Development of a methodology from LCA to a multi-criteria approach: application to electricity transition in France

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Abstract. Climate change should trigger the development of concrete arguments to justify the choice of the best energy mix, which is not the same depending on the countries involved. Life cycle assessment (LCA) uses tools that can help to define a successful energy transition, from an environmental perspective, by including a large panel of indicators. An LCA of the different sources of electricity was performed based on inventories from literature, leading to an environmental ranking of the different energies through endpoints. Four examples of energy transition scenarios corresponding to different energy demands up to 2050 were chosen for France, and compared in terms of LCA. Several multicriteria indicators were proposed for a new methodology to follow a sustainable development strategy, i.e. including economic and social parameters. The scenarios were submitted to a multicriteria sustainable assessment in order to obtain a ranking based on tuneable parameters, depending on different stakeholders' viewpoints.

1 Introduction

The public is generally not aware of the actual environmental consequences of the different energies in an electricity mix. As the subject is somewhat complicated, the available information is usually limited to the global warming indicator, due to greenhouse gases released by human activities. From a scientific point of view, it is not rigorous to limit the impacts just to a single indicator [1]. A series of questions can be raised, which should be addressed. For example:

- What is the real global ranking of the different energies, considering all impact categories?
- How can the different categories be prioritized? For instance, why should pollutants or ionizing radiations be considered as less important than global warming, given that all of them are harmful to human health and biodiversity?

Life cycle assessment (LCA) uses tools which can contribute to answering these questions, and which are helpful when seeking to define a good energy transition.

Beyond the environmental approach, it is important to include economic and societal issues. Economy cannot be ignored in this topic, because people are attached to paying the lowest possible price for their energy. Societal aspects are rather subjective and seldom examined in

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communications. We will see how the three pillars of sustainable development can be merged to define a method aimed at helping to choose the optimal energy transition, with a choice of tuneable parameters.

2 Methodology

The inventory for each energy has been modelled using SimaPro™ software with Ecoinvent database, modified by information found in the literature in order to match the reality in France (capacity installed, technologies used, real load factors, electric mix and origin of construction materials …). Each inventory follows the cradle-to-grave and process-based methodology.
Midpoints are used mostly in LCA for detailed impact studies, but Endpoints are also used for damage to ecosystems [2]. Endpoints, which aggregate different impact categories where an internationally shared consensus exists, are very useful for comparisons because of the limited number of categories. Endpoints have been used sometimes in this study, keeping in mind the traceability with upper Midpoints. The ranking goes from 1 to 10, the score 1 representing the lowest impact; it is valid for the whole article (in the same order: 1 representing the lowest price in economic comparison).
In each category (environment, economy, social), weighting factors have been taken into account, but can be easily tuned.
After giving individual scores in the three pillars of sustainable development, we will analyse the possibilities of combining them, depending simply on the viewpoint of different stakeholders, to try to find optima. This differs from most commonly used weighting methods [3-4].

3 Scenarios selection

Different scenarios were chosen for this study, based on literature references [5] and different assumptions related to the evolution of electricity consumption in the future. This are shown in Table 1.

Table 1. Share of the different energies in the electric production mix for each scenario

Scenario	Description . Until 2035 . After 2035	Energy demand by 2050 (TWh)	Year	Nuclear	Renewables	Fossils	Storage
			2018	73.0%	19.7%	7.3%	1.0%
A	AMPERE [5]	625	2035	50.0%	50.0%	0.0%	0.9%
	Slow growth of renewables and stable nuclear power		2050	43.0%	57.0%	0%	3.2%
B	AMPERE	521	2035	50.0%	50.0%	0%	2.0%
	Stabilization of nuclear power and renewables		2050	49.6%	50.4%	0%	2.0%
C	Huge increase of renewables	521	2035	49.8%	44.2%	6.0%	1.7%
	Nuclear phase-out in 2050		2050	0.0%	94.3%	5.7%	3.4%
D	VOLT [5]	625	2035	59.0%	35.7%	5.4%	0.9%
	Rise of nuclear to suppress fossils		2050	60.5%	39.5%	0%	0.7%

As the energy transition could not be completed by 2035 in France, it has been assessed until 2050. In France renewables encompass hydraulic with 12% of the production, the remaining being supplied by wind (2/3) and photovoltaic (1/3), as an assumption. Bioenergies are neglected in a simplified approach.

4 Multicriterion assessment

Sustainable development lies at the intersection of three pillars: economic, environmental and social.

4.1 Environmental score

4.1.1 Comparison of energies

Table 2. LCA Midpoints with IMPACT 2002+ for 1 kWh electricity production

Impact category	Unit	Hydro	Nuclear	Wind	Solar PV	Coal	Natural Gas	Fuel oil	Geothermal	Biogas	Solid Biomass
Carcinogens	kg C2H3Cl eq	2.05E-04	4.16E-04	8.17E-04	1.48E-03	1.10E-03	1.22E-02	3.03E-03	1.70E-03	7.83E-04	2.26E-04
Non-carcinogens	kg C2H3Cl eq	1.59E-04	1.14E-03	6.37E-04	1.86E-03	2.59E-03	1.43E-03	4.14E-03	7.02E-03	1.30E-03	2.64E-04
Respiratory inorganics	kg PM2.5 eq	1.01E-05	3.67E-05	2.69E-05	7.46E-05	2.49E-04	1.78E-04	4.59E-04	9.49E-05	2.81E-04	1.09E-04
Ionizing radiation	Bq C-14 eq	1.21E-01	7.11E+01	9.97E-02	1.24E+00	7.67E-01	1.09E+00	7.89E+00	3.59E-01	1.14E+00	1.69E+00
Ozone layer depletion	kg CFC-11 eq	8.49E-10	1.06E-07	1.23E-09	7.87E-09	4.09E-09	9.92E-08	2.12E-07	5.42E-09	3.85E-09	3.96E-09
Respiratory organics	kg C2H4 eq	3.05E-06	4.36E-06	9.66E-06	2.26E-05	8.32E-05	1.06E-04	2.46E-04	3.22E-05	1.01E-04	6.89E-05
Aquatic ecotoxicity	kg TEG water	5.20E-01	2.50E+01	1.71E+00	7.25E+00	6.51E+00	9.35E+00	4.31E+01	2.45E+02	3.14E+00	1.46E+00
Terrestrial ecotoxicity	kg TEG soil	1.95E-01	2.16E+00	6.74E-01	1.98E+00	2.97E+00	1.64E+00	9.75E+00	5.96E+01	9.39E-01	6.62E-01
Terrestrial acid/nutri	kg SO2 eq	1.49E-04	2.65E-04	2.82E-04	1.01E-03	7.78E-03	2.76E-03	1.06E-02	1.52E-03	1.18E-02	3.85E-03
Land occupation	m2org.arable	1.42E-04	2.22E-04	1.05E-03	1.50E-02	5.61E-03	5.64E-04	1.96E-03	6.45E-04	1.11E-03	2.57E-02
Aquatic acidification	kg SO2 eq	3.11E-05	6.81E-05	8.34E-05	3.30E-04	1.70E-03	8.16E-04	2.97E-03	3.17E-04	2.84E-03	5.26E-04
Aquatic eutrophication	kg PO4 P-lim	2.02E-06	3.53E-06	9.33E-06	4.00E-05	5.77E-05	1.37E-05	9.68E-05	2.97E-05	1.32E-05	2.32E-06
Global warming	kg CO2 eq	6.90E-03	1.13E-02	1.35E-02	5.49E-02	8.89E-01	5.51E-01	1.15E+00	4.27E-02	7.58E-02	1.91E-02
Non-renewable energy	MJ primary	7.80E-02	1.41E+01	1.94E-01	9.41E-01	1.08E+01	9.90E+00	1.76E+01	5.76E-01	4.76E-01	4.86E-01
Mineral extraction	MJ surplus	1.39E-03	1.54E-03	5.54E-03	2.07E-02	5.60E-03	2.21E-03	4.65E-03	1.03E-02	6.21E-03	7.08E-04

Table 3. Ranking of the energies using IMPACT 2002+ Endpoint for 1 kWh of electricity

Energy	Human Health	Ecosystem Quality	Climate Change
Hydro	1	1	1
Wind	2	2	3
Nuclear	3	4	2
Solar PV	4	6	6
Solid Biomass	5	7	4
Geothermal	6	10	5
Natural Gas	7	3	8
Coal	8	8	9
Biogas	9	5	7
Fuel oil	10	9	10

For the environmental score, we will consider 66% of the Ecosystems mark from ReCiPe method and 33% of that from Abiotic depletion in EPS 2015dx method [6].

4.1.2 Results of scenarios

LCA calculations have been performed with all the midpoint indicators of two methods. The LCA results are displayed in Endpoints only for the sake of clarity. Only global warming potential is presented.

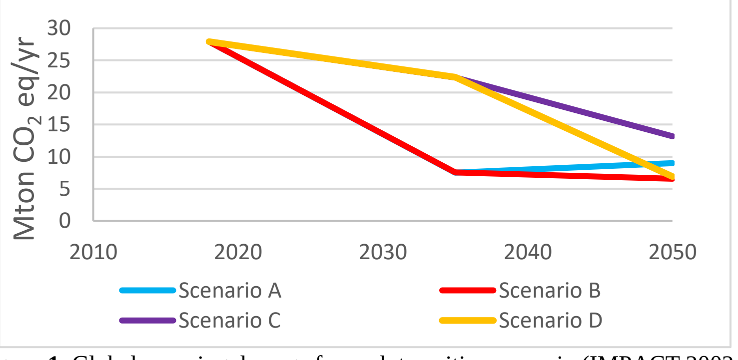

Figure 1. Global warming damage for each transition scenario (IMPACT 2002+)

4.2 Social score

Most of the parameters selected in order to assess social aspects are subjective and several techniques are used to assess the social acceptance [7]. Only three parameters have been chosen: the perceived risk of energies by the population accounting for 20% in the final ranking, human health coming from LCA results accounting for 50%, and direct jobs for 30% (indirect and induced jobs are difficult to set up). The weighting between the three categories can be tuned.

Table 4. Social score method and results

Electricity source	Perceived risk		Human health (ReCiPe)		Direct jobs		Social Score
	Score (1-5)	Ranking	Damage (DALY/kWh)	Ranking	Direct jobs/kWh	Ranking	
Hydro	4	8	1.98E-08	1	1.84E-07	9	4.8
Nuclear	5	10	6.04E-08	2	3.18E-07	7	5.1
Wind	1	1	6.28E-08	3	6.15E-07	5	3.2
PV	1	1	1.87E-07	6	6.91E-07	4	4.4
Coal	2	3	1.24E-06	9	1.86E-07	8	7.5
Natural Gas	3	6	7.28E-07	8	4.78E-07	6	7
Fuel Oil	4	8	1.54E-06	10	4.41E-08	10	9.6
Geothermal	3	6	1.53E-07	5	1.14E-06	2	4.3
Biogas	2	3	3.65E-07	7	1.01E-06	3	5
Solid Biomass	2	3	6.33E-08	4	2.36E-06	1	2.9

4.3 Economic score

Production costs were collected from several sources, but especially [8]. Technology-specific cost and performance parameters were detailed for the IPCC [9], including large variation intervals depending on the technologies, investment cost, average cost of capital, maintenance and load factors during operation, and decommissioning costs. The difficulty lies in cost estimation for energies in the future, with a number of extra parameters, which should vary in a dedicated sensitivity study.

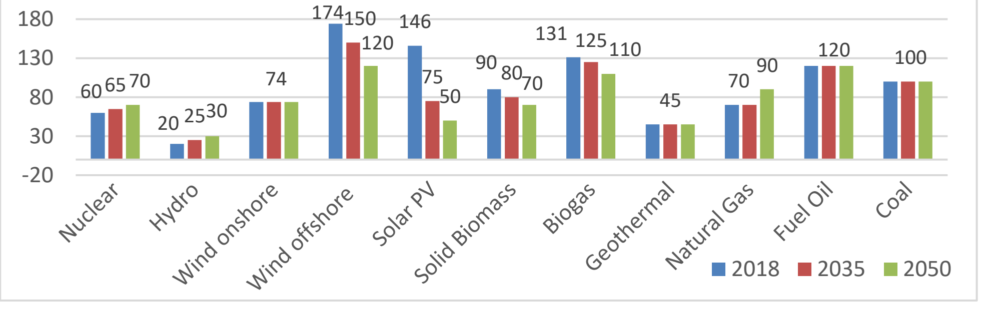

Figure 2. Projections of overall production cost of energies (€/MWh)

Table 5. Economic score of the different energies

Year	Solid Biomass	Wind	Geo-thermal	Solar PV	Hydro	Biogas	Nuclear	Natural Gas	Coal	Fuel oil
2018	6	5	2	10	1	9	3	4	7	8
2035	6	7	2	5	1	10	3	4	8	9
2050	4	8	2	3	1	9	4	6	7	10

4.4 Overall scores of energies

Beside the different energies and the three pillars of sustainable development, one should define several stakeholders viewpoints. There is no evidence for a consensus in the literature about this point, leading us to develop our own grid. For the industrialists or investors, the economic pillar is by far the most important but the others cannot be neglected to make the project be accepted. The authorities are considered to have a more balanced mindset between the three pillars, whereas the local population is more concerned by the environmental and social scores. The following weighting factors have been considered through a discussion with colleagues and partners, but not through interviews as commonly done in social sciences which can also be tuned if necessary.

Table 6. Choice of weighting criteria for decision support

Criterion	Economic	Environmental	Social
Industrial and investor approach	70%	20%	10%
Authorities approach	30%	40%	30%
Population approach	10%	50%	40%

Using the three different approaches, we were able to rank the ten energies in three different ways, depending on their overall score for the viewpoint considered.

Table 7. Multicriteria scores of electricity sources depending on three different approaches

Viewpoint	Year	Solid Bio-mass	Wind	Geo-thermal	Solar PV	Hydro	Biogas	Nuclear	Natural Gas	Coal	Fuel oil
Investors	2018	5.29	4.48	3.50	9.17	1.38	8.40	3.34	4.23	7.12	7.96
	2035	5.29	5.88	3.50	5.67	1.38	9.10	3.34	4.23	7.82	8.66
	2050	3.89	6.58	3.50	4.27	1.38	8.40	4.04	5.63	7.12	9.36
Authorities	2018	4.27	3.79	5.23	7.78	2.14	7.41	3.89	4.77	7.28	8.08
	2035	4.27	4.39	5.23	6.28	2.14	7.71	3.89	4.77	7.58	8.38
	2050	3.67	4.69	5.23	5.68	2.14	7.41	4.19	5.37	7.28	8.68
Population	2018	3.77	3.44	6.09	7.09	2.52	6.91	4.17	5.04	7.37	8.14
	2035	3.77	3.64	6.09	6.59	2.52	7.01	4.17	5.04	7.47	8.24
	2050	3.57	3.74	6.09	6.39	2.52	6.91	4.27	5.24	7.37	8.34

4.5 Multicriteria ranking of scenarios

At last, we can apply the rankings to the selected scenarios, which lead to the following results.

Table 8. Multicriteria scores for the scenarios and rankings

Viewpoint	**Investors**		**Authorities**		**Population**		**Mean value**		**Final ranking**	
Scenario	2035	2050	2035	2050	2035	2050	2035	2050	2035	2050
A	3.46	3.42	4.40	4.52	4.85	5.07	4.24	4.34	1	3
B	3.46	3.29	4.40	4.37	4.85	4.90	4.24	4.19	1	1
C	3.88	4.52	5.40	6.49	6.15	7.48	5.14	6.16	4	4
D	3.76	3.25	5.22	4.44	5.94	5.04	4.97	4.24	3	2

We can conclude that scenarios A and B are the best in 2035, with B moving to the first position in 2050 because it corresponds to a lower electricity production (593 TWh versus 684 TWh). With both methods, scenario C, despite a moderate production (553 TWh in 2050), is the worst scenario, corresponding to a large increase in renewables without nuclear energy.

5 Conclusions and policy implications

5.1 Main results

A methodology has been developed to assess the energy transition with a multicriteria approach. Starting from LCA results of energies, we have used the endpoints in the methods that propose them in order to limit the number of parameters, reducing the 15 impact categories in average to 3. This allows to make a comparison and ranking of the different energies used for the production of electricity.
The three pillars of sustainability were taken into account. i.e. environment. economy. and society, to create three independent scores, with subjective rules of weighting inside a pillar. Then they were merged with different weighting factors depending on several viewpoints: those of investors, authorities or the population.
Eventually a multicriteria assessment of the energies could be obtained, which has been applied to the energy transition with four different scenarios, enabling to discern trends and make choices between them. A worksheet has been set up to allow a wide choice of tuneable parameters, which is important to match different needs.
A multicriteria analysis and decision depends significantly on the chosen input variables and many assumptions; there is clearly no claim to absolute results in the ranking of energies.

5.2 Prospects

This work aimed at contributing to the development of a methodology, but is just a starting point for further discussions. Other parameters could be developed: for social issues, other relevant parameters could be added and for the environmental part, the predictable technologies and their inventories should be assessed with associated uncertainties for the future. Scores of energies and the relative weighting of parameters should be obviously evaluated by a larger panel of citizens and treated through a different mathematical approach like the Analytic Hierarchy Process (AHP) (3). Finally, this study could be broadened to other countries, with possibly very different energy mixes.

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