Nuclear in its wider context

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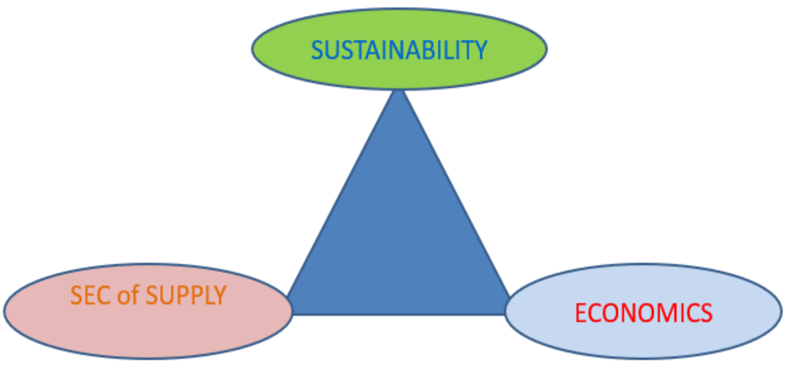
Table of contents

1 About « Sustainability »

The often-used definition of *sustainability*, particularly at EU strategic level, is by far too short-sighted. Sustainability is indeed frequently perceived as one of the three pillars of the energy trilemma for energy policy as illustrated by the figure below, the others being the economics and security of energy supply. By doing this, sustainability is considered a synonym of environmental concerns, with the sole focus on the impact on the ecological aspects. In short, according to that approach, to be sustainable one must be green and green means sustainable.



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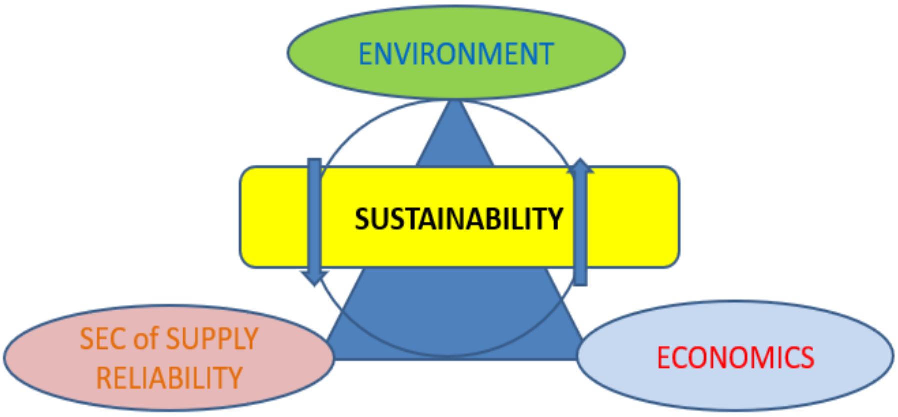
A more comprehensive definition of sustainability is necessary, properly encompassing the three pillars all together. The principles of the Brundtland's Report "Our Common Future" 1987 provide sound guidelines: the original definition of Sustainable Development is:

• development meeting the basic needs of all and extending to all the opportunity to fulfil their aspirations for a better life.

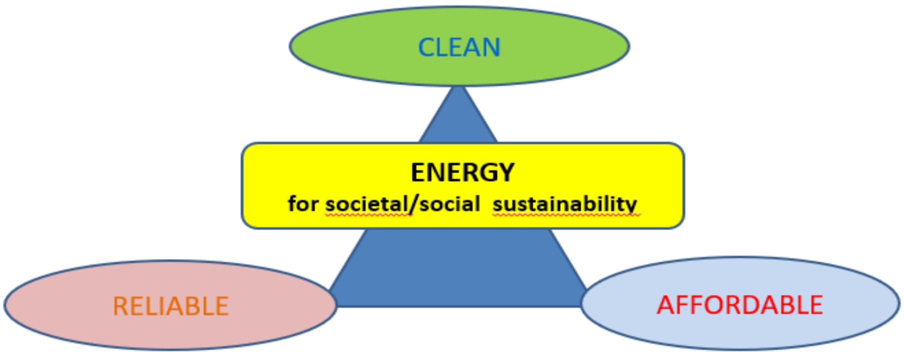
• development meeting the needs of the present without compromising the ability of future generations to meet their own needs,

Underneath these principles, it would be wise to build the definition of overall societal/social sustainability of energy by referring to the three pillars of a sound energy policy: (i) environment protection, (ii) economics and affordability of energy, (iii) security and reliability of supply. This is no more than logical since, quite simply, without secured access to energy at reasonable cost for the proper functioning of a society of welfare, the energy provision cannot be sustainable in the literal sense. 'Proper sustainability' must be the result of a balance between the three pillars, and these pillars are interacting with each other, as illustrated in the figure below.



Energy is the necessary blood for the functioning of our society, it needs to be affordable for the economy and users (enterprises and households), reliable to be available in quantity and quality when needed, and obviously respectful of the environment. Clearly, as part of the energy provision picture, one should strive to reduce the amount of energy needed to keep society running properly. Wasting energy should be reduced where possible, and more efficient energy conversion technologies should be welcomed. Therefore, energy efficiency is a major endeavour to pursue proactively. Already over the last decades, a decoupling between the gross domestic product (GDP) and the energy consumption has been observed locally in developed economies, which is all very commendable but realistically looking at the demography worldwide and the legitimate hope for better access to energy for all, there is no doubt that the overall amount of energy consumed worldwide will further increase. And, even in developed countries, where more will be done with less energy, the trend is to go towards more electrification (e.g. digitalisation, electric cars, heat pumps…) to replace the use of fossil fuels, avoiding air pollution, especially in large cities, and targeting "an economy with net-zero greenhouse gas emissions" by 2050.

So, an energy source could be considered as 'properly sustainable' if it complies with the three criteria of cleanliness, affordability and reliability. No single source of energy is perfect from an all-criteria perspective. It is a matter of balancing the pros and cons for each of the criteria and strive for a fair optimised balance. Regrettably, many people put their priority on just one of the three pillars of the triangle. Environmental campaigners will focus on the environmental protection pillar, industry on the cost and reliability of supply of energy, households on the affordability… but one thing is certain, at this moment there is no silver bullet… will one appear in the future? … betting on it is a major risk for the society. It seems reasonable for now to keep all options open at a time when there are too many parameters and unknowns in the equation, even more in the present geopolitical context and a tendency for a less open international trade framework. One must be lucid and honest looking at solutions available on the shelves and evaluating risks in the promised solutions in terms of technical/economic feasibility and timing. The figure below illustrates the wider concept of sustainability for energy: **C**lean **A**ffordable **R**eliable **E**nergy for societal/social sustainability[2].



As a matter of fact, applying the triangle of the three pillars to compare the diverse sources of energy between them is not enough. Indeed, energy policy is taking place in a wider context encompassing political governance, consumer behaviour, acceptability and permitting… What needs to be done is to comprehensively contemplate the triangle to judge the societal/social sustainability of the whole integrated energy system, by considering the interactions between the diverse sources constituting the system. This is particularly true for the electricity system where the diverse forms of production are linked through the grid and the market and are impacting each other. The effect of this linkage is much dependent on the market design and influenced by policy driven measures, such as subsidies and other support methods.

The overall or 'proper sustainability' of the whole system should first be analysed based on a level playing field, neutral in terms of technologies, where each source is considered as objectively as possible versus the three pillars, without a priori exclusion. Policy making decisions on the energy mix should be made only afterwards, if justified. What we observe mostly is the inverse: policy choices of energy sources are made upfront without proper analysis of the sustainability of the whole system, distorting the picture and making a proper analysis to support decision impossible.

To illustrate this, one may consider the cost of the intermittency of renewable energy sources (photovoltaics and wind). Decisions have been made, in a number of countries, to massively support their deployment because they are "clean for the environment" as the sole criterion. The policy driven initial deployment, paid by the electricity consumer and/or the taxpayers, is claimed to have allowed

[2] https://www.wecareeu.org

a strong reduction in the cost of the electricity produced by wind turbines and solar panels, soon reaching so-called ‘grid parity’, justifying further investments on an economic, market based, principle. ‘Grid parity’ is a wrong metric as it ignores the fixed system costs. A more proper metric would be ‘cost parity’[3]. The cost estimate usually used is the LCOE (Levelized Cost of Electricity – see also § 2.3) at the output of the wind turbine or solar panel. This LCOE just considers the necessary average revenues to balance the investment and operation costs of a given technology. It does not reflect the costs of the electricity to be produced by other means when there is no wind or sun (noting a wind turbine has a “capacity factor equivalent at full capacity” of less than 25% onshore and 40% offshore, and a solar panel 15% - average figures for Europe) and the opportunity cost of driving the other generation means out of the merit order[4]. As an alternative rule of thumb, one might also add to the LCOE of the wind turbine or solar panel the cost of producing electricity by a “dispatchable source”, e.g. a biofuel plant or an electricity storage facility coupled with the renewable source to compensate for the intermittency during the time there is no wind or sun, so as to reach a global load a factor equivalent of 85 % (a reference figure for a dispatchable source).

But, the above would even not be enough to properly take the cost of intermittency into account. Indeed, the addition of large amounts of intermittent renewable sources is also impacting the costs of the electricity system as a network with its mandatory adaptation of the grid, transmission and even more distribution, to the decentralised production. This is a rather complex issue to tackle. A number of studies have started to look at this. We will refer to and detail them in the next sections.

2 The Climate Challenge (avec contribution de A Berger)

Climate is the result of phenomena occurring in the atmosphere, oceans, ice, soil and the living world, as well as their complex interactions. The driving force behind climate is the energy that the earth receives from the sun. In addition, greenhouse gases, such as carbon dioxide (CO_2), methane and water vapour, contribute to the intensification of the greenhouse effect that causes the current global warming. These are two of the reasons why climatologists are interested in Climate-Society relations and the energies available to us on Earth.

In February 2023, the concentration of CO2 in the air reached 420 ppm, which is 50% higher than the pre-industrial concentration (280 ppm). In 2021, CO2 emissions in Europe will be around 3,600 MtCO2eq, including 720 MtCO2eq from the supply of electricity, gas, heat and cooling. In Belgium, these emissions were around 110 MtCO2eq, including 20 MtCO2eq from the above-mentioned industries. According to the IPCC's 2023 report, the average temperature recorded at the Earth's surface between 2011 and 2020 was 1.1°C higher than during the 1850-1900 period, which marks the start of the industrial era. At the current rate, it will be difficult to keep global warming below 2°C (compared to the time before the Industrial Revolution in1850), and if nothing changes, the world will be heading for a temperature rise of 3.2°C by 2100. 42% of greenhouse gases emitted since 1850 have been emitted since 1990. To stay below 2°C, carbon neutrality must be achieved by 2070. Man is indeed and ‘unequivocally’ responsible for global warming. The impacts of global warming are already visible and are more serious than expected. Extreme events such as heatwaves, droughts and extreme

[3] https://iea.blob.core.windows.net/assets/a22dedb8-c2c3-448c-b104-051236618b38/WEO2013.pdf, pp 218-219

[4] The merit order is explained below.

rainfall have multiplied. Sea levels rose by 20 cm between 1900 and 2020 and will continue to rise for centuries.

The Kyoto Protocol, signed in 1997, required Belgium to reduce its greenhouse gas emissions by 7.5% over the period 2008-2012 compared with the 1990 reference period. In 1999, under the impetus of the Greens, the government also reached an agreement to phase out all nuclear power in Belgium after 40 years of operation (between 2015 and 2025), which became law in 2003. This is despite the fact that, using a total life-cycle analysis, nuclear power is a very low-carbon means of producing electricity, in the region of 5 to 10g CO2/kWh, compared with fossil fuels (coal 800 to 1000g CO2/kWh, and gas 400 to 450g CO2/kWh). Wind power is also very low-carbon, of the same order of magnitude as nuclear power, whereas solar power is 5 to 6 times more carbon-intensive.

After Kyoto, the European Union pursued a voluntarist policy of reducing greenhouse gases by promulgating increasing decarbonisation targets: 20% by 2020 (the 3x20 package), 55% by 2030 (Fit-for-55) and carbon neutrality by 2050 (Net Zero). Once adopted by the European Union, these targets are binding and translated into 'national' targets for each Member State. It is important to note that in addition to decarbonisation targets, the European Union is also adding targets for renewable energy penetration and energy efficiency. For 2020, these targets were also 20% (hence the 3x20 label for 2020). For 2030, the target for renewable energy as a proportion of overall consumption is 42.5% (with an additional target of 2.5%), and the target for reducing energy consumption is 12% of projected 2020 needs by 2030. The European approach is a mixture of the goal to be achieved (decarbonisation) and the means to achieve it (renewable energy and energy efficiency). The renewable energy and energy efficiency targets are binding at the overall European level but are not necessarily translated into binding targets at the national level in the Member States (with the exception of the 3x20 package, which has been translated into binding targets for each Member State). A governance mechanism should enable the European target to be achieved through a shared effort and peer pressure. Given the differences of opinion between Member States on nuclear power, it is generally omitted or excluded from European energy policy texts. To put it simply, green policy (the European Green Deal) generally excludes the only massive source of decarbonised and controllable energy from European funding, despite the promotional dimension of the Euratom Treaty and Article 194.2 of the Treaty on the Functioning of the European Union, which stipulates that each Member State has a free choice of energy mix. The main reason for this state of affairs is that the European Commission, which alone has the power to propose European regulations, is anticipating the difficulties that its proposals will encounter during the debates in the European Council and Parliament. As long as certain Member States maintain their dogmatically anti-nuclear positions, this phenomenon will continue. However, the multi-crisis situation (climate, health, COVID, energy) with its societal and social impacts in 2021-2023 could change the situation, in particular under the impetus of an Alliance of pro-nuclear Member States formed in May 2023. Initially made up of 12 Member States under the leadership of France, with a number of other Member States as observers (including Belgium under the 2003 Nuclear Phase-out Act), this Alliance will no doubt open up to other members in the future.

In 2021, electricity generation in Belgium (94 TWh, of which 22 TWh was exported) was 16% higher than in 1997. The share of output from nuclear power stations has remained roughly unchanged, at around half of total output, thanks to power increases when steam generators were replaced; the share of thermal power stations has fallen to half that of nuclear power stations, with 25% more installed capacity. As for intermittent renewable energies that cannot be piloted, their production is a third of that of nuclear power, which in view of their installed capacity (double that of nuclear power) translates into an overall capacity factor that is six times lower (approximately 1/2 for offshore wind power, 1/4 for onshore wind power and 1/8 for photovoltaic solar power). Gas-fired power stations, which are also necessary to compensate for the intermittent nature of renewable energies, but which emit 40 times more CO_2 /kWh than nuclear power stations, mean that in 2021 the mix had an average emission rate of around 130g CO2/kWh. Note that in 2022, among our neighbours, this rate was 85 gr in France (due to electricity mainly from nuclear sources) and 385 gr in Germany (after the total shutdown of its nuclear fleet and its replacement by intermittent renewable energies supplemented by lignite, coal and gas).

It can be argued that in a global CO2 market at European level (Emissions Trading Scheme), the carbon footprint of an individual means of electricity production is of little importance as long as the overall footprint of all sectors combined is reduced. Over time, as the reduction in allowances diminishes, the system should therefore be virtuous. But since we know that the electricity generation sector is one of the easiest, if not the easiest, to decarbonise, it is essential to optimise this decarbonisation in terms of time and cost, so as not to penalise the overall economy and society as a whole.

For the near future in Belgium, the extended (long-term) operation of Doel 4 and Tihange 3 should make it possible to maintain 2 GW, which produce around 15 TWh. If the other 30 TWh of historical nuclear capacity (Doel 1 and 2, scheduled for shutdown in 2025, Doel 3, shutdown in October 2022, Tihange 1, scheduled for shutdown in 2025, and Tihange 2, shutdown in January 2023) were to be produced by gas (new thermal power stations are under construction), this would lead to total emissions almost double those currently produced by gas-fired power stations, assuming constant electricity consumption, which is predicted to increase as a result of the growing electrification of energy needs. Any increase in the use of intermittent renewable energies to replace nuclear power will not only take time, but will always have to be combined with the use of gas, as the means of mass storage of electricity have not yet been demonstrated. And that's without mentioning the real costs of deploying these intermittent renewable energies, which become uneconomic above a certain threshold, as will be explained later in this chapter.

3 The Economics: from LCOE to "system costs" to "full cost"

3.1 LCOE: definitions, basic principles and some global figures

The cost of electricity produced by a power plant or equipment, called the LCOE – the levelized cost of electricity (at the output of the facility) - is calculated using a formula taking into account the investment capital for the construction of the installation, from design to commissioning, the operation and maintenance costs, including fuel and manpower, the dismantling and long term waste management costs.

The construction costs are first calculated as an overnight cost, assuming the facility is built in one single "night". The costs are then corrected (increased) to take account of the cost of financing (e.g. a loan) using a discount rate. The discount rate varies as a function of the risk nature: it can be as low as 3% for projects which are considered socially very acceptable or necessary, compared to up to 10% for projects with more risks in terms of costs and delays, or less socially acceptable – which is currently the case for nuclear projects.

Costs of dismantling and long-term waste management are evaluated long time before they will have to be paid for. These costs are also evaluated as overnight costs. Funds are collected over the full duration of the operation of the facility and carefully managed to allow the amount to grow following compound interest rules[5]. The longer the facility is operated, the longer funds are accrued, which is beneficial as the cost of dismantling is not much affected by the duration of operation, which also applies but to a lesser extent to the cost of waste management.

The advantage of long lifetimes of facilities (up to 60 years and even 80 - for a nuclear plant versus 20 for a wind turbine or a solar PV) does not really translate into the LCOE, because costs coming later in time have a reduced effect due to the discount rate (applying this time in the other way) than for costs coming earlier in time, in particular, those coming before the plant is commissioned. So, if one wants to visualise the benefit of a long lifetime, it is easier to consider that the costs of each year of production once the capital cost is repaid, is basically limited to the operational and decommissioning and waste management costs. One should also recall that, while upfront costs of construction weighs on the shoulder of the investor, once the investment of a facility has been made, it is a sunk cost. When considering long time operation of a plant, only the extra investments to satisfy the required safety requirements need to be taken into account.

For large nuclear plants, the capital and financing cost of construction makes about 60% of the LCOE, the cost of operation and maintenance about 20%, the fuel cost 10%, and the decommissioning and waste management also 10%. This explains why nuclear plants are most economic when they run full load the maximum of the time, serving as baseload facilities[6].

This is a very central issue to consider when addressing the question of "flexibility" of nuclear – meaning its adaptation to the requirements of intermittent sources of electricity. These sources produce on random basis but have priority to enter the electricity system due to their almost zero marginal cost (merit order based on the marginal operation costs) or even because they have granted priority. Going to high penetration rates of intermittent renewable will force other facilities, mainly nuclear ones in a carbon-constrained world, to do load following, reducing their economics. As a trigger, one could consider that priority should be given on economic grounds based on full cost and not only marginal cost, as long as the carbon constraint is respected, and that therefore the nuclear plants should run base load and other facilities curtailed if needed. We will come back to this issue when looking at the price making in a market system based on the merit order.

Every five years, the IEA publishes, jointly with the NEA, a report called Projected Costs of Generating Electricity (PCGE). The last (8^{th}) edition dates from 2020[7]. The report compares the LCOE of diverse ways to produce electricity, using fossil fuels, nuclear energy, or renewable sources. The calculations are based on cost projections collected from the Member Countries of the IEA, particularly for the overnight capital costs of N^{th} Of A Kind (NOAK – number N plant in a serie) installations. Standard assumptions are used for the load factors, as well as for the duration of the construction to calculate the financing costs. Three discount rates are used allowing parametric studies. The same is done for the lifetimes of installations and the cost of CO_2 (applied to fossil fuels).

The following graphs are extracted from the report and show global consolidated results (specific figures for each country can be found in the report). Figure 3.1 shows that for the region Europe, the median LCOEs for nuclear new built, gas and solar PV are all around 70 Euros/MWh, with offshore wind

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[5] As a rule of thumb, an initial fund with a real discount rate (i.e. nominal minus inflation) of, say 3%, leads to a doubling of the fund after a period of roughly 25 years (without any additional deposits in between). When more annual deposits are added, then the final amount will be even larger.

[6] Baseload operation of a nuclear plant is usually considered as almost continuous nominal operation connected to the electricity grid. However, 'baseload' can also be considered as continuous nominal nuclear-heat production, whereby electricity and/or heat are the end products.

[7] https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

higher at around 90 and onshore wind lower at around 55 Euros/MWh[8]. These LCOEs are calculated for a medium discount rate of 7%. Higher discount rates would make nuclear less competitive due to the high financing costs associated with long construction times. Lower discount rates make nuclear more competitive. From there one can derive that the discount rate is a very central element for investors to consider. A variable discount rate, changing over time, going from a rather high value during construction to lower value once the plant is in operation, reflecting the decreased financial risk once the plant is built and operates, would therefore help investment strategies and decisions.

Figure 3.1
Median Technology Cost per region
(Source IEA Report PCEG Report 2020)

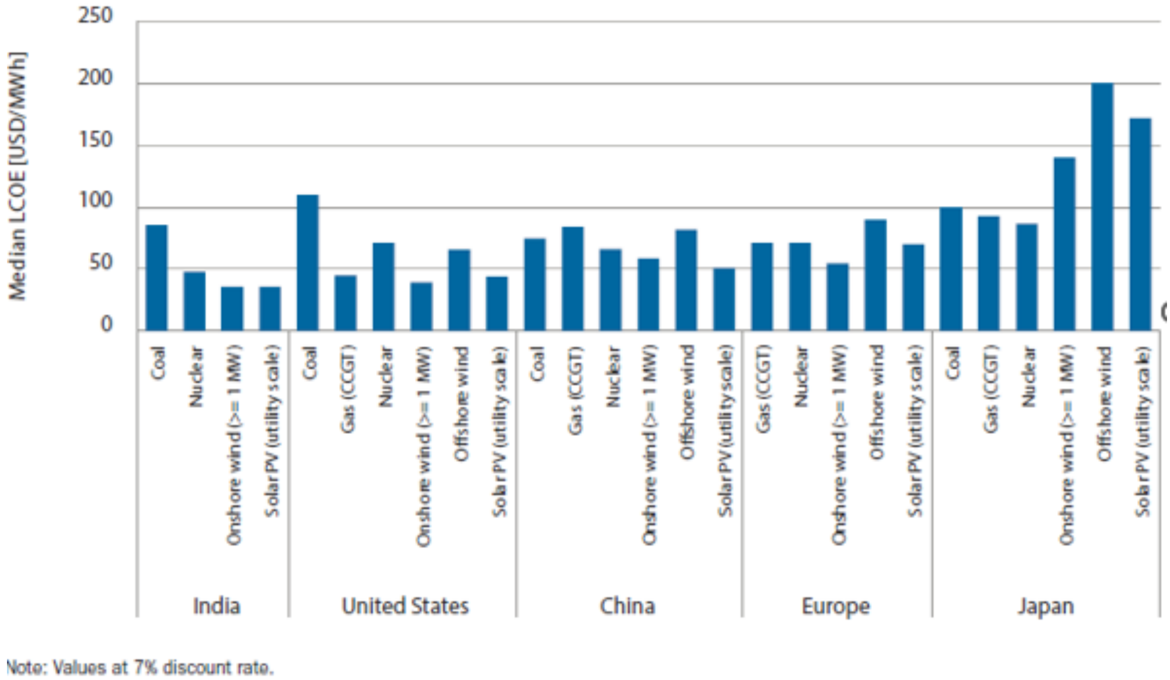
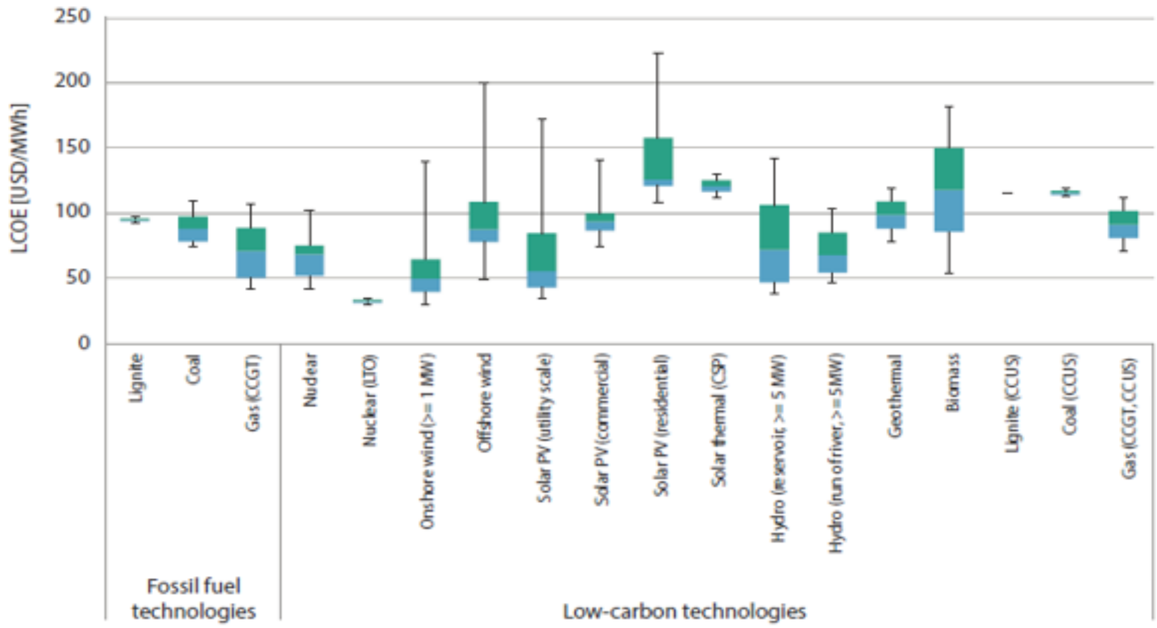


Figure 3.2 gives the LCOEs for all technologies at "world level" showing sometimes large ranges. But what is remarkable is that the most economical way to produce electricity is through long term operation (LTO) of nuclear plants, going beyond their initial design lifetime, usually beyond 40 years. The 8th edition of the PCGE of 2020 is the first time the IEA introduced the LCOE of nuclear plants in LTO in the study. Before, only new built plants were considered. The first time the concept of applying LCOE calculations to existing nuclear plants in LTO comes from a study performed in 2012 and 2013 by NEA[9] and for the European Commission in the frame of the ENEF (European Nuclear Energy Forum)[10]. The "idea" behind was to consider the cost of the refurbishment for LTO of an existing nuclear plant, refurbishment needed to get the authorisation by the Safety Authority to go beyond the 40 years of operation for an additional 10 or 20 years, as a capital investment for a nuclear facility with an expected lifetime of 20 years, instead of the 60 years used for LCOE calculations for new built. A more recent

[8] Uncertainty margins are shown in the figure 3.1.
[9] https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/7054-long-term-operation-npps.pdf
[10] https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wpen2013-14.pdf

update of the economics calculations of LTO was published by of the NEA in 2021[11]. The study provides a parametric analysis of the LCOE for the refurbishment of a nuclear plant of 1000 MWe. Figure 3.4 summarises the results. The rather low capital investment costs, with the reduced time for the refurbishment works, compared to the high capital and long construction time of a new built, as such impacting the financing costs, explains the very low value of LCOE for nuclear plants in LTO. Not allowing nuclear plants to go to LTO, if they are authorised by the Safety Authorities, leads to a heavy penalty due to the high opportunity cost of not allowing such a LTO.

Figure 3.2
LCOE by Technology
(Source IEA Report PCEG Report 2020)

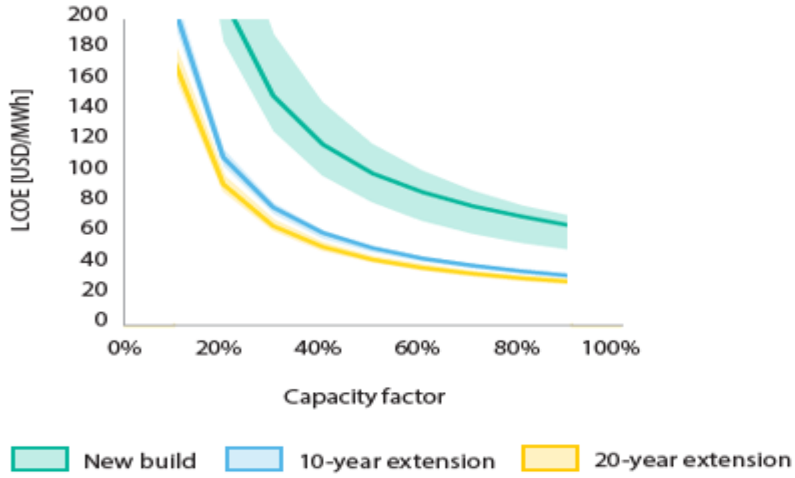


Note: Values at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. the second and the third quartile.

Figure 3.3, in addition to reflecting the much lower LCOE of a nuclear plant in LTO compared to a new built (about 50% cheaper), also shows the dependency of LCOE with the capacity factor. The less a plant operates, the more expensive is the electricity produced. The calculation is again done for a discount rate of 7% and the cost escalation at low-capacity factor is very sharp. This high dependency reflects again the effect of the high fixed capital costs of nuclear.

[11] https://www.oecd-nea.org/jcms/pl_60310/long-term-operation-of-nuclear-power-plants-and-decarbonisation-strategies?details=true

Figure 3.3
Cost of nuclear new built and LTO versus load factor
(Source IEA PCGE Report 2020)



Note: Values at 7% discount rate. Lines indicate median values, areas the 50% central region.

Figure 3.4 summarizes the combined effects of the LTO period, the overnight capital investment for LTO, the discount rate and the capacity factor on the LCOE.

Figure 3.4
Parametric sensitivity for LCOE values for LTO
(Source NEA LTO Report 2021)

Overnight LTO investment costs (USD/kWe)	LWR LTO LCOE (USD/MWh)					
	LTO period = 10 years			LTO period = 20 years		
	Discount rate			Discount rate		
	3%	7%	10%	3%	7%	10%
	Capacity factor = 85%					
450	29.4	31.2	32.6	26.4	28.6	29.7
700	33.4	36.1	38.3	28.7	31.4	33.8
950	37.4	41.1	44.1	31.0	34.7	38.0
	Capacity factor = 75%					
450	31.9	33.9	35.5	28.4	30.5	32.2
700	36.5	39.5	42.0	31.0	34.2	36.9
950	41.0	45.1	48.5	33.6	37.9	41.6
Min	29.4			26.4		
Max	48.5			41.6		

Note: These values have been computed assuming a refurbishment period of two years, fixed O&M costs of USD 85/kWe, variable O&M costs of USD 1.5/kWe, front-end fuel costs of USD 7/MWh and back-end fuel costs of USD 2.33/MWh, consistent with the values for new build projects considered in IEA/NEA (2020). The overnight LTO investment cost includes other plant enhancements beyond LTO and 5% of contingencies. Decommissioning costs are not included as they have largely depreciated during the initial design lifetime.

The conclusion is that nuclear plants should preferentially operate in baseload and as long as possible (if authorised by the independent Safety Authority). At least large nuclear plants. Things may be somewhat different for SMRs (Small and Modular Reactors) but this remains to be properly studied.

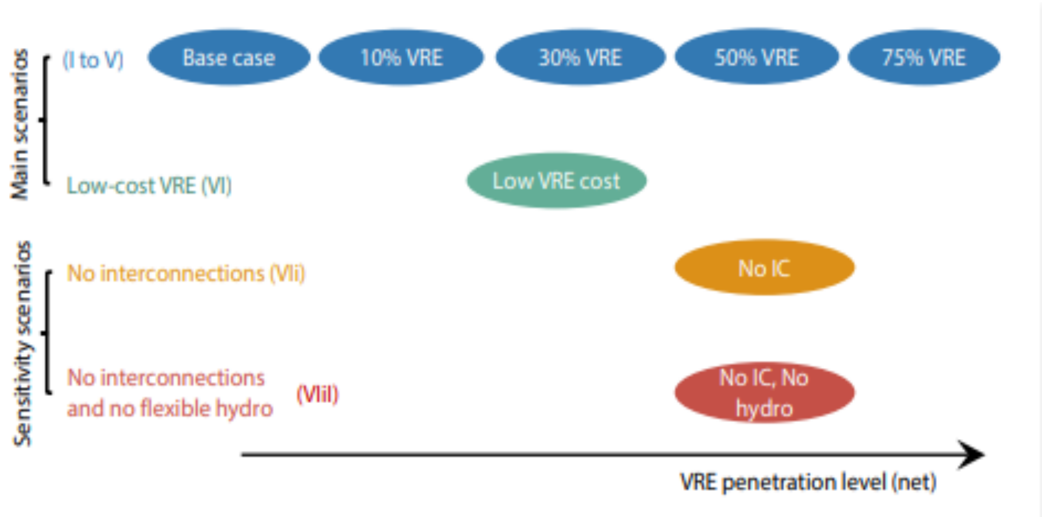
This then leads to say that nuclear plants, from an economic point of view, are not the best way to come in support to the intermittency of renewables, by doing load following. Flexibility might be organised at the level of a multi-producers (nuclear and renewables)/multi-users (electricity and heat processes) system (so-called hybrid system), where the nuclear plant runs baseload, switching from electricity to heat, and where the flexibility is offered by heat users switching on and off. It remains to be seen if such users are willing to do so, based on their economics and considering their technical constraints.

3.2 Beyond LCOE: System Costs

In 2019, the Nuclear Energy Agency of the OECD published a report "System Costs with high shares of Nuclear and Renewables"[12]. The aim was, by means of a fictitious but very instructive exercise, to evaluate the cost impact of increasing shares of intermittent renewables from a system perspective, covering the LCOE and the additional costs induced by the intermittency on the electricity system beyond the generation facilities (profile costs, balancing costs, grid costs). The study looks at a greenfield situation where the electricity system is imposed to be decarbonised at 50 gr CO_2/kWh (2050 target). The weather (wind and sun) conditions are taken from the real case of France during a real meteorological reference full year. The same applies for the electricity demand curve. The average or median costs of the diverse sources of electricity production are taken from the IEA PCGE report data (version 2015). A first base case, searching for the optimised generation mix, has as only constraint the above-mentioned CO_2 limit. Then, the share of Variable Renewable Energy (VRE) in the mix is successively increased (imposed) to 10, 30, 50 and 75% of the annual share of generation expressed in TWh. The delta is then mainly covered by nuclear energy as being the best decarbonised source. Figure 3.5 summarizes the cases studied.

Figure 3.5

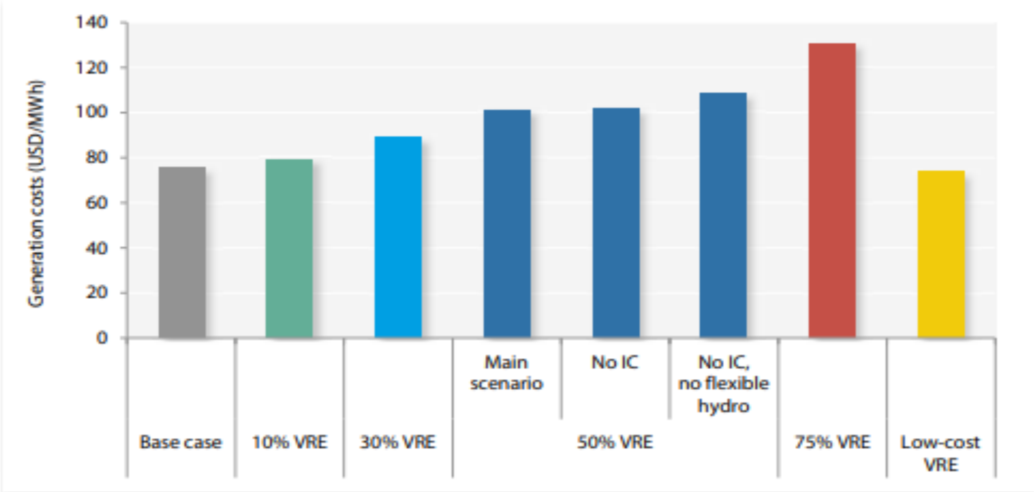
Different scenarios considered in the 2019 NEA System Cost Study



[12] https://www.oecd-nea.org/jcms/pl_15000/the-costs-of-decarbonisation-system-costs-with-high-shares-of-nuclear-and-renewables?details=true

The results for the overall system cost (in USD/MWh) are shown on figure 3.6. The 'Base Case', which mix, for the cost parameters chosen, consists of mainly nuclear, hydro and some gas fired plants, does not require variable renewables (wind and solar) to satisfy the 50gr CO_2/kWh emission limit. That mix turns out to be the cheapest solution. Forcing in more variable renewables increases the system cost.

Figure 3.6
Resulting outcome for the System Cost from the NEA 2019 Study



The main reason is that the needed installed capacity is multiplied by a factor of three going from the base case to the 75% renewables, and the overall costs, LCOE plus additional system costs, are doubled. The study also shows the large operational volatility when more renewables are brought into the electricity system, with 37% of the time (over a year) in excess generation for the 75% case, meaning that during that time the price of electricity will be negative, forcing producers to curtail their production. The more renewable sources are installed, the more their value decreases, as they are all producing at the same time when there is wind and sun, so competing against each other (sometimes referred to as self-cannibalisation), which is not the case for dispatchable facilities if the capacity planning is properly done.

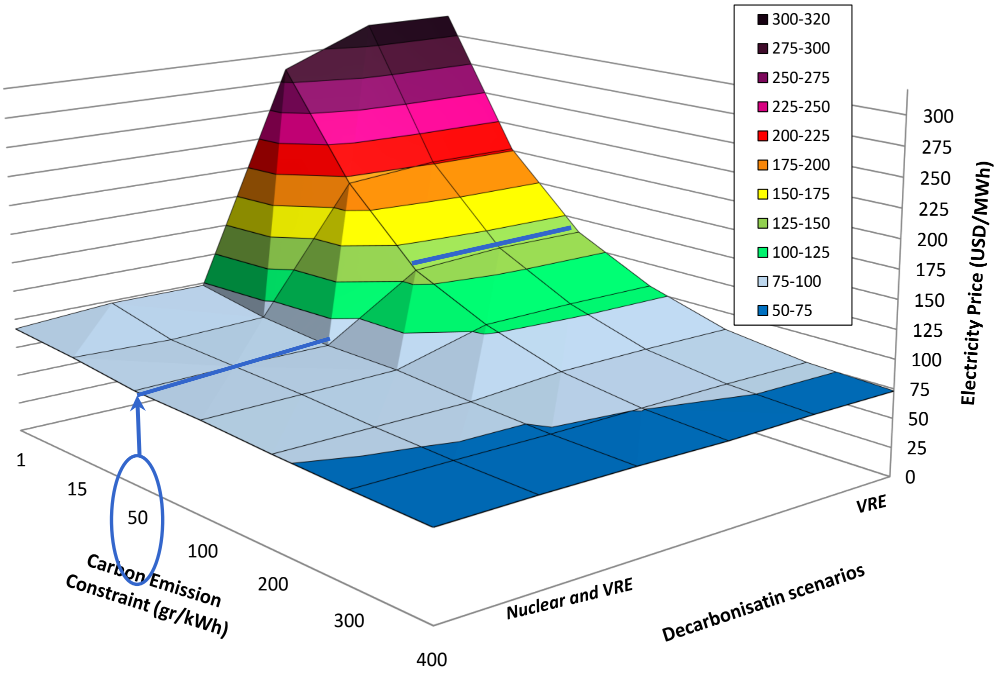
This negative impact of high penetration of renewables on the economics at system level was also shown in the scenarios done by the French Transmission Operator RTE end of 2021, where the average cost of a MWh in scenario 50% nuclear / 50% renewables is lower than in the 100% renewable case, due to the system costs.

To anticipate the criticism that the cost parameters chosen in the main scenarios of the study may appear as favouring nuclear over renewables, an extra case favouring renewables and battery storage was considered (called the low VRE cost scenario in figure 3.5). The extra case assumed cost reduction of 60% for PVs, 50% for wind offshore and 33% for wind onshore – versus the IEA PCGE 2015 numbers. In this scenario, the variable renewables sources enter the system endogenously (not as an imposed fraction). It results in an overall installed capacity about equal to the base case, where now some nuclear capacity is replaced by wind and solar for the same electricity production (in TWh). As reflected in the Figures 3.5 and 3.6, the study shows that, with the cost assumptions taken, a penetration of intermittent renewables remains economic if the share is below 30%.

These outcomes, and particularly the last one just mentioned, is confirmed by a study by MIT[13] which shows two important facts: first the importance of the relative capital costs of nuclear and variable renewables, second that the more one wants to decarbonise the electricity generation mix, the more expensive it becomes with more variable renewables in the system. The study shows, with the cost assumptions taken, how excessively expensive the system becomes without any nuclear generation. This is illustrated by Figure 3.7 below for the region of New-England (USA), also available in the 2019 NEA System Costs study. One axis relates to the decarbonisation target from 400 to zero gr CO_2/kWh, another to the penetration of variable renewables (zero up to 100%) and the last to the generated electricity cost. It shows that between 40 and 60 % of intermittent renewables, the costs increase dramatically, showing there an economic limitation to their penetration beyond a typical value of 50%, this one depending much on the geographic location and the costs assumptions taken, mainly capital costs.

[13] https://www.sciencedirect.com/science/article/pii/S2542435118303866 and https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf

Figure 3.7
Price of Electricity in function of the decarbonisation objective
and share of variable renewable sources versus nuclear
(Source NEA System Costs Study 2019)



3.3 Going even further: External Costs

Other costs, beyond LCOE and System Integration Costs need also to be considered. This includes a wide range of costs, some being easily quantifiable, others only qualitatively estimated. The NEA issued a report in 2018[14] evaluating aspects such as air pollution, land-use impact, security of supply, social impact in terms of employment and growth, … Other aspects such as potential safety related costs need also to be considered.

Already in 2013, the previously mentioned study[15] for the European Commission, estimated the range of external costs for normal operation (including front and back-end of the fuel cycle), thus adding to the LCOE and system integration cost, between 1 and 4 Euros (2012)/MWh for nuclear, compared to 40 for coal, 20 for gas, 10 for PV and 2 for wind. One might object that the cost of a nuclear accident, even with a very low probability of occurrence, renders this evaluation not relevant. The study, however, also looked at this issue using the method of Pr F Lévêque of Mines Paris Tech described in his book Nuclear On/Off[16], based on the Bayesian probabilistic theory, whereby he considers past nuclear accidents as study cases in the Bayesian statistical philosophy. Together with the estimated cost of a nuclear accident by IRSN[17], it comes down to an additional cost range between 0,3 and 3 Euros

[14] https://www.oecd-nea.org/jcms/pl_14998/the-full-costs-of-electricity-provision
[15] https://www.mech.kuleuven.be/en/tme/research/energy_environment/Pdf/wpen2013-14.pdf
[16] Nuclear On/Off, Section 2, Pr François Lévêque, Dunod, Paris, 2013
[17] https://www.irsn.fr/sites/default/files/documents/actualites_presse/actualites/EN_Eurosafe-2012_Massive-releases-vs-controlled-releases_Cost_IRSN-Momal.pdf

(2012)/MWh. This figure is compatible with the evaluation given by the French Court of Auditors (Cour des Comptes) in 2014[18], between 1 and 2 Euros/MWh. Summing all the quantifiable external costs for nuclear therefore leads to an increase of around 10% of the LCOE figure.

This more than suggests that the slogan that solar and wind power are cheap because wind and sunshine are cost-free and that nuclear power is overly expensive needs much more careful consideration and serious analysis.

4 Cost is not price: the market bias

What matters for the electricity consumers (households, commercial and service sectors and industry) at the end is the price on the electricity bill. Today, in liberalised markets, the wholesale price is fluctuating and does not relate anymore to the total cost of production. This is due to the electricity market launched stepwise in the European Union at the turn of the century. Before that time, the electricity system was mainly made of large public sector producers or private companies with a monopoly granted by the authorities, vertically integrated, and having an obligation of reliability of supply. The technologies were mainly fossil based thermal power plants (coal and gas), hydropower where possible and nuclear power facilities. Nuclear was designed for the baseload, coal for the semi baseload and gas for the peak load, as it made sense with the fixed and variable cost structures of the different technologies. The merit (priority) order – calling nuclear first, then coal, then gas, properly reflected this fact. It made good sense in order to build financing reserves for future investments in high capital-intensive technologies, as the price is set by the last plant called upon to meet the demand. When demand was low, the price was reflecting the low cost of nuclear, when demand was high the price reflected the price of gas, allowing nuclear (and coal) plants to earn money for future investments. In regulated markets, the merit order was used for 'efficiency' reasons, as it reflected the increasing cost of generation, with increasing instantaneous demand. In liberalized markets, however, the merit order also determines the instantaneous wholesale price obtained from the intersection of the merit-order supply curve and the demand curve. This is called marginal-cost pricing, which is perfectly logical from an economics viewpoint in perfect competitive markets.

The logic of the liberalised market, however, was drastically challenged by the forced penetration of intermittent renewables, very much pushed at European level. Rather than relying on CO_2-emission penalties to make CO_2-emission technologies pay for their external costs as the major instrument, the EU decided in addition to impose exogenously quota for shares of renewables, to some extent counteracting the CO_2 EU Emission Trading System (ETS).

The antinuclear stand in some Member States, did not help the overall decarbonization process. In those countries, as far as low CO_2 emitting technologies are concerned, the imposed renewables replaced nuclear, without reducing the heavy CO_2 'polluters' such as hard coal and lignite, the reduction of which would have been a 'wiser' (and less costly) environmental approach.

From an overall systems perspective, the strange development over the last decade has been that the (hoped-for) liberalized competitive electricity market was completely distorted. Pretending to run the system as if it was a perfect market, but with major distortions, has led to strongly fluctuating wholesale prices, effectively showing that the theoretical energy-only market concept is not realistic and that one has to resort to all kinds of artificial new capacity-investment mechanisms to guarantee timely

[18] https://www.ccomptes.fr/fr/publications/le-cout-de-production-de-lelectricite-nucleaire-actualisation-2014

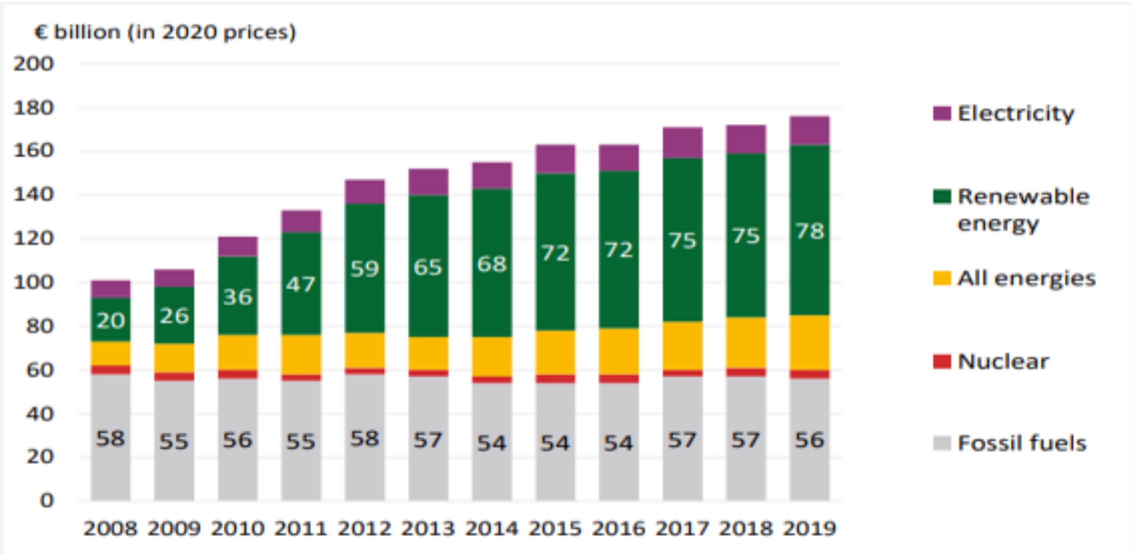
investments. This whole poorly designed decarbonization and electricity market coupling has come at a high subsidy cost… to be paid by the consumers at the end, in a way or another.

Over the last ten years (up to 2019 - the last year before the Covid crisis) the European Court of Auditor report[19] shows that 700 billion Euros have been spent in subsidies/support for renewable energy over the 12 years since 2008, and about the same figure for fossil fuels (but this for sure includes all uses of these fuels – not only electricity production). For renewables it basically relates to electricity production, which is not the case for fossil fuels which also includes mobility and other uses of heat. Subsidies for nuclear are hardly visible on the figure 4.1 below, extracted from the report. The figure for renewable subsidies matches with the well-known figure of 500 billion Euros for Germany alone over 20 years from 2005 on[20] (not counting the additional 600 billion[21] more needed to build the extra transmission lines to bring wind power from the Baltics to the industry in the south). for the transmission. Noticeably the figures of subsidies for renewables are permanently increasing year after year.

Figure 4.1

Energy Subsidies in the European Union

(Source European Court of Auditor 2021 Report)



Source: ECA based on the *Study on energy subsidies and other government interventions in the European Union*, October 2021.

The imposed introduction of renewables via targets, and their subsidies, induce a major bias in the functioning of the market, leading to market disfunctions and even market failures. Furthermore, the merit order gives priority to the market for renewable sources based on their low marginal cost (they are considered as very cheap because "wind energy and sunshine are cost-free"). But the fact that the intermittent sources are 'forced' into the market leads to artificial distortions of a natural optimized merit order. Also, the fact that many renewable sources via guaranteed long-term contracts are not exposed to the wholesale price in term of revenues, even allows them to bid negative prices into the

[19] https://www.eca.europa.eu/Lists/ECADocuments/RW22_01/RW_Energy_taxation_EN.pdf

[20] Over the period 2013-2021, the annual amount in Germany was over 30 b€ per year. (Ref BDEW)

[21] 150 billion already spent and 450 more as per the German Court of Auditors (2023)

day-ahead market. It would no longer be the case if the system costs of the intermittency would be included, in the same way that the cost of CO_2 is included for fossil fuels used for electricity production.

As a result, one may say that the electricity market as initially designed is not working properly anymore. This was said at the highest level by the European Commission (President Von der Leyen statement) in the wake of the energy crisis of 2022, even if underneath the statement internal German politics might be detected (the decision to close all nuclear plants leading to a higher reliance on Russian gas to cope with the intermittency of renewables).

What should be done is to ensure there is again a clear coupling between cost and price, and that all costs are taken into account and not hidden via subsidies, of which some are coming from debts to be recovered later via the taxpayer. The consumer needs to know precisely what he pays for.

In a maybe simplistic way, but to illustrate the principle, one might look for a new design of the electricity market (or system) where the diverse forms of electricity production would enter on equal footing without bias. In such a market dispatchable plants and intermittent sources would need to play in the same way – therefore intermittent sources might have to come in with their piggy-bag containing the (system) costs for the management of the intermittency they induce. A first step might be to always work with so-called Balance Responsible Parties (BRPs), such that the intermittent sources are required to contract for their own imbalances. For new investments, some sort of long-term contracting (in the sense of Contracts for Difference) may be a good idea to explore to start with. But at the end, the full real cost of the electricity delivered to the consumer by each source of generation need be the driver for a necessary redesign of the market, without hidden subsidies and distortions.

Interesting considerations on the competitiveness of nuclear power in electricity markets can be found in the recent IEA report "Nuclear Power and secure energy transitions", published in June 2022, thus after the Russian invasion in Ukraine.[22] (Chapter 3, "The Competitiveness of Nuclear Energy"). Also to note is the IEA introducing the concept of "VALCOE" (Value-Adjusted LCOE), which is a simplified pragmatic metric introduced by the IEA to incorporate system effects.[23]

5 Security aspects in a global world

The last pillar of the triangle for a sustainable energy policy is related to the security of supply of energy. This covers issues such as the timely and reliable supply of energy when needed for the proper functioning of the society, in quantity and quality. It also covers the front end of the energy production and delivery to the users, particularly the secure availability of and access to resources and materials needed for this production and delivery.

Nuclear power plants are dispatchable, a feature sometimes already incorporated into the designs (such as in France or Germany), sometimes not originally foreseen, but still possible after agreement of the nuclear Safety Authorities (Belgium). It means that, within certain limits, they can adapt their production to the demand. Except during periods of maintenance or repairs, the nuclear plants are able to deliver 100% of their nominal power, working in baseload, as this is their economic optimum. It may happen that a plant is shut down and unavailable for a long period, during which interconnexions with neighbouring countries are then vital to allow imports-exports of electricity, which is foreseen by the European solidarity clause. But, over a lifetime of 40 or 60 years, the load factor of a nuclear plant

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[22] https://www.iea.org/reports/nuclear-power-and-secure-energy-transition.

[23] https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, Chapter 4.

is between 80 and 90%, or even more in some cases. The IEA uses the generic figure of 85% in their studies of Projected Costs of Generating Electricity. Nuclear plants have a degree of technical flexibility to perform load following, but they are less flexible than gas power stations. For these reasons, with more and more renewables and in absence of massive storage capacities, gas is better adapted to ensure the required flexibility for load following, but with emission of CO_2. In that sense, in a way, intermittent renewables and nuclear energy may be complementary but also somewhat incompatible. This is one more reason for the need to revisit the design of a deeply decarbonised electricity market, as actually, it mixes apples and pears: large centralised dispatchable nuclear plants, designed to work in baseload, with smaller decentralised intermittent renewable sources, depending on the weather conditions, but having a kind of priority to access the grid.

Small and Modular Reactors (SMRs) may be more flexible, depending on their design[24], but it remains to be proven in the coming decade. What may foster flexibility overall is to work at system level. Hybrid Systems are integrating different production means (typically nuclear and intermittent renewables) and different uses (power and heat). In such systems, the nuclear component would work in base load and switch from direct heat production (for district heating or industrial uses) to power production when there is no wind or sun.

On the front end, there are no short-term concerns with the uranium resources, including because further exploration will identify new sources, even if geopolitical evolutions may impact the access in some countries. Every two years the NEA and the IAEA issue jointly the Red Book[25] providing details. For the longer term, particularly as nuclear power and heat production is expected to increase worldwide, recycling would become necessary. Recycling means closing the fuel cycle, linking the back end and the front end. Spent nuclear fuel still contains very valuable resources, a lot of uranium and plutonium. If spent fuel is considered as waste, these materials are spoiled and, as such waste is highly radioactive for very long periods (hundreds of thousand years), it must be permanently stored in deep geological repositories. Instead spent fuel may be reprocessed to extract uranium and plutonium which may be recycled to fabricate new fuel. There is experience of this process. Actual water-cooled thermal neutrons reactors can use MoX (mixed oxides) fuel using recycled plutonium. In Europe, France and The Netherlands are reprocessing their spent fuel. Belgium did it in the past before a political moratorium brought it to an end.

But the real prospect for recycling is to use the plutonium fuel in fast neutrons reactors. These reactors are called breeders, as by converting fertile uranium (U-238) into fissile plutonium, they “produce” more fissile material that they consume. In fact, these reactors, combined with the recycling, use the full potential of the uranium ore, not only the fissile part (U-235, 0.7% of the Uranium in the ore), but also the fertile part (U-238, 99.3%) by its conversion in plutonium. If this is widely applied, there are no time limit anymore in the access to resources as the time span is multiplied theoretically by a factor of 100… meaning that there is nuclear fuel available for 5000 years. And there is also no geopolitical consideration anymore for access to resources, since the source material is spent fuel, which is owned by a given country.

And to be complete one may also mention the potential of converting Thorium (Th-232) into fissile Uranium (U-233) which might then also be used for fuel nuclear reactors.

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[24] Fast neutrons reactors are not submitted to Xenon transients affecting thermal neutrons reactors. In addition, SMRs being of lower rated power level (less than 300 MWe), a fleet of SMRs may be seen as more flexible than large reactors.

[25] https://www.oecd-nea.org/jcms/pl_28569/uranium-resources-production-and-demand-red-book/

6 Conclusion

Nuclear energy is ‘sustainable’ in a long-term perspective. Indeed, it matches the three pillars of the social/societal sustainability: it is clean as being highly decarbonised, it is economic while considering the global energy system costs, and it is secure from a supply perspective and reliable (dispatchable)[26].

The question of using nuclear energy or not is mainly a political decision. Using nuclear energy, because it is associated with highly technical and complex industrial processes, with long lead times and heavy capital investments early into the development and deployment phases, requires long term stable vision for investors, being public or private, to engage. The question can be a kind of self-supporting or self-defeating circle. To make the difference, at one point in the circle, a clear strategic political decision is necessary. And for this to happen policy makers need be properly briefed on the pro and cons, not only of nuclear energy, but of the global energy system, using the ‘proper’ sustainability triangle as a guide. Might this chapter help as a starting point.

[26] Nuclear Safety and Waste Management aspects are to be treated in other papers. Using probabilistic and lifecycle analysis approaches, nuclear energy is globally less impactful than many other energy sources, industrial sectors, and human activities. Solutions exist for the safe management of highly radioactive, particularly via deep geological repositories as demonstrated in Finland. Research and Development is pursued on ways to reduce the radiotoxicity and lifetime of nuclear waste, in particular via the MYRRHA project in Belgium.