Scenarios for an energy transition

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Developed on behalf of decision-makers or whistleblowers, scenarios describe stories that could happen. They involve assumptions about the socio-economic future of humanity and must take account of constraints, the main one being the threat of man-made climate change.

Why scenarios?

The need for an *energy transition* has been recognised for two main reasons: the prospect of resource depletion and the threat of climate disruption caused by the accumulation in the atmosphere of greenhouse gases emitted by human activities. The two are combining to force the *decarbonisation of* a global energy system that is 80% based on fossil fuels: coal, gas and oil, which are found in limited quantities in the earth's crust and which burn, releasing CO_2.

The current energy transition is part of an evolution that began in the last third of the 18th century. Technological revolutions profoundly altered society. Initially essentially agrarian, it then became industrialized and more educated in an economy based on services, information, knowledge and leisure. This *economic transition*, also known as "development", affected only a minority of humanity in the 19th and 20th centuries. In the 21st century, it is on the way to reaching global proportions and will shape future energy demand.

Development is accompanied by a *major demographic transition*. This transition, which has been completed in Western or Westernised countries where the population is stagnating or declining, is underway in the world's most populous countries, with the exception of Africa. *Extensive urbanisation* completes the picture. Few people are needed to work the land, so jobs and services are in the cities. Urbanisation already affects 55% of humanity, and this percentage could reach 75% by 2050. Some megacities have as many as thirty million inhabitants, posing specific problems.

The current energy transition has barely begun. Unlike its predecessors, particularly those that led to the industrial revolution, it will not be spontaneous. We would like it to be intelligently planned. Reducing our primary energy mix from 80% to less than 20% fossil fuels, which generate greenhouse gases, calls into question a number of fundamentals. What energy sources will replace coal, oil and gas, which are abundant and, until the turn of the millennium, inexpensive? Are we heading for a rare and expensive form of energy? How long will this take?

To answer these questions, both public authorities and companies are basing their thinking on scenarios. According to Nebojsa Nakicenovic (IIASA[a]): "a scenario is a plausible description of the future, based on a coherent set of assumptions about crucial relationships and the forces that determine developments (e.g. technological changes, prices, etc.)".

Scenarios are neither forecasts nor projections. They can be divided into two categories: continuity scenarios, which take account of the inertia of energy systems, and breakthrough scenarios, which are more or less free of this inertia by being prescriptive. They describe the way to reach a given state by imposing strong constraints: level of finite energy consumption, level of primary energy production, greenhouse gas emission ceiling not to be exceeded, share of electricity in final energy, ideology...

Many bodies publish scenarios. They include official institutions, financial players, energy companies, international bodies and campaigning NGOs. So it's hardly surprising that the results are so varied.

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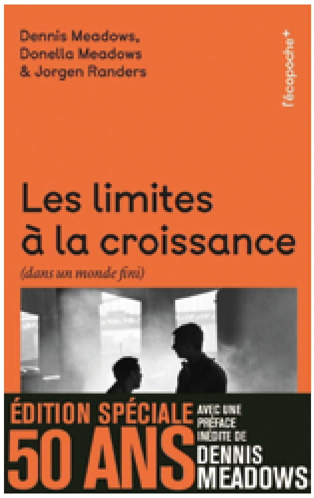

The *Limits to Growth* report, commissioned by the Club of Rome in 1972.
left: the group responsible for publishing the report. From left to right: Jørgen Randers, Jay Forrester, Donella Hager-Meadows, Dennis L. Meadows and William W. Behrens III. Behrens III (Photo: Club of Rome)
right: cover of the book in French, republished in 2022, with an unpublished preface by D. Meadows.

Start, goal, strategy

A scenario is expected to present trajectories describing changes in economic or physical quantities over the coming period: GDP, energy production, gigatonnes of CO_2 emitted, average global temperature… Including complex socio-economic elements and taking account of the interrelationships between human activity and the climate, scenarios are often developed using numerical models, following the example of the pioneering work of Dennis Meadows and the Club of Rome [1]. The announcement in 1972 of a global collapse around 2025 caused a stir, especially as we were still in the post-World War II period known as the "Glorious Thirty".

The initial state, data and trends, should reflect the situation at a certain date. However, because of the ups and downs of economic life, scenario writers tend to rely on broad trends obtained from rolling averages(b). Extending this trend over long periods provides 'laissez faire' or '*business as usual*' (BAU) scenarios, which it is almost universally accepted can only lead to disaster.

Once the origin has been defined, there is a wide variety of possible trajectories, which diverge the further they are from the starting point. The image of the ponytail is obvious from the illustration of scenarios in Figure 1. Institutes specialising in foresight explore numerous variants, resulting in a wide range of possible futures in terms of economic and/or climate data. However, the energy transition imposes constraints on the point of arrival.

Energy demand is an important element in defining the end state. It depends on the number of human beings and the degree of development. If we simply extrapolate the trend observed at the start of the 21st century, by 2050 a population of around 10 billion (6 billion in 2000) [2] would consume at least 22 Gtoe (compared with 14.5 in 2019). Such a prospect is difficult to accept with the current proportion of fossil fuels, and is incompatible with the climate constraint accepted by a majority of scientists and many decision-makers.

To preserve resources and limit climate change, we need to reduce consumption compared with current trends and decarbonise energy sources. This second condition is the subject of the 2015 (Paris) and 2021

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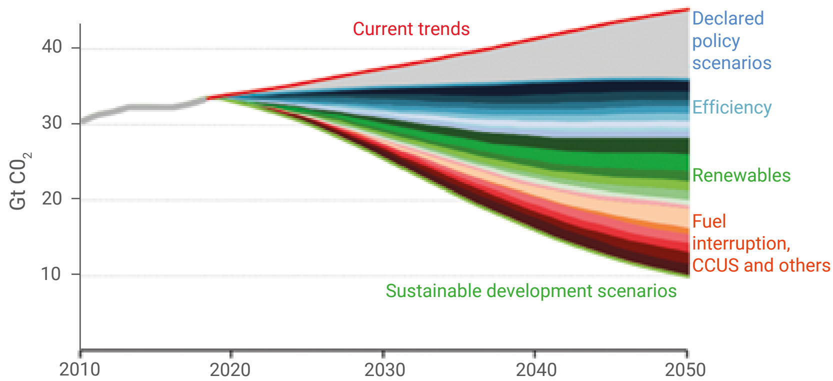
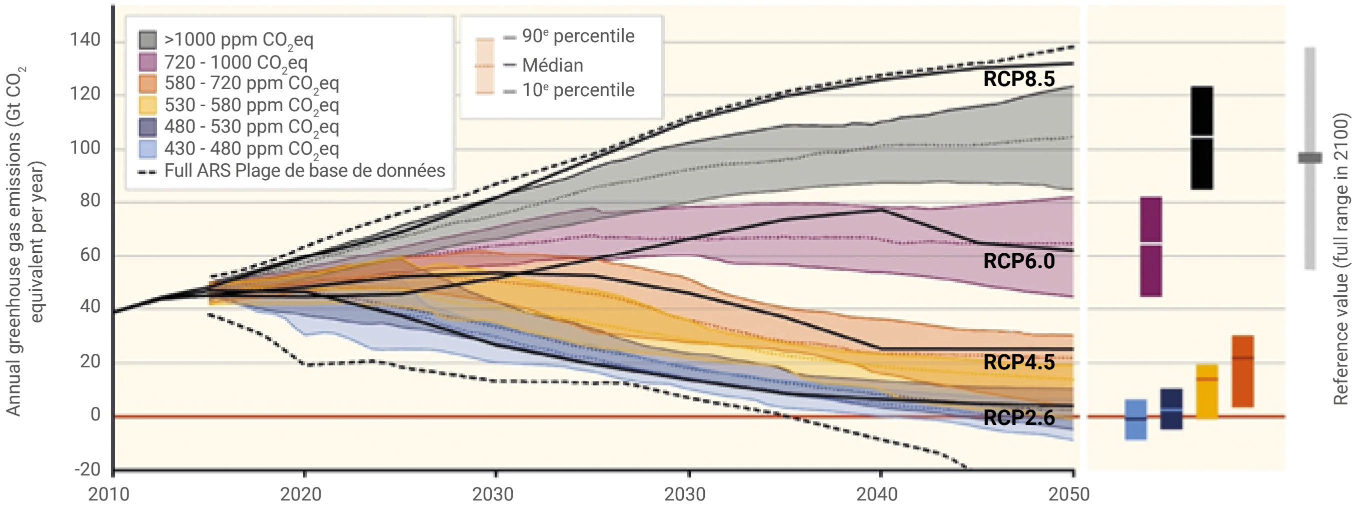


1. The bevel strategy in the scenarios of the International Energy Agency (IEA): reducing in annual CO_2 emissions in relation to government pledges. Three bevels: efficiency, renewables and, under the same heading, switching from coal to gas, carbon capture and storage (CCUS), and others including nuclear.



2. Range of annual greenhouse gas emission trajectories in CO_2 equivalent (IPCC). In black, trajectories (*Representative Concentration Pathways* - RCP) leading to a given radiative forcing in W/m² (e.g. RCP2.6 corresponds to an additional radiative forcing of of 2.6 W/m² between now and the end of the 21st century).

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(Glasgow) agreements, in which governments committed to reducing greenhouse gas emissions and phasing out coal.

In the absence of a miracle cure, a global strategy[3] is to assign to each family of technologies an objective represented by one or more "bevels" of avoided carbon, which represent as many "wedges" to be driven in. Driving in a wedge means gradually and linearly reducing CO_2 emissions over 50 years, compared with a "business as usual" scenario, until they are reduced by 1 Gt of carbon per year (in 2000, annual emissions to talled around 7 Gt worldwide). A 'solution' to the greenhouse effect must have the potential to drive at least one wedge. Table 1 specifies the effort required for a corner to be driven in using technologies that are already well developed industrially or are likely to reach this stage over the next few decades.

This strategy can be found, explicitly or implicitly, in most scenarios (fig. 1) where it interferes with a multitude of other goals. With many degrees of freedom at his disposal, the scriptwriter has the choice of vigorously combating the trends observed in the initial state (rupture) or partially accommodating them(continuity). Other considerations come into play: the vested interest of a player in the energy sector, the influence of lobbies, militancy, etc.

	avoiding1 Gt/year of carbon in 50 years represents :	Examples of related problems[c]
Fossils	Converting 40 Mtoe of coal into 40 Mtoe of gas	
	Equipping 20 GWe of fossil-fired power stations with CCS (Carbon Capture and Storage).	Transport and sequestration of an additional 7,5 10^6 t CO_2
Nuclear	The commissioning of eight EPR reactors	Social acceptability
Renewables	The commissioning of 20 Mtoe of biomass (wood for energy and biofuels)	
	The commissioning of 50.000 2 MW wind turbines	Social acceptability
	The commissioning of 3.000 km² of photovoltaic panels	

Table **1. Quantification of some bevels for France.**

Some global scenarios

The roadmaps of the Intergovernmental Panel on Climate Change (IPCC)

At the COPs *(Conferences of the Parties*) organised each year under the aegis of the United Nations Framework Convention on Climate Change (UNFCCC), the reports drawn up by the IPCC serve as the basis for discussions. They contain a reasoned and up-to-date synthesis of climate science, and refer to a wide range of scenarios assessing the consequences, in terms of CO_2 emissions, of various energy and economic policies. As expected, the emission trajectories up to 2100 form a "ponytail" (fig. 2). The IPCC communicates on Representative *Concentration Pathways* (RCP), which serve as a reference for possible changes in greenhouse gas concentrations in the atmosphere.

The models translate the increase in the concentration of excess radiative forcing[d] in the year 2100 into a probable rise in global temperature. In order not to exceed a temperature differential of 2°C compared with

Source [Gtep] IEA data	Total production in Gtep		20 Gtep scenario in 2050	Comments
	2000	2017		
Fossil fuels (gas. oil. coal)	8	11.5	4	Cancellation of CO_2 emissions if capture and sequestration
Traditional biomass	1.1	1.4	2	Mainly wood
Hydraulics	0.57	0.92	1.3	Doubling compared to 2000
Nuclear	0.68	0.61	6.35	Factor 10 compared with 2017
New renewables (solar. wind. biomass)	0.03	0.47	6.35	Factor 13 compared with 2017
Total	**10.38**	**14.9**	**20**	**On the road to 20 Gtoe by 2050**

Table **2. Estimated changes in world primary energy production from 2000 to 2050** according to the "20 Gtoe" scenario of Jean-Marie Loiseaux *et al.*

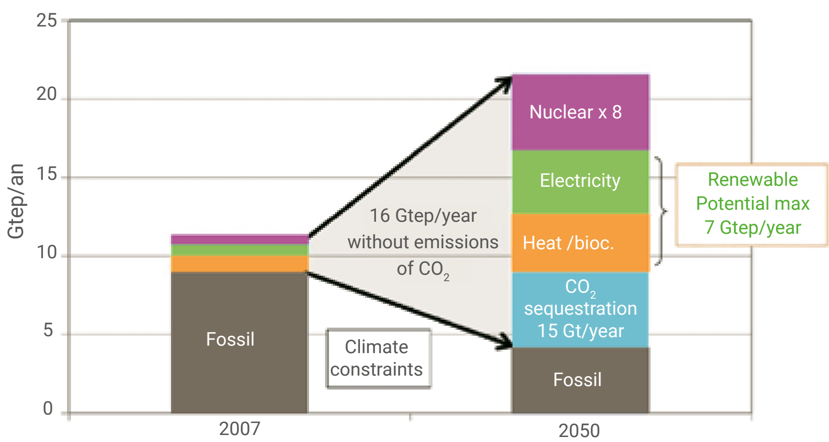
1880, the RCP 2.6 trajectory (forcing of 2.6 W/m²) shown in Figure 2 should be followed. In 2018, the IPCC published a report on the environmental, economic and social impacts of a temperature rise voluntarily limited to 1.5°C [4].

Physicists' studies

Scenarios are often drawn up by economists assisted by mathematicians. Yet the energy transition involves questions of physics and technology. As such, it is of interest to physicists. As part of the CNRS's "Interdisciplinary Energy Programme", Sandra Bouneau and her co-authors [5] have divided the world into four categories of countries: rich, emerging rich, emerging and poor. In each category, the population is divided into high, moderate and low levels of consumption. The contrainations on the end state in 2050 are primary energy production limited to a value of just over 20 Gtoe (232 500 TWh) and a halving of CO_2 emissions compared with 2007. The result of their analysis is summarised in Figure 3: without CO_2 sequestration and a high proportion of nuclear power in electricity production, the energy and environmental objectives cannot be achieved simultaneously.

Table 2 above summarises the results of a similar approach by colleagues in Grenoble (Daniel Heuer and Jean-Marie Loiseaux, private communication). The first two columns show existing data on world primary energy production, by type of source, in 2000 and 2017. The third column, for the year 2050, is based on the assumption of major efforts on energy efficiency, CO_2 capture and sequestration, new renewables and nuclear power. To do this, they assume :

- global primary energy demand of 20 Gtoe, including an improvement in energy efficiency of more than 50%;
- halve the production of fossil fuels compared to the year 2000;
- a balance between nuclear and new renewables, after setting the production of traditional biomass and hydroelectricity at a plausible order of magnitude .



3. Energy mix in 2050, according to S. Bouneau *et al* [5].

Scenarios targeting 100% renewables

This grail of environmental NGOs [6, 7] and a number of other bodies is not simply a return to the situation that prevailed before the industrial revolution. The difference lies in the generation of electricity by hydro, wind and solar power. But to achieve their objective, these scenarios require a sharp reduction in final energy consumption per inhabitant per year, from 40 to 24 GJ (from 16.1 to 9.5 MWh, i.e. from 0.95 to 0.6 Tep). These values can be compared with those in Table 4 (p. 43), which gives the global projections for the IEA's NZE (Net Zero Emissions) scenario. Primary energy consumption would fall from 14.3 Gtoe in 2019 (or 1.9 toe/

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capita or 22.5 MWh/capita, for a world population of 7.5 billion) to 13 Gtoe (or 1.3 toe/capita or 15.1 MWh/capita, for a population of 10 billion) in 2050.

Two levers would contribute to this.

Firstly, **energy sobriety**, achieved through a political will supported by a population massively converted to the benefits of ecology. Developed countries would return to minimal consumption thanks to a rejection of technology, combined with a conversion to a bucolic and frugal existence imposed by rigorous restrictive measures. "Passive" housing would become the norm, while transports, for both people and goods, would be limited and provided by "soft traffic".

Then **improving the efficiency of installations** which is a matter of technology, the results of which are constrained by the laws of physics. Decarbonisation would be achieved by the widespread substitution of renewable energies for fossil and nuclear energies.

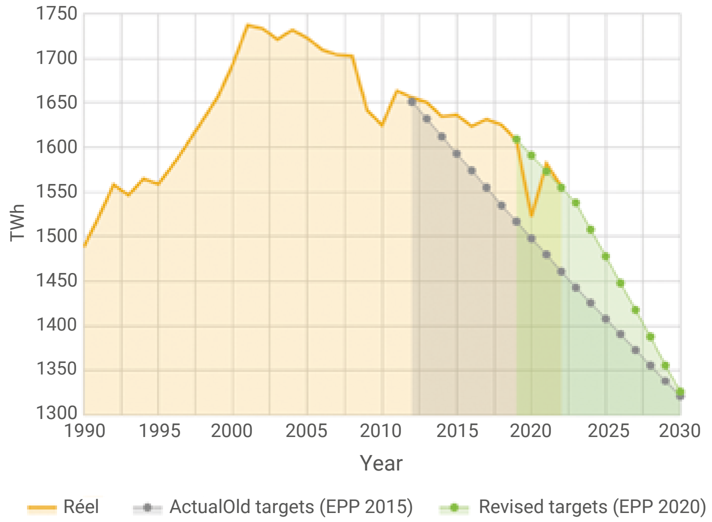
Given what is at stake, the relevance, soundness and practical feasibility of implementing these levers at the required level must be examined objectively, rationally and without bias.

Scenarios for France

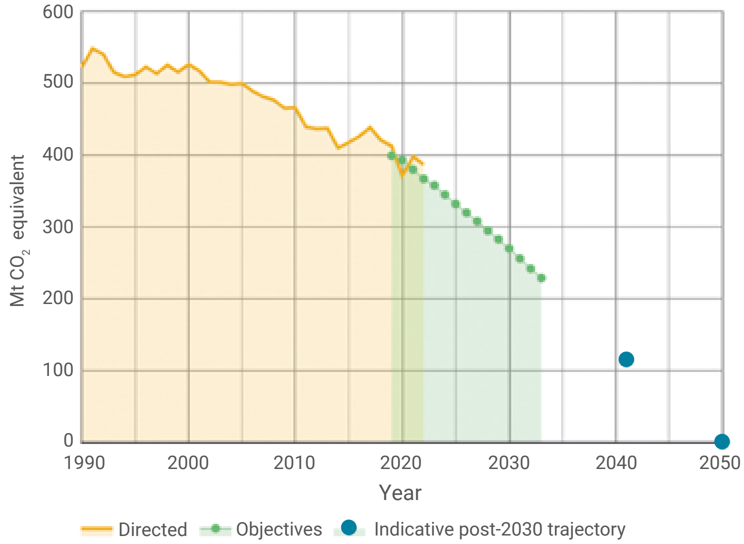
In France, the LTECV[e] of 2015 stipulated that final energy consumption would be halved between 2012 and 2050 (degrowth?), that greenhouse gas emissions would be reduced by 40% between 1990 and 2030, and that by 2035 the share of nuclear power in electricity supply would be reduced to 50%. Before turning to the different scenarios developed for France, it is interesting to look at changes in final energy consumption (Fig. 4) and net greenhouse gas emissions (fig. 5) since 1990, compared with the targets set by the initial 2015 version of the PPE (Programme Pluriannuelle de l'Énergie) and the revised 2020 version[f]. Figure 4 shows that, in order to achieve the target initially set, the slope of the downward trajectory has had to be increased to take account of the real trend in final energy consumption. This raises an initial question: would it be sufficient to update the slope in order to define a relevant trajectory towards the target?

There are two categories of scenarios, whose figures for 2050 are compared in Table 3 with the objectives of the LTECV.

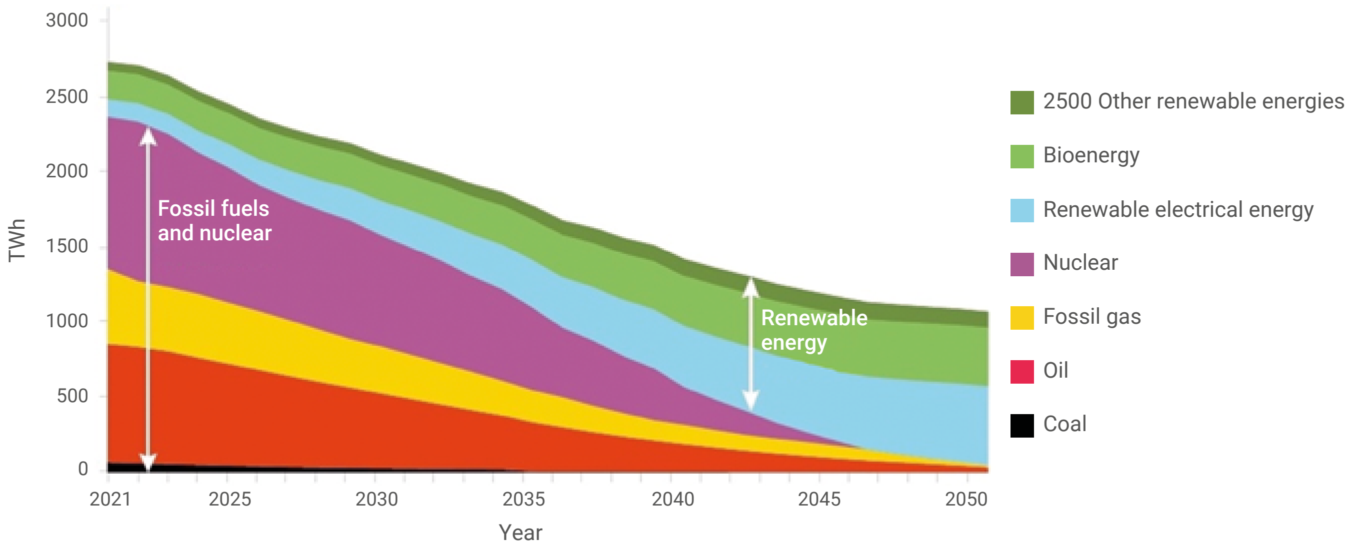
- Legalistic scenarios have been drawn up by ANCRE[g], for example, where it is noted that the reduction in the share of nuclear power, as required by law, and the delays in implementing a large solar component mean that gas will have to be used for at least ten years [8], which is a very short time to make new installations profitable (which should therefore be subsidised). Greenhouse gas emissions from the electricity system increase significantly during this period. RTE (Réseau de transport de l'électricité) recently published six scenarios with or without nuclear power for electricity alone [9], which show that the



4. change in final energy consumption in France since 1990 (yellow curve), compared with the objectives of the 2015 EPP (black circles) and the 2020 EPP (green circles).
Source: www.observatoire-climat-energie.fr/energie/consommation-denergie/



5. change in net greenhouse gas emissions in France since 1990, compared with the targets set by the National Low Carbon Strategy (SNBC) and adjusted in 2023.
Source: www.observatoire-climat-energie.fr/global/emissions-nettes.



6. evolution of primary energy in the negaWatt scenario. In 2050, it is divided by 3. Final energy, including 50% renewable energy, is divided by 2.

lowest cost is obtained with 50% nuclear power, the legal maximum. For its part, the negaWatt association [10], which has just abandoned the idea of drastically reducing electricity consumption, still recommends extreme thermal insulation of buildings and insists on the need for a change in societal behaviour. After the rapid and definitive phase-out of nuclear power, electricity supply would come from renewables[h], with growth far outstripping the current trend (fig. 6). By 2050, rooftop photovoltaics will have reached a level of 120 GW, with decentralised production expanding rapidly. Storage to compensate for intermittency would be achieved by partial conversion into gas, methane or hydrogen *(power to gas)*. ADEME is moving in the same direction, with a 100% renewable scenario for electricity[i] [11].

- Other scenarios are outside the scope of this law, such as certain ANCRE scenarios or NegaTep [12], which envisages an increase in the use of electricity in a context where the end state is defined on the basis of reasonable extrapolations of the current situation. The aim is to cut emissions by a factor of 4 by 2050-60, by drastically reducing the use of fossil fuels, mainly hydrocarbons, since France has already phased out coal, with only

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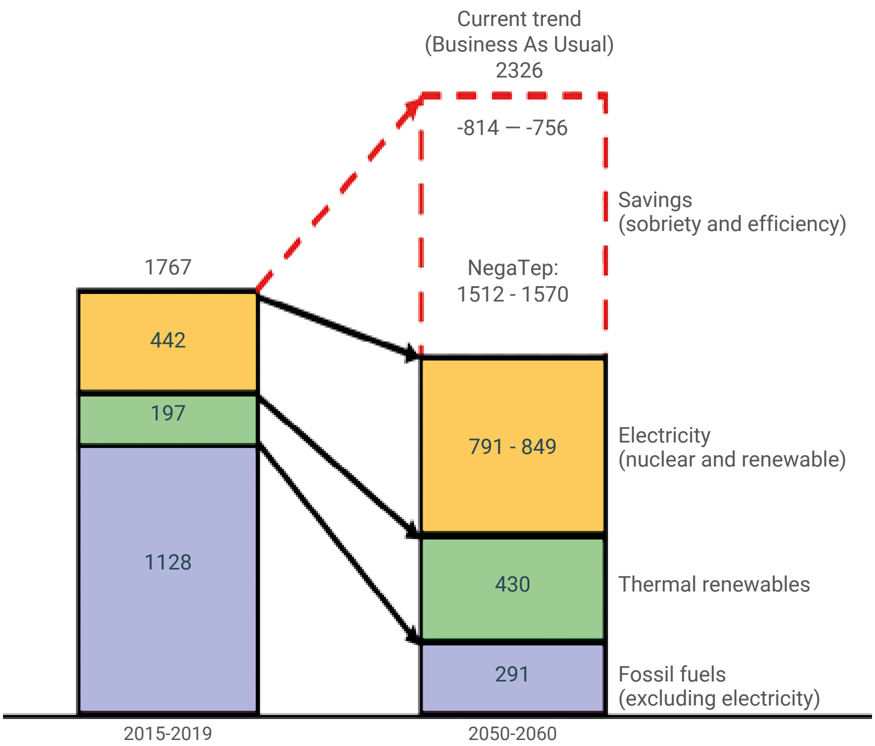
	SITUATION IN 2019	SITUATION IN 2050					
		Trend	LTECV objectives	negaWatt 2022	ANCRE Scenarios LTECV	ANCRE Scenarios ELEC-V	NegaTep 2021
Electricity (TWh)	489 + 58 (export)	900	NC	500	640	650	790-850
Primary energy excluding electricity (TWh)		2035		450			886
Total final energy (TWh)	1651	3152	954	900	954	1303	1512-1570
Total primary energy (TWh)	2849	4885	NC	950		2535	2930
primary energy per capita (MWh)	44	81		16			47
CO_2 emissions (Mt/year)	306	640	< 37	35	92	92	91

Table **3. Comparison of the figures predicted for France in 2050 by different scenarios with the objectives of the Energy Transition Law for Green Growth (LTECV) of 2015-2020.**

“In France, annual primary energy consumption of around 250 Mtoe (~ 2900 TWh) leads to annual final energy consumption of around 150 Mtoe (~ 1750 TWh).”



7. Simplified trend in final energy consumption in France, according to NegaTep, by energy source or vector (data in TWh). Nuclear power would account for 80% of electricity supply.

(a) International Institute for Advanced Systems Analysis, https://iiasa.ac.at. This organisation has recognised expertise in the development of scenarios.

(b) The consequences of the coronavirus epidemic in 2020 could well call into question this way of setting initial conditions.

(c) Various articles in this dossier are specifically devoted to an in-depth discussion of these issues.

(d) The forcing is the equivalent of a solar flux differential at the Earth's orbit compared with the 1880 level.

(e) Energy transition law for green growth (2015), currently under review.

(f) https://cutt.ly/stat-gouv-bilan-energetiq2022

(g) The role of ANCRE (Alliance Nationale de Coordination de la Recherche pour l'Énergie) is to determine which areas of research and development will be priorities over the coming decades and will require appropriate funding. It brings together representatives of the main public and private research bodies.

(h) In an article in issue 60 of *Reflets de la physique*, N. Maïzi and F. Briens examine, among other things, the effect of a high proportion of intermittent renewables on the reliability of the electricity grid .

(i) All-electric renewable energy has also been championed in the United States by Mark Jacobson, *Proc Natl Acad Sci USA* **112**(49) (2015) 15060-15065.

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a small amount left over. Final energy consumption will fall by around 15% (fig. 7), rather than the 50% target set out in the LTECV, which is considered unrealistic.

Global energy projections

The challenges posed by the fight against global warming and the depletion of resources can only be met on a global scale. To get the full picture, we need to broaden our vision of the current situation and the various projections for France up to 2050, shown in table 3, p. 41.

Table 4 shows the current situation and projections at global level, using IEA data and in particular the figures for the "Net Zero Emissions by 2050" scenario (June 2021). It should be noted that in this scenario (right-hand column of Table 4), carbon neutrality will only be achieved in 2050 if there is a drastic reduction all the more so in a context of continued demographic growth) in primary and final energy consumption, and a 22-fold increase in the production of solar PV and wind power.

It should be noted that the current trend continues to follow the so-called reference scenario ("Business As Usual", B.A.U., third column of table 4), with an average annual increase in primary energy consumption of + 1.5%, and with fossil fuels that emit large quantities of CO_2 still in the majority (78% in 2040).

Conclusion

The literature is full of a multitude of scenarios, which have in common that they are based on future socio-economic developments that are partly predictable. They differ in terms of the ideologies or interests behind their development, and in terms of the methodology used. What is their purpose?

One of the reasons for this is to support decision-making. Manufacturers and governments draw up scenarios for this purpose, or commission them from specialist institutions. Another purpose is to alert public opinion. This was the aim of the Meadows-MIT study. The IPCC reports also play this role, particularly the

	Situation in 2019	Projections for 2040 World Energy Outlook 2019 (IEA)			NZE scenario 2050
		WEO 2019 Reference scenario (B.A.U.)	WEO 2019 Announced Pledges scenario (APS)	WEO 2019 Sustainable Development Scenario (SDS)	Roadmap to zero net emissions by 2050 (IEA)
Population (billions)	**7.5**	**9.2**	**9.2**	**9.2**	**10.0**
Total primary energy (TWh)	**166 600**	**223 000**	**206 000**	**155 000**	**151 000**
Coal	44 500	52 090	43 950	17 100	4700 (including 3900 CCUS)
Oil	52 400	65 430	57 230	35 370	11 800
Gas	38 100	56 370	51 700	36 770	16,700 (including 11,950 CCUS)
Total fossil fuels (TWh)	**135 000 (81 %)**	**173 890 (78 %)**	**152 880 (74 %)**	**89 240 (58 %)**	**33 200 (22 %)**
Biomass and waste H_2 + synthetic fuels	**12 800**				**(528 Mt H_2 eq.) 25 800**
primary energy per capita MWh/year	**22.5**	**24.2**	**22.4**	**16.9**	**15.1**
Emissions Gt CO_2/year	**36**				**0**
Electricity (TWh)	**27 000**	**42 824**	**41 373**	**38 713**	**71,200 (of which 20% for H_2)**
Solar PV	730 (630 GWp)	3658	4705	7208	23 500 (14 500 GWp)
Wind	1430 (700 GW)	4258	5226	8295	24 800 (8300 GW)
Hydro	4300	5923	6098	6934	8500
Biomass	500	1256	2049	3658	7570
Nuclear	2700	3597	3475	4409	5500 (812 GW)
Fossils	17 340	23 712	19 820	8209	1330 (CCUS)
Total final energy (TWh)	**120 800**	**157 500**	**147 350**	**114 800**	**95 600**
Industry	45 000	56 350	54 250	42 000	44 500
Transport	33 900	46 300	41 900	30 400	22 200
Building	35 800	47 000	43 700	35 800	23 900
Other (Agriculture, non-energy uses)	6100	7 850	7 500	6 600	5000
Final energy per capita (MWh/year)	**16.1**	**17.1**	**16**	**12.5**	**9.5**

Table 4. **Projections of world energy consumption according to three development scenarios for 2040, and the IEA roadmap for carbon neutrality in 2050.** (sources: www.iea.org/, https://cutt.ly/iea-reports-2019 and https://cutt.ly/iea-reports-2050)

1• D.H. Meadows, D.L. Meadows, J. Randers et W.W. Behrens III, *The limits to growth*. En français : *Halte à la croissance ?* Fayard (1972). *Les Limites à la croissance (dans un monde fini)*, réédition mise à jour, avec une préface inédite de Dennis Meadows, éditions Rue de l'Échiquier (2022).

2• *World Population Prospects*, United Nations, New York, 2015 revision.

3• S. Pacala et R. Socolow, *Science*, **305** (2004) 968-972.

4• *Global Warming of 1.5°C*, IPCC special report (mis à jour en mars 2020).

5• S. Bouneau *et al.*, *Annales de Physique* **34** (2009) 1 ; S. Bouneau *et al.*, *Reflets de la Physique* **36** (2013) 30-35.

6• *The energy report: 100 % renewable energy by 2050*, WWF Ecofys (2011)

7• *Révolution énergétique*, Conseil Européen des Énergies Renouvelables et Greenpeace International (2009).

8• *Scénarios de l'ANCRE pour la transition énergétique* (2013), www.allianceenergie.fr/

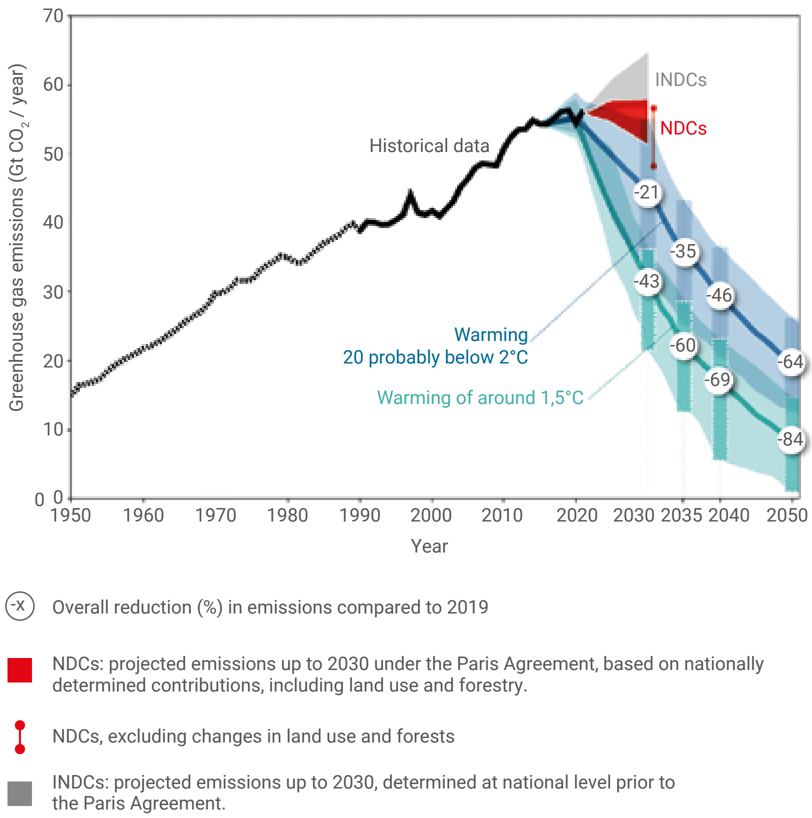
9• *Futurs énergétiques 2050 : les scénarios de mix de production à l'étude permettant d'atteindre la neutralité carbone à l'horizon 2050* (2021), RTE, https://cutt.ly/rte2050

10• Synthèse du scénario *néga*Watt 2022, www.negawatt.org

11• *Un mix électrique 100 % renouvelable ? Analyses et optimisations, ADEME* (octobre 2015).

12• Collectif Sauvons le climat, *NégaTep, pour réduire les émissions de CO_2 de la France d'ici 2050-60*, Les unpertinents (2021).

13• *Climate Change 2023: Synthesis Report*, IPCC, AR6 SYR (2023), Genève.doi:10.59327/IPCC/AR6-9789291691647.



8. historical trends in global greenhouse gas emissions since 1950, projected emissions to 2030 based on nationally determined contributions, and emission reductions required by the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [figure1, page 18, of a United Nations Technical Report in preparation for COP 28, https://cutt.ly/unfccc-resource-2023-pdf].

very pessimistic 2023 report [13]. Some environmental NGOs are posting roadmaps that must be followed if they are to achieve their vision of a human society that is closer to nature and nuclear-free. Whether it's to make a decision, to warn or to impose a course of action, a published scenario is likely to reflect the more or less preconceived ideas of the person commissioning it. There is not always room for rationality.

Since 2020, the health crisis resulting from the Covid-19 epidemic, followed by the war in Ukraine, have put a strain on the economies of developed countries and certain emerging countries. The problem of the energy transition is thus posed in a new way. Different scenarios will undoubtedly be necessary, but the challenge at global level remains to construct a plausible trajectory for a radical reduction in greenhouse gas emissions (fig. 8), by combining the measures determined at national level. This modelling work forms the basis for negotiations at international climate conferences, the last of which, COP 28, was held in Dubai at the end of 2023.