Does intermittent electricity jeopardise grid stability?

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The electricity transformer substation at the Argentat dam (Corrèze, France).

Intermittent sources of electricity (solar photovoltaic and wind power) supply electricity grids in very different ways to dispatchable sources (hydro, nuclear or fossil fuel power plants).
This article sets out these specific features and gives some indications of the solutions that will need to be implemented to guarantee grid balance in the event of strong growth in intermittent sources.

A little history...

Public electricity networks came into being at the end of the 19th century in Europe and the United States. following a bitter "Battle of the Currents" between Thomas Edison, an advocate of direct current, and George Westinghouse and Nikola Tesla, advocates of alternating current, the latter won the day for three fundamental reasons:

- The invention of soft-iron core transformers by the Frenchman Lucien Gaulard made it possible to raise voltages very easily, opening the way to long-distance electricity transmission with very low line losses;
- the zero crossing of the alternating current twice a period has made it possible to build simple and effective switching devices (circuit breakers), making it easier to extinguish the electric arcs that occur when contacts are separated;
- and above all, Nikola Tesla's ingenious invention of three-phase systems made it possible to create rotating electromagnetic fields of \Rƒ•èR• modulus (i.e. with no alternating component), and thus opened the way to the construction of very high-power alternators and synchronous or asynchronous motors of simple and robust construction.

Three-phase grids have thus become the basic technology throughout the world, even if direct current has recently found applications that alternating current cannot satisfy, in particular for very high voltage submarine or even underground links, due to excessive energy losses

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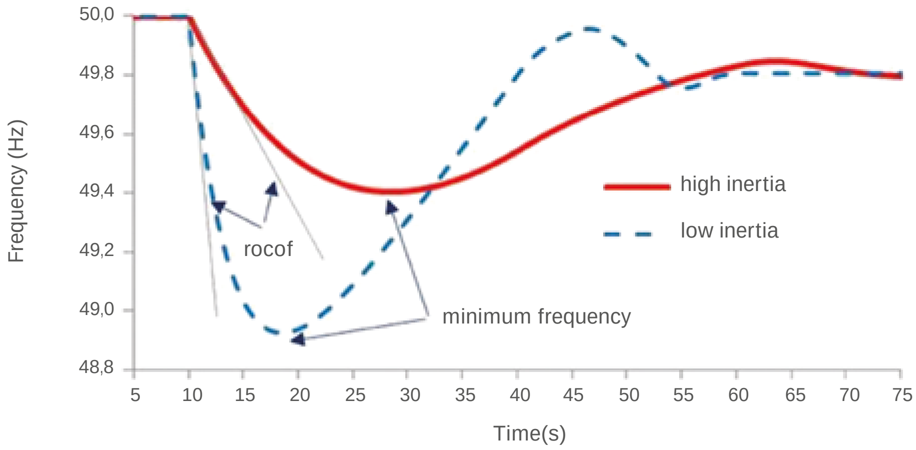

1. Typical appearance of a power loss transient.
("rocof" : rate of change of frequency). (Source : EDF).

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in the cables. (These links have become essential for the electrical interconnection of countries separated by inlets or for connecting offshore wind farms located far from the coast).

The laws of instantaneous balance on a three-phase network

A three-phase electrical system is made up of a set of alternators connected by electromagnetic coupling to a network that supplies receivers.All the alternators operate at the same instantaneous frequency, proportional to their speed of rotation. This so-called "synchronous" frequency, whose variations are propagated throughout the network in a fraction of a second (at a speed close to that of light in a vacuum), is the common parameter that determines and characterises the instantaneous equilibrium of the system.

As electricity cannot be stored as such, this balance also implies that production must be exactly equal to consumption at all times. Voluntary corrective action cannot be instantaneous, so the system naturally reacts by adapting its frequency to balance power (see detailed explanations below): the frequency drops if production is lower than consumption, and increases if consumption is higher. But this frequency adaptation is limited by the very narrow tolerances of acceptable variations around the nominal frequency of 50 Hz: less than ± 0.5 Hz under normal operating conditions, with maximum excursions limited to ± 1 Hz in exceptional, degraded situations of very short duration.

This is where an essential physical parameter comes into play: the
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grid, supplemented to a lesser extent (a few percent of the total) by that of the synchronous and asynchronous motors of the industrial installations supplied by the grid. This is why the overall inertia of an electrical system depends on its load: the higher the demand, the greater the number of alternators and motors connected to the grid, and therefore the greater the overall inertia. This inertia acts in two complementary ways:

- by a "mechanical" stabilising action: the inertia of the rotors opposes sudden variations in their speed of rotation, and therefore in the frequency, which is strictly proportional to it. This gives the power regulators of the machines driving the alternators time to compensate for imbalances in frequency and power between generation and consumption;
- by an "energetic" self-regulating action: the rotors are natural flywheels that store kinetic energy. In the event of a drop in frequency, i.e. in their speed of rotation, they lose part of this kinetic energy, which is naturally and immediately transferred to the grid by electromagnetic coupling, without any action being necessary.

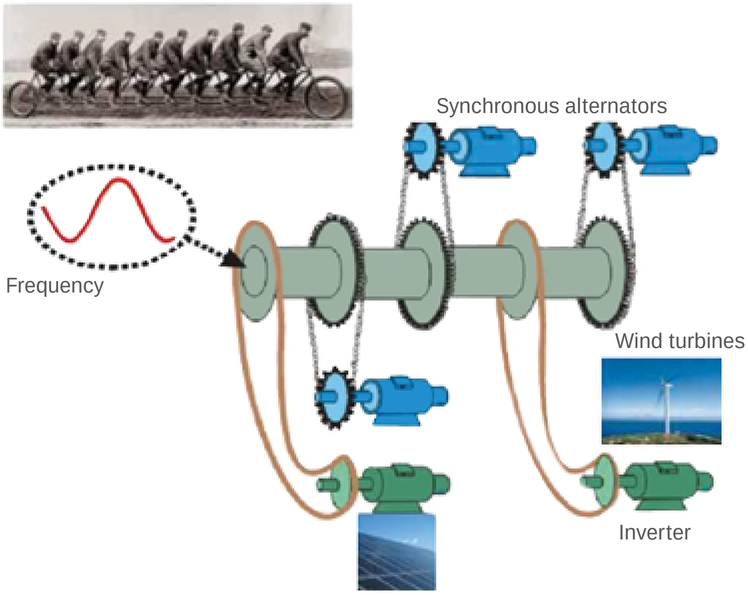
The typical impact of inertia on the frequency transients of a network is illustrated in Figure 1, which shows that the lower the inertia, the faster the frequency variation and the deeper the frequency drops during the transient, so the more the system is destabilised.

As an indication, the minimum frequency is reached in 10 to 15 seconds on the (large) French mainland grid, which is strongly inter-connected to the European network, but in well under 5 seconds on the (small) isolated networks in the French overseas departments and territories, powered by small machines whose rotors have little inertia. (Note: variations in frequency propagate across the grids at a fraction of the speed of light; the frequency can therefore be considered to be practically homogeneous at all times).

Impacts of intermittent electricity on grids

The inclusion of intermittent and random wind and/or photovoltaic electricity sources in the grids has two main consequences.

1- Their variations in power are added (algebraically) to those of demand, and it is therefore this accumulation that must be compensated for by various means: dispatchable means of production (i.e. whose power can be modulated at will, known as "back-up"), energy storage/unstorage, shaving off certain non-priority consumption, and importing or exporting electricity. Intermittent electricity generation is usually uncorrelated with demand : even if it can sometimes help to meet demand (for example, in the case of air conditioning systems powered by photovoltaic electricity in summer when the sun is at its zenith), this production mostly occurs at the wrong time: it is low in winter when demand is high, and abundant in summer when demand is



2. Illustrative illustration of the differences between synchronous coupling of alternators and non-synchronous coupling of power inverters. (Source: EDF).

low. This increases the power modulation needs of the other balancing resources mentioned above.

2- But the most important effect from the point of view of the instant stability of the system is the reduction in its overall inertia. This reduction is due to the replacement of some of the dispatchable means using alternators by intermittent means with no inertia of their own and no natural synchronous reduction capabilities, because they are coupled to the grid *via* power electronic inverters that are not synchronously coupled to the grid, as illustrated in figure 2.

However, it is possible to partially provide the inverters with some of the alternator capacities in the following two ways.

- Wind turbine inverters can be fitted with an electronic "synthetic inertia" extraction system. Strictly speaking, this is not inertia in the mechanical sense, but a system that temporarily slows down the rotor of a wind turbine in order to extract some of its kinetic energy, which is then re-injected into the grid, (this is equivalent to the energy contribution made by alternator rotors). This system, which is not widely used at the moment, is of interest in view of the high penetration rates of wind-generated electricity in the grids,
- The power of wind turbines and photovoltaic panels can also be modulated by adding other electronic controls. But this modulation is only certain when the power is falling: in fact, upward modulations can be countersquared by fortuitous and very rapid drops in the primary sources of wind (the power delivered by a wind turbine is proportional to the cube of the wind speed, and therefore very sensitive to the latter) or sun (cloudy periods, for example).

To sum up, although some modulation capacities can be implemented, they remain partial, less efficient and much more complex to use than those of alternators. In any case, the reduction in overall inertia that will result from their increasing use will in the future be a major factor in reduction of the instantaneous stability of electrical systems, increasing both the amplitude and the speed of frequency variations (fig. 1). ›\M/\®M'è|M èRM3R• |Q J •|3 3•´M M3R• (|è• *

What are the limits to the integration of intermittent electricity into the grid?

A large number of studies have been published on this subject, but the vast majority of them are limited to a purely statistical balance between production and consumption, comparing the average quantities of electrical energy produced and consumed by time slot. This is a necessary preliminary step, but it is highly inadequate, because it has nothing to do with the balance of instantaneous power, which is played out over times ranging from a few seconds to tens of seconds, as explained above and is governed by the laws of physics (electricity, electromagnetism, rational mechanics, etc.) However, very few organisations in the world have the necessary skills to tackle these physical studies, which are extremely complex when it comes to large grids.

The most comprehensive and accomplished study in this respect is the one published in June 2015 by EDF R&D [1]. It covers all the interconnected grids of thirty-four European countries up to 2030 and is based on more than thirty years of combined weather data. It represents a highly instructive first step, the main findings of which can be summarised as follows.

A penetration rate of 40% for wind + photovoltaics is possible as a spatial average over the whole of the European plate, under certain conditions such as :

- maintaining dispatchable resources (using energy stocks rather than variable flows) to ensure 60% of annual production on average,
- wind turbines' contribution to power regulation *via* their "synthetic inertia",
- modulation of their output power and that of the photo voltaic,
- reinforcements and/or creation of new interconnections to increase imports/exports,
- recourse to demand load shedding (voluntary disconnection of

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receivers). On the other hand, for economic reasons, massive recourse to energy storage does not yet seem essential by 2030.

However, this average annual penetration rate of 40% conceals very wide variations in instantaneous penetration rates, which physically determine the dynamic equilibrium of networks: for example, the maximum permissible instantaneous penetration rate in European spatial average varies from around 25% when demand is very low (i.e. when the network has little mechanical inertia, because few alternators and motors are connected to it) to around 25% when demand is high to almost 70% when demand is very high (in which case the grid has high inertia because a large number of alternators and motors are connected to it). This result clearly confirms the crucial role of inertia.

> “ A 40% penetration rate of wind + photovoltaics is possible on an annual and spatial average across the whole of Europe, under certain conditions. ”

It should be noted, however, that the above instantaneous rates, which range from 25% to 70% as a European spatial average, do not preclude local rates that may be much higher in certain countries and at certain times, if they are offset elsewhere by interconnections. This is particularly possible in countries with "small" grids that have very little power but are strongly interconnected with neighbouring grids that are much more powerful. The most enlightening example is that of Denmark, which is very strongly interconnected to the powerful German, Swedish and Norwegian grids, *via* interconnections that are also very powerful and that can, on their own, ensure the instantaneous balance of the electricity market. This has already enabled the Danish grid to operate with 100% wind-generated electricity at certain times of the year... Obviously, this situation cannot be extrapolated to the major grids, including France's.

At this stage, a question arises: "Will it be possible to go further in terms of the instantaneous penetration rate of wind and/or photovoltaic electricity? "This interrogation is largely conflated with another: "Will it be possible to operate grids with very low inertia, or even with no inertia at all? "This would be a real technological "Copernican revolution". A number of R&D programmes designed to answer these questions have been launched, as part of cooperative ventures under the aegis of the European Union. These include the :

- MIGRATE [2] and OSMOSE [3], which aim to study and then test, using demonstrators, the stability of a network with a massive proportion of intermittent electricity, involving a very high proportion of generation resources coupled by electronic power inverters. this involves a very high proportion of generation resources coupled by power electronic inverters;
- EU-SysFlex [4], which aims to study the systemic integration of smart grid technologies (see article p. 140), energy storage/de-storage, production and consumption flexibilities, etc.., including all aspects: technical feasibility, environment (minimising CO_2 emissions from electricity mixes), security of supply, regulations, costs, market functionnement, etc.

The results of these projects were published in December 2021. They set out the possible avenues to be explored and the results obtained from theoretical studies, digital simulations and experiments on mini-grids. But this is only the first step, which must be followed up by further studies and experiments before full-scale deployment on real networks in operation is possible, while guaranteeing the security of supply for consumers who will continue to need to be supplied. There is still a long way to go, and it is impossible to say more at this stage.

Huge technological and economic challenges lie ahead...

The first of these is, as has already been widely emphasised, the question of the weakening or even virtual disappearance of inertia that would follow the widespread coupling of generation resources *via* power electronics. For example, work in progress on the MIGRATE and OSMOSE projects is leading to the need to develop new types of 'grid-forming' inverters capable of simulating the behaviour of alternators (except for their inertia), whereas the grid following inverters currently in use require grid frequency and voltage references in order to operate.

On the other hand, the very short response times of power electronics in general, and inverters in particular, are an undeniable advantage when it comes to power regulation. It is already possible to regulate power very effectively using electrochemical batteries combined with inverters, which are capable of injecting or absorbing power steps in less than a second. In other words, they are able to act on the instantaneous power balance ' \ | the grid frequency has had time to change significantly (fig. 1). However, this type of operation implies that the overall time constants of the networks are always sufficiently greater than the time constants of the power settings, so that the networks retain sufficient mechanical inertia.

To go further, i.e. to operate with no inertia other than the very low inertia of the receivers being supplied, would mean that power settings would have to be virtually instantaneous and that all the inverters connected to the grid would have to be synchronised at exactly the same frequency at all times, within ultra-short timescales.

It is quite likely that it will be possible to operate micro-grids in this way. However, extrapolating this to large interconnected European grids, which could include tens of thousands of inverters over a distance of several thousand km, raises questions of feasibility outside which are usually complex and which no one can currently say will be satisfactorily resolved. And even if this were to be the case, the instantaneous stability of these networks will, by its very nature, be inferior to what it is at present, because we would be replacing a three-phase system that is physically self-synchronised by magnetic coupling of all the connected alternators, *via* very high-energy signals (the power currents circulating in the grid), with artificially created synchronism to drive the inverters *via* an additional digitised control layer that has to react almost instantaneously. This computerised layer operating at very low energy levels would be intrinsically vulnerable to both electromagnetic interference and cyber-attacks, despite all the precautions and countermeasures put in place. It is therefore to be feared that such a development would almost certainly degrade the stability and resilience of electrical systems compared with the current situation, and consequently the security of supply for electricity consumers.

There are also other challenges to overcome, including the following two.

- The ability of generation facilities to remain connected to the grid in the event of very high transient current demands, such as those encountered when large industrial motors are started up and, above all, in the event of short circuits on the grid. In this case, this capacity is essential insofar as most of these short-circuits are fugitive, as they depend on atmospheric conditions (thunderstorms, in particular). It is therefore imperative that these means of production do not become disconnected so that they can immediately resume their normal production. However, power inverters do not tolerate currents that are more than 20% higher than their rated current (due to thermal heating of the electronic components), unlike alternators, which tolerate transient currents that are up to six times higher than their rated current. A palliative solution is being considered to give inverters the overcurrent capacity they lack: for example, adding electrochemical batteries to them to perform this function...
- Inverters operate by "chopping" DC currents, which generates current harmonics (resulting from the decomposition of chopped currents into Fourier series). However, the most efficient technologies use increasingly high chopping frequencies, inducing increasingly high harmonic frequencies, which have several major disadvantages, in particular:
- distortion of voltage and current waves, which deviate further and further from sinusoids and can seriously disrupt certain receivers;
- emissions of electromagnetic interference capable of disrupting wired or aerial transmissions;
- local thermal heating ("microwave" effects).

Palliative solutions also exist in these areas: the use of filters that eliminate - or at least greatly attenuate - high-frequency voltage and current interference components. But these filters would have to be multiplied for a very large number of inverters...

To sum up, the R&D programmes currently underway aim to determine the feasibility of what is without exaggeration, to be described as a "Copernican revolution" in the principles, technologies and management methods of instantaneous network balance and security. Will it be a success? It's too early to say, especially as technological success will not be enough: the costs of these technologies will also have to be economically bearable, as electricity has become a commodity whose price will have to remain acceptable to consumers. ▮

1• A. Burtin et V. Silva, “Technical and Economic Analysis of the European Electricity System with 60 % Renewables”, EDF R&D Technical Report (17 juin 2015). DOI:10.13140/RG.2.1.2213.6166

2• www.h2020-migrate.eu/

3• www.osmose-h2020.eu/

4• www.h2020-bridge.eu/

Smart grids
What are they?

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Smart electricity grids integrate information and communication technologies to adjust the flow of electricity between producers and consumers. They provide greater flexibility, reliability, accessibility and lower costs.

The term "smart grids" has an evolving meaning.

Historically, electrical networks have been equipped with analogue and then digital automatic control systems, designed to monitor their parameters (frequency, voltage, current, etc.) and initiate automatic control actions to keep these parameters within the required ranges, or to protect them when they fall outside these ranges to avoid damaging consequences for the safety of people and property. These devices can be seen as the precursors of very rudimentary 'intelligences', which are nonetheless highly effective because of the speed of their automatic actions.

But it was with the introduction of intermittent and highly variable wind and photovoltaic electricity sources that the concept of the "smart grid" really came into its own.

This introduction has brought with it new constraints in terms of forecasting and real-time management of their production, as well as new technologies for connection to the grid, *via* electronic power inverters which, unlike synchronous machines (alternators) which are naturally self-synchronising through electromagnetic coupling, will have to be synchronised and controlled artificially via additional digitised control systems.

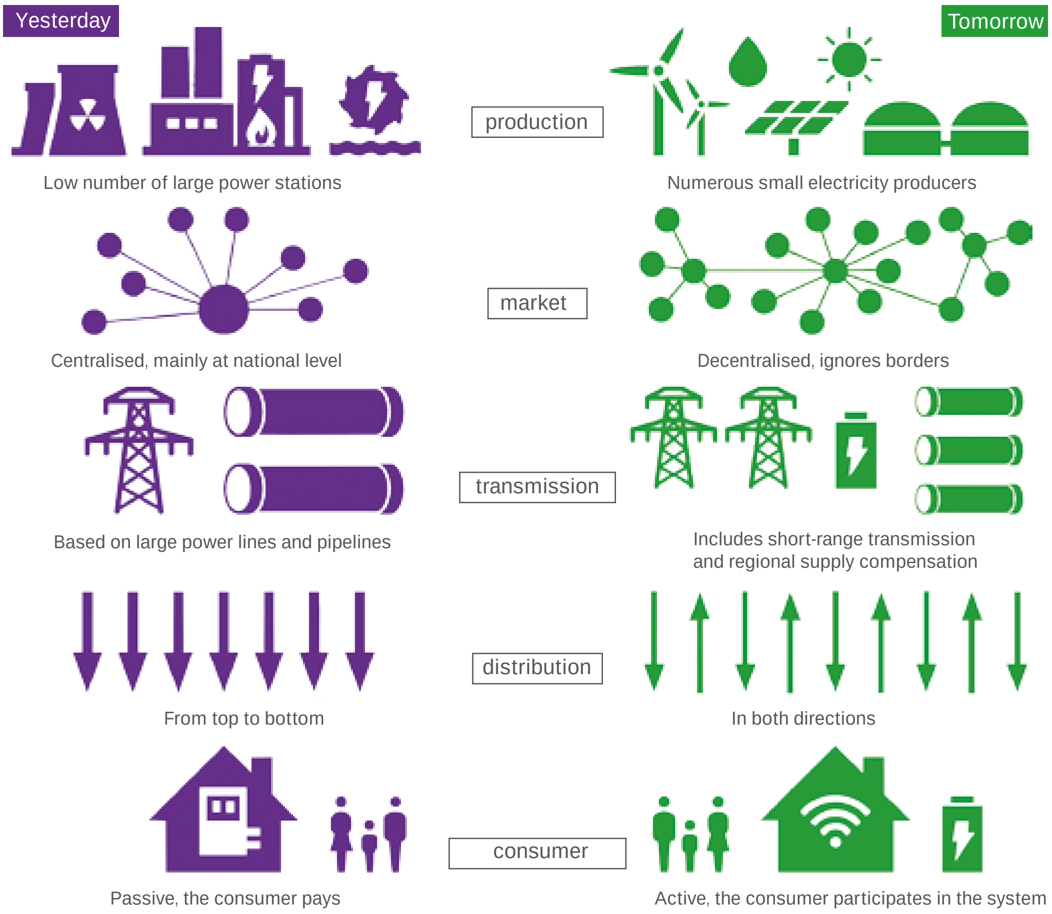
Furthermore, it will no longer be enough to simply adapt instantaneous power to consumption, the management method that has prevailed until now. A more active management of consumption will have to be called upon to play an active part in balancing the network's production and consumption *via* load shedding, postponements, energy storage and energy withdrawal, in the face of the variability of intermittent sources. The 'intelligence' required will therefore no longer simply manage technical constraints, but will have to include contractual and commercial functionalities: load shedding or load postponement, whether for professional or domestic use, will require the agreement of consumers, who will be paid for this service. They will even be able to become suppliers to the grid if the batteries in their electric cars are used to support it during periods of high consumption. Once again, this will require new digital capabilities to control these exchanges.

In short, networks are going to have to become increasingly flexible in order to manage :

- power variations of increasing amplitude;
- intermittent means of production;
- consumption will become more flexible;
- energy storage and withdrawal ;
- increased electricity exchanges with neighbouring countries.

All of this is subject to technical constraints (staying within the required parametric ranges), safety constraints (guaranteeing the necessary margins at all times), and the management of commercial aspects between suppliers and consumers, all *via* digitised exchanges.

The hyper-complexity of this multi-factorial management within very short timescales (a few seconds), which is essential to preserve the instantaneous balance of the networks, can only be envisaged *via* a multitude of sensors constantly measuring network parameters, actuators capable of rapid corrective action, Linky-type communicating meters measuring exchanges between networks and consumers, etc. The whole system will be



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Characteristics of a smart grid (right) compared with the traditional electricity system (left).

controlled by a computerised telecommunications layer that includes sophisticated AI software to optimise all exchanges at the lowest possible cost for producers, grid operators and consumers. The term "intelligent network" will then take on its full meaning in its most general version...

However, this extremely ambitious theoretical objective raises major questions about feasibility, particularly with regard to :

- control *via* the computerised telecommunications layer of the tens of thousands of inverters that could one day replace synchronous machines on a massive scale across Europe. This is currently a matter for R&D, and its operational feasibility on large networks has not yet been established;
- the hyper-complexity of the operation of such "intelligent" networks, the software mastery of which is not yet a given either due to the multitude of AI software that will interfere;
- cyber-protection of the computerised telecommunications layer equipped with AI, which will be a prime target because of its strategic role and its multi-entry structure on the scale of the European continent...

It is understood that these future "smart grids" will have to continue to guarantee a very high level of functional reliability equivalent to that currently prevailing, at a cost that remains sustainable.

In conclusion, "smart grids" conceal major unknowns and raise considerable challenges, the outcome of which it is currently impossible to predict or guarantee. This is a long-term undertaking.

In the meantime, only a gradual and cautious development, in a step-by-step approach resolving difficulties and validating solutions one after the other, can be envisaged. At the same time, the networks will have to continue to perform their function in a safe and sustainable way!

Nevertheless, the applications that are easiest to implement, such as the "intelligent" management of exchanges between network operators and consumers, should appear in a few years' time, with the widespread use of Linky. But much remains to be done... ▮