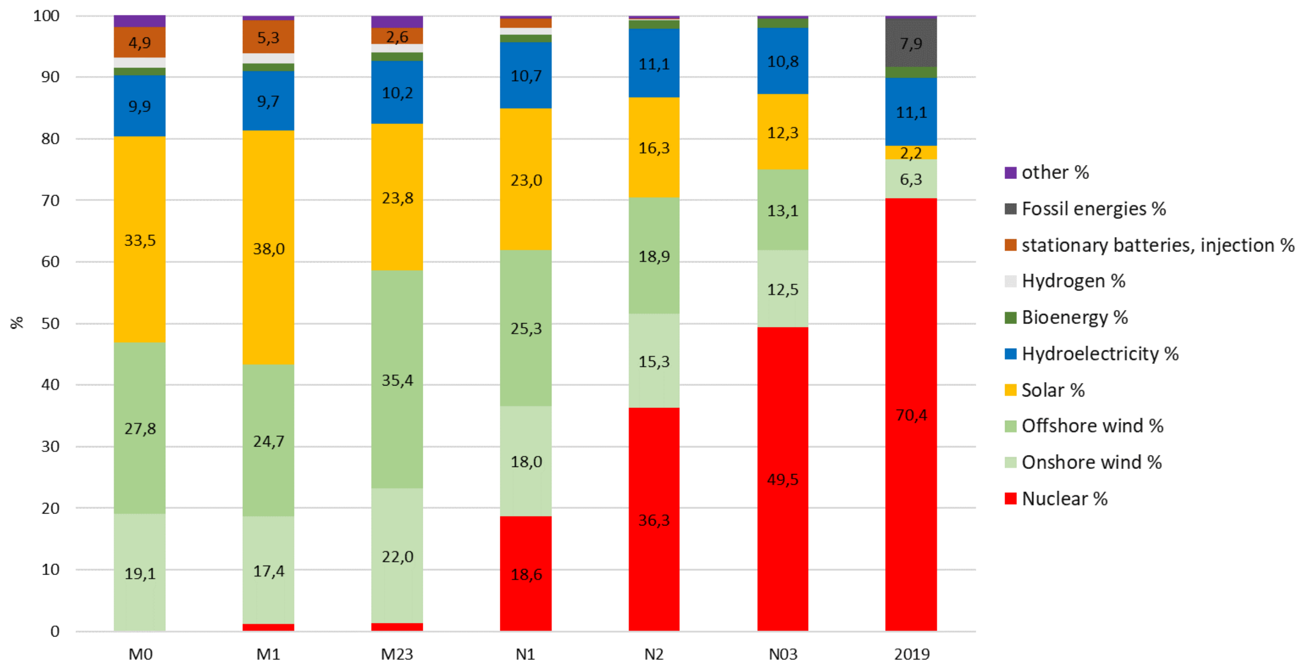

Figure 1 Origin of French electricity in %, RTE scenarios 2060, and situation in 2019.

However, the percentage comparison is misleading because the quantities produced are different. Figure 2 compares the electricity mix in TWh. The M1 scenario, which is based more on photovoltaics, requires a higher overall production, while the scenarios with new nuclear power require less production. The French electricity consumption is, however, the same in the six scenarios for 2060 (the case of 2019 is separate). The explanation lies in the losses due to storage and peak shaving (unused production), which are more critical with more wind power and photovoltaics [11].

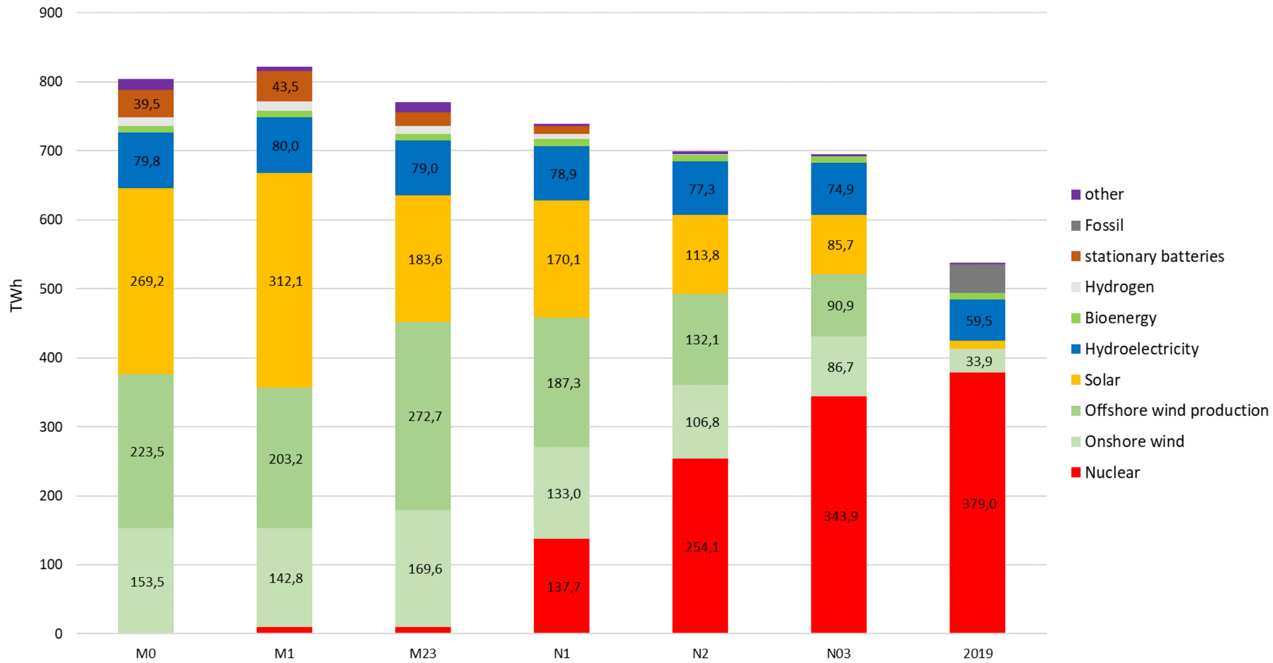

Figure 2 Origin of French electricity in TWh, RTE scenarios for 2060, and situation in 2019.

Considering the load factors of the different means, the instantaneous balance between supply and demand, peak shaving, losses, and storage, the required installed capacities in GW are described in Figure 3. It can be seen that the total installed capacity will have to be much higher in 2060 than in 2019: it will be between 1.7 and 3.8 times higher, while consumption will only increase by 35%. This is essentially due to the low load factors of wind and photovoltaic, and to the uncertainties of the weather, which require more capacity to provide a minimum amount of power at all times. Power-to-gas installations exist for the electrolysis of water to store electrical energy in hydrogen. This can then be used directly or converted back into electricity in power plants similar to the actual gas power plants (power to gas to power). The exact numbers of installed power and generation are given in Appendix 1.

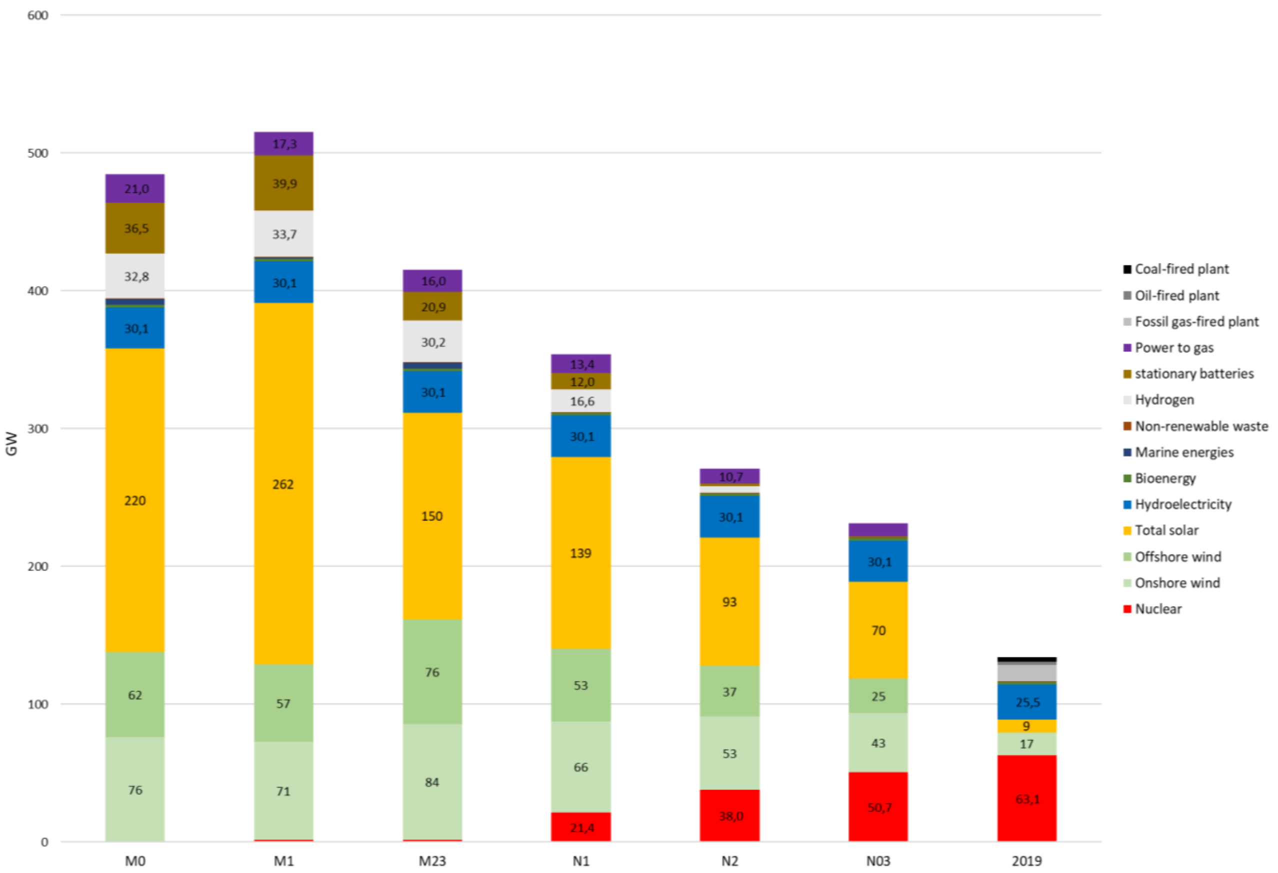

Figure 3 Installed electricity capacity in France in GW, RTE scenarios for 2060 and situation in 2019.

2.2 Environmental Impacts Related to the Production of Electricity

Actually the first source of energy in the world for the production of electricity is coal; its combustion causes a lot of pollution and CO_2 emissions which contributes a significant part to global warming [12]. In France, the actual production of electricity from coal and fuel oil is very low, but the output from methane (natural gas) is not negligible. The atmospheric pollution induced by methane is limited, but the CO_2 emissions are not insignificant. CO_2 emissions from French electricity production are about 19 Mt of CO_2 [13] per year, representing about 7% of French energy sector emissions [14], and less than 5% of total French emissions estimated at 400 Mt per year [15]. However, these data only concern the use phase and not the impacts of the production infrastructure; taking them into account, the total is 26 Mt [3]. In the future, one could think that a 100% renewable system would not emit any pollution or CO_2 emissions. This is not the case: all installations have environmental impacts on construction, maintenance, and end of life.

Regarding only the greenhouse gas emissions according to electricity production, the Intergovernmental Panel on Climate Change has published estimates [16], the median value of which appears in Figure 4 for the energy sources relevant to this study.

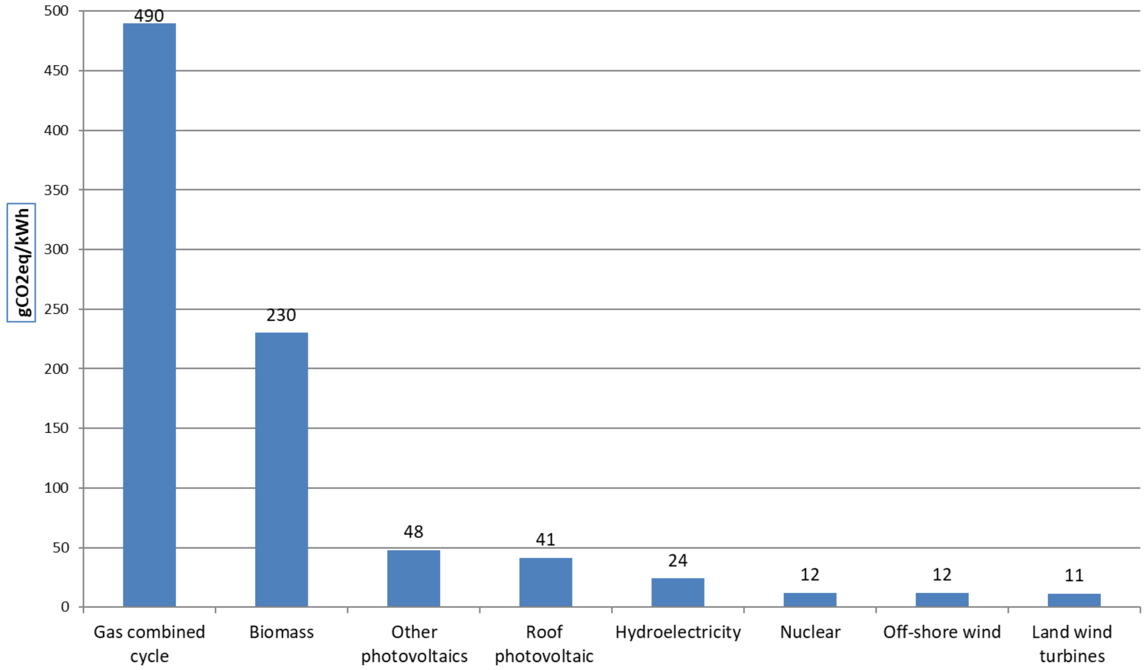

Figure 4 Greenhouse gas emissions from 1 kWh of electricity by source, median values, in gCO_2eq/kWh, from IPCC [16].

Environmental impacts are primarily related to the use of materials for infrastructure construction. The production of steel, for example, is particularly polluting and generates CO_2 emissions. Several authors have focused on the materials needed. For example, Olivier Vidal estimated the required masses of concrete, steel, copper, and aluminium by synthesizing different scientific studies [17]. His results appear in Figure 5. It can be seen that renewable energies require more materials than fossil and nuclear energies. These results are confirmed by other studies [18-20].

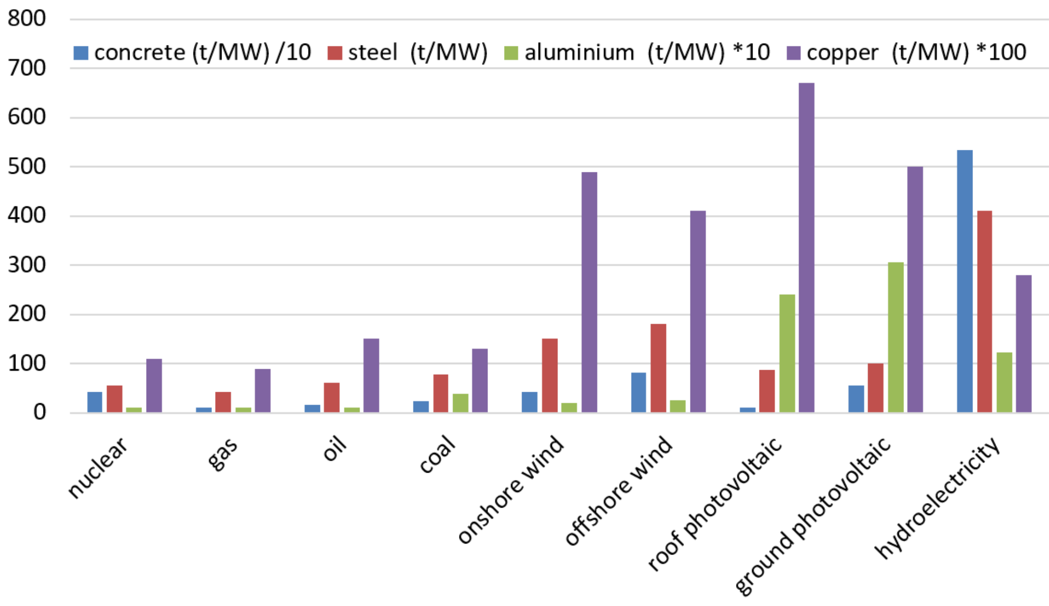

Figure 5 Comparison of the quantities of concrete, steel, aluminum, and copper in terms of the installed capacity (values from Oliver Vidal [17]).

Generally speaking, the environmental impacts estimated by the Life Cycle Assessment concern the usual operation of the installations, excluding accidents. Thus, a hydroelectric dam failure, a gas explosion, or a Chernobyl-type nuclear disaster cannot be taken into account. Concerning atomic waste, it is legitimate to ask the question of the burden left to future generations, but the Life Cycle Assessment can hardly take into account this aspect since the nuclear waste managed currently has very few consequences on living beings. In France, nuclear waste is scheduled to be buried as part of the "Cigeo" project, and it is assumed that the long-term impact on living organisms will be minimal [21]. This assumption is, of course, debatable because the scientific approach can never be specific in having correctly taken into account all the parameters concerning the future [22]. Another, more futuristic hypothesis is that nuclear waste could be made harmless by transmutation [23]. The choice of nuclear power, therefore, reflects confidence in future nuclear safety and less confidence in the feasibility of a system powered only by renewable energies.

2.3 Assumptions for Life Cycle Assessment

The environmental impacts of the different scenarios are computed using the life cycle assessment Simparo software and the Ecoinvent database. It uses update 3.8, but the rapid evolution of some technologies may not be taken into account; this is a limitation of this study.

Two approaches were used to estimate the impacts: according to the production in Watt-hours, or according to the installed capacity in Watts.

In the first case, the software considers the known load factor and lifetime of the means of production, the functional unit is "generate 645 TWh of electricity for one year". As electricity production and consumption can vary from one year to the next depending on weather conditions, the LCA method uses averages based on weather and electricity consumption statistics.

In the second case, the lifetime of the means of production has to be considered; the functional unit is "generate 645 TWh of electricity every year for 60 years".

As the impacts due to operation are very low (no fossil fuel combustion, low fuel extraction only for nuclear), the effects of electricity production in 2060 will come essentially from the construction and end of life of the infrastructure; the two methods should give similar comparison results.

The impacts of the power grid are not taken into account. However, wind power and photovoltaics, dispersed over a vast territory, require more electricity transmission lines and grid development. The impacts of non-nuclear scenarios are therefore a little underestimated. Other authors have studied LCA in the electricity sector similarly [24, 25].

Many Life Cycle Impact Assessment methods exist, the “CML-IA baseline” method is used, it is often used by specialists. The CML method was proposed by the Center for Environmental Science of Leiden University. In addition, the “allocation point of substitution” method (APOS) is used, with the “cut-off” (LCA-A) method. In this prospective study, the consequential method (LCA-C) could be interesting, but the results are pretty different and more delicate to analyse [26]. The global geographical location has been chosen. 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 LCIA method: abiotic depletion for minerals and fossil fuels, global warming, ozone layer depletion, human toxicity, aquatic ecotoxicity in fresh water and marine, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication. Explanations on these impacts have been given in a previous paper [27]. The choice of impact indicators is complex [28]. What are the most critical 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 effect has its unit (CO_2 for global warming, Joules for fossil fuels, Sb for abiotic depletion, CFC for ozone...). Perhaps some criteria should be considered more important than others. For example, eutrophication is probably not caused significantly by electricity production.

3. Comparison According to the Amount of Energy Produced

3.1 Impacts of the Same Amount of Electricity

This part of the work compares the environmental impacts due to the production of the same quantity of electricity (for example, 1 kWh). The comparison is limited to the most commonly used means of production in the scenarios (wind, photovoltaic, nuclear, and hydroelectric). It was necessary to select from the Ecoinvent database the means of production closest to those envisaged by RTE:

- Wind onshore 1-3 MW turbine, France. This power may seem low and not very representative of the wind turbines of the future, but models with a power of more than 3 MW give worse and less plausible results.
- Wind offshore 1-3 MW turbine, Rest of World. This power is also low, but the other types of offshore wind turbines give the same results.
- Photovoltaic roof, 3 kWp, Single-Si, France. This monocrystalline type is now more commonly used than polycrystalline photovoltaic cells. The other possibilities in the Ecoinvent database, including polycrystalline, give similar results.
- Photovoltaic open ground, 570 kWp, multi-Si France. It corresponds to large central photovoltaic power stations.
- Nuclear, Pressurized Water Reactor, France. These are nuclear reactors of the type used in France. Future reactors are likely to have similar impacts.
- Hydroelectric, alpine region, France. This category corresponds to the production of electricity by hydraulic dams.

Figure 6 shows the results in percentage. It appears that photovoltaic is the most impactful energy among those studied. These results may be surprising, they are due to a higher consumption of materials as shown in Figure 5. Be careful not to deduce that photovoltaic is negative in the energy transition: fossil fuels have been excluded from the comparisons because they are not used in the scenarios; photovoltaic is better than coal on almost all criteria [28], and better than gas regarding global warming [16]. On the other hand, the impact of the technology used varies a little [28]. Moreover, they will probably decrease with technological progress [29]. Regarding CO_2 emissions per kWh of photovoltaic, the Ecoinvent database may overestimate them [30]. Hydroelectricity has the least impact, followed by nuclear power. These results confirm other studies [31], including those of the Joint Research Centre (JRC) of the European Commission's science and knowledge service [6]; it provides in 2021 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 a reference for the LCA of atomic electricity.

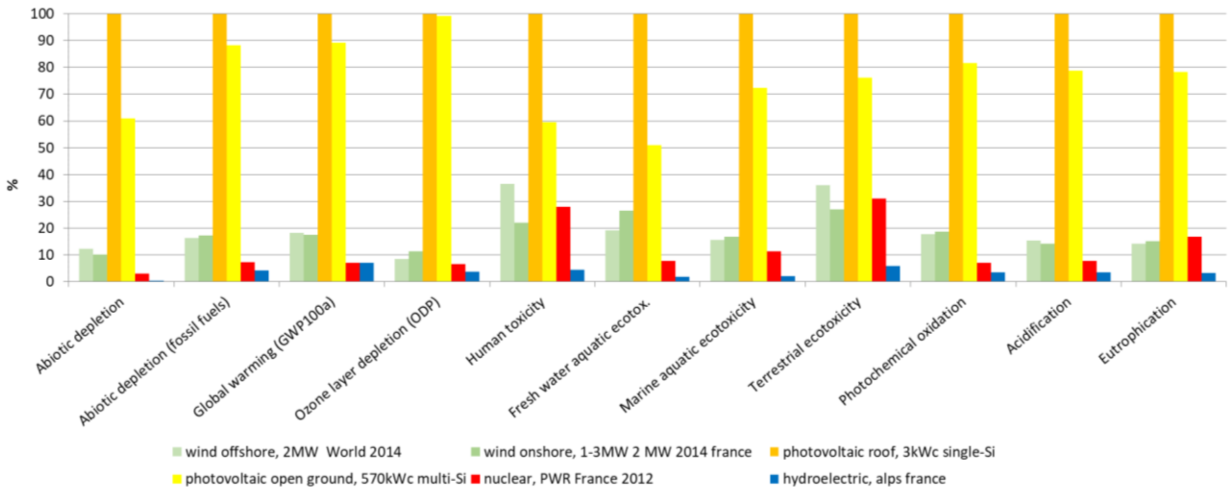

Figure 6 Comparison of CML environmental impacts of producing the same amount of electrical energy, computed by Simapro/Ecoinvent.

To consider other environmental criteria, including ionizing radiation of nuclear power plants, the RECIPE Life Cycle Impact Assessment method can be used instead of the CML one. The results presented in Figure 7 are computed by Simapro/Ecoinvent using the RECIPE LCIA method [32]. As it considers 22 criteria, in order not to make the figure more complex, only offshore wind and ground-based photovoltaic were considered. It is not surprising that the impacts related to water consumption are more closely associated with hydroelectricity. Nuclear power is the worst on marine eutrophication and ionizing radiation. However, it is accepted that, in regular operation, excluding accidents, this radiation has no consequences (radioactivity exists naturally and is not necessarily a problem at low doses). Finally, on 18 of the 22 criteria, photovoltaic still has the most substantial impact.

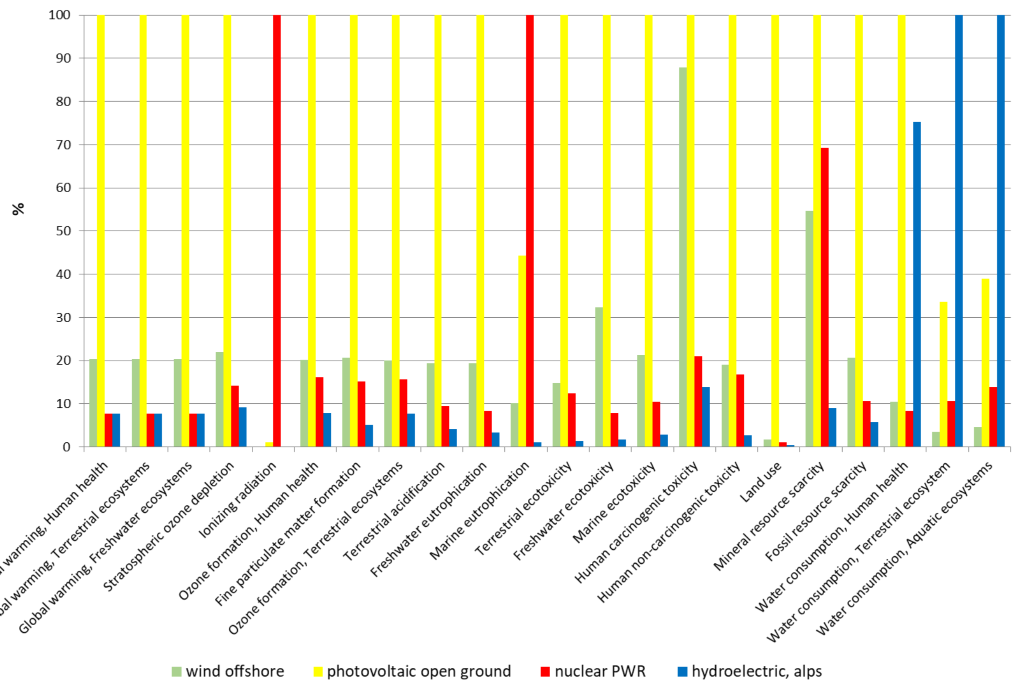

Figure 7 Comparison of RECIPE environmental impacts of producing the same amount of electrical energy, computed by Simapro/Ecoinvent.

3.2 Impacts of the Different RTE Scenarios

The RTE scenarios mainly use the energy sources previously written, but not only. The following choices were made from the Ecoinvent database:

- Hydroelectric, run of river, France. The impacts of run-of-river hydroelectricity are slightly lower than those of Alpine dams, so they are distinguished. RTE did not detail the future share of hydropower between dams and run-of-river. A share of 50% for each is considered, similar to the current share.
- For bioenergy, it concerns wood, biogas, and waste. "Bio methane, low-pressure burned in a micro gas turbine 100 kW" was chosen. This choice does not correspond precisely to reality, but the quantities of electricity produced are small, so the results should be little affected.
- Marine energies are absent in the database used, "Hydroelectric, alpine region, France" has replaced them; they probably have similar impacts in the case of tidal plants. This category is therefore used twice.
- The Non-renewable wastes are considered with «Electricity municipal waste incineration, France».
- The electricity production from hydrogen, vehicle to grid, and injection from stationary batteries are not in the Ecoinvent database regarding the energy in watt-hours. They were neglected. As can be seen in Figure 2, the electricity production with vehicle-to-grid and by hydrogen is low. It is more questionable for stationary batteries. Then the impacts of the scenarios that use them the most underestimate the environmental effects, especially the M0 and M1 scenarios and, to a lower degree, the M23 and N1 scenarios. This will confirm the conclusions.

The Simapro software has been configured with these energy sources associated with the annual quantities in watt-hours of Annex 1, for each scenario. This makes it possible to compare their environmental impacts. Figure 8 shows the results in percent. On all criteria, it can be seen that the ecological effects are proportional to the installed power presented in Figure 3, that this is due to the low load factor of wind power and photovoltaics.

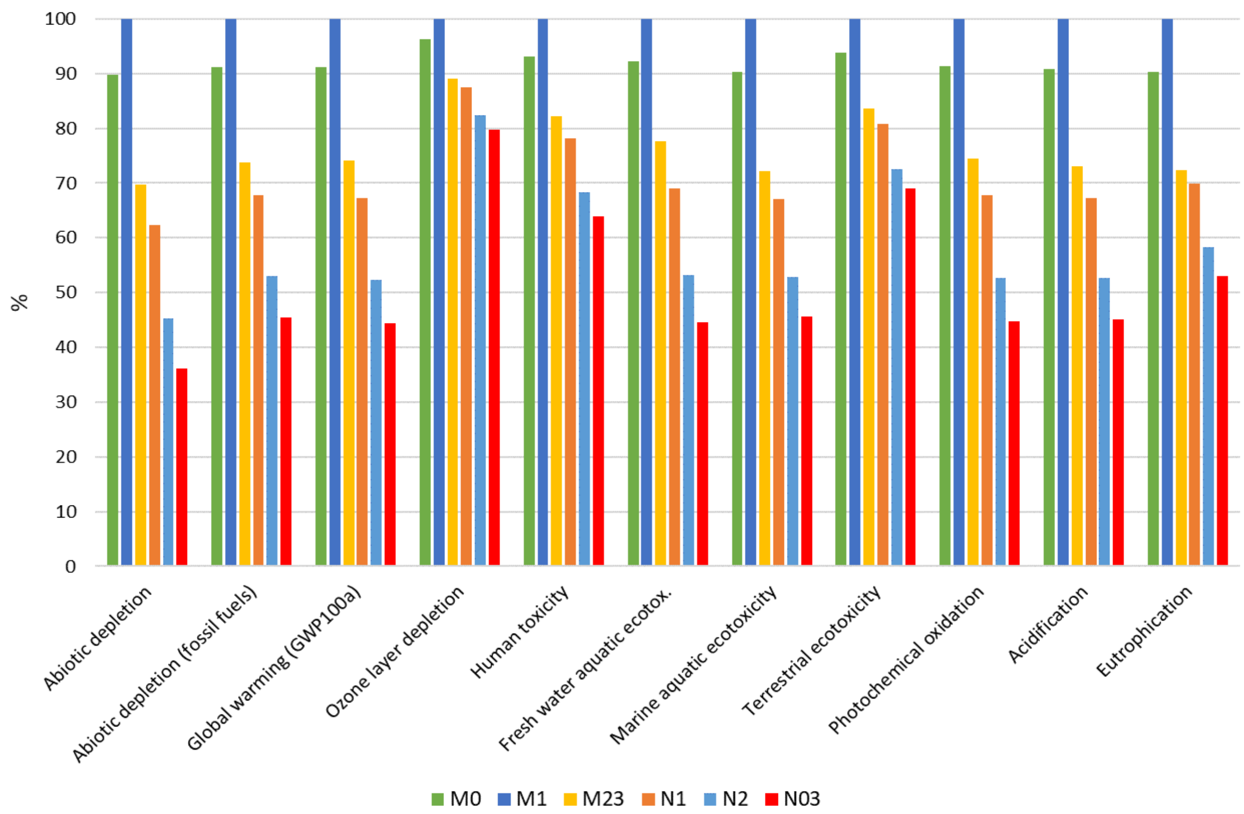

Figure 8 Environmental impacts of the RTE scenarios, relative to the amount of produced energy, computed by Simapro/Ecoinvent.

The worst scenario is M1, which relies most on photovoltaics. The more the scenarios use nuclear power, the less environmental impact they have, consistent with the results in Figure 6, with the quantities of materials needed presented in Figure 5, and with previous studies [8, 27]. This style of comparison appears in the RTE studies only for the global warming criterion: the RTE studies show slightly less differences between the scenarios (according to RTE, the best N03 at 6.8 g of CO_2eq per kWh is 62% of the worst M1 at 10.4 g) [3], but they are globally in the same trend.

To better understand where the impacts come from, the M1 and N2 scenarios have been separately analysed. Figure 9, in the M1 scenario, most impacts are due to photovoltaic, even though it represents only 38% of the production. In the N2 scenario (Figure 10), photovoltaic is also the most impactful, although it represents only 16% of the production. Bioenergies, represented by biomethane in the estimations, have a significant role in impacts, despite low production. The incineration of non-renewable waste to produce electricity also has disadvantages; however, this waste exists and must be treated even if no electricity is produced.

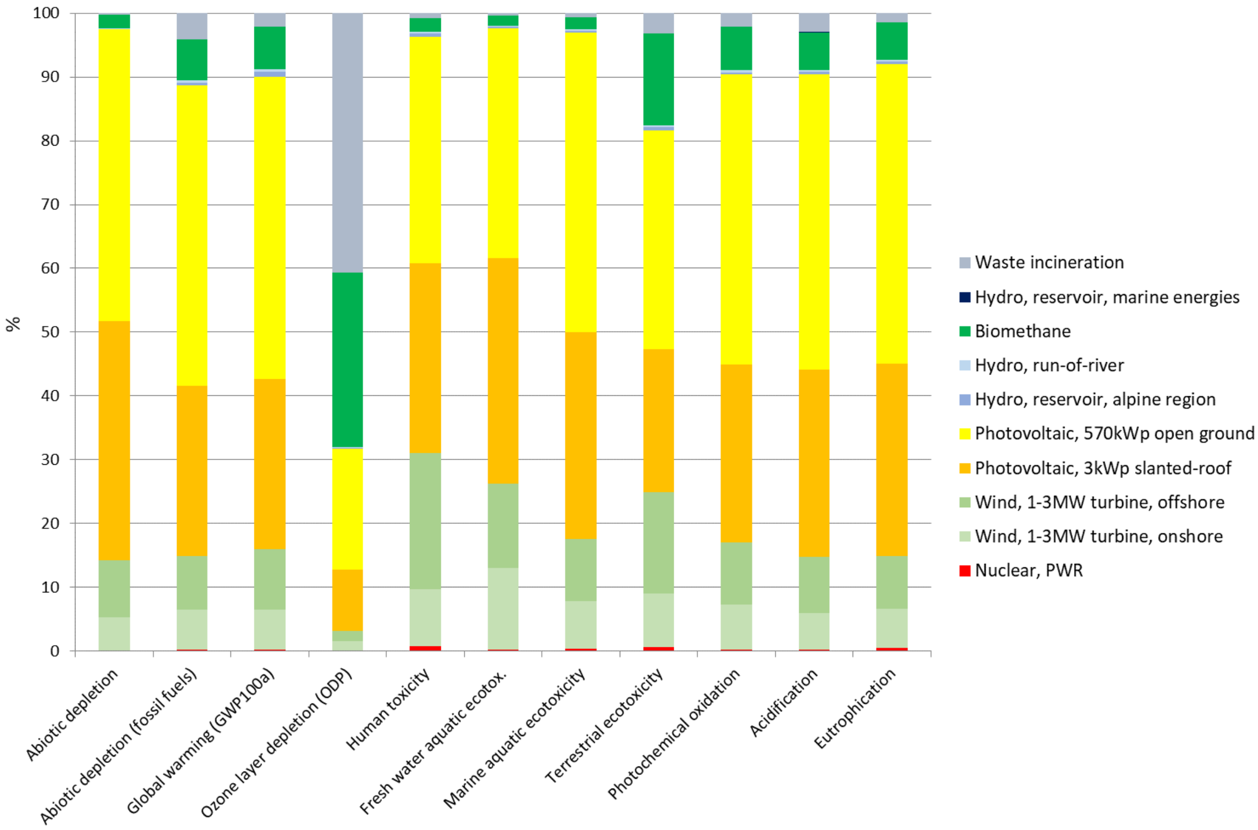

Figure 9 Causes of the environmental impacts of scenario M1.

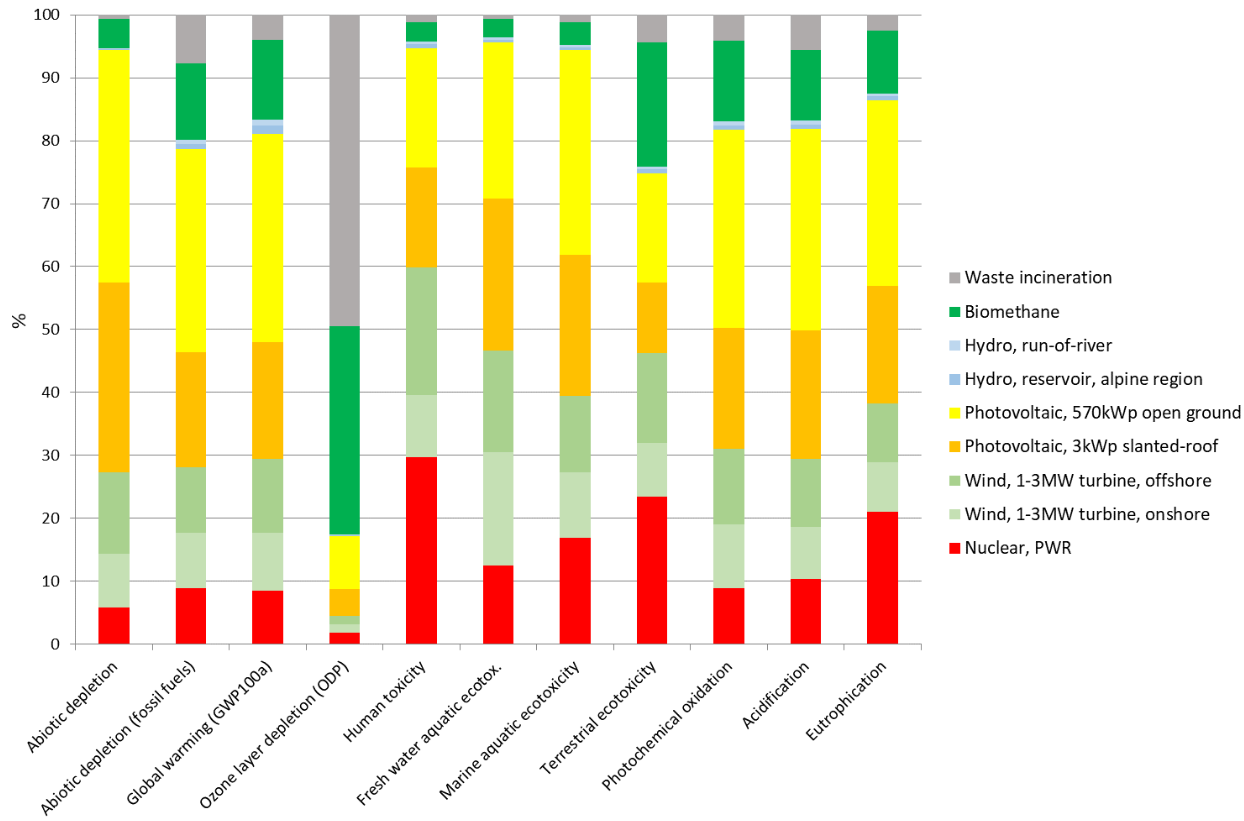

Figure 10 Causes of the environmental impacts of scenario N2.

4. Comparison According to Installed Capacity

4.1 Comparison of Infrastructure Impacts for the Same Installed Capacity

Another way to compare environmental impacts is to compare the scenarios in terms of installed capacity (in Watts) and not the energy produced (in watt-hours). In the previous paragraph, the Ecoinvent database was used, which includes the load factor and the life span of the installations, to know the impacts of a quantity of electricity produced (in Watt-hours). Now, the effects of the construction and the end of life of the production devices in relation to the installed power (in Watts) are considered. As the energy sources used do not use fossil fuels, the impacts of operation are very low compared to the impacts of the infrastructure. This approach, therefore, neglects the impacts of nuclear fuel production, but it is known that most of the impacts of nuclear power come from infrastructure [6].

It was again necessary to choose in the database the means of production closest to those envisaged by RTE:

- Offshore wind: the fixed and mobile parts for 2 MW wind turbines available in the Ecoinvent base are separately used.
- Onshore Wind: wind turbines of 4.5 MW were chosen; this high power minimizes the relative impacts.
- Solar roof: A 3 kWp Single-Si installation is considered.
- Solar Ground: The impacts of a ground-mounted photovoltaic installation are given for the area used. A peak power of 100 W per m^2 is considered, relatively favourable to photovoltaic (RTE considers 50 to 100 W per m^2).
- Nuclear: A French pressurized water reactor of 1 GW is available. In reality, scenario N03 comprises conventional PWRs and new SMRs that do not exist in the database, so PWRs are considered.
- Hydrogen to power: Hydrogen power plants are not available in the Ecoinvent database because this type of plant does not yet exist. It can be assumed that the operation will be close to current gas power plants; a gas power plant of 100 MW is considered.
- Hydraulic run of river: A “hydropower plant” of 237 MW was chosen.
- Hydraulic alpine dam: a sample of various types of dams in Switzerland is taken into account.
- Bioenergies are represented by gas power plants of 100 MW, with the same principle as biogas.
- Batteries: Lithium-ion batteries are being considered on the global market. As Ecoinvent works by battery mass while RTE considers their power in Watts, a mass of 300 W per kg was chosen, according to the scientific literature [33-35].
- Marine energies are considered as hydroelectric dams.
- Waste-to-energy plants are neglected: they are not included in the database and represent a very low capacity, and almost the same in the 6 scenarios (thus not affecting the comparison).
- Power-to-Gas installations allow the production of hydrogen from electricity. These devices presently exist only in an experimental way and there is no data in the Ecoinvent database. It does not appear possible to consider them. The M scenarios that use them the most are therefore advantaged in the comparisons.

Figure 11 compares the environmental impacts of 1 GW of selected infrastructure. The lifetime of the installations is not taken into account. Rooftop photovoltaic remains the most impactful. But wind, nuclear and hydroelectricity appear here relatively more impactful than in Figure 6. However, the long life span of nuclear and hydroelectric power plants is not considered here; their good load factor is not involved either (it allows for less need of installed power).

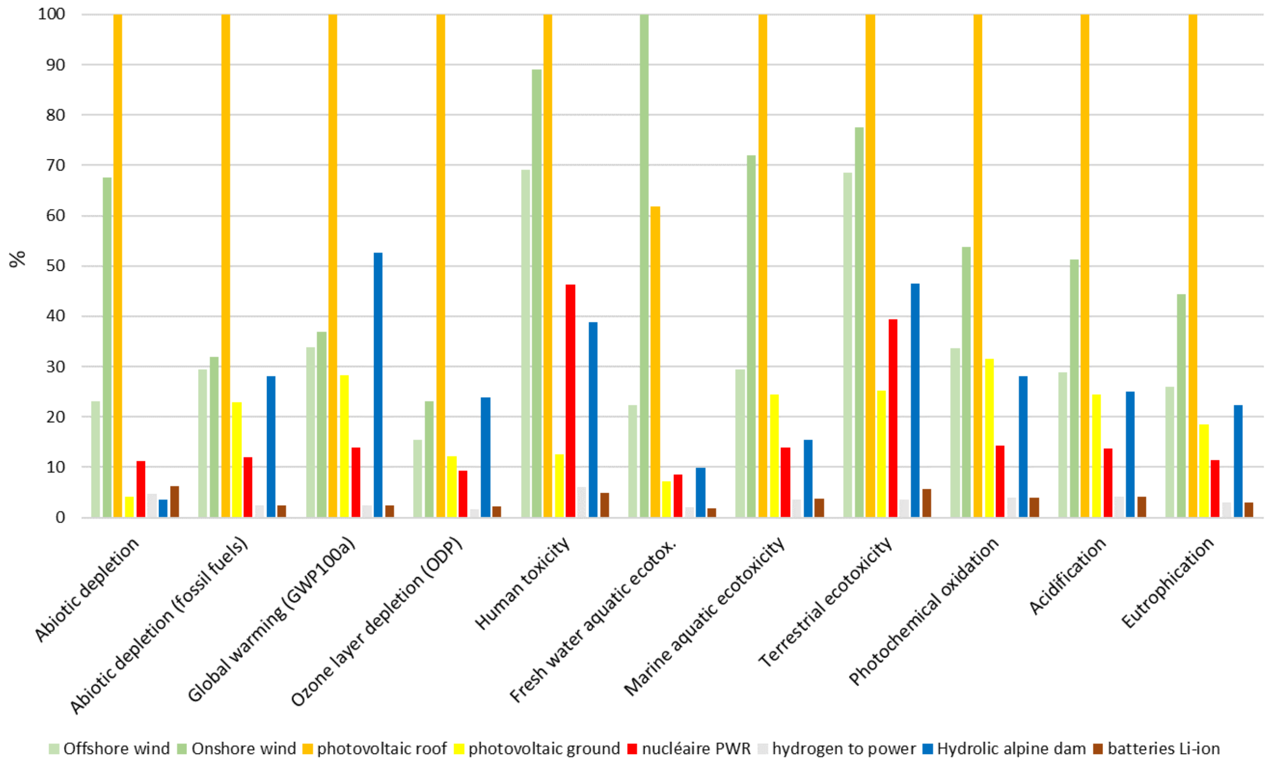

Figure 11 Comparison of CML environmental impacts of 1 GW of infrastructure, according to Simapro/Ecoinvent.

4.2 Comparison of the Impacts of the Different RTE Scenarios on the Installed Capacity

The Simapro software has been configured with these energy sources associated with the installed capacities in Watts of Annex 1, for each scenario. This makes it possible to compare their environmental impacts. The aim is to determine the best electricity mix constant over a long period. It is therefore necessary to consider the lifetime of the installations. Although some nuclear reactors in the USA have been authorized to operate for 80 years, the used basis is the conventionally accepted lifetime of 60 years for a nuclear reactor [36], the installed capacities have been multiplied by a coefficient related to the lifetime of the equipment. For example, if the lifetime of a photovoltaic panel is considered equal to 30 years, the power to be installed has been multiplied by 2. Table 1 summarizes the lifetimes considered from the references [6, 11, 13, 21, 33, 37]. The lifespan of bioenergy and hydrogen to power is considered to be the same as that of gas power plants (30 years); the lifespan of marine energy is considered to be the same as that of hydroelectric dams (80 years), which is probably optimistic and favourable to the M scenarios.

Table 1 Considered lifetime of electricity generation installations.

means of electrical production	nuclear	wind	photovoltaic	hydroelectricity	bioenergies	marine energies	hydrogen to power	batteries
Lifetime (years)	60	25	30	80	30	80	30	20

The final results are shown in Figure 12. For the 6 scenarios for 2060, the rankings between the scenarios are the same as in Figure 8: the more significant the infrastructure, the more significant the environmental impacts. It is therefore not surprising that the M1 scenario, which requires the most installed power, is again the most impactful, followed by M0 and M23, while the scenarios with nuclear power, which require less installed power, have less impact.

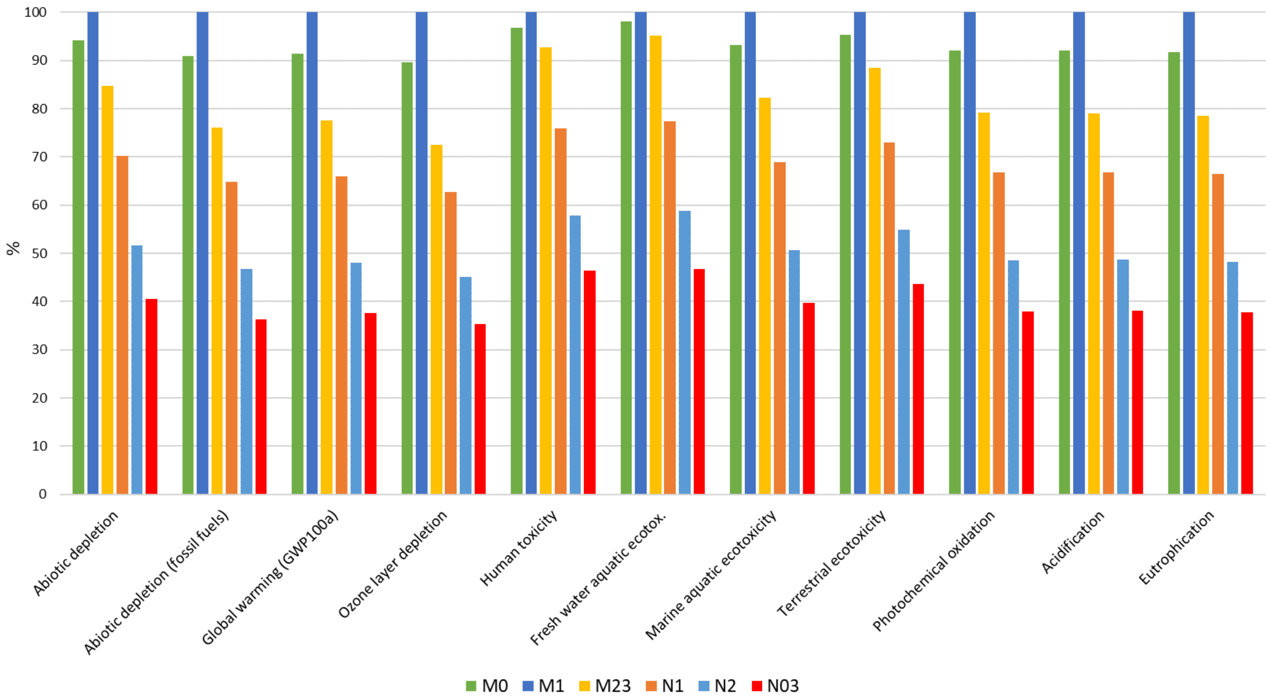

Figure 12 Environmental impacts of the RTE scenarios, relative to the installed capacity, computed by Simapro/Ecoinvent.

5. Conclusion and Policy Implications

Six scenarios have been proposed for electricity generation in France in 2060, assuming a 35% increase in consumption. Three scenarios consider new nuclear reactors, while the other three rely mainly on wind power and photovoltaics. The total power required is higher without nuclear power, due to the low load factor of photovoltaics and wind power, and the need for storage facilities.

This study attempts to compare their environmental impacts objectively. To do so, this work is based either on the electrical energy produced or on the installed capacity. Standard Life Cycle Assessment methods and criteria have been used.

The conclusions are in the same direction and confirm what could be suspected: the environmental impacts are largely proportional to the quantity of used materials. The systems that require the most installed power have the most impact. Moreover, for the same installed power, photovoltaic systems have more impact. The scenarios with the highest use of photovoltaics are therefore the worst. However, these conclusions can be put into perspective and do not mean that renewables, especially photovoltaics, are useless or harmful: the scenarios were compared with each other, not with the current situation which uses fossil fuels. Renewable energies are, of course, preferable to fossil fuels; moreover, technologies are evolving favourably: by manufacturing photovoltaic panels in Europe, it is probable that their environmental impacts would be reduced.

Prospective Life Cycle Assessment involves a degree of uncertainty, and it is advisable to remain modest about these conclusions [29].

Assuming no new nuclear reactors are built, the system with the least environmental impact is the M23. It is the one that uses the least photovoltaic energy and the most wind energy. This scenario would involve up to 35000 masts of onshore wind turbines against less than 10000 currently in France, which requires that the populations accept them. M23 requires more offshore wind turbines, which also meet great opposition. However, the M0 scenario may require up to 250000 hectares of ground-based photovoltaics [3]. Generally speaking, to limit environmental impact, it's better to rely on wind power rather than photovoltaics.

Assuming that the construction of new nuclear reactors is accepted despite the risk of accident and waste management, the scenarios that use atomic power require the least infrastructure and materials and have the least environmental impact. If atomic waste is well managed with low impact, the higher the proportion of nuclear power, the lower the environmental impact.

List of Abbreviations

RTE	Réseau de Transport de l'Electricité (Electricity Transmission Network)
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
IPCC	Intergovernmental Panel on Climate Change
M0, M1, M23	RTE scenarios without new nuclear
N1, N2, N03	RTE scenarios with new nuclear

Appendix 1 Electric Mix and Installed Power in 2060, RTE Scenarios, and 2019

	M0	M1	M23	N1	N2	N03	2019
French demand (TWh)	803.4	822.1	770.9	739.3	699.3	695.4	538.4
French consumption (TWh)	645	645	645	645	645	645	475.2
Nuclear installed power (GW)	0	1.6	1.6	21.4	38	50.7	63.1
Nuclear production (TWh)	0	10.2	9.8	137.7	254.1	343.9	379
Onshore wind installed power (GW)	76	71	84	66	53	43	16.5
Onshore wind production (TWh)	153.5	142.8	169.6	133	106.8	86.7	33.9
Offshore wind installed power (GW)	62	56.5	76	53	37	25	0
Offshore wind production (TWh)	223.5	203.2	272.7	187.3	132.1	90.9	0
Total solar installed power (GW)	220	262	150	139	93	70	9.4
Solar roof (GW)	73.3	87.3	50.0	46.3	31.0	23.3	3.1
Solar ground (GW)	146.7	174.7	100.0	92.7	62.0	46.7	6.3
Solar production (TWh)	269.2	312.1	183.6	170.1	113.8	85.7	11.6
Solar roof (TWh)	89.7	104.0	61.2	56.7	37.9	28.6	3.9
Solar ground (TWh)	179.5	208.1	122.4	113.4	75.9	57.1	7.7
Hydraulic installed power (GW)	30.1	30.1	30.1	30.1	30.1	30.1	25.5
Hydroelectric production (TWh)	79.8	80	79	78.9	77.3	74.9	59.5
Hydraulic production dam (TWh)	39.9	40	39.5	39.45	38.65	37.45	29.75
Hydraulic production run of river (TWh)	39.9	40	39.5	39.45	38.65	37.45	29.75
Bioenergy installed power (GW)	1.9	1.9	1.9	1.9	1.9	1.9	1.6

Bioenergy production (TWh)	9.8	9.8	9.8	9.8	9.8	9.8	9.7
Marine energy installed power (GW)	4	1	4	0	0	0	0
Marine energy production (TWh)	11.5	2.9	11.5	0	0	0	0
Non-renewable waste installed power (GW)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Non-renewable waste, production (TWh)	1.8	1.8	1.8	1.8	1.8	1.8	2.2
Hydrogen installed power (GW)	32.8	33.7	30.2	16.6	4.6	0	0
Hydrogen, electricity production (TWh)	13.1	13.9	11.2	7.4	1.5	0	0
Vehicle-to-grid, injection (TWh)	1.9	1.9	1.9	1.9	1.8	1.8	0
stationary batteries installed power (GW)	36.5	39.9	20.9	12	2.1	0.5	0
stationary batteries, injection (TWh)	39.5	43.5	20	11.4	0.2	0	0
Power to gas installed power (GW)	21	17.3	16	13.4	10.7	9.5	0
Fossil gas-fired installed power (GW)	0	0	0	0	0	0	12.1
Fossil gas-fired plant production (TWh)	0	0	0	0	0	0	38.6
Oil-fired plant installed power (GW)	0	0	0	0	0	0	3
Oil-fired plant production (TWh)	0	0	0	0	0	0	2.3
Coal-fired plant installed power (GW)	0	0	0	0	0	0	3
Coal-fired plant production (TWh)	0	0	0	0	0	0	1.6
Total installed power (GW)	484.8	515.5	415.2	353.9	270.9	231.2	134.7

Author Contributions

Dr. Bertrand CASSORET analyzed the RTE scenarios, laid the foundations for the LCA and analyzed the results. Dr. François BALAVOINE took part in the LCA and writing of the article.

Competing Interests

The authors have declared that no competing interests exist.

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