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Electric power generation and storage between research status, taxonomy and competing interest: A review

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Abstract

To produce sustainably, an optimal solution must be determined that ensures that the production of future generations is not compromised. New demands and the introduction of renewable energy imply adding energy storage to regulate the grid. This review aims to synthesise the state of the art of research on energy production and storage with information and expert opinions available to the general public, with an application to the French model. French publications online are used for illustration. A comparative analysis is proposed to recommend ways to improve technicality and to guide decision-makers on the levers to be favoured for each specific storage needed, taking into account the principles defined by the United Nations to define Sustainable Development. Solutions considered rustic can also contribute to the optimisation of energy resources by mechanically storing energy, but the choice of decision-makers will always be fundamental to imposing either soft or hard changes, whereas some attitudes seeking only to favour present advantages are the very antithesis of the principle of sustainability.

Keywords: Decarbonisation, development, energy, energy storage, production, sustainable, taxonomy;

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1. Introduction

Sustainable production means at least the reduction and, at best, the elimination of negative impacts on human health and the planet (Yilan et al., 2020). The principle of sustainability consists of finding and implementing solutions in the present that do not compromise the possibilities of future generations. To reduce the impact on resources and the environment, regardless of the industry or activity involved, the waste generated in the design, production, use and disposal phases must be reduced. The notion of sustainability of a product can thus be modelled using indicators including economic, environmental and social parameters, taking into consideration aspects sometimes considered as subaltern, such as the impact on natural eco-systems (extraction of raw materials, consumption of non-renewable resources, disposal processes and possible dumping, non-recycled or non-recyclable materials ...). Generally, as in the search for the economic optimum, it is neither the least expensive nor the most sophisticated choice that represents the optimal solution. This optimal solution must ensure the best compromise between all the parameters.

A pessimistic view of the human ecosystem considers that by directly or indirectly depleting raw materials, the human activity of producing goods and services generates a lot of waste in the environment, threatening the survival of our species and the whole planet. The consequences of our actions on the environment today determine the world in which the next generation will live. Attitudes such as 'whatever it takes', implemented in some countries to allow their economies to get through the confinements of the COVID pandemic, have limited the social impacts in the short term. However, the principle of sustainability is the very antithesis of the principle of, in French, 'après moi le déluge' (after me the Flood), since it is about ensuring the viability over time of the triptych environment – society – economy.

1.1. Conceptual background

A corrective view seeks to make consumers aware of the environmental impact of each of their purchases. Kuralt (2021) analyses, in an application comparing the situation in Slovenia and the European Union, the impact of the labelling of genetically modified organism products on a legal level and the perception and understanding of the final consumers. Indeed, without awareness and relevant information, the consumer, even when he thinks he is acting for the preservation of the environment, is sometimes mistaken. In France, in the 1990s, when the 'Green Point' appeared on the packaging of industrial products, many people thought that it meant the product, or at least its packaging, was a recycled product. This encouraged them to buy it rather than a similar product without the Green Point mark on the packaging. Most of them behaved in this way until they understood that this simply meant that the producer of the packaging had paid its tax to the organisation in charge of collecting taxes on packaging (Eco-Emballage), as compensation for the absence of selective sorting at the source. This confusion has contributed to blurring the message about the importance of making responsible choices.

A systemic vision specifies that the reduction of the environmental impacts of an activity or a product must be considered during its entire life cycle: during the design phase, during manufacture, during operation and end-of-life treatment. The question of the relevant size is preponderant and determines the size of a part of the product during each stage of the life cycle. Thus, in certain townships, heating networks intended for the heating of individual diffuse habitats are created (Mahapatra & Gustavsson, 2008). The network is not profitable for a single owner but becomes profitable when a critical amount of heat is produced. This optimisation is based on the search for the optimisation of expenditure items and the reduction of losses (Lu et al., 2021).

Every human activity impacts the environment. Reading this paper is not neutral in terms of CO_2-equivalent emissions ($eqCO_2$), just as writing it was not. A report by the international organisation Greenpeace in 2017 (Cook et al., 2017), partly reproduced in World-Coop (2017), shows that writing professional emails over a period of 1 year contributes to the emission of greenhouse gases (GHGs) up to 140 g of $eqCO_2$ (Le Guern, 2011). In 1 year, the spam sent around the world is as polluting as 3 million thermal cars. This represents 0.2% of the total GHGs produced. It should be noted that electricity production is globally responsible for 43% of these GHGs (Greenly, 2022). In the same way, 1 hour of online video represents the same electricity consumption as a refrigerator in 1 year. A character moving in a virtual universe consumes 10 times more energy than an inhabitant of a country like Cameroon. To allow a video clip to be viewed 3 billion times, the annual production of a thermal power plant is necessary.

To fight against global warming and climate change, the desire to decarbonise the world economy implies the substitution of fossil fuels with renewable energy sources (RES), accompanied by the electrification of heating and transport. However, this shift to electric power implies a considerable increase in electricity consumption (Strielkowski et al., 2021). The term 'renewable' applied to energy production refers to the use of non-exhaustible and rechargeable resources. These are, among others: solar, wind, kinetic potential energy (difference in level between two bodies of water), geothermal, plant matter, biomass, wave and tidal forces, ocean currents, temperature differences and magnetism.

From a macroeconomic point of view, both energy demand and production have entered a phase of uncertainty and change. To provide a complete picture of the situation, this paper is organised as follows: after having outlined the situation in the energy sector, the paper will address the issue of energy storage as a tool for sustainable development. First, it will review the existing technical solutions for the production and storage of electrical energy and their respective advantages and disadvantages. Chapter three will present the environmental considerations and the public tools developed based on the French example. Then, a comparative analysis is proposed to advocate the research tracks' improvement in technicality.

1.2. Purpose of the study

This review attempts a synthesis between the state of the art of research on the production and storage of energy, on the one hand, and the information and expert opinions available to the general public, on the other hand. The example of French online publications is used to illustrate this section.

2. Materials and method

This study is a review of the literature that synthesises the state-of-the-art research on electric power generation and storage between research status, taxonomy and competing interests.

3. Results

3.1. The energy sector

The electric energy sector has entered a phase of uncertainty, as it is undergoing profound changes due to the surge in demand for electric energy linked to the overall improvement in living conditions and the decarbonisation of the economy. Indeed, the electricity obtained from RES provides fluctuating and intermittent energy, which causes difficulties, such as frequency problems, that can be solved by adding technological energy storage systems (Saigustia & Robak, 2021).

The emergence of new consumer uses, such as an electric vehicle (EV) charging, is changing the game. Generally, the charging of EVs and some hybrid electric vehicles (HEVs) starts as soon as they are connected to the electrical grid. Thus, the energy demand appears as soon as the user returns home. This often occurs during peak electricity consumption hours and often at the end of the day. At these times, renewable energy production is not at its peak, especially in winter and especially if it is photovoltaic. This increase in peak demand may require local control operations when the user is connected to a local grid and thermal plant restarts when the user is connected to the general grid (Huang et al., 2020).

Not all new electric power demands are related to large investments. The deployment of certain household appliances can also have a significant impact on electric power demand. The COVID crisis, as well as the increase in the amount of fine and ultra-fine dust released in urban areas, is leading to an increase in the use of air cleaners. As the number of air cleaners increases, the energy consumed by them also increases (Kim et al., 2019a, 2019b). The same happened with the widespread use of cell phones, Internet boxes or any other type of household appliance, such as refrigerators in the middle of the previous century. All of them run on electricity and are destined to become, if not universal, at least a mass-market deployment. All the more so since the criteria for acquiring these devices often price, as shown in Kim et al. (2019a, 2019b), before the presence of an ecological label. To encourage consumers to opt for energy-efficient appliances, for example, in South Korea, air purifiers with good energy efficiency have been subject to a monetary incentive policy. This has increased the market share of this type of air cleaner.

Any change generates a reaction of behaviours aimed at prolonging the present situation. This is also the case in the energy sector. As the environment is a major common concern, research and development in the field of fossil fuels are also trying to green its production. Thus, synthesis gases (syngas) are produced from biomass gasification processes. One of the advantages of this technique is the use of CO_2 to produce syngas by the Fischer–Tropsch synthesis (FTS) (Neuner et al., 2021). This process can be applied to sustainable feedstock, such as biomass or hydrogen, obtained by electrolysis and powered by renewable electricity.

The increase in energy demand is also linked to the increase in population, the development of emerging countries and the increase in average per capita consumption (Al Shaqsi et al., 2020). At the current rate, energy storage requirements will become three times the current values by 2030 for which very special devices and systems are needed.

3.2. Existing technical solutions and their respective interests and disadvantages

The questions of technical improvement are always topical in the field of power electronics. Converters allow the integration of renewable energies, electric mobility (rail, road) and the storage of electric energy (Afonso et al., 2021). Among the questions to which more optimal answers remain to be discovered or refined are the quality of production, including system unbalance, voltage fluctuations, voltage sags, low power factor, harmonics and inter-harmonics, frequency variation of the AC supply voltage, transient overvoltages and inrush currents. Specifically, RES production (solar and wind generation) requires technical solutions for improving power quality and grid reliability. The research on solid-state and hybrid transformers is still voluminous and is the subject of many issues. It is therefore not covered in this paper. Instead, they focus on charging systems and optimal typologies to store energy: uninterruptible power supply and optimisation of uses, such as lighting and electrical machines.

3.2.1. Decarbonised energy production

The different sources of electrical energy production do not have the same impact on the environment. Electricity is often produced in power plants by the transformation of a primary source (gas, oil, nuclear, hydro, wind...) (Speicht, 2022; Waier & Ferrari, 2021). According to Cook et al. (2017), each main mode of electrical energy production presents risks, as listed in Table 1. The table also presents, in the synthesis of the reports (Schlömer et al., 2014), the average GHG emissions in grams of CO_2 equivalent to the production of 1 kW of electrical energy.

Table 1. Risks and GHG are related to electrical energy production way

Electricity generation	Main risks and environmental inconvenient	Main advantages	g eqCO_2 /kWh
Coal	Fossil resource, non-renewable; air pollution; landscapes disfigurement	Generation availability	820
Gas	Fossil resource, non-renewable; air pollution	Generation availability	490

Nuclear	Environment and human health; non-renewable resources use; important costs of increasing investment due to the identified incidents.	Generation availability; weak CO_2 emissions	12
Hydro-electricity	Consumer of natural spaces; productivity ceiling reached (remaining margins for small local generations)	Weak CO_2 emissions	24
Geothermal energy	Not possible everywhere; seismic risks in case of fracturing	Constant and renewable generation	38
Force of tides	Not yet in the maturity phase	Weak impact on CO_2	17
Syngas	Multiple transfers from a vector to another one	Trapping of CO2	200
Biomass	Need of row material transport; mobilised natural resources	Energy self-sufficiency for countries with developed agriculture	230 (700 if coal use)
Fuel cell	Unsustainable if supplied with natural gas	Carbon-free emission process	0 (intrinsic)
Wind (onshore and off-shore)	Noise; visual impact on the environment; intermittency	Renewable and inexhaustible; weak impact on CO_2	12
Solar	Recycling to refine; intermittency	Renewable and inexhaustible; weak emissions in CO_2	45

Source: Greenly (2022).

Each actor or lobbying force militates for its interests. Thus, for Greenpeace, the risks of resorting to nuclear power are considered unacceptable, as are the high investment and maintenance costs. For its part, the European Commission has considered classifying nuclear energy as low-carbon energy (Malingre, 2021). It adopted the Taxonomy Regulation in 2020: classification of economic activities with a favourable impact on the environment with the idea of encouraging 'green' investments. On 2 February 2022, is integrated into the project the production of electricity based on gas and nuclear power, specifying that their role was to facilitate the transition to renewable energy and climate neutrality. The text has been sent to the European Parliament and the European Council, which can file objections until the end of May (minimum). If there are no objections, the delegated act will enter into force and these two energy vectors will be able to be labelled to attract private investment in sustainable activities. Several international organisations have already indicated their disagreement in principle.

Hydroelectricity is considered cleaner than a generation from a thermal plant (Jhouette, 2022). However, only small-scale projects could still be realised, for example, in micro-grids or associated with specific consumption centres. In this report, geothermal energy is considered renewable and constant where it can be easily obtained. On the other hand, the use of biomass on a large scale is considered unsustainable because of the consumption of resources and the need for transportation. The same is true for fuel cells fuelled by natural gas, which, intrinsically, do not emit GHGs, but whose raw material consumption can lead to emissions, according to some sources, of up to 660 eq-gCO_2/kWh (Groupe La Poste, 2021; Jhouette, 2022).

While each production method has advantages and disadvantages, on the whole, these must be put into perspective and local situations must also be considered. In some situations, the advantages may outweigh the disadvantages. For example, biomass is used directly for collective heating (García-Maroto & Muñoz-Leiva, 2017) where there is a clear socioeconomic interest and no need for long-distance transport.

In China, it has been measured that onshore wind energy emits 98% less GHG than energy produced from fossil fuels. Their development would thus allow a reduction by more than 80% of the amount emitted by the energy mix (reference, 2020). Improved turbine performance also allows for an additional reduction of about 20% of GHG (Xu et al., 2022).

The energy production modes can be considered in terms of their renewability. Three families emerge:

- The 'real' RES, such as hydraulic, tidal, wind and solar energies; these energies can be captured without having to emit pollutants since nature itself produces them continuously. Other avenues could be exploited and are for the moment mainly used to harvest small quantities of energy: residual heat (Yazawa et al., 2021), living bodies (Proto et al., 2019; Tomono, 2019) and magnetism (Kurman, 2021).
- RES with consequences on the environment, such as geothermal energy when it resorts to hydraulic fracturing processes to re-inject cold water in-depth, which can cause earthquakes (Mandiuc et al., 2018), as in Alsace (Galbet, 2021), biofuels (which reduce the surface area of cultivable land to the detriment of human food) and biomass (since it is a question of burning fermentable matter and therefore emitting atmospheric pollutants and also contributing to deforestation).
- Fossil energies are use non-renewable resources on the scale of the industrial process or human civilisation (oil, gas, coal in its various forms, uranium and other raw materials from soil extraction processes).

Bio-fuels are not necessarily globally advantageous for the reduction of GHG production. The question of giving them an environmental label arises, especially since the label is sometimes linked to the volume of biofuel produced and marketed (da Silva Lima et al., 2020). This can lead the consumer into an imbroglio of choices. They are encouraged to use one fuel or another and one technical solution or another for its environmental qualities until they learn that it is not so.

Many ideas, intentions and actions are themselves in contradiction with their injunctions. For example, the idea of charging for carbon in the name of the polluter-pays principle may seem motivating to contribute to the reduction of CO_2 emissions. But, in addition to the shortcomings of the markets, which can speculate on the price per ton of gas emitted, pricing amounts to conducting repression policies instead of respecting the principles of the Farmer's curve: acting in prevention to reduce the occurrence and in protection to reduce the severity. Apart from the repression aspect, offsetting GHGs by capturing and storing carbon is not a preventive solution but a corrective measure. It is possible to store CO_2 massively, permanently and rapidly in basalt reservoirs or basaltic volcanoes (Holford et al., 2021). This corrective solution, as well as the one consisting in reusing the excess CO_2 emitted by an FTS synthesis, aims at reducing the impact of human activities on climate change.

The question of nuclear power arises. This solution is unsustainable because of the life span of the waste produced concerning the useful phase of use and the one necessary to produce the raw material. Because of the increase in the need for electrical energy, it is becoming topical again, especially in France, a country that has always favoured this technological choice for its electricity supply. There is a controversy concerning the inclusion of nuclear energy among renewable energies. An increase in its share of the energy production mix helps to reduce carbon emissions, due to its low GHG content (Table 1). This aspect of the technology is one of the arguments in favour, while the nuclear waste generated is one of the arguments against this solution (Vieira da Rosa & Ordinez, 2022). On the other hand, some countries are opting for a revival of nuclear energy, such as Pakistan, for which the only solution to mitigate climate change is nuclear energy, as the technology is considered mature and has only advantages: continuity of production, profitability, strict safety standards and respect of the environment. It should therefore eventually replace not only fossil fuels but also all other energy sources (Khurshid, 2020).

Current industrial research in the field of new reactors is focused on thorium and the creation of small reactors (World Nuclear Association, 2021). Fusion instead of fission is still not fully operational. It still does not offer the promise of clean energy for all (Bigot, 2019). One path to accelerate the development of this process would be to achieve self-heating of the fusion reaction. The reactions of fusion of light nuclei and fission of heavy nuclei are the two dual solutions for producing energy from the atom. The two processes have developed independently without having addressed all the environmental and economic impacts, whereas a hybridisation of these two principles could lead to a relevant solution (Blandinski et al., 2020). In some countries, for example, in Colombia, many thermoelectric power plants must be maintained in service to meet the energy demand. RES is still in the early stages of development (Barrozo Budes et al., 2020). Solar energy harvesting as a primary source of energy is also changing habits in many countries, for example, Cuba (Gerra & Iakovleva, 2019; Shklyarskiy et al., 2021).

The issue of energy production is not limited to electricity transmission networks covering vast territories. Autonomous systems, often powered by diesel plants, also seek to contribute to efforts to reduce the impact of human activities. Decarbonisation affects all production sectors. Thus, off-shore plants are often powered by their wind turbines and energy storage in the form of hydrogen tied to electrolysers and fuel cell stacks as well as heat recovery units can be used (Riboldi et al., 2021).

3.3. The storage of electrical energy

In the same way, the question of energy storage on autonomous sites arises. Zator (2021) presents an example of a building producing part of its own electricity needs in which the autonomous photovoltaic production covers half of the needs. The relevance of storage by batteries and heat storage in domestic hot water buffer is based on the estimation of the instantaneous energy costs. A solar photovoltaic system is an electronic device that works primarily to convert photonic energy into electrical energy using a solar energy source. For stand-alone operation, it must be combined with a storage system to meet the demand. The storage system can be a battery (Savard et al., 2018) or supercapacitors (Nordin et al., 2021) to allow a long lifespan.

In the context of increasing the use of electrical energy, the issue of storage of this energy, which is not easy to store by nature (flow of electrons), becomes relevant at the production sites and at various points of the network and to the end-user. The deployment of energy storage facilities in the electricity distribution network associated with RES sources allows for reducing transmission losses (Mikulski & Tomczewski, 2021).

Electrical energy storage systems (EESS) can be classified according to the nature of the medium used to store the transferred energy and the energy carrier:

- Fluid-based (pumped hydraulic and compressed air storage);
- Electrochemical (batteries, hydrogen);
- Mechanical (flywheels, springs, suspended weights [Menéndez et al., 2020; Morstyne & Botha, 2021]);
- Electrostatic (supercapacitors);
- Electromagnetic (Superconducting magnetic energy storage – SMES).

For large-scale storage, three technical solutions are interesting: two per fluid and one per battery.
1) Almost all current large-scale EESS consists of pumped hydro-energy storage (PHES) (Barbour et al., 2016; Bruninx et al., 2015; Coburn et al., 2014; Kose et al., 2018). This solution is highly energy-efficient, ranging from 75% to 80%. It can store large quantities of energy, up to several hundred GW. On the other hand, it requires the neutralisation of very large natural areas. The principle used to store and release energy is shown in Figure 1, describing an example in the case of hydraulic storage with high and low tanks. The principle is based on the displacement of water bodies and gravity. It is also necessary to have a natural water supply to compensate for losses due to evaporation or absorption by the soil. At the inlet, the electrical energy supplies a pump that raises the water from a low-lying reservoir to a second upper reservoir. At the exit of the system, to recover the energy potential contained in the water of the upper reservoir, it is enough to make it flow towards the lower tank via a

turbine, which then releases electrical energy.

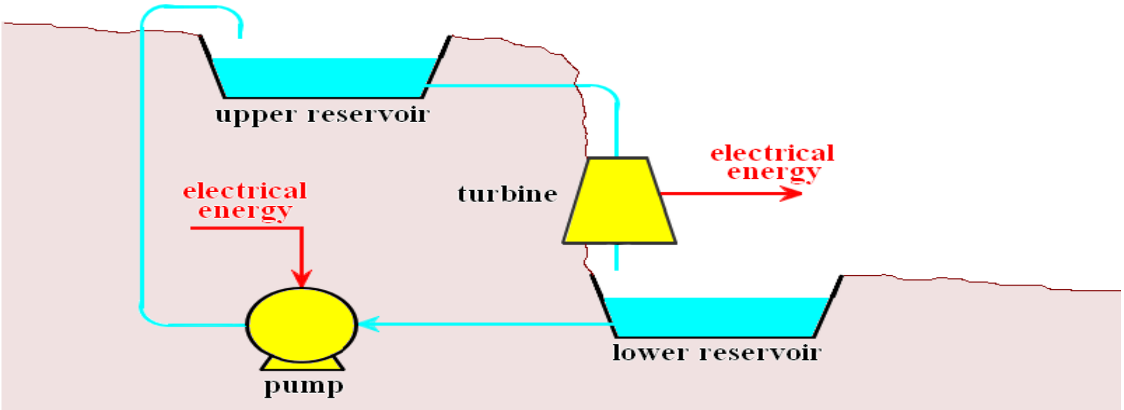

Figure 1. Schematic diagram of energy transfers in a PHES

2) A compressed fluid stores energy in potential mechanical form. When the fluid is expanded, it releases the stored energy. This principle is widely deployed in compressed air energy storage (CAES) (Chen et al., 2016; Morris & Tosunoglu, 2012; Mozayeni et al., 2017; Patil & Ro, 2018; Réveillère & Londe, 2017; Rublack et al., 2016). The principal diagram of energy transfer is shown in Figure 2. It is often air that is used as a fluid because of its good compression capacities and availability. At the inlet, the excess electrical energy on the network feeds a compressor that compresses air. This pressurised air is then stored in a large container, either underground or above ground. This container can be an underground cavity, such as a watertight cavern or an old unexploited mine. To recover the energy contained in the compressed air, simply let the compressed air escape into the ambient air through a turbine. The rotating mechanical energy is then transformed into electrical energy using an electrical generator. The overall energy efficiency is between 40% and 50%. This performance is achieved if the heat generated by the compression of the fluid is stored or reused elsewhere. Indeed, the compression of the air increases its temperature. The temperature of the stored compressed air always ends up reaching the temperature of the container by entropy. When the air is recovered, it must then be warmed up, since decompression involves cooling. The overall energy balance of an adiabatic CAES includes the thermal energy stored at compression in positive and that used to heat the air at decompression in negative. The overall efficiency varies between 40% and 50% in the absence of recovery of the heat energy generated during compression.

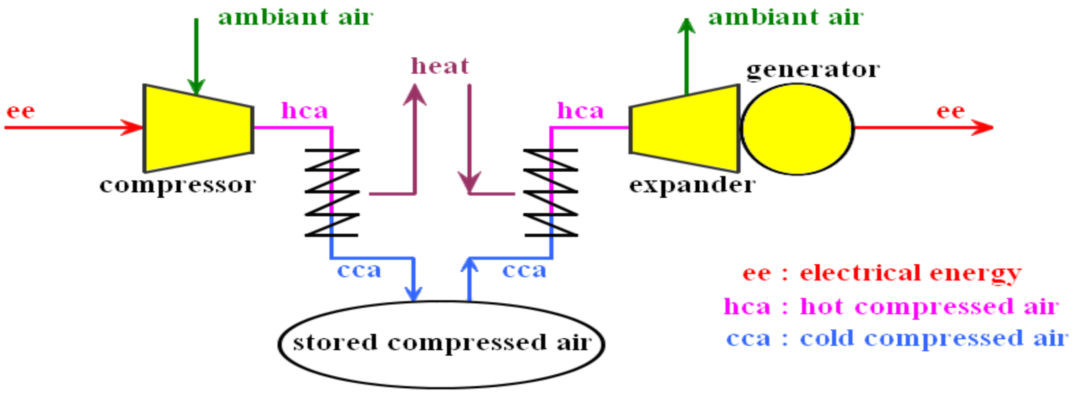

Figure 2. Schematic diagram of energy transfers in an adiabatic CAES

Abandoned mines, especially in coal mining areas, can be put to good use as high-capacity energy storage plants (Saigustia & Robak, 2021).

3) Batteries are electrochemical devices commonly used to store electrical energy. A battery is composed of several cells that chemically store electrical energy. Different technologies are deployed, such as lead-acid, which is the oldest of them, NiMh, lithium-ion and others (Fan et al., 2020; Savard et al., 2019, 2020; Savard & Iakovleva, 2019). Other technologies are currently being studied to increase mass-energy density and lifespan, for instance, sodium-sulfide or zinc-air (Morris & Tosunoglu, 2012). The principle of a battery energy storage system (BESS, Figure 3) is to store excess energy in a large number of batteries when the energy produced by renewable energy plants exceeds the demand and redistribute it to the electricity network when the power demand is greater (Anaya & Pollitt, 2015; Kim et al., 2019a, 2019b; Mostert et al., 2018; Sokol et al., 2017). These systems can also be installed locally, close to the source of consumption, centralised in large storage centres or distributed as close as possible to consumption sites. This solution also allows for ensuring energy autonomy in any autonomous or isolated system. The energy efficiency with the proven lithium-ion technology is over 90% (Mostert et al., 2018).

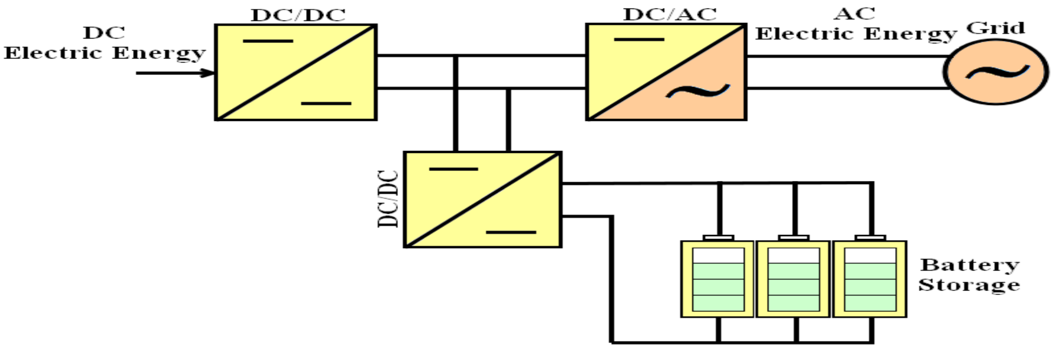

Figure 3. Schematic diagram of energy transfers in a BESS

Each of these technologies does not appear at the same level of maturity. If the PHES are rustic and have been used for decades, the BESS technology is now almost mature. However, it cannot be said that the technology of the CAES, whose sites are still few on Earth, is perfectly mastered. Nevertheless, it is relevant to measure, today, whether this solution is already as efficient in terms of management as the other two.

A fourth mechanical method, simple and very old in its principle, can also be compared. Indeed, among the types of energy storage, suspended weight energy storage (cuckoo clock principle) is a very inexpensive energy storage option and requires a minimal volume (Ruoso et al., 2019). PHES and CAES solutions have a better high storage capacity. However, these solutions require further feasibility studies, especially in terms of safety (Saigustia & Robak, 2021).

Finally, a fifth family of electrochemical solutions allows large-scale energy storage. The hydrogen produced by electrolysis can either be stored in its state or mixed with the methane transported in the pipeline networks, or be transformed into methane by methanation reaction. The feasibility of the first sub-solution is being studied, with concentration rates varying from one country to another (Lu et al., 2021). The surplus of electrical energy production is used to electrolyse water and produce hydrogen. Then, by methanation with CO_2, this hydrogen is combined to produce a syngas, which can then be stored. The efficiency of the transfer process can reach up to 44%. It is related to the operating time of the anaerobic digestion plant, the chosen standby strategy and the recovery or not of the internal waste heat, for example, by storage via a diathermic oil circuit or transformation into electricity (Candelaresi et al., 2021).

These five solutions are shown in Table 2, obtained in part from (Mueller et al., 2015), the column specifying the unit investment cost per kilowatt hour presented (Luo et al., 2015).

Table 2. Comparison of five technical solutions for energy storage on a large scale

Large-scale storage solution	Advantages	Disadvantages	Relevance of storage	Investment cost $/kWh (Luo et al., 2015)
PHES	Technical maturity; large capacity; high lifetime	High cost; low power and energy density; neutralisation of territories	Seasonal	5–100
CAES underground	Quite good technical maturity; high capacity	Variable efficiency; water-tightness required; large volumes	Seasonal	2–120
BESS	Quite good technical maturity; high capacity	Resources and recycling	Daily	200–400 (lead acid) 600–3,800 (Li-ion)
Energy storage by suspended weight	Low cost; very long life	Technical immaturity; low power and energy densities	Daily	-
Syngas, hydrogen	High efficiency; the multiplicity of sources; high capacity	Leakage and safety problems; technical complications in storage; high cost	Seasonal	2–15

Table 3. Comparison of three technical solutions for energy storage on a large scale

Medium and small-scale storage solutions	Advantages	Disadvantages	Storage relevance	Investment cost at kWh (Luo et al., 2015)
Supercapacitors	Fast charge and discharge	Cost	Time	300–2,000
Flywheel	Lifetime	Cost	Time	1,000–5,000
SMES	Significant return	Low temperatures	Time	500–72,000

Concerning the respective performances of the different electrical energy storage solutions, some solutions are better suited than others for low and medium-capacity uses. They are listed in Table 3. These solutions are also a function of the possible duration for the restitution. Thus, for short discharge times (less than 1 hour), supercapacitors, SMES and flywheels are relevant. Used in line, for the operation of a power network, these solutions make it possible to eliminate small operating faults (temporary overloads, micro-outages) and allow the regulation and smoothing of production. For needs consisting in supplying power for periods of less than a day, flywheels and batteries are the most suitable solutions. Indeed, if a battery can be discharged in 1 hour if it is solicited under its nominal current, for 1/20th of this nominal current, it can supply energy for 20 hours.

For seasonal and long-term needs (less than a year), chemical storage solutions (hydrogen, synthetic gas), PHES and CAES are relevant. Indeed, these are the only solutions that can store very large quantities of power and that can provide high power. This mode of storage allows for reducing big climatic problems (fog installed for several weeks, as was the case in some valleys of the French Alps during winter 2017). It can also be used as a backup if all or part of the network is down (following a natural disaster, for example). For more regular uses, these storage modes reduce the disadvantages associated with the cyclability of renewable energy and allow the power grid to be regulated, whether it is a global grid or a micro-grid. These points of choice are listed in Table 4. The technical solutions for storing electrical energy in dedicated premises (thus excluding CAES and PHES) are thus the following:

- Batteries (lead-acid, lithium-ion and other emerging technologies);
- Flywheels;
- Supercapacitors;
- SMES.

Apart from battery-based solutions, these are all solutions that can be used to avoid network faults for short periods.

Table 4. Possible solutions for medium capacity storage

Duration	Needs	Appropriate solutions
Short (<1 hour)	Suppression of specific faults	Supercapacitors, flywheels, SMES
Medium (<1 day)	Regulation and smoothing	Flywheels, batteries
Long (<1 year)	Regulation, intermittency, failures	H2, syngas, CAES, PHES

In a context of intermittent sources injection into the networks and the search for an economic optimum, concomitant with the requirements of better respect for the environment to reduce the climatic impact of human activities, it is becoming necessary to store the electrical energy produced to reconcile the maintenance of the quality of supply of electrical energy (voltage regulation needs), to reduce the impact of consumption peaks on production and to take into account the intermittent nature of renewable energies. Occasional voltage drop impacts during which the supplied voltage could be reduced for a short time can be catastrophic in certain applications (Happach et al., 2021; National Grid, 2017). Various solutions other than the construction of substations have been proposed (Bartłomiejczyk et al., 2022). In certain countries, this happens quite frequently (up to about 50 times per year). This phenomenon results from the activation of the protection devices of the electricity transmission and distribution networks. Voltage dips severely deteriorate the quality of the distribution network and can cause major damage to users. To mitigate these voltage dips, faults due to short circuits should be reduced and the fault clearing time should be reduced (Fsaha, 2020). The best protection against this phenomenon is to react at the point of consumption (Lin, 2016).

3.4. Comparison of these technical solutions for electrical energy storage

According to the IEA report (Collinson, 2000), electrical energy can be stored at the source for small wind turbines, knowing that a wind turbine can produce between 1 kW and 10 MW depending on its size, its technology and its environment (Sosso et al., 2020), to smooth out production and to avoid wind-related hazards (strong gusts requiring the disconnection of the blades or reduced wind) but also to avoid injecting energy into the network during off-peak periods when the price of the kilowatt hour can sometimes be negative (JET, 2018; Primeo Energie, 2022) within the framework of the deregulation and liberalisation of the electricity markets. This storage device can be connected to the grid (smoothing production out) or injected as needed (sale at optimal price time).

For photovoltaics, the question of storage is essential for micro-grids and autonomous structures. It is also an issue for grid-connected solar plants. In this case, the need for storage, as in the case of wind turbines, is for low energy and high power. In stand-alone, the power and energy requirements are smoother. Storage is the critical function of this mode of electrical energy supply (Avramenko et al., 2021; Kovalev et al., 2019).

One approach is still being optimised: the principle of Vehicle to Grid. This solution consists in using the EVs and HEVs connected to the grid as storage, as unused potential electrical energy. As a reminder, a car spends almost all of its time at a standstill. The energy stored in the vehicle can thus be used to supplement certain needs on the grid, in exchange for a fee for the vehicle owner (Bhoir et al., 2021).

The choice of the solution must be informed by the needs quantified in terms of quantity of energy, charge and discharge rates, number of cycles, power to be supplied and supply time. Each solution is adapted to a range of needs (Collinson, 2000). If it is a question of meeting the demand of a few seconds to a few minutes, the flywheel technological solution is fully relevant, with efficiencies of the order of 80% (Waier & Ferrari, 2021) comparable to that obtained with batteries, whether with steel flywheels rotating at a few thousand revolutions per minute or flywheels made of composite materials (speed 10 times higher). Lead-acid battery technology is long mature and cheap. But they have the disadvantage of having a low-performance quotient in energy and power densities (Collinson, 2000). On the other hand, the use of SMES devices always has the disadvantage of using low temperatures, to place the superconductor below its critical temperature, giving it zero resistance.

Some countries have already decided to develop their energy storage offer. This is the case in the United States, where an organisation, the DOE (2022), precisely monitors the quantity and distribution of devices installed each year. Its reports show that the PHES solution was strongly developed between the 1970s, starting with a capacity of 200 GWh, and 2015 when it stagnated at about 1,200 GWh. This confirms that this solution can no longer be deployed in the future, except for small stations, as this storage solution has its limits in terms of possible locations. BESS storage continues to grow, from less than 1 GWh in 2010 to nearly 6 GWh in 2020. The potential for growth remains significant, especially since the two main technologies used are flow batteries (Fan et al., 2020) and sodium-based batteries, ahead of Li-ion batteries. Thermal storage solutions are evolving in parallel, reaching 35 GWh of capacity in 2020.

To conclude this chapter, it is necessary to recall that existing energy storage solutions do not emit additional GHG. These storages allow to smooth the demand to consume less at times when electricity is expensive on the market (on-site storage), to supply the market with energy at expensive times to benefit financially (storage at the source or on the grid), to allow the resilience of the installations from the avoidance of micro-outage to the preservation of the site in case of long supply disruption (Lin, 2016).

3.5. Environmental considerations and the public tools developed

3.5.1. The appearance of sustainable development as a global concern

The notion of sustainable development appeared in 1972, at the United Nations Conference on the Human Environment in Stockholm. This international meeting was the first occasion to discuss the impacts of human activities on the environment. It drew attention to the importance of preserving the environment to enable sustainable economic development and led to the Stockholm Declaration and Action Plan for the Human Environment and several resolutions (UN, 1972), setting out 26 principles including:

- Principle 13: 'To achieve more rational management of resources and thus improve the environment, States should adopt an integrated and coordinated approach to planning their development, to ensure that development is compatible with the need to protect and improve the environment for the benefit of their people';
- Principle 18: 'Science and technology, as part of their contribution to economic and social development, should be applied to the identification, prevention and control of environmental hazards and the solution of environmental problems, for the common good of mankind';
- Principle 24: 'International issues concerning the protection and improvement of the environment should be dealt with in a spirit of cooperation by all countries, large and small, on an equal footing. Cooperation through multilateral or bilateral arrangements or other appropriate means is essential for the effective control, prevention, reduction and elimination of adverse effects on the environment resulting from activities in all fields, with due regard to the sovereignty and interests of all States'.

Sustainability was recognised as a major global concern by the Brundtland Report in 1987. The concept was reinforced in 2015 by the United Nations Sustainable Development Goals 2030 (Gonçalves & Silva, 2021).

In the meantime, particularly in the 1990s, the notion of sustainable development was introduced into French thinking but was not enshrined in legislation. Although the principle of sustainable development was introduced into territorial governance through approaches, such as municipal environmental plans and environmental charters, reconciling economic, natural resource and sociological aspects, followed by energy–climate plans at the territorial level, they did not allow for a lasting change in the impact of human activities on the climate. In the latter case, local authorities were required to take measures to reduce the impact of automobile traffic emanating from other authorities and crossing their territory. The question then arose as to how to act without having the leverage to do so. The efforts made thus led to collections of good intentions and contributed to the feeling of a 'punitive ecology' (Bonnamy, 2021) that should impose new constraints on everyone, even the most virtuous of citizens.

3.5.2. The way in which the public authorities apply sustainable development in France

It was necessary to wait many years before the legislation of different nations referred to sustainable development. For example, in France, it was not until 2010, with the so-called 'Grenelle 2' law, that the transition to renewable resources to produce electricity was identified. Then, in 2018, the 'Law for Energy Transition and Green Growth' takes up the idea, however just by considering the paradigm shift as a tool to contribute to what is designated as 'green growth'. This relaying of the energy transition as a small part of a larger, but also fuzzier and more 'catch-all' whole has introduced confusion into the prioritisation of energy choices (Pwc France, 2021).

In the meantime, particularly in the 1970s, after the first 'oil shock', which saw the price of an oil barrel quadruple from $2.5 to $12 in 6 months, the French Government pursued its desire to reduce dependence on oil. This desire for autonomy concerning fossil fuels has led to dependence on uranium and to develop the nuclear industry. This raw material is available more globally and is more easily stored in its crude state than crude or refined oil. The strategic stocks of uranium allow for a break in supply of about 4 years (Sfen, 2022) without affecting the production of electricity, which is mostly of nuclear origin, whereas the stocks of fossil fuels only represent a little less than 4 months of consumption (Kaeser, 2016).

In terms of technological maturity, oil as a source of energy production has reached a threshold and is beginning to see its total unit production cost increase because it is becoming difficult to find new deposits of quality oil. On the other hand, the improvement of yields and production volumes for wind and solar energy show that this mode of production is becoming mature. In less than three decades, the production costs of onshore and offshore wind power are expected to decrease by 37%–49% (Wiser et al., 2021).

A new risk is currently emerging, that of replacing dependence on oil and uranium with dependence on lithium and rare earth, which are indispensable in the current mature technologies for storing electrical energy using electrochemical batteries. But seeking autonomy in this field is met with local opposition, as in Serbia, where a lithium mine project is receiving an extremely hostile reaction from the population because of the major environmental damage that this type of exploitation causes. The same problem is happening in Portugal. Indeed, the basements of the country seem to contain the greatest density of lithium on the European continent. But this metal is buried under arable land. Its extraction would thus compromise not only agriculture but also the social life of the impacted regions. And European public opinion, if it accepts that the Quechua people in the north of Chile be deprived of water for food and agriculture in the Salar de Atacama Desert (the most arid in the world) to allow the extraction of lithium (Reporterre, 2021), is not ready for the same techniques to be implemented in the heart of Europe (Ambrose, 2022).

Furthermore, public acceptance differs depending on whether the CO_2 compensation is achieved through reforestation (favourable) or the establishment of renewable energy production sites (reluctant), or energy efficiency projects. The same is true if the projects are carried out locally or in distant countries (Schwirplies et al., 2019).

Thus, in the environmental field, a new label is being developed for financial activities ('Greenfin France green finance' label), containing several criteria for obtaining it (scope and nature of activities), which will make it possible to provide subsidies, for a total amount of 20 billion euros, to labelled activities and thus qualified as 'green'. The financing of companies whose activities are deemed to be polluting is automatically excluded from the label (nuclear and fossil fuels). The label must guarantee the green nature of investment funds used for the common good through transparent and sustainable practices (Ministère de la Transition écologique, 2021).

However, the fight against climate change requires a reduction in the use of fossil fuels that emit GHGs. Today, to guide political choices, different scenarios are considered, ranging from a 100% production by RES to a 50% share of nuclear power. Based on the World Energy Scenarios 2019 (World Energy Council, 2019), several scenarios are considered, all aiming at reducing the amount of GHG emissions (Colin et al., 2019). In their French version (Lauvergeon, 2021), they become seven ambitions. The first ambition focuses on the issue of energy storage, aiming to encourage breakthrough innovations in storage systems, considered an essential element for the success of the energy transition.

In the middle of February 2022, the French Republic President announced in Belfort a guideline to achieve the country's climate commitments. The choice falls on the construction before 2050 of six new nuclear reactors, with an option for eight additional ones. These reactors will be built on the European pressurised reactor model, the French prototype of which, however, took 10 years of delay for a multiplication of the budget by more than four. Indeed, it was to be commissioned in 2012. It has just been postponed again to mid-2023. Initially, it was to cost 3.4 billion euros. It will cost at least 19.1 billion euros, according to the Court of Auditors, a state body responsible for ensuring the proper use of public money and informing citizens (Moreina, 2022). At the same time, around 50 wind farms are to be set up off the French coast. Nuclear power, which already dominates energy production in France, will remain so for a long time to come to limit GHG emissions. This is the political choice that is currently retained.

3.5.3. Comparative analysis to recommend ways of improving technicality

Because of its political, strategic, military and sociological choices, each nation has developed its energy production tools, favouring one solution or another. Some examples of the situation in 2019 are presented in Table 5 using the data recorded by the IEA (2019).

Table 5. Imports and local production of energy sources (millions of tonnes of oil equivalent), for selected countries, in 2019 (IAE, 2019)

Nation	Oil	Coal	Gas	Bio-waste	Nuclear	Hydraulic	Geothermy	RES[a]
France	96.2	7.3	48.9	18.8	10.4	4.9	0.5	0.3
Cameroun	5.3	0	1.9	7	0	0.5	0	0.1
China	764	2,122	251	127	91	109	19	77
Cuba	8.1	0	0.8	1.6	0	0	0	0.1
Germany	94.4	56.6	80.1	32.6	19.6	1.7	0.3	15.5
Italy	85.3	6.6	62.1	15.1	0	4	5.4	9
Korea	188.5	80.6	48.4	6.7	3.8	0.2	0.2	1.7[b]
Russian Fed.	564.9	267.1	639	10.3	54.8	16.7	0.1	0.1
United States	1,279	349	863	112	220	25	9	3.7
World (10^3)	96.2	7.3	48.9	18.8	104	4.9	0.5	4.3[c]

[a] Wind and Solar energies.

[b] Included 0.1 Heat production.

[c] Included 2 Heat production.

The role of political decision-makers is to favour one technological solution over another with the benefit of relevant decision support tools. They are not technicians but decision-makers. 'Technocracy' is often criticised for electoral reasons, which sometimes leads to choices that are neither optimal from a technical point of view, nor a societal point of view, with the risk that decisions are guided by ideological choices (Mailafia, 2021). The role of scientists is to provide the right elements to help in the decision, knowing that the final choice remains with the Politician (or the Head of the company in microeconomics) who must have a more global vision of the consequences of his decision. The decision-maker must also show the direction to be followed and provoke technological leaps, invention and innovation.

If the top decision-maker of a Japanese electronics company had not expressed his need to be able to listen to music while playing golf without disturbing other players, the invention that fulfilled his wish would not have appeared until much later. More recently, if a virus had not caused a pandemic, messenger-RNA technology would not have been exploited for many decades. Thus, just as a bicycle-friendly policy cannot be conceived without secure parking, the widespread use of electric energy cannot be conceived without its storage at all levels: production, intermediate and at the point of consumption. At the end of the 20th century, a technological lock prevented the development of LEDs as a source of domestic light: without blue light, no white. As soon as it was possible to cover the entire visible spectrum, LEDs took off and the disappearance of thermal bulbs and intermediate solutions called low consumption was initiated. In Europe, this disappearance was protected by a Directive (European Parliamant, 2009), which accelerated the technological change. Storage is an essential tool for electric energy to contribute to decarbonisation, as recommended (Lauvergeon, 2021). It must be developed both at the source, online and at the consumption sites, as well as in autonomous installations.

The French electric power net operator, RTE, is currently experimenting with the 'virtual line' principle. The principle consists of storing electrical energy in a part of the network where production is higher than demand and restoring this energy in a part of the network where demand is higher. This avoids transporting energy from one end of the network to the other and allows the cables to be sized for lower currents. As an experiment, three automatically controlled storage battery sites are distributed across the grid. Flow sensors inform the central system in real-time and optimisation algorithms define the control law for each site (Danielo, 2021). This experiment is related to thinking about the development of sub-networks that are only partially connected to each other.

The article (Calero-Pastor et al., 2017) states that it is preferable to focus on systems rather than on individual products to ensure better efficiency of environment-friendly policies. Thus, labels, such as those for energy efficiency, can combine several environmental impacts to encourage the consumer to make an informed purchase. But beware of possible abuses. Indeed, the producers of Roquefort cheese do not appreciate at all that their product is given a very unfavourable nutri-score in France, whereas other multi-processed products are better rated, because of the composition of the cheese itself and its salt content (Cougard, 2021).

There are performance indicators in clothing, in the same spirit as those deployed to evaluate electrical appliances, housing energy consumption, food nutri-score, CO_2 levels of road vehicles or tire performance (Gonçalves & Silva, 2021). The article (Strielkowski et al., 2021) specifies that the levers for the development of RES act on economic, legal and political factors, social acceptance and the negative ecological impact of the project's creation of energy plants. Public acceptability of RES will occur if and when the optimal use of renewable technologies reduces environmental impact, produces minimal secondary waste and is sustainable for current and future economic and social needs.

New commercial opportunities appear for companies and individuals, with the appearance and development of the market of the sharing economy and peer-to-peer energy, with some consumers also becoming producers of electrical energy. Thus, a commercial offer of a pack including the purchase of an electric car, a photovoltaic system and a battery storage unit is developing. A study carried out on the Italian case shows that to make this investment profitable, it is necessary to drive 25,000 km/year without public aid (Scorrano et al., 2020).

The multiplicity of technical solutions at small, medium and large scales is combined with different needs between storage at the production, network and consumption sites, knowing that production and consumption can be concomitant, both in the case of autonomous operation and connected to the network. To assess the suitability of the different options, they need to be considered concerning the United Nation's principles of sustainable development. Table 6 presents an evaluation of these different solutions, giving a value from 1 to 4 with the respect to each principle, in the same spirit as the evaluation of the criteria used in the Efficiency Framework for Quality Management method (Savard et al., 2018, p. 2), i.e.:

- No approach or procedure at the beginning (score of 1);
- Defined approach and implementation (score of 2):
- Defined, implemented and measured approaches with segmented indicators exist and meet defined objectives (score of 3);
- A defined, implemented, measured approach meets defined objectives with a sustainable achievement (score of 4).

Principle 13 addresses the integrated approach to planning. The 18th identifies risks to the common good. Principle 24 calls for cooperation between countries, while countries retain their sovereignty.

Table 6. Comparison of different storage solutions concerning sustainable development objectives

Technical solution	Implementation area				Principle 13	Principle 18	Principle 24	Overall score
	Production	Regulating	Consuming	Local production				
PHES	Yes (nu-clear)	Yes			More possible margin	Floods, neutralised space	Rarely the case	1.3
CAES		Yes			Rehabilitation of wastelands	Waterproofing	Rarely the case	1.6
BESS	Yes	Yes	Yes	Yes	Implementation possible on all same sites	Explosion (mastered)	Possible if international willingness	3
Weight	Yes	Yes	Yes	Yes	dito	Spotted at the same site		3.3
Syngas, H2	Yes	Yes			Re-use of leakage resources, use of CO2	Leaks, explosion	dito	2
Supercapacitors			Yes		Possible if willingness to do	Marginal	Reproductive system	3.3

			□□■			
Flywheel	Yes	Yes	same □□■	Projections □□■□	dito □□■□	3
SMES	Yes	Yes	Difficult (cooling benches) ■□□	Magnetic leakage □■□□	dito □□■□	2
Heat	Yes	Yes	dito □□■	Explosion (controlled) □□■□	dito □□■□	3

The solutions that appear most relevant are, therefore, for storage on the production sites and online storage on the network, BESS (score of 3/4) and the weight system (3.3); for storage on the consumption sites, the same two plus supercapacitors (3.3), flywheel and heat networks (3). Finally, for small-scale production, whether connected to the grid or not, these are the same solutions except for supercapacitors, which do not store energy (kWh) but power (kW). Thus, the mechanical storage solution, by suspended weight, is a solution that deserves to be studied in the same way as the other more technological ones.

4. Conclusion

This article presents a synthesis of the state of research on the production and storage of electrical energy, combined with the information available to the general public, with a focus on the French case. If the notion of sustainable development has been integrated by consumers for a long time, the succession of decisions and their time scale gives an impression of vagueness and incoherence in the decisions, also coming from a not always clear boundary between scientific and technical advice and decision-makers, the latter sometimes favouring some specific paths rather than more relevant solutions.

Rapid decarbonisation and improved resilience can be achieved by maintaining prosperity and sustaining profits and growth (Stuchbery & Irwin, 2021). There are several solutions for energy production, operation and storage. Each solution has advantages and areas for improvement. Each solution is adapted to certain uses and scales. None of them claims to be universal. For example, even if to date this solution is nearly not developed, a flywheel storage solution should be preferred for storage at the user's site to ensure the quality of the power supply, but not to ensure seasonal smoothing on the network due to the intermittent nature of certain RES. Research and experimentation are still needed to improve the productivity, efficiency and responsiveness of supply sources, storage means and usage techniques. This last point concerns both users, some of whom are also becoming producers and network operators, who can optimise infrastructures by using storage sites distributed throughout the network. A universal convergence of the solutions to be retained would allow reducing the marginal cost of production and spreading these solutions all over the world.

As a matter of principle, decisions should not compromise the possibilities of future generations through the present use of resources. As a major contributor to climate change, energy production and consumption must be addressed with clarity by decision-makers. Decision-makers can accelerate (or not) changes in habits towards more virtuous consumption patterns. Decision-makers and practitioners must select specific storage technologies, taking into account the size of grid networks, customer demands, storing capacity, their advantages, cost, limitations, lifetime and impacts on the environment in the short, medium and long term (especially in the case of final waste). The European Commission is finalising its Taxonomy regulation allowing for the labelling of certain energy production methods, giving them a 'green' label meaning that they are part of the energy transition. But these choices will not be accepted by all stakeholders, whose arguments have been mainly recalled here. The final objective of all these aids and research informing decision-making is ensuring the sustainability of our civilisation, to contribute to avoiding the disaster announced following a runaway temperature of the atmosphere and climate disruption.

Remark

The authors would like to clarify that this article was written in January and February 2022, before the tragic events in Ukraine.

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