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PHOTOVOLTAIC SOLAR POWER:

25% of the world's electricity low-carbon in 2050!

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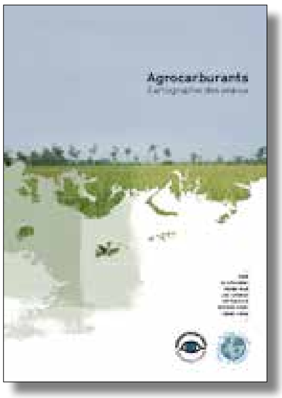

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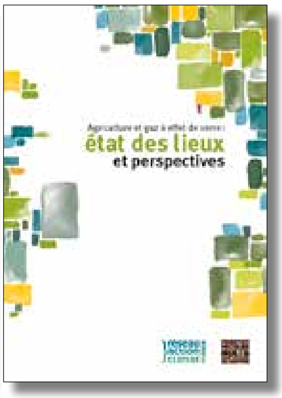

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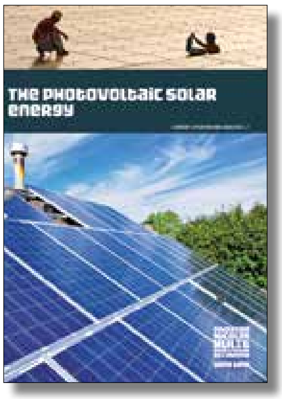

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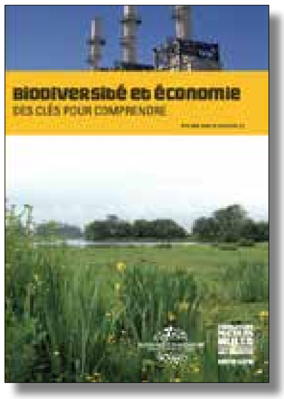

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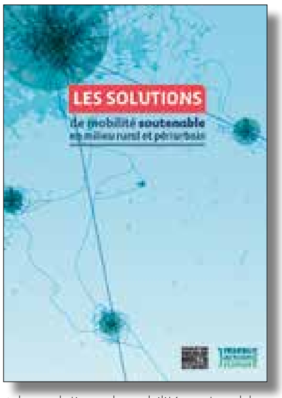

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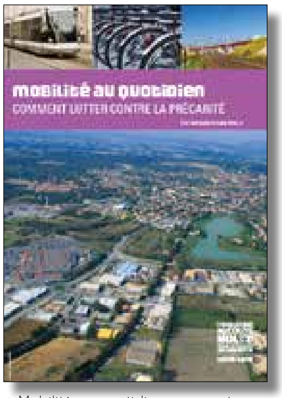

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EXECUTIVE SUMMARY

On the eve of COP21, there is no longer time to question the reality of climatic disorders; solutions must be implemented. Moreover, even today, more than 1.3 billion human beings have no access to electricity. How can we provide the energy services essential to those who are deprived of them, without any carbon emissions? Long considered too expensive and posing technical problems due to its intermittency, photovoltaic solar energy has in recent years undergone developments which give reason to doubt this diagnostic. What's more, due to future progress it is estimated that it could provide at least 25% of the world's electricity in 2050[1] instead of the 5% envisaged in most long-term planning scenarios.

Photovoltaic solar power, an increasingly competitive energy

Although the first discoveries regarding photovoltaic solar energy date from the 21st century, this source of energy has long remained confined to the niche market of the space industry. The electricity produced by photovoltaic power was far more expensive than that coming from other technologies (gas, coal, nuclear).

1. Out of a total electricity consumption range of 35 to 40 PWh in 2050 (extrapolated from the scenarios of WEO 2014).

At the start of the 21st millennium, the levelized cost of a photovoltaic installation was about $750 per MWh compared with less than $70 per MWh for other types of production. Subsidies (especially in Europe) and industrial and technological progress then made it possible to expand the market for photovoltaic power and initiated a continuous fall in costs, which are now approximately the same as those of conventional production facilities.

The current and future technical developments described in detail in this study make it possible to expect a 20% to 40% reduction in the initial capital cost of a photovoltaic installation by 2030. On the 2050 horizon, based on market trends, the cost will be halved. Moreover, many manufacturers expect the lifetime of photovoltaic power plants to be lengthened, from 25 years (the service life currently adopted for calculation of the levelized cost) to possibly 30 or even 40 years.

These two developments will inevitably reshape the electricity and energy landscape profoundly compared with the current view. The levelized cost of a ground-based photovoltaic installation could be between US$50 and US$35 per MWh in 2050, and the cost of a residential installation between US$70 and US$50 per MWh.

Conversely, the costs of conventional production facilities will on the whole increase. These mature technologies will see no breakthrough in competitiveness gains, while certain components of the cost of these facilities will increase (safety requirements for the nuclear industry, allowance for a carbon cost for gas- and coal-fired power stations, particulate emission reduction standards for coal and growing pressure from civil society against the extraction of fossil fuels).

CAPITAL COST AND LEVELIZED COST

Two economic statistics make it possible to evaluate the competitiveness of an energy production installation. The initial capital cost, on the one hand, is decisive for the decision to launch a project. It is calculated in US$ per MW installed. The levelized cost (or discounted cost of energy), on the other hand, includes not only depreciation of the initial capital cost but also operating costs (maintenance, cost of primary energy) relative to the total kWh produced over the life of the installation. The levelized cost (expressed in US$/MWh) takes into account a discount rate which has the special feature of greatly reducing future costs, and thus proves unfavorable to solar energy due to the magnitude of the initial investment.

PHOTOVOLTAIC POWER: A DIFFERENT KIND OF ENERGY!

The photovoltaic technology is based on physical principles completely different from those of other electricity production facilities. The latter are based on the classic laws of physics, using mechanisms occurring on a macroscopic scale: operating an alternator to produce electricity. The difference between the technologies is the force used to cause the rotor to turn (wind, water, steam produced by the combustion of coal, gas or nuclear fission reactions, etc.). Photovoltaic power, on the other hand, is based on quantum physics which governs the behavior of matter on or below the nanometric scale. Now, this physics is in no way similar to that which we "experiment with" every day. That makes photovoltaic power a different kind of energy. Far more modular than the others (a 1 W or 1 GW installation can be manufactured), it can still benefit from technological breakthroughs. The other production facilities, based on mature technologies, can only experience continuous improvements. This special feature of photovoltaic power means that this industry is far more similar in its development dynamics to electronics industries – which experience exponential cost reductions - than to energy industries.

Photovoltaic solar power: a clearly sustainable energy from the economic and environmental viewpoints

The competitiveness of photovoltaic power being ensured, it is important to check that the necessary investments to make this energy a significant part of the electricity mix are feasible. Note, first, that an energy sector technology has never experienced such development, which makes it more similar to the specific development process of the electronics world, in both its speed of market penetration and the pace of innovation. In 15 years, the installed capacity has been multiplied by more than 100, to 186 GW at the end of 2014, including more than 40 GW installed in 2014 alone (a record year for investment, at US$136bn). This is the order of magnitude of the coal-fired power station capacity installed in China each year (and about 15-20% of the equivalent electricity production). This process is gathering momentum, moreover. Based on simply maintaining the annual investment level of 2014, combined with expected cost reductions, we obtain a cumulative total of 4,000 to 6,000 GW installed by 2050 (including installations to be renovated).

This scenario is really conservative because it means assuming a halt in growth in investment in photovoltaic power despite the substantial increase in its competitiveness. A capacity range of 6,000 to 8,000 GW would make it possible to meet 20-25% of estimated global electricity demand in 2050[2]. In light of the information brought together in the present study, this target seems easily attainable from an investment viewpoint and desirable from the economic viewpoint.

The study also reviews the existing literature concerning the availability of the raw materials required for such a photovoltaic power plant program and the issue of the energy return on investment. According to figures from the MIT, the first point is apparently not a major obstacle for technologies based on silicon (the second most abundant element on the planet). As regards the energy return on investment, already satisfactory, it is set to increase, thus reducing the carbon content of photovoltaic electricity (currently between 30 and 70 g of CO_2 per kWh). This clearly places this energy source in the club of energies with a sufficiently low carbon content[3] to enable us to stay on track for global warming of less than 2°C.

Intermittency, a major obstacle to the growth of photovoltaic power?

A photovoltaic system produces only in the daytime and more in summer than in winter. This production may vary from one hour to the next as a result of changes in sunlight (e.g. passing clouds). This can cause problems of balance between supply and demand and hence at the level of electricity grid management. In order to clarify this issue, the study investigates the following three dimensions of the electricity system.

1. What is the capacity of a mature grid for coping with intermittency?

Analysis of the French grid, typical of a mature and efficient grid, shows that the current transmission systems of developed countries (equipped to manage significant fluctuations in supply and demand) can already tolerate approximately 5% to 8% of consumption supplied by photovoltaic installations without setting up a new system. At the level of distribution systems, on the other hand, a match between consumption density and production density is a rule that it is important to obey in order to ensure unconstrained deployment of photovoltaic systems.

2. Can consumption be made flexible to move in step with production fluctuations?

Consumption management (for individuals and industrial firms) makes it possible to further increase the market share of photovoltaic power in the electricity mix. By processes currently being developed, this involves either forcing the consumption of certain electrical appliances at the time of photovoltaic production peaks (in the middle of the day) or eliminating demand at off-peak production times (at night).

Most consumption management techniques are well known and, in some cases, already employed notably in France (management of hot water cyl-

2. 6,000 to 8,000 GWc represents a production of approximately 8 to 10 PWh (assuming average insolation equivalent to 1350 kWh per kWc) out of a total electricity consumption range of 35 to 40 PWh in 2050 (WEO 2014 scenarios).

3. On the 2050 horizon, we should aim at an electricity production facility mix for which the carbon content is less than 100 g of CO_2 per kWh and as close to 50 as possible.

inders and development of demand response schemes). Moreover, they have significant potential for development, which should be increased by changing national regulations to enhance their economic value.

3. How to improve electricity storage?

To date, the most economical means for "storing electricity" are hydraulic pumping stations, but their growth potential is limited. Recent developments regarding electrochemical storage could radically change ways of smoothing out intermittent production such as photovoltaic power. Long regarded as a costly technology, usable only for specific applications, electrochemical storage has in the last three or four years seen a rapid improvement in its competitiveness, like photovoltaic systems. For example, in 2015 firms such as Tesla and LG Chem posted capital costs of US$300-350 per kWh stored (versus about US$1000 per kWh stored five years ago). There are still significant prospects for development.

Several reports show that for a capital cost of less than US$200 per kWh stored, battery storage provides a more competitive solution than a back-up with fossil-fueled thermal equipment.

Finally, electrochemical storage has the huge merit of providing a response to the initial needs of the inhabitants in countries which have no structured electricity grids. Like for mobile phones which made it possible to avoid developing very costly infrastructure, this is a truly historic opportunity.

MANAGING CONSUMPTION MEANS CHANGING OUR WAY OF CONSIDERING ENERGY!

In the world of the electricity system as it has been developed since Edison's first electric power station in 1882, consumption is variable and production adjusts. With photovoltaic power it is production which is variable. Can electricity consumption adapt to production? Yes, to some extent: some of the services provided by electricity can cope with a time lag in the supply of electricity. Examples are the need to wash linen or heat domestic water and the housing unit (if it is well insulated). There is clearly an intrinsic flexibility in the use of the various devices and real benefits from managing consumption.

WHY IS THERE A DIVERGENCE BETWEEN THE PERCEIVED COST OF THE BATTERIES AND THEIR ACTUAL COST?

Whereas the capital cost observed in the market is around US$300-350 per kWh for the lithium technology, the 2015 reports of the IRENA or the IEA on storage technologies and batteries regard the capital cost as around US$600-800 per kWh. This divergence can be explained by the fact that the batteries' electronic fundamentals confer on them a speed of innovation faster than the time for analysis by the conventional energy world. So long as batteries were expensive, their market and their impact remained anecdotal. The continuous rapid improvement in the cost of this equipment has resulted in practically an on-off dynamic: they can go very quickly from having a lack of visibility to having a major impact on the electricity system.

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The transition to photovoltaic power, a turning point that must not be missed by the authorities and by industry!

The simultaneous technical and economic development of the photovoltaic power, consumption management and electrochemical storage technologies is changing the prospects for the electricity systems of tomorrow. A first effect can already be seen, with the rapid deployment of small individual devices, and elsewhere in the construction of high-capacity power plants ordered by wealthy sunny countries. This trend points to radical changes which will concern the developed countries' electricity systems. The big operators and managers of these systems, like the public authorities, must become aware of this potential for development, and facilitate it rather than ignore it or, even worse, combat it. Like it or not, some households, economic stakeholders and local authorities are thus acquiring a capacity for and an interest in becoming their own electricity producers. By allowing each actor to manage part of their electricity needs (or even energy needs thanks to the development of the electric car), the prospects for the development of photovoltaic power are radically changing the relationship between the electricity consumer and producer, a relationship that at present reflects the dominant role of the electricity system.

Those who do not make the transition soon enough will be poorly positioned in the energy organization of tomorrow. Numerous stakeholders, including large banks such as Goldman Sachs, Citigroup and UBS, have become aware of both the potential of these changes and the risk for those firms not taking them into account.

More seriously, a scenario in which photovoltaic systems were deployed by ignoring or merely bypassing the current centralized electricity system would definitely not be optimal for society. Regarding this, the legislation which will supplement the Energy Transition Act in France will have a responsibility, in particular, for encouraging such a deployment within the framework of an adaptation of the national and European electricity systems. The changes that this study glimpses for the near future therefore require a strengthening of public policies concerning the deployment of photovoltaic systems, electricity storage, consumption management, and tariff links with the grid.

A fantastic hope for those who do not yet have access to electricity, provided that it be viewed from a decentralized perspective as close as possible to the needs

More broadly, these developments represent a fantastic opportunity for developing countries, and in particular the 20% of the global population who still do not have access to electricity, by enabling them to have control of their supplies. Regarding this, it should be remembered that what is important is not electricity in itself, but the services that it can provide: lighting, access to telecommunications (mobile phones in particular, which are a decisive factor in the African economy, access to knowledge via internet), crop irrigation, conservation of foodstuffs and healthcare (via hospital facilities capable of operating in satisfactory conditions of hygiene, having refrigeration areas and sewage treatment facilities), etc.

Such services would be provided far more rapidly and efficiently by innovative solutions based on small photovoltaic installations coupled to storage with easily transportable backup thermal systems. Whereas several decades are needed to build an electricity grid, a few weeks are sufficient to set up a small system based on photovoltaic power and energy storage.

This local approach, according to a leopard-spot pattern, i.e. with uniform distribution throughout the territory, would then gradually lead to interconnection, but not necessarily as extensively as in the case of a centralized system. Above all, it could be deployed for a lower cost, involving the local populations and gradually developing an industrial fabric notably for management and maintenance of the installations. Finally, this more modular electrification would allow populations to make use of electricity and improve their standard of living without necessarily radically changing their life style. They would be able to adapt the use of renewable energies to their perspective, which is not foreseeable in the case of centralized deployment plans which are inevitably approximate in their allowance for specific local features.

1. INTRODUCTION: SUMMARY AND CONTEXT

1.1 Purpose of the publication, scenarios used and methodological notes

The challenge now is no longer to prove global warming but to find solutions in order to limit it while allowing humanity to keep on making progress. The levers of action are well known: more sober and efficient life styles, energy efficiency of buildings, agroecology, development of renewable energies, etc. The main issue is to find the right solutions to actuate these levers.

In this report, Fondation Nicolas Hulot investigates photovoltaic solar power, which is one answer for the production of low-carbon energy. It deserves special attention because it is one of the rare renewable energies which (i) in the past few years has confounded the forecasts (notably with regard to cost reduction) and (ii) has very great malleability: a photovoltaic power system can be placed on a smartphone to produce a few watts or in open country to produce several hundred million watts (megawatts). It can generate electricity very close to points of use or in a centralized facility to supply a power grid. It can therefore meet a great variety of needs and generate development opportunities representing a radical change from conventional centralized power systems supplying consumers via vast grids, involving more or less extensive overall control.

The purpose of this study is to see to what extent photovoltaic solar power could represent a substantial proportion of global electricity consumption by 2050, taking into account, in particular, the economic aspect, the availability of resources, and intermittency management issues.

Benchmark scenario used in this report for global energy consumption in 2050.

At present, final energy demand represents about 110 PWh, of which 18% for electricity (i.e. about 20 PWh). As regards photovoltaic solar power, it supplies scarcely 1% of electricity consumption.

In the World Energy Outlook 2014, the International Energy Agency (IEA) considers several scenarios for energy trends between now and 2040. The Current Policies Scenario foresees no changes from current policies. The New Policies Scenario considers a continuation of the existing policies and the implementation of measures already planned but not yet implemented. The 450 Scenario consists in adopting measures to effectively limit the global increase in temperature by 2100 to 2°C compared with the pre-industrial global temperature.

All these scenarios factor in an increase in the share of electricity in final energy consumption due to the appearance of new uses and the electrification of new regions in the world[1]. For example, electricity consumption could reach 35 PWh according to the 450 Scenario and 40 PWh according to the New Policies Scenario,[2] i.e. from 23% to 24% of the final energy consumed in the world.

In each of these scenarios photovoltaic solar power represents between 3% and 6% of electricity consumption, i.e. between 1.3 and 2.0 PWh.

In order to evaluate to what extent photovoltaic solar power could contribute to global consumption, we shall assume electricity consumption ranging between 35 and 40 PWh in 2050[3].

1- As a reminder, at present more than 1 billion people still have no access to electricity.

2- 1 PWh = 1 petawatthour = 1,000 billion kWh

3- The idea is of course not to validate or invalidate the work of the WEO (especially since the latter stops at 2040 whereas the present study goes up to 2050), but to have a consistent order of magnitude with which to compare projections concerning photovoltaic solar power, the subject of the present study.

Methodological notes on the performance of this study.

The study covers the outlook for global expansion of photovoltaic power by 2050 for ground-based (industrial) and roof-based (residential) installations. It does not include data relating to concentrated solar power. This technology adds an aspect of complexity (the part for concentrating light) which appears more as a limiting factor for its deployment. Moreover, this technology has not experienced the rapid expansion hoped by some stakeholders. The present study also does not include data relating to the new uses which are appearing at present (e.g. the smartphone), because the latter will probably remain marginal in volume compared with electricity production connected to a grid (whether it be a national grid or the electricity network of a house in the context of decentralized production).

The study first examines the economic data of photovoltaic power to assess to what extent an increase in the competitiveness of this technology could enable it to expand, and whether the necessary financing could be obtainable. We then check whether these economic results could be compatible with the availability of raw materials, the energy return on investment and issues related to intermittency, namely the inherent integration capacity of power grids, demand management and electrochemical storage. If only electrochemical storage is discussed, this is not because the FNH considers it as the only appropriate storage solution but because of the similarity of the electrochemical storage facility manufacturing industry with the photovoltaic module manufacturing industry. Regarding the integration capacity of the grids, the study was mainly based on data concerning France. However, this does not make it impossible to establish concepts applicable to the grids of developed countries in general.

Finally, the last part gives a few ideas regarding changes in the landscape of the electricity industry and the prospects offered by the development of photovoltaic solar power in non-electrified regions.

This study was carried out following extensive bibliographic work and numerous interviews with experts from the world of industry, grid managers and the research world. For some charts, the FNH has included not only the data from published reports but also data from work by experts. The latter are in this case identified as level 1, 2 or 3 experts because they express their views as individuals having expertise and not in the name of the organization in which they work. We specify that the FNH has not produced data in the present study but has rather produced summaries of data collected from various sources (published reports and experts) and established scenarios (regarding changes in the installation cost of photovoltaic power, the photovoltaic capacity installed worldwide, the cost of electricity production by a photovoltaic installation) based on this data and its assessment of the experts' analyses.

Let us specify, finally, that this study aims to outline global trends in terms of orders of magnitude, and that each of the points presented would deserve being examined in greater detail.

1.2 The sun and mankind: a relative match between solar irradiance and human establishment

The sun inundates the earth with a quantity of radiation equivalent to several thousand times the world's energy consumption. This potential is theoretical: absorption by the atmosphere and darkening by clouds reduce it locally. And the sun does not shine at night. However, the energy received on the ground remains three orders of magnitude greater than the world's energy consumption. The question then is whether the correlation between solar irradiance is consistent with the establishment of populations. *Figure 1* shows the existing correlation. Admittedly, it is not perfect, but since photovoltaic power is not the only solution and since the question is examined on a global level, this data shows us that photovoltaic power can play a major role in humanity's energy supply. Moreover, a recent MIT report[4] highlights a negative correlation between per capita GDP and solar irradiance : the poorest countries at present are those with the most solar resources.

However, these correlations are based merely on average insolation. But insolation varies during the day, from one day to the next and throughout the year. Although the solar resource is, on average, fairly well distributed (unlike other energies, such as oil!), it is at first sight not obvious how to use it to make it a source of energy supply for humanity. The purpose of this report is clearly to understand what it is possible to do faced with this complexity, and the conceivable changes required sooner or later to make photovoltaic power a low-carbon energy source supplying humanity.

4- (MIT, 2015) CITATION MIT15 \l 1036

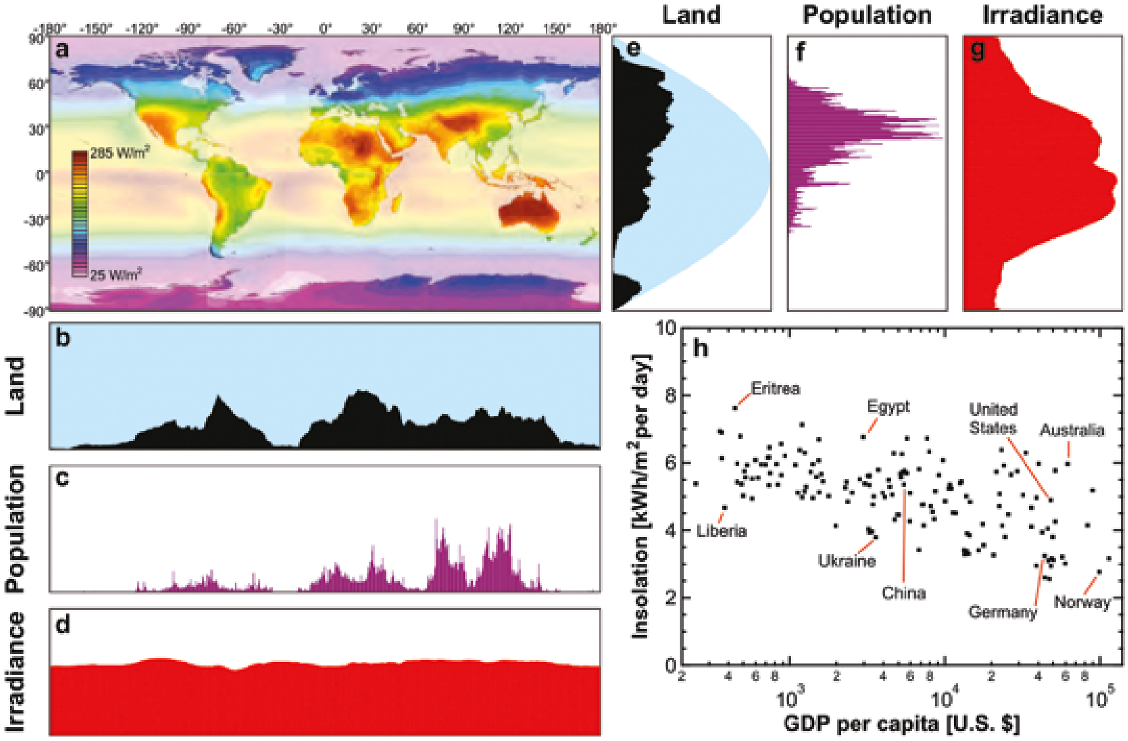


FIGURE 1 : COMPARISON BETWEEN THE DISTRIBUTION OF THE EARTH'S SURFACE, POPULATION DENSITY AND SOLAR IRRADIANCE AND COMPARISON OF INSOLATION AS A FUNCTION OF PER CAPITA GDP, FROM "THE FUTURE OF SOLAR ENERGY", MIT, 2015

1.3 The physical concepts on which photovoltaic power is based

Before exploring the prospects for development of photovoltaic power, it is necessary to summarize the physical properties underlying this technology and recent technical and economic developments. In 1839 the physicist Antoine Becquerel and his son made the first observation of the photovoltaic effect which is manifested by a change in the electric properties of a semiconductor material when it is subjected to radiation. This results in the appearance of an electrical voltage. It was not until nearly 50 years later, in 1883, that Charles Fritts manufactured what can be called the first photovoltaic cell in history. It was formed of selenium and gold, and had an efficiency of about 1%[5]. At that time, the phenomenon was still only partially understood. The effects were described, but the fundamental physical causes remained unexplained.

In 1905, Albert Einstein proposed a scientific explanation – for which he received the Nobel Prize for Physics in 1921 – using the concept of the photon (a "particle" of light). Photovoltaic effect is due to an interaction between light and the nanometric structure of matter. This understanding, and engineer Russel Ohl's discovery, in 1939, of the P-N junction – an arrangement of matter in a so-called semiconductor configuration – led to Ohl's filing, in 1941, of the first patent for a photovoltaic cell. The concept of a photovoltaic cell based on the photoelectric effect and a particular arrangement of matter came into being.

It is important to understand the specific fundamental features of photovoltaic energy, because they have important implications for its development. All other means of electricity production use macroscopic mechanisms to produce electricity: causing an alternator to operate to produce electricity. The difference between the technologies lies in the force used to drive the rotor:

- Wind for wind generators;
- Water for hydroelectric dams, tidal power plants, marine turbines and wave energy converters;
- Steam generated using the energy released by the combustion of coal/gas/wood/oil, by nuclear fission reactions, or by concentration of the rays of the sun (thermodynamic solar power);
- Direct combustion of liquid petroleum products in engines (mostly diesel).

The common feature of all these means of production is that they use mechanisms occurring on a macro scale (cm, m, km) and governed by the laws of conventional physics[6], which describes the world that we all see. Conversely, photovoltaic power uses phenomena occurring on a nanometric scale[7], the scale of electrons themselves. This has several implications:

- Photovoltaic power is far more modular: a 1 W or 1 GW installation can be manufactured (one billion times larger!);
- Photovoltaic power is based directly on quantum physics, i.e. the physics governing the behavior of matter on or below the nanometric scale[8]. Now, quantum physics is in no way similar to the physics which we "experiment with" every day. In this nanometric world, you can slow down light, pass through walls, etc.[9] In fact, the potential of this world is far vaster than that of the conventional world consisting of turbines, wind generator vanes and concrete dams. That makes photovoltaic power a different kind of energy, as we shall see further on.

1.4 The various technologies and uses of photovoltaic power

Photovoltaic technologies are divided into two major categories:

- Technologies based on wafers, i.e. thin slices of material assembled alongside one another;
- Technologies based on thin films, for which the component parts are "deposited" atom by atom, like depositing several coats of paint on a wall.

At present, the wafer technology (in blue and orange on *Figure 2*) is the main technology in the market, with thin films (in green) confined to a limited level. There is often talk of competition between these two main types of technologies. According to several experts we met, this competition will eventually disappear through convergence of the "thin film" and "crystalline silicon" technologies (we can already see this appear in hybrid technologies such as heterojunction, which involves depositing amorphous silicon on crystalline silicon or multijunctions which combine other materials on crystalline silicon).

Uses of photovoltaic power

Due to its great malleability, photovoltaic power can be implemented in devices ranging from a few watts to several hundred megawatts (1 million watts). A distinction is made between the following uses:

- Ground-based power plants from a few MW to several hundred MW.
- Roof-based installations from a few kW to a few hundred kW. The smallest installations are generally for residential buildings, whereas the biggest are on tertiary and industrial buildings.
- On-board installations, as is traditionally the case on satellites.

Regarding on-board installations, recent developments offer new possibilities for the incorporation of photovoltaic systems, due to innovations including photovoltaic cells as close as possible to the points of use.

5- Approximately the conversion efficiency of photosynthesis performed by chlorophyllic plants.

6- Apart from nuclear reactions which make use of particle physics for steam generation. On the other hand, electricity production is still performed by a conventional mechanism of steam generation causing rotation of a turbine, which actuates an alternator.

7- 1 nanometer = 0.000,001 millimeter

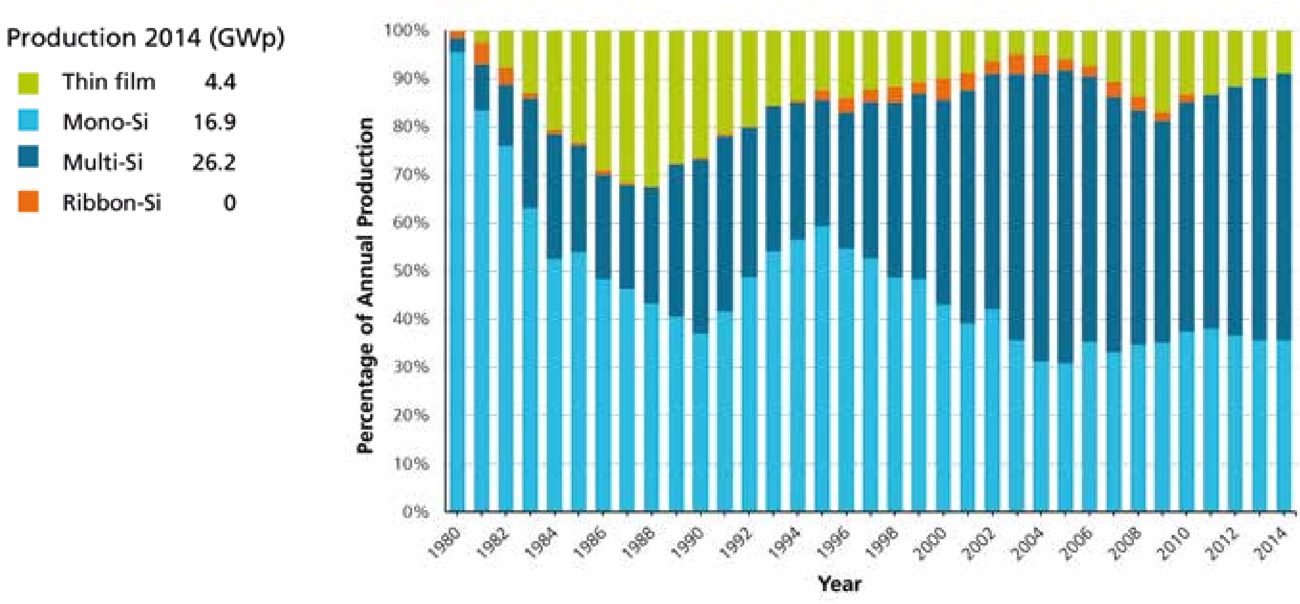
8- In current photovoltaic cells, the thickness of the photoactive parts ranges from one micron to about one hundred microns.

9- In quantum mechanics one is not in a single state (hot or cold, at the top or at the bottom), but one is with certain probabilities in all the possible states simultaneously. The tunnel effect, for its part, is due to Heisenberg's uncertainty principle which describes the uncertainty inherent in the nanometric world regarding position and speed, energy and duration, etc.

- Companies such as Microsoft and Sunpartner Technologies are developing photovoltaic films capable of generating part of the electricity consumption of mobile phones. For mere voice use, phones can be practically 100% autonomous.
- The inclusion of photovoltaic cells in building materials allows greater architectural flexibility than with conventional photovoltaic panels.
- Photovoltaic cells are incorporated in means of transport to provide part of their energy consumption.

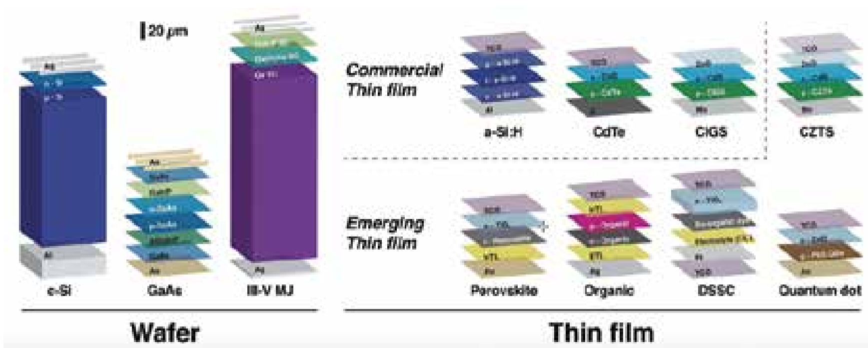
These new uses, representing only a small part of the installed capacity (driven mainly by the electricity production sector), do not come within the scope of this study. Note, however, that they could represent a powerful driver of innovation for the whole sector, because their business model is completely different from that of ground-based power plants and residential installations. This is because, while consumers will be attentive the competitiveness of a photovoltaic installation designed solely to produce electricity, it is highly likely that they will not hesitate to add a few dozen euros to have the latest smartphone producing part of the electricity that it consumes (even if that electricity is far more expensive than that taken from the grid).

‣ **FIGURE 2 :** MARKET SHARE TRENDS FOR THE MAIN PHOTOVOLTAIC TECHNOLOGIES IN THE CELL PRODUCTION MARKET, FRAUNHOFER INSTITUTE, 2015.



‣ **FIGURE 3 :** DIAGRAMS OF THE MAIN EXISTING PHOTOVOLTAIC CELL TECHNOLOGIES (MARKETED OR IN DEVELOPMENT): "THE FUTURE OF SOLAR ENERGY", MIT, 2015*

* Each diagram shows the various layers forming the photovoltaic cell, and their relative thickness.



2. OVERVIEW AND PROSPECTS FOR DEVELOPMENT OF PV: THE ECONOMIC AND PHYSICAL DATA

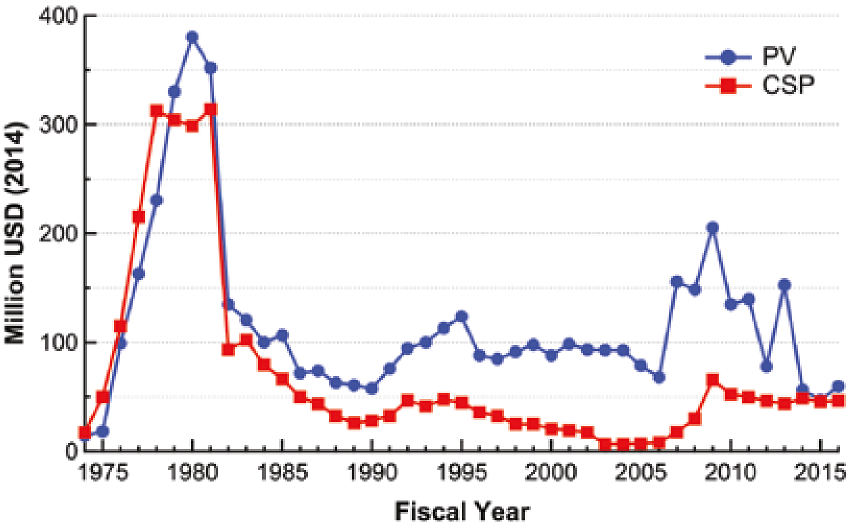
The photovoltaic power industry was long confined to a niche market, but its performance and competitiveness have changed enormously in recent years. As we shall see in this section, photovoltaic power is already at present a competitive means of electricity production in several countries. It still has significant prospects for development.

Conversely, the costs of conventional production facilities are generally increasing. This is an inherent feature of mature technologies for which no massive gain can be expected. The physical principles of thermodynamics will not be exceeded. The 30% to 50% efficiencies already achieved correspond to the theoretical maximum. Any improvements will therefore be merely continuous improvements. On the other hand, certain cost components of these installations will continue to increase due to:

- Increased security and safety requirements for the nuclear industry, at all stages of the complete cycle;
- Gradual allowance for the cost of greenhouse gas emissions for gas- and coal-fired power stations will increase their cost;
- The installation of carbon capture and storage systems for power plants burning fossil fuels (and provided that their economic profitability and sustainability on a global scale are proved, which is not yet the case);
- The introduction of standards for reduction of particulate emissions due to coal-fired electric power stations.

The photovoltaic technology, as we have described it in the previous section, is based on completely different physical principles. All other means of electricity production are based on conventional mechanics for the strictly electricity generating part. Quantum mechanics, the physics on which photovoltaic technology is based, offers major potential for development, making it possible to further improve the competitiveness of this technology.

FIGURE 4 : INVESTMENT IN RESEARCH ON SOLAR TECHNOLOGIES BY THE US DEPARTMENT OF ENERGY (EXCLUDING FUNDAMENTAL RESEARCH), THE FUTURE OF SOLAR ENERGY, MIT, 2015



2.1 From a niche market to a competitive industry in several countries

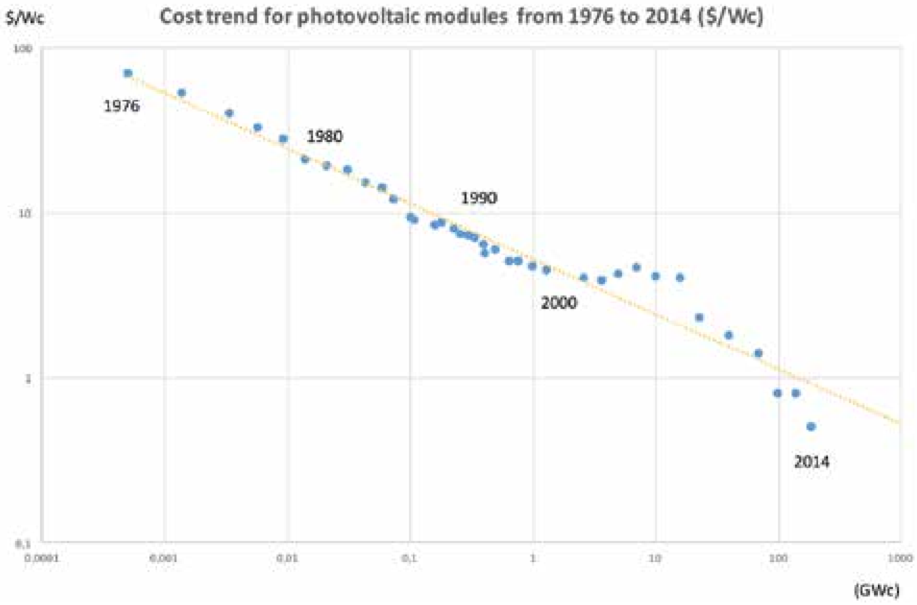
2.1.1 Photovoltaic power, long confined to a niche market

On 4 September 1882, Thomas Edison put into operation the first electric power station using coal as the source of primary energy to supply lighting for buildings around Wall Street. The production of the first electric power stations was immediately used to meet humanity's main uses (lighting, then transport and the operation of machines), and on a massive scale (districts and then entire cities were rapidly electrified, e.g. for lighting).

Photovoltaic power, meanwhile, remained for a long time confined to the niche market of the space industry, being first used in 1958. The low efficiency (about 5% at the time) and the associated cost meant it was not possible to envisage massive use for the main electricity needs of humanity.

In the 1970s and 80s, many countries looked for alternative energy solutions to oil. France, which had invested heavily in solar energy, setting up the Comes (Solar Energy Commission), was at that time one of the leaders in this field. A large number of photovoltaic concepts were conceived at this time. However, due to the combination of a preference for nuclear power (also motivated by military reasons), the oil countershock and the high cost of solar technologies, almost all research in this area was discontinued. France was not a special case, as shown by investment changes in the budget of the US Department of Energy devoted to solar power.

Accordingly, from the 1980s to the end of the 1990s, renewable energies in general and photovoltaic power in particular were completely ignored by energy producers and energy policies.



▸ **FIGURE 5 :** COST TREND FOR PHOTOVOLTAIC MODULES AS A FUNCTION OF CUMULATIVE INSTALLED CAPACITY. DATA: FRAUNHOFER INSTITUTE, MIT, IEA. ILLUSTRATION: FONDATION NICOLAS HULOT

2.1.2 Support programs allow access to a sufficiently large market to push down costs

In the 2000s, the launch of support programs, in Europe in particular, provided photovoltaic systems with a market size enabling it to enter cost regions compatible with a mass market. This also highlighted a dynamic that has existed for the past several decades.

The production costs of photovoltaic systems fall when market size increases. The reasons for this are diverse (non-exhaustive list)[10].

- The production of electronic goods allows automation and an increase in the size of production plants. Production in a 100 MW or 1 GW plant does not entail the same cost per watt produced.
- The R&D investment made possible by the increase in market size means that the quantities of materials used (and hence the related costs) can be reduced without detracting from the performance and quality of photovoltaic modules.
- Also, R&D makes it possible to improve energy efficiency, contributing to cost optimization.

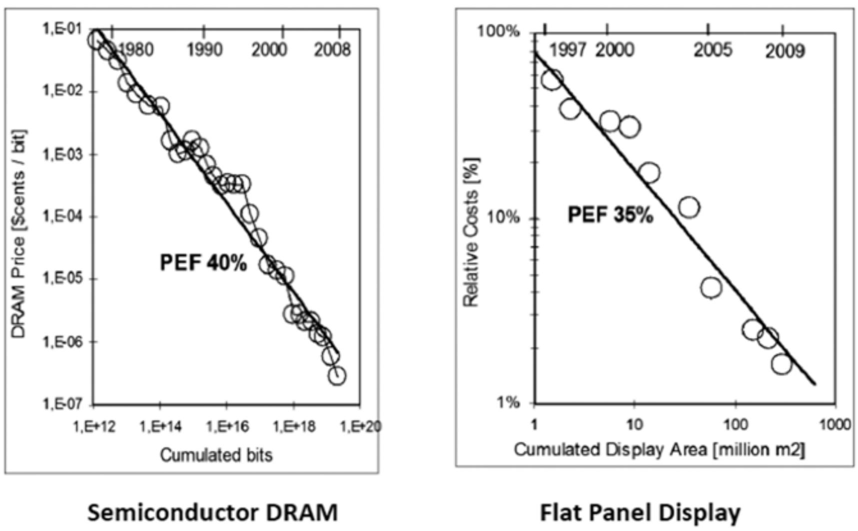
We find the same phenomenon as in more conventional electronics markets (see *Figure 6*).

10- These various points and others will be examined in greater detail in Part 2.2.

Market size has also had an impact on industries related to photovoltaic power such as the procurement of silicon. Until 2008, due to the small size of the photovoltaic market and its lower quality requirements than for microelectronics, silicon producers simply used scrap from the production of electronics silicon to supply the photovoltaic sector. Growing demand in this sector soon created tensions related not to a problem of raw material procurement[11] but to the industry's organization. The decision of silicon producers to create facilities dedicated to photovoltaic systems made it possible to solve the procurement problems and develop an industry fully adapted to this sector. This initiative was essential in order to continue to improve the competitiveness of silicon photovoltaic cells. Today, the solar power industry represents about 300 kT of silicon per year, whereas the electronics industry generates a production of only 40 kT per year! This trend, among others, makes it possible to now say that photovoltaic power has become an optoelectronics segment in its own right.

11- Silicon is the second most abundant element in the earth's crust.

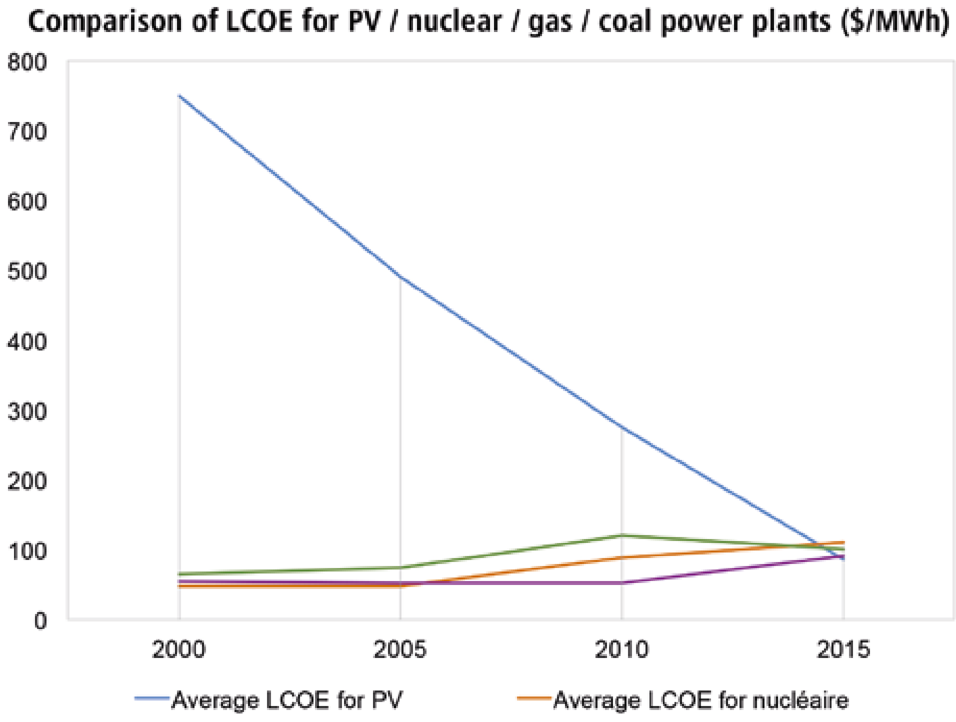
▸ **FIGURE 6 :** COST TREND FOR DRAM TYPE MEMORY USED IN COMPUTERS AND FLAT PANEL DISPLAYS AS A FUNCTION OF THE CUMULATIVE SIZE OF THEIR RESPECTIVE MARKET, WINFRIED HOFFMANN, ASE, 2014



‣ **FIGURE 7 :** COMPARISON OF THE LCOES OF PV/NUCLEAR/GAS/COAL, FRAUNHOFER INSTITUTE. DATA BASED ON BUYBACK TARIFFS FOR GROUND-BASED PV INSTALLATIONS IN FRANCE, LAZARD, TCDB (EXCLUDING COST OF CO2), IEA ETP 2015. ILLUSTRATION: FONDATION NICOLAS HULOT.

ANALYSIS: THE LCOE OF A NEW PHOTOVOLTAIC SOLAR POWER SYSTEM HAS FALLEN FROM ABOUT US$750 PER MWH IN 2000 TO ABOUT US$85 PER MWH AT PRESENT.

* LCOE = Levelized Cost Of Energy = Life-cycle cost of a means of production obtained by discounting its production over its lifetime. In the references used to plot this graph, the discount rate for the LCOE is in a range of 6% to 8% depending on the reference, when such data is available.



2.1.3 Photovoltaic power is now competitive in many countries

Until recently, the electricity produced by photovoltaic systems was a very expensive energy compared with other electricity production technologies (gas, coal, nuclear), as shown by *Figure* 7. Therefore, photovoltaic power was not economically viable without state subsidies.

In 2015, this is no longer the case in many countries: the LCOE of photovoltaic power is approximately the same as that of other conventional means of production.

In some countries, this competitiveness is even far greater, as suggested by the data concerning certain recent calls for bids:

- In Austin, SunEdison won a PPA[12] to sell its electricity at US$50 per MWh (this price includes federal support via a tax credit, and is equivalent, excluding this aid, to US$70 per MWh.
- In Dubai, ACWA Power won a PPA at about US$60 per MWh without subsidies. According to certain competitors, the competitive financing rate obtained by ACWA Power explains these levels, but even without that, the best other competitors were at US$65-70 per MWh.

In fact, as we shall see subsequently in this report, the potential of photovoltaic power for the coming years has been thoroughly changed by comparison with what could be imagined just three years ago.

12- PPA: Power Purchase Agreement = agreement between a producer and a marketer for the purchase of electricity over a given period at a given price

THE LCOE (LEVELIZED COST OF ENERGY)

The competitiveness of an electricity production unit is impacted by two types of economic data: (i) the size of the initial investment (expressed in US$/W), which, depending on the financing conditions, will have an impact on the decision to launch the project or not[1], and (ii) the levelized cost (LCOE) of production of a kilowatt hour (kWh) over the lifetime of the equipment which produces it.

The LCOE, therefore, includes not only depreciation of the initial capital cost but also operating costs (maintenance, cost of primary energy) over the life of the installation relative to the total kWh produced. In the present study, it is calculated with a discount rate of 5% (a rate taking into account the cost of capital and the cost of debt needed for financing). Overall, the LCOE can ensure a certain comparability between various means of production for the life-cycle cost of production.

Some stakeholders consider that the LCOE for photovoltaic solar power and those for conventional means of production (nuclear, gas, coal) are not comparable[2], because the production profiles are not the same. It would therefore be necessary to compare the LCOE for photovoltaic solar power to which would be added the LCOE for back-up facilities (see below).

Photovoltaic systems produce energy in a manner varying with time: the average production profile of photovoltaic systems on the national level has a bell shape, the amplitude of which varies from one day to the next (depending on the overall intensity of insolation). This variation is random although perfectly predictable the day before. To ensure the supply of electricity linked to the consumption profile of electricity demand on the national level, it is therefore necessary to supplement photovoltaic electricity production with back-up systems[3]. Even if demand is highest during the period of photovoltaic power production, it is necessary to ensure a minimum level of production at night.

Conversely, for conventional power stations (coal, gas and nuclear), the LCOE is based on base-load operation, i.e. they operate continuously at a constant capacity. To ensure the supply of electricity linked to the consumption profile of electricity demand on the national level, it is necessary to supplement base-load production in the daytime due to the fact that consumption is highest in daytime. It is possible to have variable gas- and coal-fired production during the daytime, in line with consumption. However, this greatly increases the cost of production (mainly because fixed costs must be recouped on a smaller volume of electricity), and that resembles the extra cost of the back-up system for photovoltaic solar power. For nuclear power, due to technical constraints[4], it is necessary to add dedicated means of production to meet demand when it exceeds the base-load production. This extra cost also resembles the extra cost of the back-up system for photovoltaic power. So, basically, we can say that, in 2015, new photovoltaic, nuclear, gas- and coal-fired installations have similar production costs.

1- These factors are analysed in the following two parts.

2-However, these comparisons are systematically made and, as we shall show, are not meaningless on a basic level.

3-A back-up is a means of production used to compensate for the inadequacy of a main means of production to meet demand.

4-Regarding this point, note that the LCOE for the nuclear industry in France does not take into account a back-up which is essential for it and which was designed for it specifically because of (i) its relative inflexibility and (ii) its surplus capacity at night. These back-up systems are the 4 GW of Pumped Storage Power Stations (PSPS's).

2.2 Recent and future cost trends for a photovoltaic module

From manufacture of the cell to start-up, there are three basic cost components of a photovoltaic module.

- The photovoltaic modules, which themselves include the cells producing electricity and glasses to protect those cells and a frame to maintain overall leakproofing.
- The inverters, which can convert the direct current produced by the modules into alternating current flowing in our electricity grids.
- The "Balance of System" comprises all other costs (electric cabling, connection to grids; civil engineering, structure; installation; design, planning, administration, taxes, etc.).

This section reviews recent developments which have made it possible, for each of these cost components, to improve the competitiveness of photovoltaic power, and future developments. The competitiveness drivers in the coming years are not viewed similarly by the various experts.

- For some of them, competitiveness developments will be due to the improvement in industrial processes at the levels of both the production of the various equipment items (modules, inverters) and installation.
- For others, technological innovation regarding cells will be the driver for competitiveness.
- Still others think that the improvements will come from a mixture of these two aspects[13].

13- This graph gives an idea of the cost breakdown for a ground-based photovoltaic installation. Of course, this breakdown varies for each installation.

2.2.1 Improvement in the efficiency of photovoltaic cells

However, the efficiency values identified in *Figure 9* are not those of marketed cells nor the modules. In general, there is a difference of about 3% to 6% between the efficiency of a cell in the laboratory and the efficiency of an industrial module. At present, the efficiency of industrial modules for technologies based on crystalline silicon is around 15-21%, and around 12-15% on thin films. The shortfalls in the efficiency of industrial photovoltaic modules compared with cells in the laboratory can be explained by:

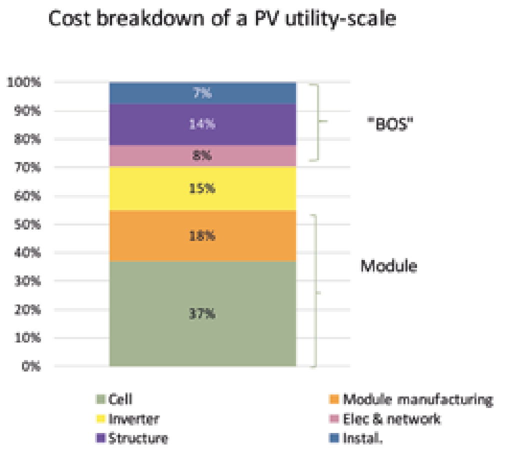
- The existence of larger and more numerous defects in an industrial cell than in a "hand-made" laboratory cell;
- Phenomena of absorption and "degradation" of the quality of the cells once encapsulated in a module

Coming efficiency improvements

Figure 9 shows that the efficiency of cells at the laboratory level has generally stagnated in the 2000s. Conversely, the efficiency of modules has gradually increased *(Figure 10)*. This confirms the assertion of some experts that, in recent years, the improvement in efficiency is due more to an improvement in industrial processes for implementing the technologies than to innovation on the cells.

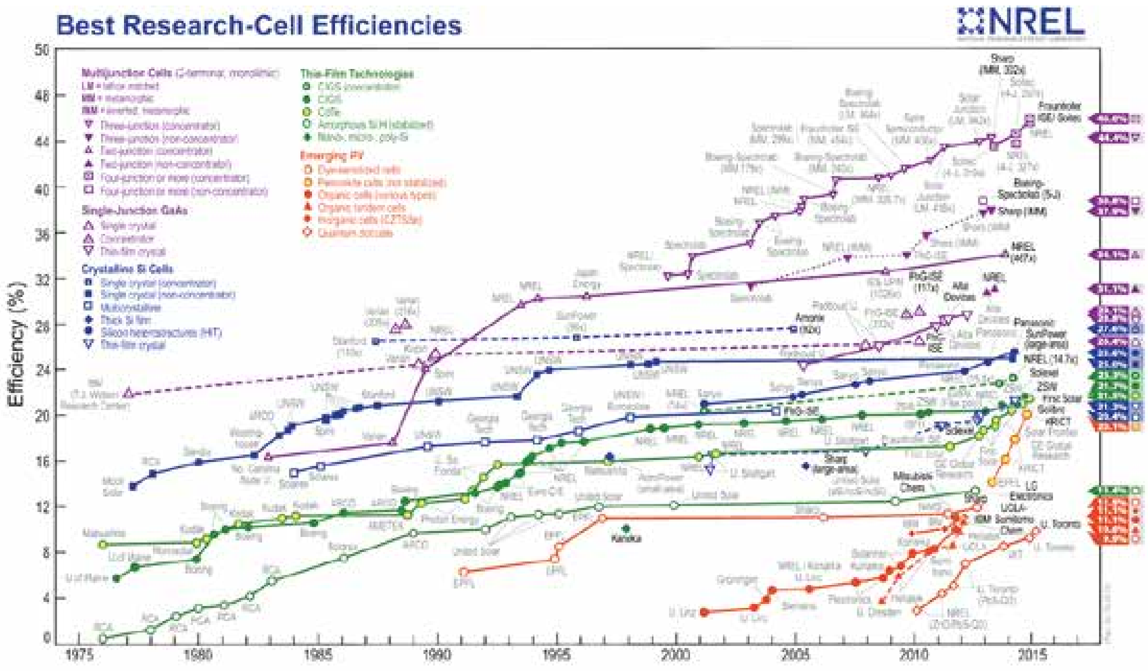
▸ FIGURE 8 :
COST BREAKDOWN OF A GROUND-BASED PHOTOVOLTAIC INSTALLATION EXCLUDING GENERAL AND ADMINISTRATIVE COSTS. SOURCE: ADEME, MIT, ITRPV, FRAUNHOFER INSTITUTE. ILLUSTRATION: FONDATION NICOLAS HULOT*

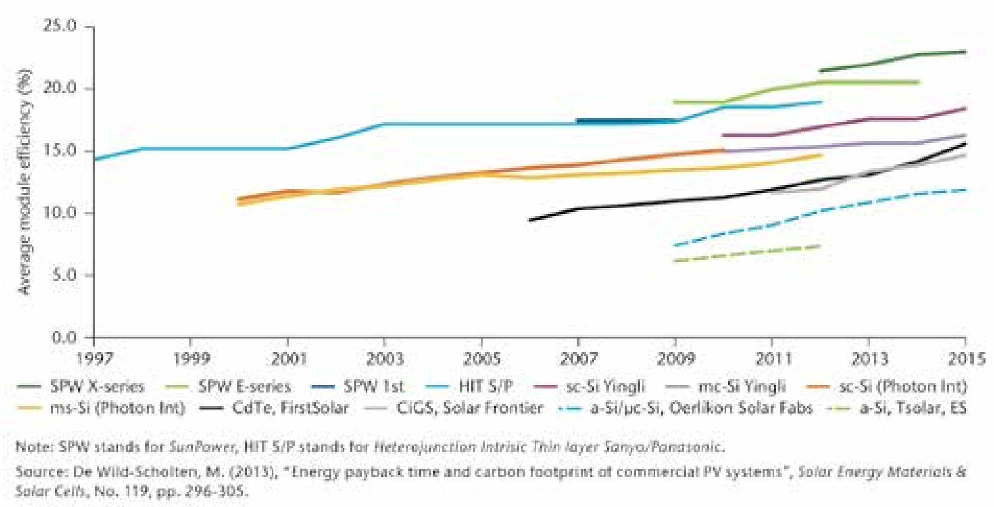
* This graph gives an idea of the cost breakdown for a ground-based photovoltaic installation. Of course, this breakdown varies for each installation.



▸ FIGURE 9 :
BEST LABORATORY EFFICIENCY TRENDS FOR PHOTOVOLTAIC CELLS, NREL, 2015.

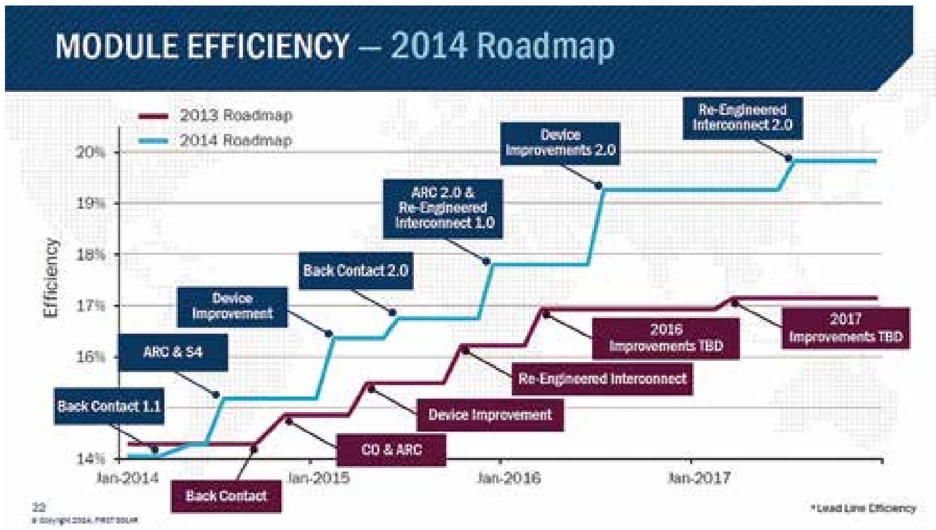
ANALYSIS: THE LABORATORY EFFICIENCY OF SILICON-BASED CELLS (IN BLUE) HAVE INCREASED FROM ABOUT 14% IN THE 1970S TO ABOUT 25% AT PRESENT. THE DATA IN PURPLE CORRESPOND TO THE EFFICIENCY OF CONCENTRATED SOLAR POWER AND DO NOT COME WITHIN THE SCOPE OF THIS STUDY.





▸ FIGURE 10 : ENERGY EFFICIENCY TRENDS FOR THE MAIN COMMERCIAL MODULES SINCE 1997*, "TECHNOLOGY ROADMAP - SOLAR PHOTOVOLTAIC ENERGY", IEA, 2014

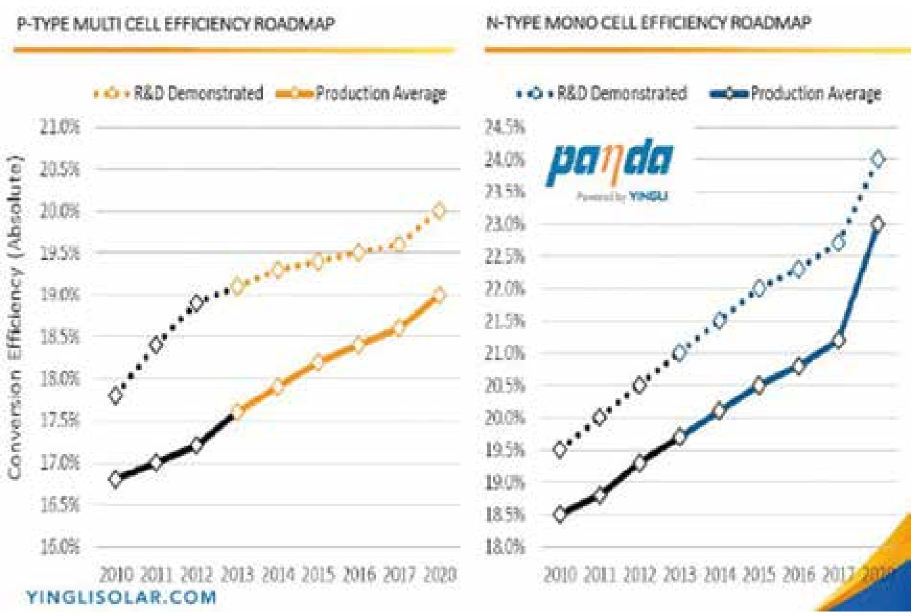
* sc-Si = monocrystalline silicon, mc-Si = polycrystalline silicon, a-Si = amorphous silicon



▸ FIGURE 11 : 2014 ROADMAP OF THE ENERGY EFFICIENCY OF FIRST SOLAR CELLS, 2014*.

ANALYSIS: NOT ONLY DOES THE 2014 ROADMAP IDENTIFY ALL THE IMPROVEMENTS TO BE MADE BY COMPARISON WITH THE UNCERTAINTIES OF 2013, BUT IT ALSO FORESEES AN EFFICIENCY 15-20% HIGHER THAN THAT OF THE 2013 ROADMAP.

* ARC = anti-reflection coating; TBD = To be done; CO = coating



▸ FIGURE 12 : 2014 ROADMAP OF YINGLI CELLS, 2015

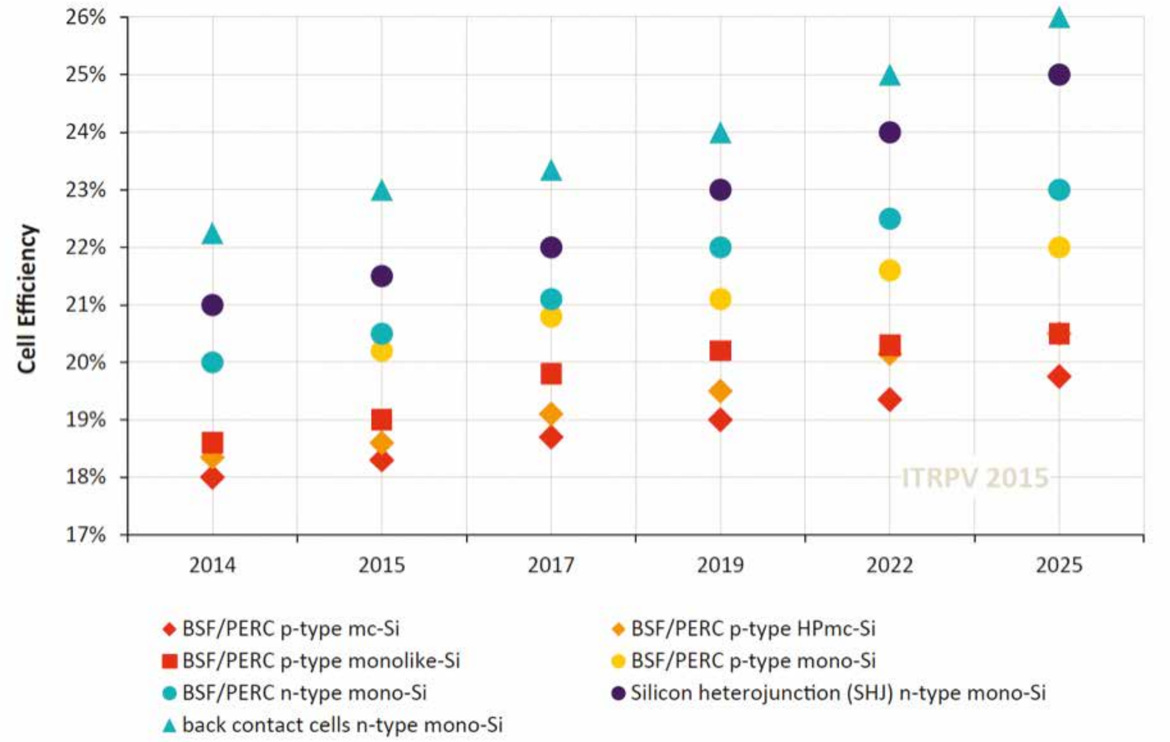


FIGURE 13 : PROSPECTIVE EFFICIENCY TRENDS FOR PHOTOVOLTAIC CELLS ON THE 2025 HORIZON, "INTERNATIONAL TECHNOLOGY ROADMAP FOR PHOTOVOLTAIC", 2015*

* mono-Si = single-crystal silicon, mc-Si = polycrystalline silicon

In recent years, however, innovations at the research and development level have made it possible to significantly improve the efficiency of some technologies. This is the case for thin films, notably for the technology of First Solar, which recently revised its roadmap upward, and for the roadmap of Yingli, one of the leading producers of photovoltaic cells using the crystalline silicon technology.

The data of the ITRPV[14] presented in *Figure 13* point in the same direction. Moreover, the indications of the Yingli roadmap regarding one of its technologies show the importance of innovation concerning the cells in improving their competitiveness. This confirms the experts' estimates of a revival of the innovation driver in the competitiveness of photovoltaic systems and of an improvement in module efficiency, from a range of 15-20% to 20-25% in the next 5-10 years.

14- ITRPV = International Technology Roadmap for Photovoltaic: groups together photovoltaic system manufacturers over the entire value chain to study technological developments relating to photovoltaic power.

Longer-term, the experts are more divided. Some see a flattening out at 30%, because they are not convinced, or are very cautious, regarding the ability to implement new photovoltaic technologies making it possible to exceed the theoretical efficiency of a standard cell (single-junction)[15]. Others think that we shall have photovoltaic modules with an energy efficiency above 30% on the 2030 horizon and exceeding 50% on the 2050 horizon. The work and areas of development of some laboratories aiming to implement new methods with the most abundant possible raw materials and "common" equipment suggest that it is possible to achieve an efficiency of 40% to 50%.

15- The efficiency of single-junction cells as designed at present is limited to 30%. This is what is called the Shockley-Queisser limit, named after the physicists who proved it. Cells using concentrators now manage to exceed this efficiency, because their theoretical efficiency is higher. However, concentration technologies are not an approach privileged by the FNH because of the extra complexity added by concentration. Moreover, the cost of these technologies is still far higher than that of cells without concentration.

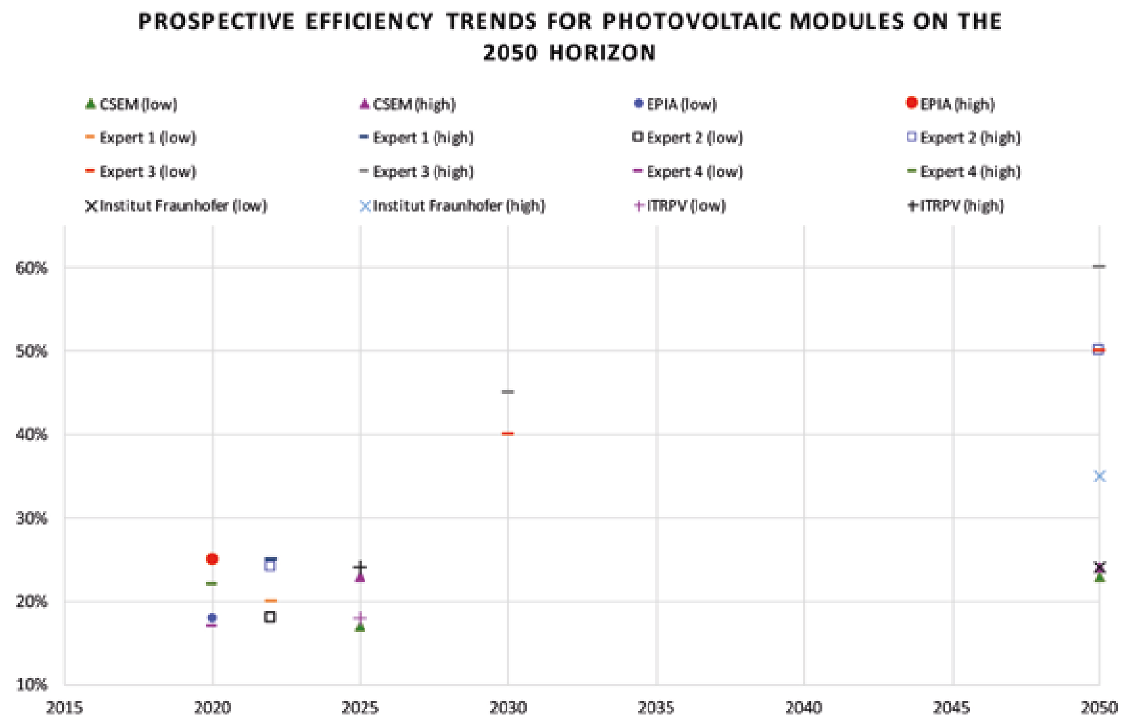


FIGURE 14 : PROSPECTIVE EFFICIENCY TRENDS FOR PHOTOVOLTAIC MODULES ON THE 2050 HORIZON, ITRPV, FRAUNHOFER INSTITUTE, CEA, EPIA, CSEM, EXPERTS SURVEYED. ILLUSTRATION: FONDATION NICOLAS HULOT.

ANALYSIS: THE PROSPECTIVE EFFICIENCY TRENDS SHOW A TREND IN A 20-25% RANGE WITHIN 5-10 YEARS, AFTER WHICH THERE ARE MAJOR DIFFERENCES DEPENDING ON EXPECTATIONS REGARDING THE DEPLOYMENT OF CELLS EXCEEDING THE 30% LIMIT.

An improvement in efficiency can have an impact on various cost components.

- The first concerns the Balance of System (BOS) part (see sub-section 2.2.4 below).
- The second concerns the cells' cost per watt. Developments at the laboratory level always take place under the constraint of production costs: the extra production cost for a cell of higher efficiency should not result in an increase in the cost of the unit production capacity in US$/W nor in the LCOE (also related to the systems' lifetime). *Figure 15* shows that even a significant increase in the cost of producing a cell can result in a substantial fall in the cost per watt due to improved efficiency.

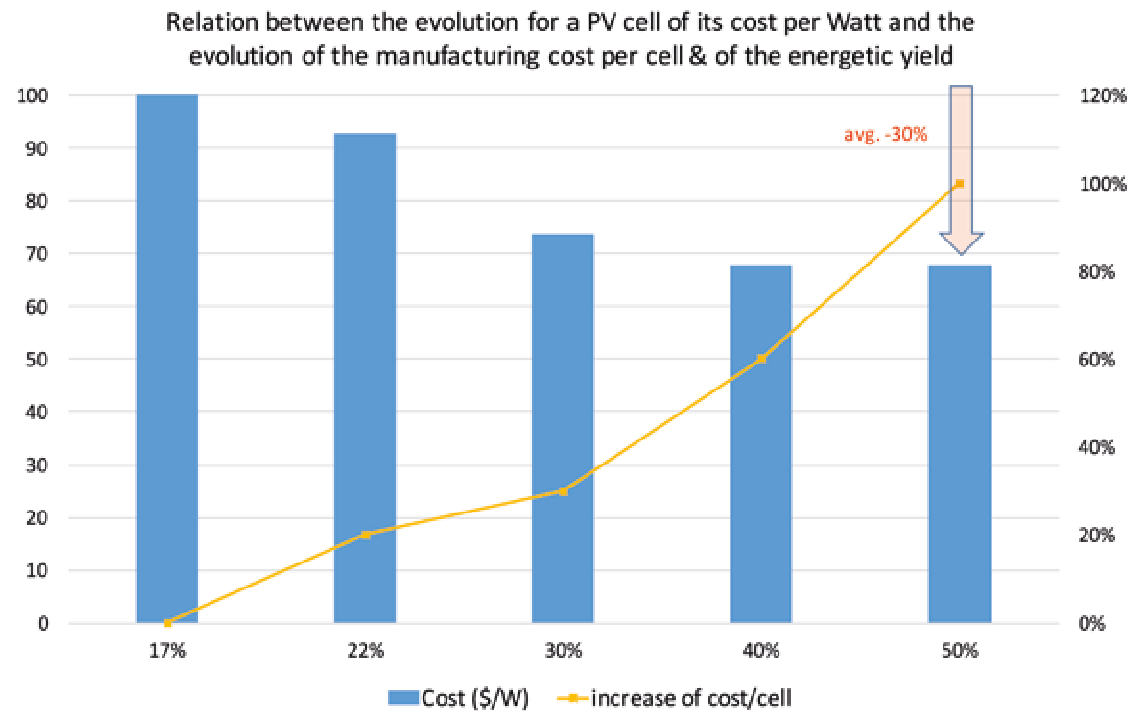


FIGURE 15 : TRENDS IN THE PRODUCTION COST OF A CELL IN US$/W (BASE = 100) AS A FUNCTION OF TRENDS IN THE UNIT COST OF MANUFACTURING A CELL (IT IS CONSIDERED THAT THE SIZE OF THE CELLS IS THE SAME RELATIVE TO THE VARIOUS EFFICIENCY LEVELS) AND ITS EFFICIENCY (THE EFFICIENCY LEVELS OF 17% AND 22% CORRESPOND APPROXIMATELY TO THE EXTREME LIMITS OF THE EFFICIENCY RANGE OF SILICON PHOTOVOLTAIC CELLS).

IF WE TAKE A CELL WITH AN EFFICIENCY OF 17% WHOSE COST PER UNIT POWER IS ADOPTED AS A REFERENCE AT 100 AND IF WE ASSUME THAT INCREASING THE EFFICIENCY OF THIS CELL TO 50% IMPLIES INCREASING PRODUCTION COSTS BY AROUND 100%, THE COST PER UNIT POWER OF THIS NEW CELL WILL BE 30% LESS THAN THAT WITH 17% EFFICIENCY.

2.2.2 The impact of improvement in industrial processes on the competitiveness of photovoltaic power

Reduction in cell production costs

This is still a very important area of research. Some experts consider it the key area. The goal is to reduce the quantities of materials used to manufacture cells, the quantities of materials used at the production machinery level (consumables) and the number of steps necessary for the production of a cell, and to improve production quality.

Improving product quality

Improvements in product quality can limit defects and the resulting losses while bringing the efficiency of industrial cells closer to that of cells produced in the laboratory.

Reducing material quantities

The reduction in the quantities of materials used in cells concerns, above all, technologies using crystalline silicon. In technologies using thin films, the cost driver in terms of material consumption is the consumables of manufacturing equipment.

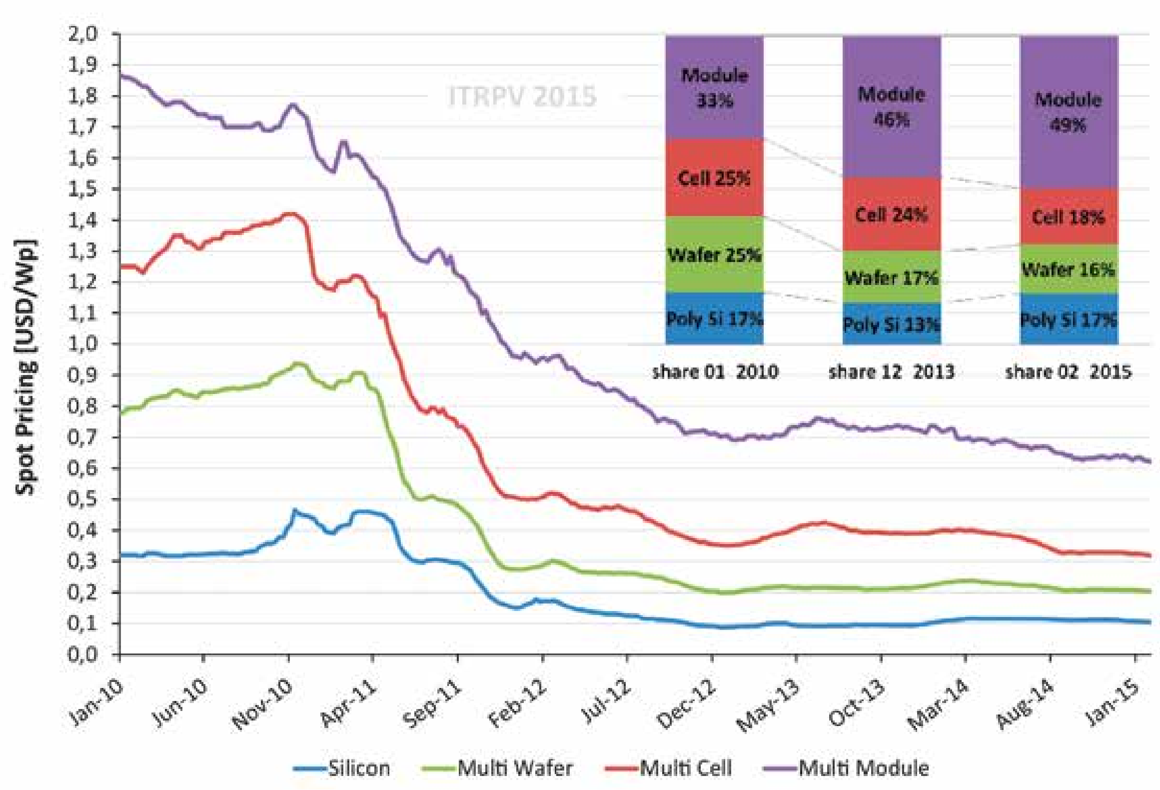
At present, the polysilicon and wafers account for about two-thirds of the cost of a cell. A reduction in silicon thickness will therefore have a significant impact on the cost of producing cells. The wafers used in silicon-based technologies typically have thicknesses of approximately 150-180 µm[16]. According to many experts, in the next 5-10 years the thickness of silicon could fall to 120 µm for single-crystal and 150 µm for polycrystalline. According to the experts, to go below 100 µm radiation capture must be improved. At present, research is focusing particularly on anti-reflection and radiation capture strategies, and on reducing internal recombinations by means of a higher quality of the crystal lattice[17].

16- (MIT, 2015) CITATION MIT15 \l 1036 p28, (International Technology Roadmap for Photovoltaic, 2015) CITATION Int15 \l 1036 p. 10

17-(MIT, 2015) CITATION MIT15 \l 1036 p. 25

▸ **FIGURE 16:** SPOT PRICE TRENDS FOR THE MAIN COMPONENTS OF A PHOTOVOLTAIC MODULE, ITRPV, 2015*

* Cost of a module = cost of polysilicon (blue) + cost of producing the wafer from polysilicon (green) + cost of producing the cell from the wafer (red) + cost of producing the module from the cell (purple).



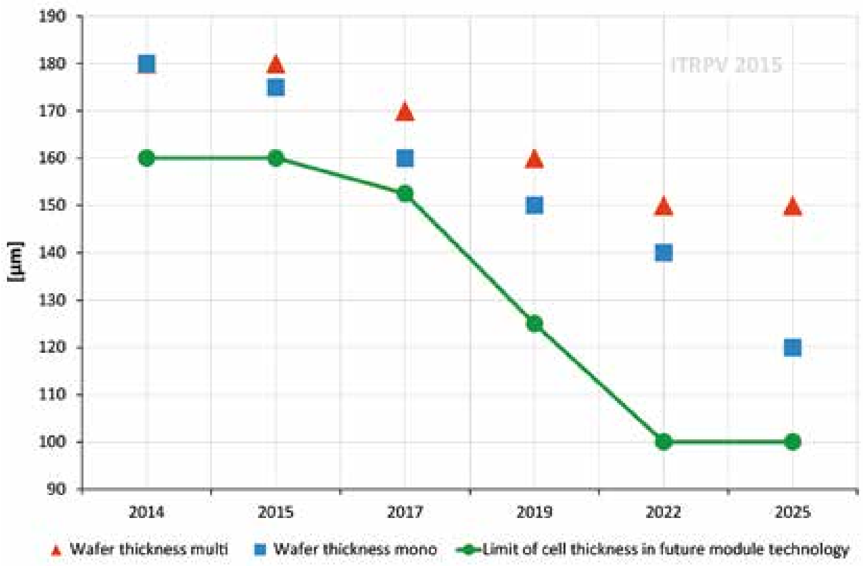


FIGURE 17 : PROSPECTIVE TRENDS IN SILICON THICKNESS FOR CRYSTALLINE SILICON PHOTOVOLTAIC CELL TECHNOLOGIES, ITRPV, 2015.

A reduction in the thickness of silicon from 180 µm to 120 µm in the next 10 years would cause a fall in the cost of modules by about 10%, assuming that the decline in thickness resulted in a decline, in similar proportions, in 50-75% of the cost of producing wafers[18].

These projections do not take into account potentially radical changes such as, for example, those of the French company S'Tile[19]. This firm has developed an innovative fabrication process (soon in the pilot phase of industrial validation of the technology) which makes it possible to reduce the silicon thickness to 40 µm by using a ceramic substrate with a sintered silicon powder base. This technology, if it materializes, is the first example of a merger of the thin film technology with technologies related to crystalline silicon. It could reduce the cost of producing a module by 30%.

Reduction in the quantity of consumables[20] used in production processes

The consumables in the photovoltaic module production process from the polysilicon production stage can also permit cost reductions. Laboratories such as the CEA and CSEM[21] are researching these issues. For example, the stage of ingot sawing to produce wafers is a heavy consumer of cutting wire. Developments have been made with diamond-coated cutting wires to save a few percent on production costs by extending the lifetime of these consumables.

18- A smaller quantity of silicon implies a smaller quantity of energy for wafer fabrication. The wafer fabrication process consists of melting silicon in crucibles, followed by solidification of the ingots and, finally, cutting out the ingots into wafers. While the last part of the process is only slightly impacted by the reduction in thickness, the first part, very energy-hungry, is impacted.

19- http://www.silicontile.fr/la-technologie/la-cellule-integree/

20- A consumable is an item used during the production process which becomes worn over time and must be replaced. For example, wafer fabrication requires a cutting out step using a special wire. This wire is a consumable: it becomes worn and must be replaced.

21- CEA = Commissariat à l'Energie Atomique et aux Energies Alternatives; CSEM = Centre Suisse d'Electronique et de Microtechnique.

Reduction in the number of production steps, and automation

The series of steps from polysilicon production to the module involving human intervention is a source of non-quality. Each step and each transfer from one step to another entails a risk of damaging the products and, overall, either reducing production efficiency and hence increasing production costs, or increasing the defects in the product and reducing its performance in terms of durability and energy efficiency.

Automation is a first step to improve product cost and quality. All the stakeholders see this trend on the horizon in the next few years, generating competitiveness gains for photovoltaic power. Surveyed stakeholders also expect an increase in the unit size of plants, from 1 to 5 GW on a 2030-2040 horizon, here again producing effects of scale which will improve the competitiveness of photovoltaic power.

▸ **FIGURE 18 :** : ONE-STEP FABRICATION PROCESS FOR A POLYCRYSTALLINE WAFER, 1366 TECHNOLOGY

Together with automation, laboratories and manufacturers are also working on a reduction in the number of production steps, which gives gains in terms of costs, energy consumption and quality improvement. A promising example is the US-based company 1366 Technologies. It has developed a fabrication process for polycrystalline silicon wafers which permits a reduction from four steps with 50% silicon losses to a single step with no loss of silicon. This also allows gains in product quality thanks to improved wafer uniformity and homogeneity.

This technology is already producing results, and a 250 MW production plant is planned. Its potential has not gone unnoticed: Chinese and Japanese investors[22] have forged an alliance with this firm, because such a process would effectively be a major breakthrough for photovoltaic power in general and for the polycrystalline silicon technology in particular. These disruptive innovations suggest potential for technologies other than polycrystalline silicon.

2.2.3 Inverters

To be capable of injecting the electricity produced by photovoltaic modules, it is necessary to adapt the characteristics of the electricity produced. Photovoltaic modules produce direct current, whereas the power grid and building installations use an alternating current at a frequency of 50 Hz. To convert direct current to alternating current, a power electronics device is used: the inverter.

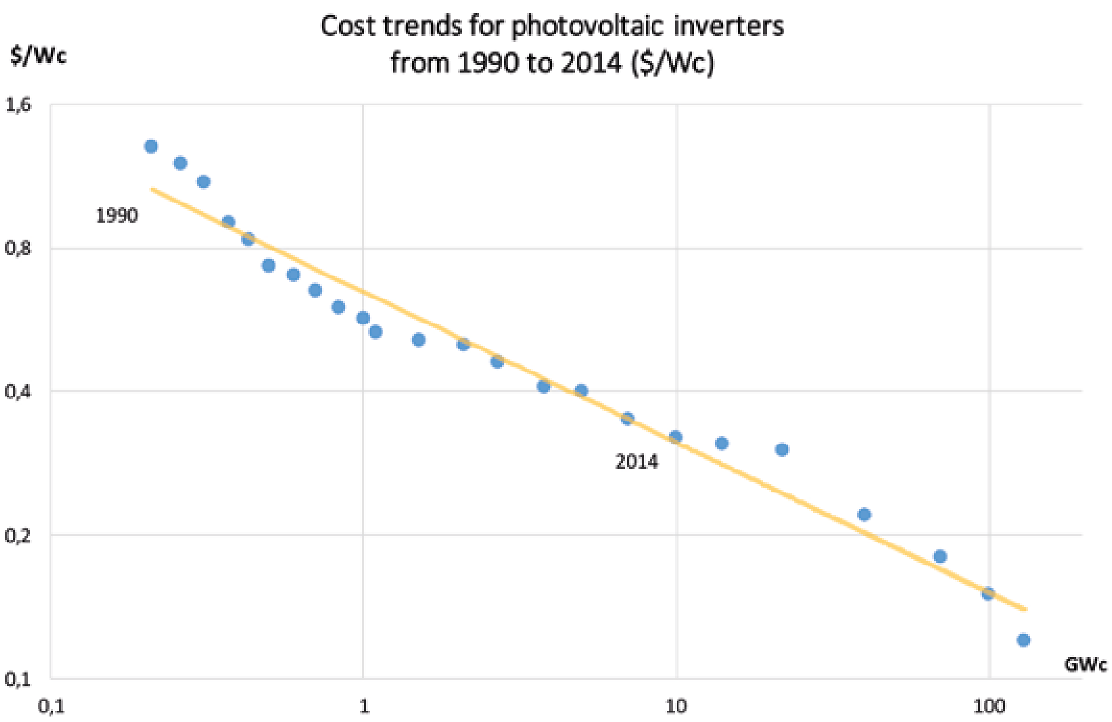
An inverter is not used merely to convert direct current to alternating current. It can also include control and interface equipment to improve the performance of photovoltaic installations. The latest developments allow inverters to contribute to stabilization of the power on the grid, and produce reactive power[23].

Inverters are also experiencing cost trends similar to those for photovoltaic modules according to market size.

Here again, the technical fundamentals of the inverter industry, namely power electronics products, explain the cost trends as a function of the increase in market size. Not the amplitude of the trends, but their linear relationship.

22-Haiyin Capital and IHI Corporation.

23- A device which produces work consumes so-called active power. However, just as an electron rotating in a copper coil generates a magnetic field, so the use of alternating current in our equipment can, in particular, generate magnetic fields that are associated with the device's reactive power. This is an important parameter for the stability and overall optimization of a power grid.



▸ **FIGURE 19 :** COST TRENDS FOR PHOTOVOLTAIC INVERTERS. DATA: FRAUNHOFER INSTITUTE, MIT. ILLUSTRATION: FONDATION NICOLAS HULOT.

Inverter improvements

The main future developments are a generalized voltage increase from 1000 to 1500 V allowing a reduction of approximately 10% in capital costs related to the inverter. Another development expected over the next 5 to 10 years is an increase in inverters' service life from 10 to 15 years. Further productivity improvements, especially regarding the design to help improve inverter maintainability (since this equipment is one of the main maintenance points) will make it possible to continue to bring down inverter costs.

A new device has appeared in the residential market: micro-inverters. Their advantage lies in their direct incorporation in photovoltaic modules, thereby eliminating installation costs. Sunpower, in particular, has developed a module for the residential sector allowing a "plug-and-play" mode for easier installation. However, some stakeholders are still skeptical regarding the economic and technical viability of these micro-inverters.

Another factor which does not necessarily result in a reduction in the capital cost of inverters but which makes the overall economic equation more competitive is the incorporation of new systems at the inverter level: better monitoring and better communication for an improvement in the photovoltaic power plant's performance, and inclusion of a service to help with network stabilization.

2.2.4 Other costs, "Balance of System"

The "Balance of System" comprises all the other cost components of a photovoltaic module = electrical cables, the structure on which the module rests, the land, labor for installation, the transformer and miscellaneous engineering costs and administrative expenses (including taxes).

For the "Balance of System", it is not so much the "production" of the various items (very labor-intensive) which will play a role in pursuing competitiveness, as the standardization of installation processes, effects of scale and … improved professionalism. The developers themselves recognize the fact that the photovoltaic industry, especially its installation component, is still young and needs to improve in order to optimize its industrial processes.

One example concerns setting up of the metallic structures bearing the photovoltaic panels. Technologies have been developed allowing the use of metallic piles drilled directly in the ground, without a concrete structure, using machines that automatically adjust the position of the piles. These innovations have been able to reduce by 20% to 30% the costs of the structural part while improving the environmental impact (no concrete foundation)[24].

Reduction of installation and maintenance costs

Installation

The installation costs for ground-based power plants represent a significant proportion of the cost of a photovoltaic installation, whether it be a large ground-based installation (approx. 10%) or a small residential installation (approx. 25%).

24- Neoen has implemented this technology at its Cestas location in southwest France.

Automation of tasks such as precise positioning of the structures' metallic piles by machines will be extended only marginally to other parts of the installation phase. This phase will always remain labor-intensive. On the other hand, improving professionalism and increasing the skills and efficiency of installers is still a major lever for improving competitiveness.

Regarding this we note major differences not only due to differences in labor costs, but especially due to differences in levels of professionalization. Whereas in France installation costs are about US$0.9/Wp[25] for a total cost of US$4/Wp (for a roof-integrated residential installation), in Germany costs are about US$0.2/Wp (for on-roof installation), for a total cost of approx. US$2/Wp, while the United States is closer to France than to Germany in terms of costs[26]. The 2015 study by the MIT on the future of solar power also mentions this clearly: these cost differences are because of due to differences of efficiency and professionalism. In France there are already stakeholders which stand out and will act as a driving force[27].

Professionalization will provide both cost reductions and an improvement in the quality of installations. This is a normal tendency for an industry that is still young.

Maintenance

Maintenance is also a source of improvement in competitiveness at the levels of both cost and impact on the service life of an installation. One of the components requiring the most maintenance in a photovoltaic installation is the inverter. Recent improvements at the level of inverter design will be able to optimize maintenance costs and hence the lifetime and overall performance of the installation.

25- ADEME data

26-(MIT, 2015) CITATION MIT15 \l 1036

27- One stakeholder reported costs of US$2.1/Wp for a 9 kWp building-integrated installation with a significant reduction in installation costs. The same stakeholder mentioned that switching from a building-integrated system to an on-roof system would make it possible to save up to 30% on installation costs.

Impact of improvements in the efficiency of photovoltaic modules on the costs of the "Balance of System" part

In addition to its impact on the unit cost of modules, an improvement in the efficiency of photovoltaic modules has an impact on the cost components of the "Balance of System" part. This is because an efficiency improvement decreases the size of the installation for an identical capacity, and therefore:

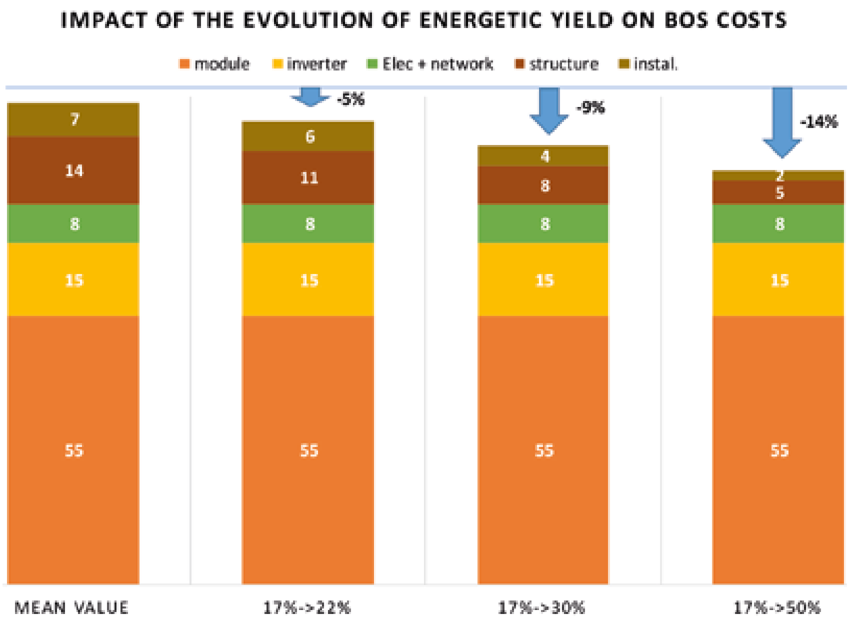
- the size of the structure per Wp, and the length of installation time and hence its cost;
- the land and civil works;
- cabling, as emphasized in the Fraunhofer Institute's study published in February 2015[28] (there is a counter-effect due to the increase in power per cable, which entails rather an increase in the unit cost of each cable, but the overall economic equation results in savings).

These gains are non-negligible. For example, increasing energy efficiency from 15% to 20% reduces surface area needs by about 25% and hence structure needs (and costs) by 25%.

More precisely, as an illustration, if we consider that the costs per watt remain fixed for the modules and for the inverter and electrical parts (which is a good basic approximation), the efficiency effect alone will, in the short term, reduce the costs of photovoltaic power by about 5% as shown in *Figure 20.*

28- One stakeholder reported costs of US$2.1/Wp for a 9 kWp building-integrated installation with a significant reduction in installation costs. The same stakeholder mentioned that switching from a building-integrated system to an on-roof system would make it possible to save up to 30% on installation costs.

▸ **FIGURE 20 :** IMPACT OF AN IMPROVEMENT IN EFFICIENCY ON BOS COSTS (THE OTHER COSTS ARE CONSIDERED CONSTANT). CALCULATIONS: FONDATION NICOLAS HULOT.



2.3 Photovoltaic power cost prospects which will make it a very competitive energy

2.3.1 An expected halving of capital costs

Allowing for the various aspects of improvement in the competitiveness of photovoltaic systems, we can draw up a roadmap for trends in the cost of photovoltaic power on the 2050 horizon. It is important to remember that every roadmap is hard to anticipate. Past experience with photovoltaic power shows us this. However, this makes it possible to realign the positioning of this technology in the global electricity and energy landscape.

Over the next 10 years, based on data analysis and expert opinions, we can indeed envisage a 20% to 40% reduction in the cost of a ground-based photovoltaic installation and a residential photovoltaic installation. Longer-term, the market trend is to a halving of capital costs.

The cost scenarios of the FNH were determined using the data collected and through assessment of these various given by the experts consulted. Each time, a high and low scenario are established (in terms of cost). They reflect (i) for the current and coming years, the cost delta existing at present from one installation to another and from one country to another due to differences in the technical skills of installers, administrative costs, etc.; and (ii) for the 2030-2050 horizon the inherent uncertainty regarding these future costs.

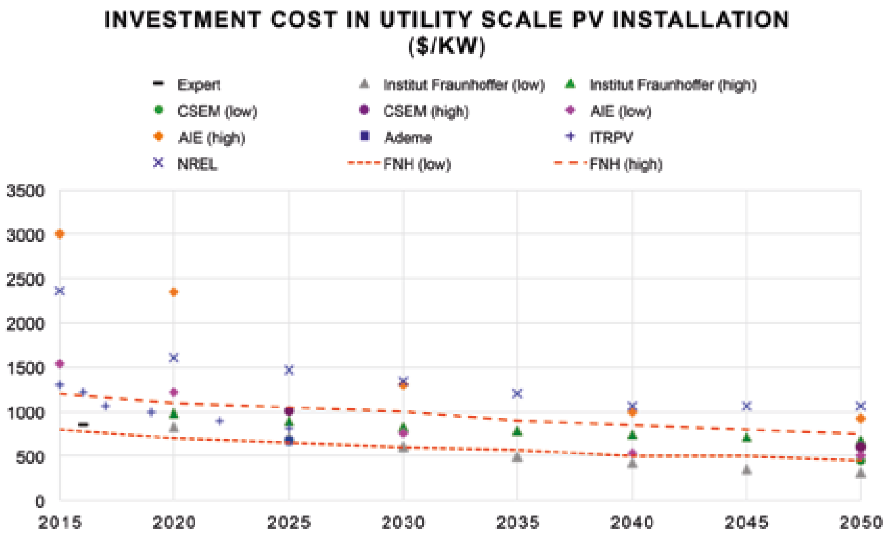


FIGURE 21 : PROSPECTIVE TRENDS FOR THE INSTALLATION COST OF GROUND-BASED PHOTOVOLTAIC POWER PLANTS. ILLUSTRATION: FONDATION NICOLAS HULOT.

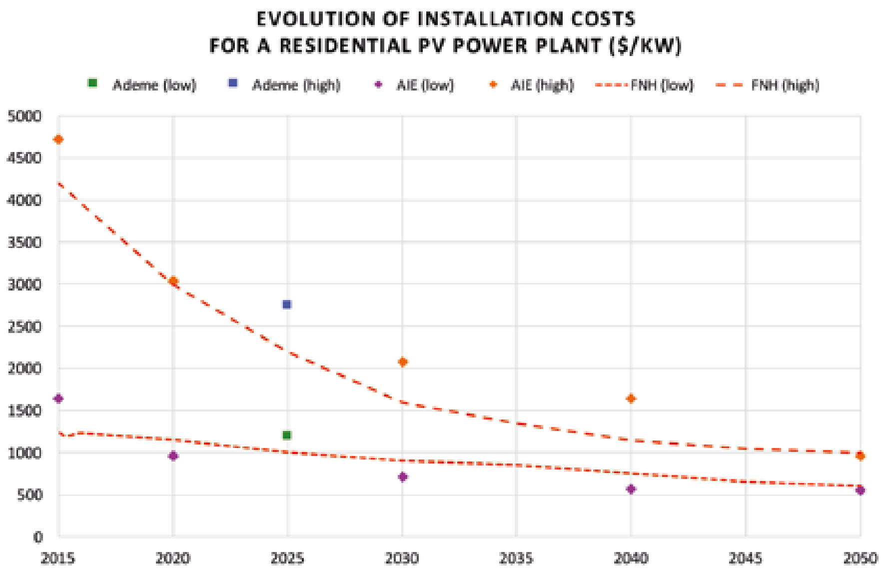


FIGURE 22 : PROSPECTIVE TRENDS FOR THE INSTALLATION COST OF RESIDENTIAL PHOTOVOLTAIC SYSTEMS. ILLUSTRATION: FONDATION NICOLAS HULOT.

ANALYSIS: THE TRENDS FOR THE INSTALLATION COSTS OF RESIDENTIAL PHOTOVOLTAIC POWER PLANTS REVEAL A SIGNIFICANT REDUCTION IN THE DIFFERENCE BETWEEN MINIMUM AND MAXIMUM COSTS. THIS REFLECTS THE CHANGE IN THE MATURITY DIFFERENTIAL OF THIS SECTOR ON THE GLOBAL LEVEL. IN 2015, WHILE GERMANY HAS COSTS AT THE LOW END OF THE RANGE DUE TO A MATURE, STRUCTURED AND COMPETITIVE SECTOR FOR INSTALLATION OF RESIDENTIAL PHOTOVOLTAIC POWER PLANTS, THE UNITED STATES IS STILL AT THE HIGH END OF THE RANGE DUE TO A FRAGMENTED MARKET, WHICH HAS NOT YET IMPLEMENTED THE CONTINUOUS IMPROVEMENT APPROACH THAT THE SECTOR UNDERWENT IN GERMANY. THIS IS AN ASPECT EMPHASIZED PARTICULARLY IN THE MIT'S 2015 REPORT ON THE FUTURE OF SOLAR ENERGY.

2.3.2 Trend for the LCOE up to 2050

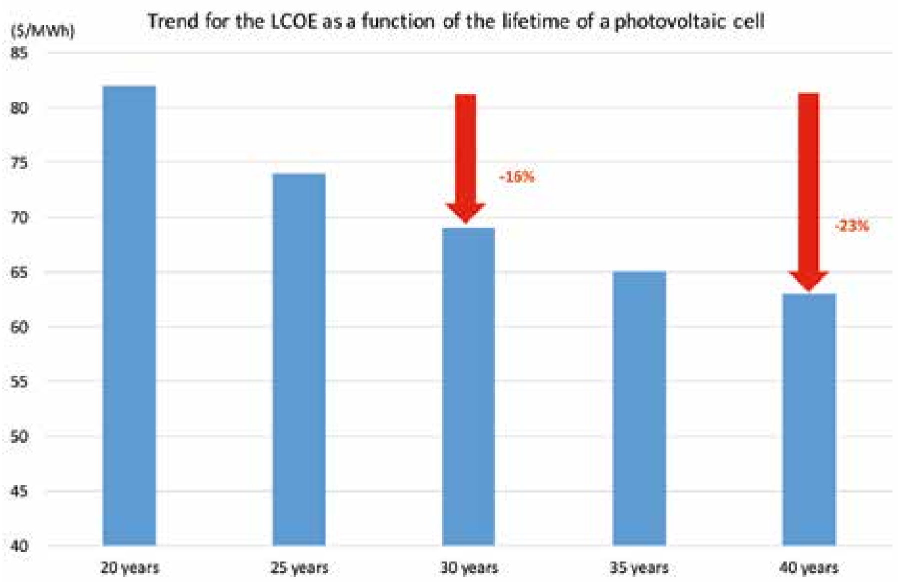
As we saw in sub-section 2.1.3, the LCOE of photovoltaic power corresponds to the levelized cost of this energy over the entire life of the equipment which produced it. It is therefore impacted significantly by the lifetime of the cells.

At present, cells are considered to have a lifetime of 25 years. This means in fact that at the end of this period, the cell will still produce 80% of its initial capacity. This lifetime is modelled on the manufacturers' warranties, which are themselves imposed by insurers and bankers. The latter have adopted this lifetime because they have sufficient historical data to validate it. In the context of buyback tariffs or 20-year PPAs, the definition of the business model sometimes even involves considering a lifetime equal to that of the installation, i.e. 20 years.

Indeed, even if a manufacturer's tests showed that the lifetime of their cells was 30 or 40 years, for the commonly accepted guarantee, the financing period and the estimate of the life-cycle cost, the figure would remain fixed at 25 or even 20 years.

Nowadays, some producers consider that their cells will last 30-40 years. In the case of silicon cells, the panels are inert: barring a sealing defect between the glass and the cells, nothing can happen. The oldest photovoltaic power plant is at Lugano in the Applied Science and Arts University of southern Switzerland. Installed in 1982 (capacity 10 kW), it still operates: after 33 years, the capacity is still about 80%. According to some commentators, the modules used contain more material and were therefore more solid. Conversely, according to others, production processes have improved and our understanding of durability issues has increased enormously. The correct evaluation is rather this second one. Whereas the guarantees correspond to an annual decline in capacity of approximately 0.9% of maximum power per year, all the developers now recognize and use in their business model a deterioration of only 0.5% per year. The Lugano power plant, for its part, corresponds to a deterioration of 0.7% per year.

It is therefore highly likely that the effective lifetime of photovoltaic power plants will exceed 25 years and that the standard will be 30 or even 40 years. The impact on the life-cycle cost of the installation is significant, as illustrated in *Figure 23*.



▸ **FIGURE 23* :** ILLUSTRATION OF THE TREND FOR THE LCOE AS A FUNCTION OF THE LIFETIME OF A PHOTOVOLTAIC POWER PLANT. CALCULATIONS: FONDATION NICOLAS HULOT.

ANALYSIS: FOR AN IDENTICAL INITIAL CAPITAL COST AND OPERATING COSTS, ASSUMING A LIFETIME OF 20 OR 30 YEARS FOR THE PHOTOVOLTAIC MODULES, WE OBTAIN A COST DIFFERENCE OF APPROXIMATELY 16% (€82 PER MWH VERSUS €69 PER MWH). THIS DIFFERENCE, WHICH SEEMS PURELY MATHEMATICAL, IS IN FACT VERY IMPORTANT FOR EVALUATION OF THE RELATIVE COMPETITIVENESS OF VARIOUS MEANS OF ELECTRICITY PRODUCTION.

* A 10 MW power plant for which the inverters are replaced every 10 years is considered in this illustration. We assume in each case an end-of-life capacity of about 80% compared with the initial capacity. The costs correspond to those of new projects undergoing development in France.

Based on the production cost trends described in the previous section, and taking into account an extension of the service life by 25 to 30, and then 40 years, it appears that the electrical and energy universe is bound to be thoroughly reshaped by comparison with its current vision. Photovoltaic system development costs have fallen rapidly below the cost of development of conventional means of production, with a deviation by a factor of 2 and more after 2040. Despite the intermittency of photovoltaic system, such a pullback would have a significant impact on the trend for the global electricity system. We shall see, moreover, in the following section, that trends in consumption management and storage could reduce the problem of intermittency and further accentuate this development.

2.4 Needs for investment in massive production of electricity

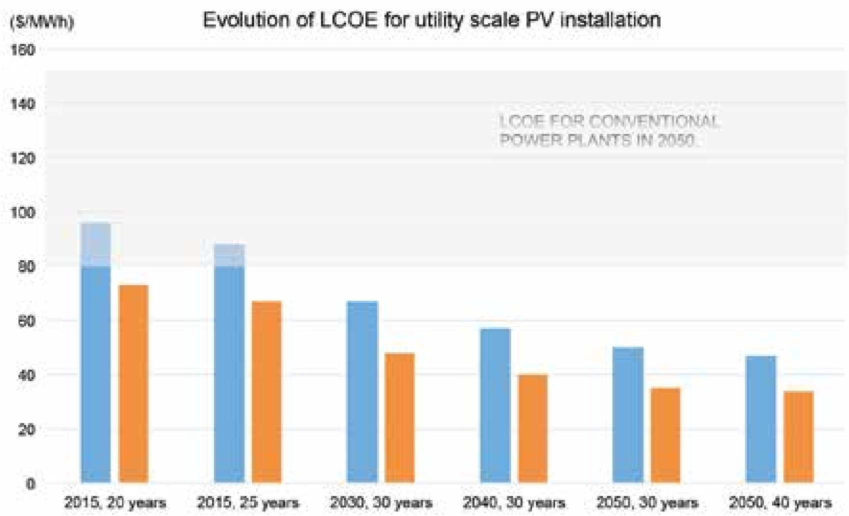
Although photovoltaic systems are already a technology competitive with conventional facilities (see sub-section 2.1.3), further improvements in its competitiveness will make it an important factor in the development of renewable energies in order to reduce greenhouse gas emissions. The question is therefore whether the necessary investments to make this energy a significant part of the electricity mix are feasible.

The first observation concerns the speed of deployment of photovoltaic systems. Never has an energy sector technology experienced such development, which is more similar to the specific development process of the electronics world, in both its speed of penetration and the pace of innovation[29]. In 15 years, the installed capacity has been multiplied by more than 100, from slightly more than 1 GWp in 2000 to 186 GWp at the end of 2014. In the last four years, this capacity has been increased more than threefold. In terms of investment, in 2014 there was a record $136 billion invested (25% more than in 2013) for a

29- In photovoltaic power, major innovations emerge and are implemented in a few years. By comparison, in the nuclear industry, the EPR began to be developed at the R&D/engineering level in the early 1990s...

FIGURE 24 : TREND IN LCOE RANGES FOR LARGE GROUND-BASED INSTALLATIONS AND SMALL (RESIDENTIAL) INSTALLATIONS. SOURCES: FONDATION NICOLAS HULOT (INSTALLATION COST SCENARIOS FIGURE 21 AND FIGURE 22 LOW LEVEL OF COSTS = ORANGE COLOR; HIGH LEVEL OF COSTS = RED BLUE COLOR), ADEME, EXPERTS, IEA, TRANSPARENT COST DATABASE, E&Y, BNEF, MIT. ILLUSTRATION: FONDATION NICOLAS HULOT.

ANALYSIS: THE FIRST GRAPH CONCERNING GROUND-BASED PV POWER PLANTS SHOWS THAT PHOTOVOLTAIC POWER IS ALREADY IN SOME CASES () COMPETITIVE WITH CONVENTIONAL FACILITIES, BUT THAT IT WILL BECOME SO SYSTEMATICALLY IN THE NEAR FUTURE. THE SECOND GRAPH SHOWS THAT THE ELECTRICITY PRODUCED BY A RESIDENTIAL INSTALLATION (WHICH CAN BE SELF-CONSUMED ON-SITE) IS ALSO IN SOME CASES COMPETITIVE WITH THE PRICE OF ELECTRICITY SUPPLIED BY THE POWER GRID (INCLUDING PRODUCTION AND TRANSPORT COSTS) BUT THAT IT WILL BECOME SO SYSTEMATICALLY IN THE NEAR FUTURE WITH A DIFFERENTIAL THAT COULD BECOME SIGNIFICANT.



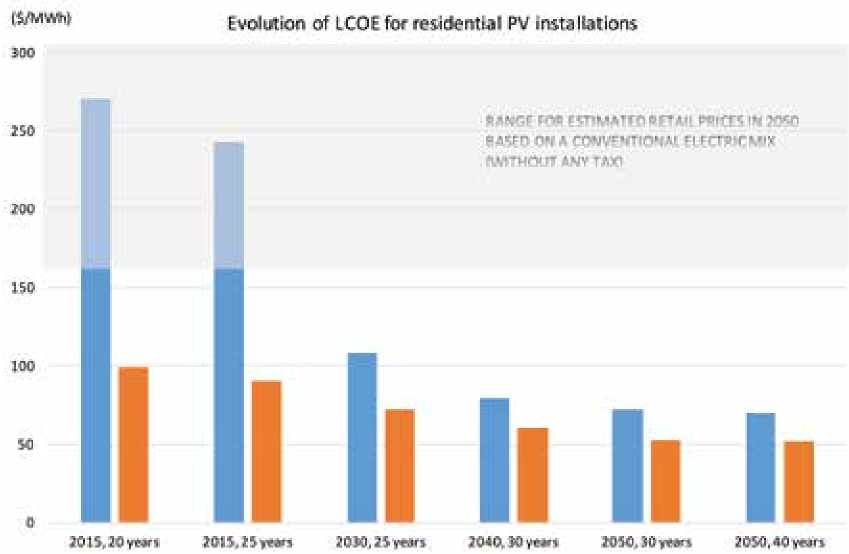
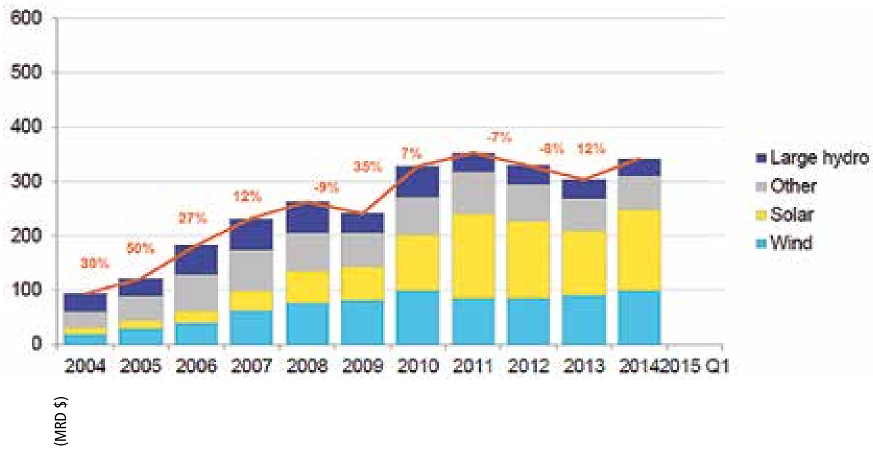


FIGURE 25 : GROWTH IN INVESTMENT IN LOW-CARBON ENERGIES, BNEF, 2015



capacity increase of about 46 GW. That represents more than half of the investments in renewable energies and about the same amount of investments in fossil-fueled electricity capacity, which have become a minority since 2007-2008 and are constantly decreasing in both absolute and relative value terms.

Figure 26 shows the growth in installed capacity for various selected scenarios.

To assess the feasibility in terms of investment, the FNH adopted two scenarios with reference to the 2014 situation.

- The first makes the assumption that an additional installed capacity of 46 GW (2014 reference) is maintained each year until 2050, while taking into account, for the investment part, the cost of renewal of capacity to be replaced[30].
- The second makes the assumption that the investment level of 2014 ($136 billion) will be maintained each year until 2050, while taking into account capacity renewal to deduce the net installed capacity[31].

We note that the installed capacity forecasts based on the two scenarios determined by the FNH (see *Figure 27*) are all at the high end of the forecast ranges (see *Figure 26*). Now, these two scenarios are generally conservative.

- The identical installed capacity scenario implies that investments in photovoltaic power are divided by a factor of 3 to 6 on the 2050 horizon (see *Figure 28*).
- The identical investment scenario amounts to stopping the increase in investments in photovoltaic power despite the major increase in its competitiveness by comparison with conventional energies. This therefore implies a higher level of investment in less competitive electricity production facilities.

A capacity range of 6 to 8 TW in 2050, which could meet 20% to 25% of global electricity demand in 2050[32], therefore seems possible based on the competitiveness data for photovoltaic systems and the required investment level.

This figure is based on pure economic analysis. It does not take into account constraints on the power grids, and intermittency constraints which might or might not limit these growth prospects.

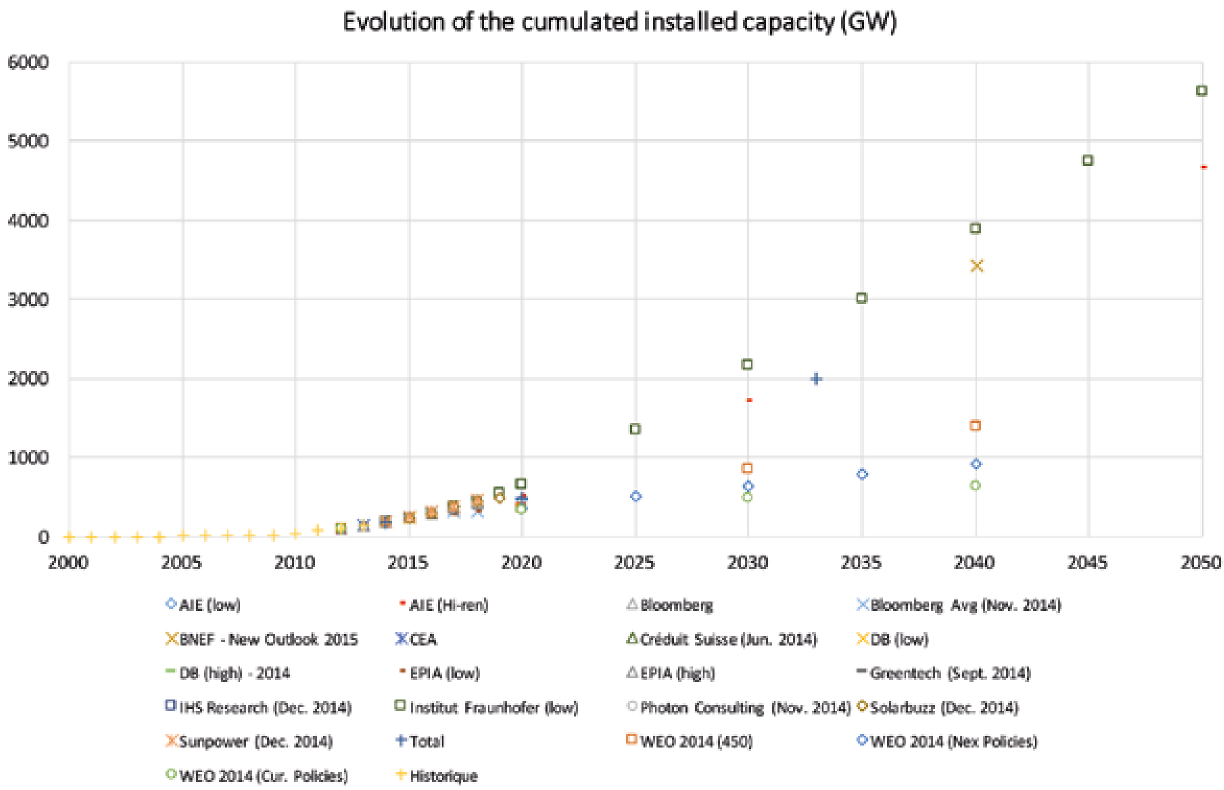
30-For the capacity to be replaced, an average lifetime of 30 years was assumed for the installations over the period.

31- Over the period 2015-2018, the average installed capacity forecasts were adopted so as not to diverge too far from the short-term forecasts.

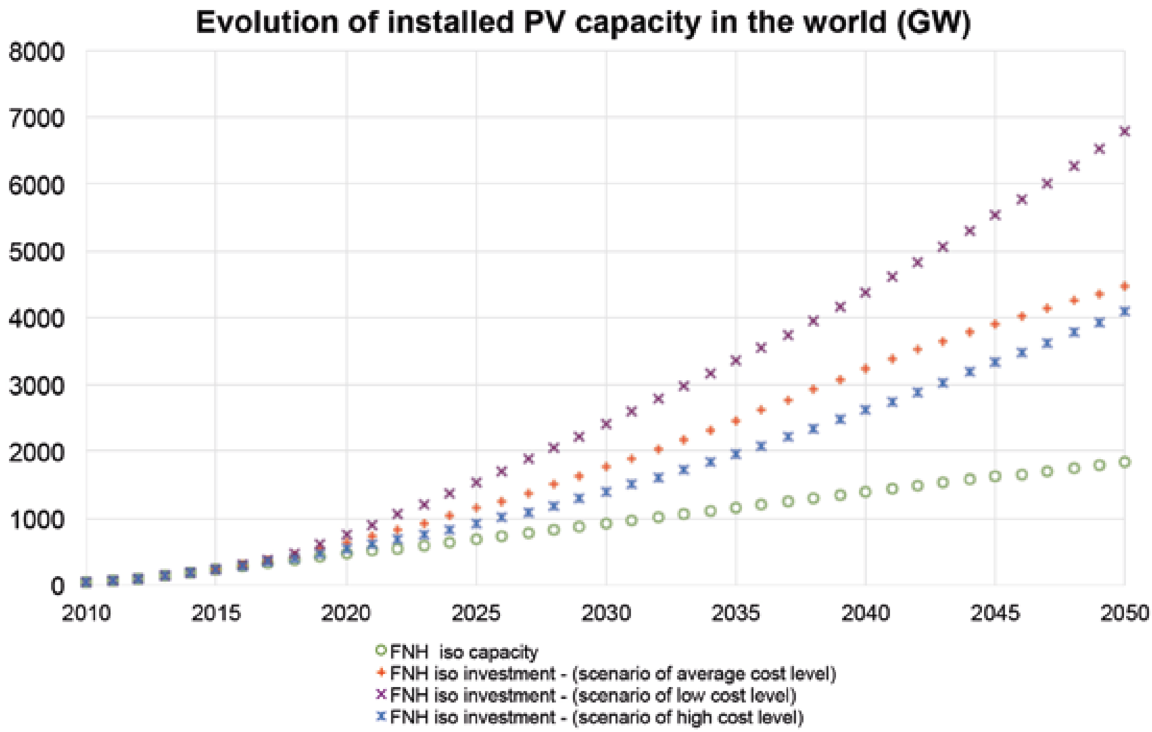
32-6000 to 8000 GWp represents a production of approximately 8 to 10 PWh (assuming an average insolation equivalent to 1350 kWh per kWp) out of a total electricity consumption range of 33 to 40 PWh in 2050 (scenarios of the WEO 2014).

FIGURE 26 : PROSPECTIVE TRENDS FOR INSTALLED PHOTOVOLTAIC CAPACITY ACCORDING TO VARIOUS SOURCES. ILLUSTRATION: FONDATION NICOLAS HULOT.

ANALYSIS: THE VARIOUS SOURCES GIVE A FAIRLY BROAD RANGE OF PROSPECTS FOR INSTALLED PHOTOVOLTAIC CAPACITY IN 2050. THE RANGE IS FROM ABOUT 1000 GW TO NEARLY 6000 GW. THE LOW SCENARIOS ARE OFTEN DUE TO PESSIMISTIC SCENARIOS REGARDING THE COMPETITIVENESS OF PHOTOVOLTAIC POWER (REFLECTING THE IEA'S CAUTION ON THIS SUBJECT IN THE WEO 2014) IN CONTRAST WITH THE HIGH SCENARIOS (SUCH AS THAT OF THE FRAUNHOFER INSTITUTE OR THE IEA IN ITS "HI-REN" SCENARIO OF STRONG DEVELOPMENT OF RENEWABLE ENERGIES).

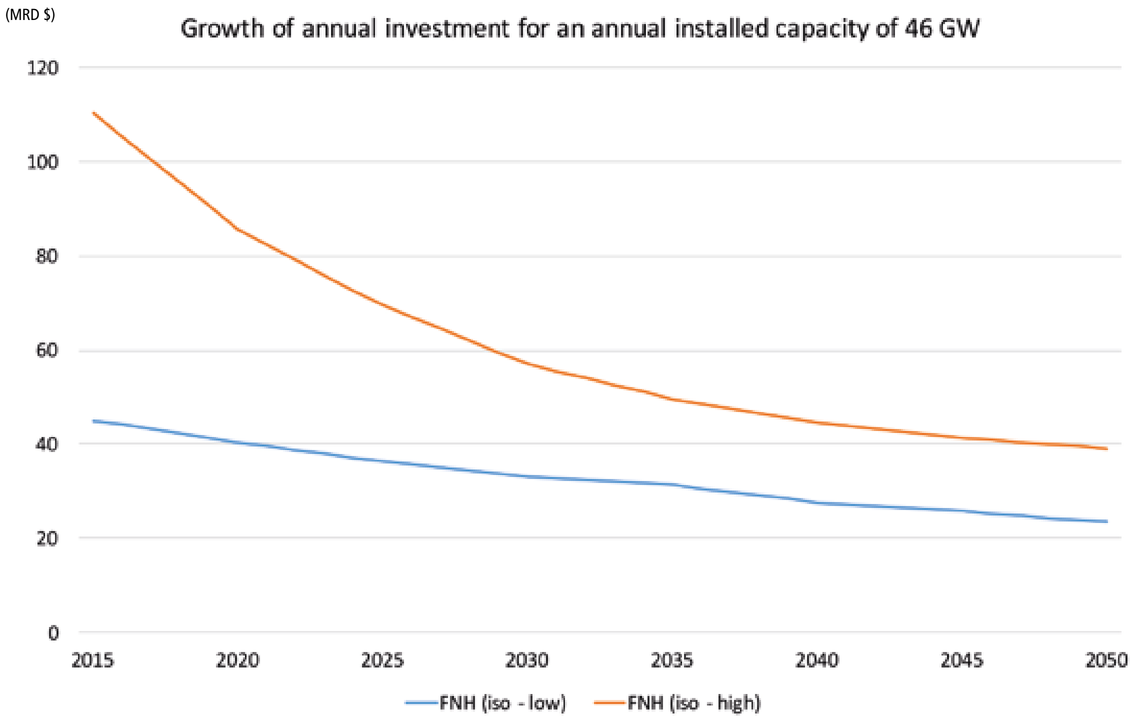


▸ **FIGURE 27** : PHOTOVOLTAIC POWER DEVELOPMENT SCENARIOS: (I) CONSTANT ADDITIONAL ANNUAL CAPACITY, (II) CONSTANT ANNUAL INVESTMENT. CALCULATIONS: FONDATION NICOLAS HULOT.



▸ **FIGURE 28** : GROWTH IN ANNUAL INVESTMENT FOR A CONSTANT ADDITIONAL ANNUAL CAPACITY EQUAL TO THAT OF 2014. CALCULATIONS: FONDATION NICOLAS HULOT.

ASSUMPTIONS: GRAPH PRODUCED ON THE BASIS OF THE CAPACITY UNIT COST RANGE FOR GROUND-BASED AND RESIDENTIAL INSTALLATIONS (SEE FIGURE 21 AND FIGURE 22) ASSUMING A 60%/40% BREAKDOWN OF THESE TWO MAJOR CATEGORIES OF INSTALLATION IN TERMS OF INSTALLED CAPACITY.



THE ISSUE OF FINANCING

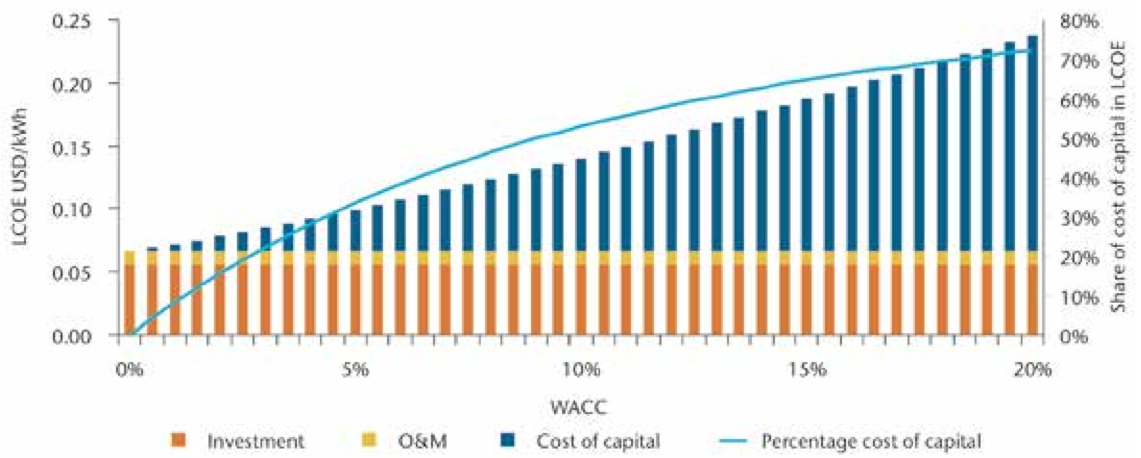
Photovoltaic installations are highly capital-intensive means of production (variable costs are practically zero), so the cost of financing the initial investment can have a very significant impact on the levelized cost of the installation. The following example shows that a reduction in the cost of financing from 5% to 2% can bring the LCOE down by 15%.

Interest rate (%)	5%	4%	3%	2%
LCOE (USD/MWh)	95	90	86	82
Evolution of the LCOE compared with an interest rate of 5%	-	-5%	-10%	-14%

Any measure capable of reducing the cost of capital therefore contributes to the competitiveness of photovoltaic power. The report by Grandjean & Canfin, “Mobiliser les financements pour le climat” (Mobilizing financing for the climate) (2015), shows that there are a large number of tools to encourage investment in green technologies and make them competitive.

▸ FIGURE 29 : CHANGES IN THE LCOE ACCORDING TO THE COST OF CAPITAL, "TECHNOLOGY ROADMAP - SOLAR PHOTOVOLTAIC ENERGY", IEA, 2014

ANALYSIS: THE HIGHER THE REQUIRED INTEREST RATE OR RATE OF RETURN (WACC), THE MORE THE COST OF CAPITAL (IN BLUE) INCREASES TO BECOME THE MAJOR COST ABOVE A WACC OF 10%. REDUCING THE WACC BY COMPETITIVE FINANCING ARRANGEMENTS, BUT ALSO BY MORE REASONABLE INVESTOR REQUIREMENTS, THEREFORE HAS A SIGNIFICANT IMPACT ON THE LCOE OF PHOTOVOLTAIC POWER.



Notes: This example is based on output of 1 360 kWh/kW/y, investment costs of USD 1 500/W, annual operations and maintenance (O&M) of 1% of investment, project lifetime of 20 years, and residual value of 0.

THE LOAD FACTOR… THE SERIOUS DEFECT OF PHOTOVOLTAIC POWER?

One important factor for characterizing the operation of an installation is what is called the load factor, which is the relation between the quantity of electricity actually produced by a production installation and the quantity of electricity that it would have produced if it had operated constantly at its maximum capacity.

For example, a 100 MW installation operating for a whole year (8760 h) at full capacity would produce 876 GWh. If, during that year, it produced “only” 600 GWh, it will be said that it has a load factor of 600/876 = 68%.

For means of production can be managed such as thermal power facilities (nuclear power stations, power plants operating on coal, gas, biomass or biogas), the load factor is the result of technical and economic optimization. A gas-fired power station and a combined cycle gas-fired plant could operate for only a few hundred hours per year and have a load factor of less than 10%, but that would cost more than for a fuel-oil-fired plant operating for the same number of hours. On the other hand, a fuel-oil-fired plant with a load factor of 90% would have a very high cost, far more than that of a gas-fired power station. Even nuclear power, which is constrained in its operating ranges, can see its load factor vary as a result of different types of use. Given the over-abundance of nuclear power in France, it must be adapted during the year, and this results in a load factor of approximately 75%, in contrast with the US nuclear fleet which can operate almost continuously at full capacity and thus achieves a load factor of approximately 90%.

For intermittent renewable energies, the load factor does not reflect a particular use but an intrinsic operating constraint: a wind turbine needs wind to produce electricity, a photovoltaic panel cannot produce electricity at night, etc. The load factor of wind turbines and photovoltaic power systems therefore depends on the quantity of wind or sunlight hours available. Typically, a good wind site combined with current wind-power technologies makes it possible to have a load factor of approximately 20% to 25% on land (it can exceed 30% offshore). For photovoltaic systems, the load factor can range from 10% to 20% (for the best sites in terms of sunlight hours). For run-of-river hydropower, the load factors range from 30% to more than 60%.

The low load factor of wind turbines and photovoltaic systems is often regarded as a drawback: a large MW capacity must be installed to obtain a few MWh. For example, to achieve the production of a 900 MW nuclear reactor, 5000 to 7000 MW of photovoltaic capacity must be installed, i.e. 4 to 8 times more!

However, such arguments are of little interest, because what counts in the end is the cost of producing electricity. With regard to the space constraint, which is often mentioned, let us take comparisons. Each year, we artificialize 100,000 ha of land in France. Artificialized land is land that has been concreted, coated, which no longer breathes, can no longer produce, which dies. This is not the case for the land on which photovoltaic panels are “planted”. Instead of artificializing 100,000 ha with concrete (roads, vacant office buildings – the Paris region has millions of square meters of such office space – etc.), if photovoltaic farms were placed there, each year approximately 100 GW of photovoltaic power capacity would be installed, representing 15% to 20% of the nation’s electricity consumption.

So, no, the load factor of photovoltaic systems is not a serious defect. It is an intrinsic characteristic which impacts in particular its cost, which is the only important factor for differentiating means of production (when, of course, it takes into account the negative externalities of each means of production).

2.5 Supply constraints and the EROI issue

Although the conclusions of the previous section are very encouraging regarding the growth prospects for photovoltaic systems, it should not be forgotten that building a photovoltaic power plant requires raw materials. What are they and what are the limits of supply (because, like all resources, they are present on our planet in a limited quantity)? Moreover, we must consider the energy needed for the production of a photovoltaic power plant. This is the EROI issue (the Energy Return On Investment).

Supply constraints

The deployment of a technology does not depend solely on its technical performance but also on the limits to the supply of the required raw materials.

All photovoltaic technologies require glass to protect the cells, plastic, steel and aluminum for the structures, concrete for the foundations and copper for electrical connections. The other elements necessary for manufacturing the cells according to the various technologies are shown in *Figure 3*.

In its 2015 study on solar energy, the MIT studied the issue of the supply of raw materials to sustain more or less substantial growth on the 2050 horizon[33].

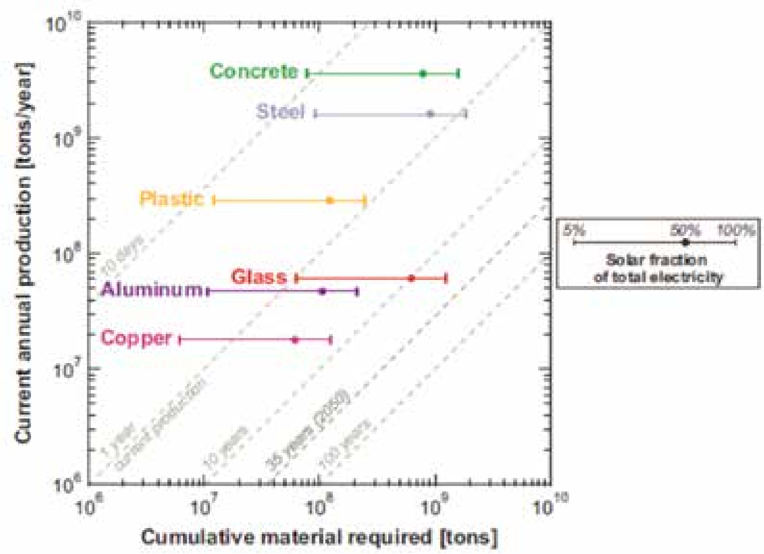
33- (MIT, 2015) CITATION MIT15 \l 1036

Given the abundance of the various elements used in photovoltaic technologies at the level of the earth's crust, the MIT identifies no theoretical constraint on deployment on the TW scale (1000 GW) in 2050. This makes the 6 to 8 TW forecast range of installed capacity in 2050 completely realistic from the perspective of supply constraints. The constraints are related rather to the availability of skilled labor and good production sites (and hence their economic feasibility).

For the materials common to the various technologies, the MIT's analysis based on quantities currently used shows that there are no particular constraints.

The data in *Figure 30* show that the cumulative needs on the 2050 horizon represent only a few years of current production in the worst case scenario for materials for which accessibility is not a problem. For example, to install 6000 to 8000 GW by around 2050, i.e. 20% to 25% of the world's electricity consumption on that horizon, the total quantity of aluminum needed corresponds to one year of current production. For the materials in greatest demand, such as glass, these results show simply that photovoltaic power could become a structural aspect of the production factors for these materials. Moreover, manufacturers are working to reduce the thickness of the glass[34] or to replace it with thinner and lighter polymers. These developments will be a factor improving the availability of materials in addition to competitiveness.

34- (MIT, 2015) CITATION MIT15 \l 1036, http://www.ceramicindustry.com/articles/94220-cutting-costs-in-photovoltaics-glass-manufacturing : whereas current technologies use glasses at least 3mm thick, the sector is tending toward 2mm glass, giving a 30% consumption gain, and polymer-base substrates.



▸ **FIGURE 30 :** MATERIALS CONSUMPTION OF PHOTOVOLTAIC INSTALLATIONS MEASURED IN YEARS OF CURRENT PRODUCTION DEPENDING ON THE PROPORTION OF PHOTOVOLTAIC POWER IN GLOBAL ELECTRICITY CONSUMPTION IN 2050 (33,000 TWH IN THE MIT STUDY), "THE FUTURE OF SOLAR ENERGY", MIT, 2015

ANALYSIS: TO ACHIEVE A PRODUCTION REPRESENTING 5% OF GLOBAL ELECTRICITY CONSUMPTION IN 2050, ONE YEAR OF CURRENT GLASS PRODUCTION IS NEEDED (IN RED ON THE GRAPH). TO ACHIEVE 50% (THE SMALL CIRCLE ON THE RED LINE) TEN YEARS OF CURRENT PRODUCTION ARE NEEDED.

For materials which are specific to a technology, the economic and industrial situation may be different.

Let us first consider silicon. This is the second most abundant element in the earth's crust. It is present in various forms of silica, and homogeneously. There is no physical or economic constraint[35]. Moreover, the MIT data are based on quantities used at present. However, given the prospect of halving the use of silicon, or even dividing it by four, (see sub-section 2.2.2), the quantity needed to supply 25% of global electricity demand in 2050 could be reduced to a few years of current production, or less.

As emphasized in the MIT report for silver, another important element in crystalline silicon cells, if the predictions by the ITRPV[36] that silver requirements could be reduced by a factor of 3-4[37] materialize, then only two or three years of current silver production would be needed to manufacture photovoltaic cells whose average electricity production would account for 25% of total consumption in 2050.

For the CdTe and CIGS thin film technologies and for GaAs technologies, on the other hand, in each case there is a limiting element requiring several hundred years of production: tellurium (Te), gallium (Ga), indium (In) and selenium (Se). Three difficulties can be seen: the question of the competitiveness of new fields to increase production capacity, the availability of labor, but above all the fact that these components are co-products of silver, copper and other metals. To increase the production of these co-products, production of the main products must be increased. Now, the economics of a mine requires exploitation of its various products. If the main products cannot be exploited, the mine will not be economically viable unless there is a very significant increase in the price of the co-products it wants to exploit. This is a difficulty which seems hard to resolve. Very with a reduction by a factor of 3 or 4 in the quantities required by peak watt compared with current data, the needs would still correspond to several hundred years of current production.

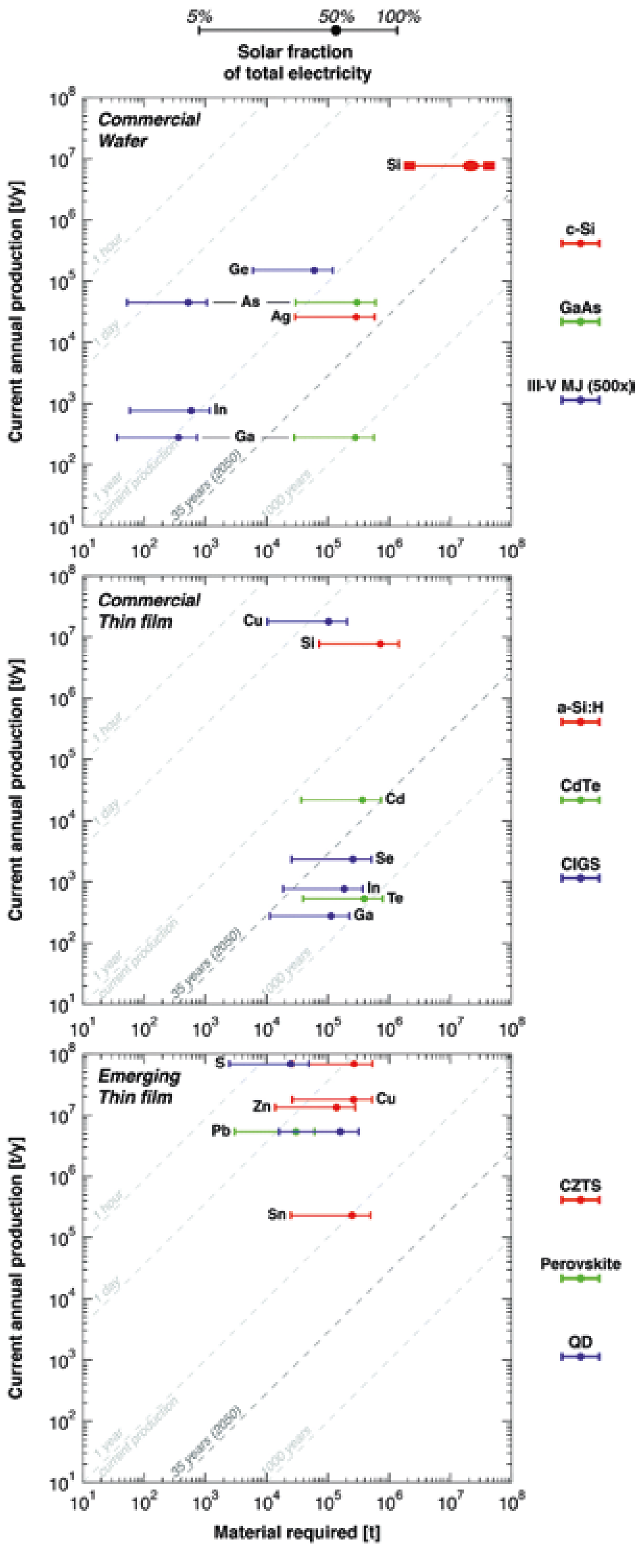
35- (USGS, Mineral Commodities - summaries 2015, 2015) CITATION USG15 \l 1036

36- (International Technology Roadmap for Photovoltaic, 2015)CITATION Int15 \l 1036

37- Such a reduction factor is not impossible. Already, the French company S'Tile has announced that its i-cell which is about to enter the demonstration phase will halve the quantity of silver per peak watt.

▸ FIGURE 31 : MATERIAL NEEDS OF VARIOUS PHOTOVOLTAIC TECHNOLOGIES DEPENDING ON THE PROPORTION OF PHOTOVOLTAIC POWER IN GLOBAL CONSUMPTION IN 2050, "THE FUTURE OF SOLAR ENERGY", MIT, 2015

ANALYSIS: THE THREE GRAPHS SHOW THE MAIN GROUPS OF TECHNOLOGIES: COMMERCIAL TECHNOLOGIES BASED ON WAFERS, COMMERCIAL THIN FILM TECHNOLOGIES AND EMERGING THIN FILM TECHNOLOGIES. ON THE RIGHT OF THE GRAPHS ARE SHOWN THE ACRONYMS OF VARIOUS TECHNOLOGIES: "C-SI" FOR CRYSTALLINE SILICON, "CDTE" FOR THE CADMIUM/TELLURIUM THIN FILM TECHNOLOGY, ETC. IN EACH GRAPH ARE INDICATED, FOR EACH TECHNOLOGY AND WITH THE SAME COLOR, THE COMPONENT MATERIALS OF THOSE TECHNOLOGIES. FOR "C-SI", THE QUANTITY OF SILICON (SI) AND THE QUANTITY OF SILVER (AG) ARE INDICATED.



This does not necessarily doom these technologies, but it will restrict their expansion, because no radical change in the mining supply of these materials is in sight at present.

The third category of cell, which is rapidly expanding in laboratories (quantum dots, cells based on perovskites in particular) has no problem of supply. This is because at present all new photovoltaic technology developments take into account the issue of materials supply (but not necessarily toxicity, especially with the lead used in perovskite-based cells).

So, looking at the universe of material constraints, the technologies using silicon have no prohibitive constraints. Even the MIT sees none in its study for photovoltaics accounting tor 100% of global electricity consumption in 2050[38].

The EROI (Energy Return On Investment)

How much energy is needed to produce 1 liter of gasoline, 1 kWh of electricity or 1 cu.m of town gas? This is the question that the EROI concept attempts to answer.

38- The MIT does not say that this is feasible at the level of the electricity system, but simply that this growth hypothesis is not subject to a physical constraint regarding the necessary raw materials.

Intuitively, it is easy to understand that if more energy were needed to build a photovoltaic power plant than the energy that the power plant would generate throughout its service life, there would not be much point in developing such a technology. Some experts consider that the energy provided by an energy solution must be at least five times greater than the energy required to implement the solution.

Without examining in detail the validity of this figure, it seems fairly clear that the ratio between the energy supplied by an energy solution and the energy spent to implement that solution must be greater than 1. In the excellent book by Deberi, Deléage and Hémery, *A History of Energy*[39], the authors explain that humanity developed through the acquisition of efficient converters "saving human energy" for other tasks and thus making it possible to obtain access to more resources. For example, the construction of sailing boats made it possible to transport merchandise with only 2-3 people when previously about ten additional rowers were needed. The (mostly human) energy spent to build the sailing boat made it possible to save far more human labor, because

39- (Jean-Claude Debeir - Jean-Paul Déléage - Daniel Hémery, 2013)CITATION Jea13 \l 1036

HOW IS THE EROI CALCULATED?

To calculate the EROI, it is first essential to take into account the energy used to extract oil, gas, coal and uranium from the ground. Next, it is essential to take into account the energy needed for the manufacture of machines capable of converting oil into gasoline, and coal, gas and uranium into electricity, or for capturing the wind and sun and converting them into electricity. But should we also take into account the means of transport, oil and gas pipelines and other networks? Should we also consider the energy supplied to the humans who maintain the installations, the grids, and the roads to travel? As you can see, the scope involved is a complex issue. It is hard to determine when to end allowance for the energy used to produce energy, since the latter is the basis of our activities! This issue of the scope of responsibility also makes it possible to relativize the ratio of 5 considered by some authors as a good EROI.

In most calculations, the scope of the EROI ends with consumption of the energy needed to build an energy production installation or to build and operate an oil or gas extraction installation. In the study by Hall and Prieto on the EROI of photovoltaic power, on the other hand, the area examined is broader. It even claims to be complete by including all the players involved in the construction of a photovoltaic power plant and hence all the related energy expenditures: energy expenses for construction, energy expenses to support the financial stakeholders allowing financing of a photovoltaic installation, energy expenses to support administrative stakeholders working "for" a photovoltaic installation (these stakeholders work on regulation, control, taxes, etc.). Each cost (in cash) is converted into this type of energy expense analysis. For example, the banker needed to work out the financing for photovoltaic installations must be able to be housed and fed, and to travel to work for the financing of photovoltaic systems. This is reflected by a cost in terms of wages, but it also generates an energy expense. There is therefore a relation between the level of expenses (in cash) and the quantity of energy consumed.

While the enlargement of the scope is interesting, it would be necessary to extend it to calculation of the EROI for all energies, in order to have comparable data.

the rowers could devote themselves to other tasks that were not conceivable before the advent of the sailing boat. It also permitted population growth by providing access to a vaster area for procuring food for an identical human investment. The EROI of the sailing boat was far greater than 1. But although an energy surplus was generated by using the wind, this surplus had to be sustainable over time, because the former rowers were now doing new activities, which were not indispensable in society prior to the sailing boat but which constituted the very essence of modern society's existence.

This image makes it possible to understand, apart from climate issues, the need to ensure that a solution that is implemented can always generate a sufficient energy surplus to maintain and even continue to develop humanity.

Two specialists on EROI issues, Messrs Hall and Prieto, have studied the EROI of photovoltaic systems in Spain for installations built between 2009 and 2011. In their very detailed study, they find an EROI of 2.41: so one unit of energy would be needed to create 2.41 units with photovoltaic systems, giving a surplus of 1.41. Therefore if, effectively, a surplus of 4 was needed to enable a civilization to continue to develop, photovoltaics would not be a viable solution in this respect.

On the other hand, French environment and energy management agency ADEME found an EROI of approximately 10 to 30[40], but without taking into account the energy expenditures allowed for by Hall and Prieto, i.e. energy expenditures over and above the mere manufacture of the photovoltaic installation (see box page 34).

Two of the most important factors in a photovoltaic installation are the capital cost in €/W and the cost of maintenance. Over the period 2009-2011, Hall and Prieto estimated the capital cost at about €5.5m/MW and operating and maintenance costs at €1.7m over 25 years. These euros correspond to energy investment. In light of the preceding investment analysis and the data from experts on the operating and maintenance aspects, 1 MW of photovoltaic power now costs about €1m and maintenance over 25 years costs generally €20K to €30K per MW per year, or between €0.5m and €0.75m over 25 years. Keeping the scope and the data of Hall and Prieto, if we take the current energy cost involved in the construction of a photovoltaic installation and that involved in its operation (although not taking into account potential savings on the other cost factors), the EROI increases from 2.41 to about 7-8. Taking into account future improvements in the competitiveness of photovoltaic systems, the extension of the panels' service life from 25 to 30 and then 40 years in 2050, we obtain the following pattern:

- Costs in 2030 according to the scenario of this report and a service life of 30 years: 10-11.
- Costs in 2050 according to the scenario of this report and a service life of 30 years: 17-18.
- Costs in 2050 according to the scenario of this report and a service life of 40 years: 23-24.

The EROI of oil decreases year after year. In contrast, photovoltaic power already exceeds the criterion of an EROI greater than 5. The latter will still improve[41] substantially over the coming years, unlike for conventional electricity production techniques.

These quick calculations call for a deeper study of the present and future data to refine the previous figures. But that will not change the identified trend. Moreover, it would be interesting to do this for other fossil energies, including carbon capture and storage, and nuclear power. Their increasing LCOEs and the likewise increasing gap with photovoltaics suggests that their EROI will be less favorable and that therefore, for humanity, this will be an energy source or converter that is less efficient than photovoltaics.

THE RELENTLESS DECLINE IN THE EROI FOR OIL

(here we consider the EROI related exclusively to the investment in the extraction installation and not accessory energy expenditures).

Until the 1930s, the EROI for oil in the United States (the main oil producer) was 100. In the 1970s, the EROI for global production was between 25 and 40. It fell to 10-30 in 2005. At present, oil sands have an EROI ranging between <1 and about 8. These figures, which do not take into account the accessory expenditures related to oil (energy costs related to financing management, energy costs related to the pollution generated, the energy used by all the stakeholders directly or indirectly involved in the project, etc.), as in the study by Hall and Prieto, therefore overestimate the actual energy surplus generated by new oil fields.

This gradual decline can be explained by the depletion of "easily exploitable" fields. The new fields require more investment, more energy to extract oil which is located at greater depths, or is trapped in rocks from which it is hard to extract it. Over time, the situation can only get worse. This is one of the problems of the oil planet. It is not so much the lack of oil that poses a problem, as the decline in the energy surplus derived from it (apart from its main problem which is CO2 emissions).

40- (Ademe, Produire de l'électricité grâce à l'énergie solaire ('Producing electricity using solar energy'), 2015) CITATION Ade15 \l 1036

41- The carbon content of photovoltaic electricity (currently between 30 and 80 grams of CO2 per kWh according to Ademe) will therefore also inevitably improve in the coming years. For sake of comparison, installations operating on fossil energies emit between 300 and 1000 grams of CO2 per kWh, nuclear power and wind power around 10 grams and hydropower about 10 grams for installations in non-humid areas or not drowning forests (in these areas, plant rotting can cause emissions of greenhouse gases, especially methane, to climb significantly).

3. CHALLENGES FACING PV: INTERMITTENCY MANAGEMENT

The above forecasts should not cause us to overlook an important characteristic of photovoltaic power, which is a potential obstacle to its expansion: its intermittency. A photovoltaic system produces only in the daytime and more in summer than in winter. Moreover, production can be highly variable from one hour to the next as a result of rapid changes in sunlight (e.g. a passing cloud). This can cause problems of balance between supply and demand and hence at the grid management level.

To obtain a realistic view of what could happen regarding the expansion of photovoltaics, we must examine three important aspects of the electrical system:

- The grid's capacity for withstanding intermittency;
- The capacity for increasing consumption flexibility to move in step with production fluctuations;
- The prospects for the development of electricity storage.

3.1 Integration into grids

To study the issue of the integration of photovoltaics into electricity grids, this report has examined the case of France, which can be extended to a mature grid in a fairly large country, and hence to most developed countries.

Integration of photovoltaics from the electricity transmission grid viewpoint

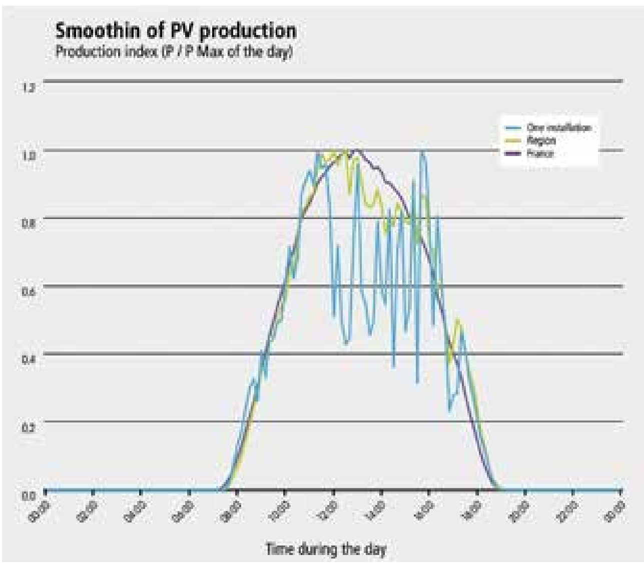
Intraday intermittency

One of the main problems of photovoltaics is its short-term intermittency. Its production can vary sharply from one hour to the next. However, this characteristic is very significantly reduced (or even cancelled out) by the transmission grid smoothing effect[42], as stressed by the RTE[43]. The national production has practically a bell shape (see *Figure 32*), similar to the (theoretical) shape of the production which would result from continuous insolation. Only the amplitude varies from one day to the next.

With regard to the transport network and on a sufficiently large level, and hence with regard to the issue of the balance between supply and demand, there is no problem of intraday intermittency.

On the other hand, a photovoltaic system produces, in theory, whatever happens (except at night). Its production has a potential impact on electrical system management when considering the power deviations relative to the daily average. This gives a measure of the levels of variability needed to maintain the balance of supply and demand (or net demand[44] for photovoltaic production).

This need for flexibility of the electrical system depends intuitively, with regard to consumption, on the differential between maximum consumption and minimum consumption. As shown by the example of a summer day of consumption in France (this is true for most countries), peak consumption is in the middle of the day, i.e. at the same time as the peak in photovoltaic production (see *Figure 33-a*). The peak in net demand will therefore tend to decrease with the penetration of photovoltaic systems, thus reducing the flexibility requirement. On the other hand, at a certain level of penetration of photovoltaic systems, a consumption trough will be generated, potentially resulting in an increase in the flexibility requirement, as illustrated by *Figure 33-c* taken from the PEPS report[45] and corresponding to a typical weekend day.



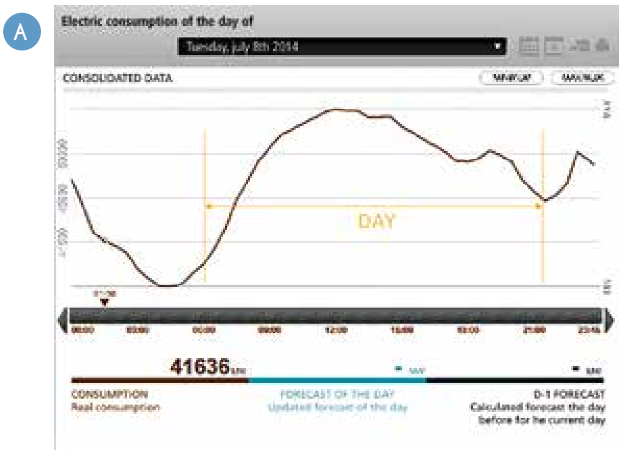
▸ **FIGURE 32 :** SMOOTHING EFFECT ON THE PRODUCTION CURVE OF ALL PHOTOVOLTAIC INSTALLATIONS THANKS TO THE ELECTRICITY TRANSMISSION SYSTEM, RTE

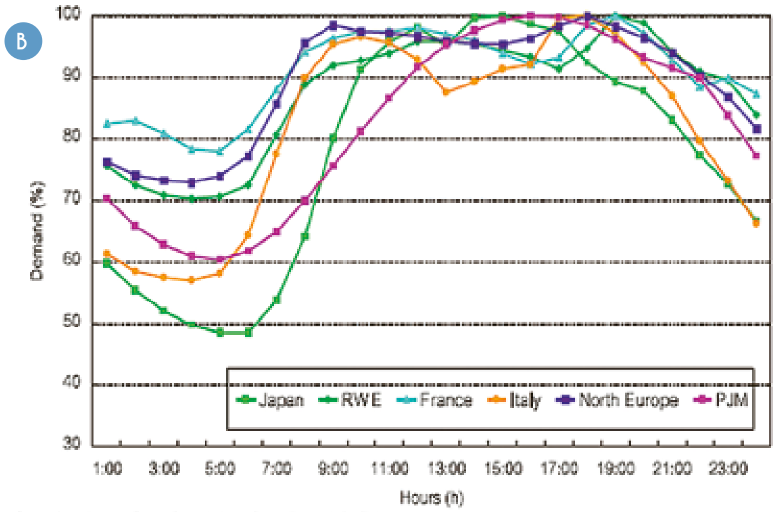
42- The photovoltaic production seen by the transmission grid is the sum of the production of the connected photovoltaic installations. The smoothing effect is due to the fact that the production of the installations varies on the whole independently of one another: a fall in photovoltaic production at one location in France will be offset by an increase in another location. Short-term variations are therefore smoothed out in this way.

43- (RTE, 2014) CITATION RTE14 \l 1036

44- The net electricity demand is the result of the overall demand from which is subtracted the so-called "fatal" production, i.e. the production which occurs whatever happens (as is the case for photovoltaic solar power).

45- (Ademe - DGCIS - ATEE, 2013) CITATION Ade13 \l 1036





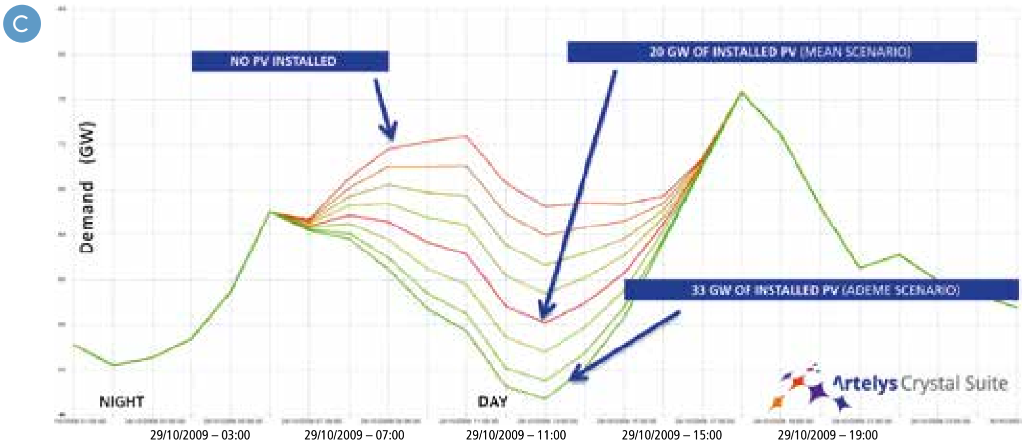


FIGURE 33 :

A CURVE OF ELECTRICITY DEMAND IN FRANCE

B LOAD CURVE FOR VARIOUS REGIONS IN THE WORLD; SOURCE: IEC*

C CHANGE IN THE CURVE OF NET DEMAND FOR PHOTOVOLTAIC PRODUCTION ACCORDING TO THE RATE OF PENETRATION FOR PHOTOVOLTAICS. SOURCES: RTE AND ADEME

* (International Electrotechnical Commission, 2011)CITATION Int11 \l 1036

Intuitively, it is understandable that the daily flexibility requirement is not necessarily increased by photovoltaics. The simulations performed within the framework of the PEPS report show that, in France, the daily flexibility requirement with 20-25 GW of photovoltaic power is equivalent to that without photovoltaic power (see *Figure 34*). We can basically indicate that a level of penetration equivalent to 20-25% of the power demand at peak consumption (about 100 GW in the case of France, for example), i.e. 5% to 8% of consumption (which is about 450 TWh in all), does not increase the flexibility requirement by comparison with a situation without photovoltaics. There is therefore in theory no constraint up to these levels of penetration on the French grid and on any mature grid[46]. According to the RTE experts and the studies they have performed internally, the daily flexibility requirement for capacity is not impacted more than at present for the rates of penetration mentioned above.

46- The above analysis is valid for a trouble-free reference situation and therefore implies a mature grid ensuring security of electricity supply.

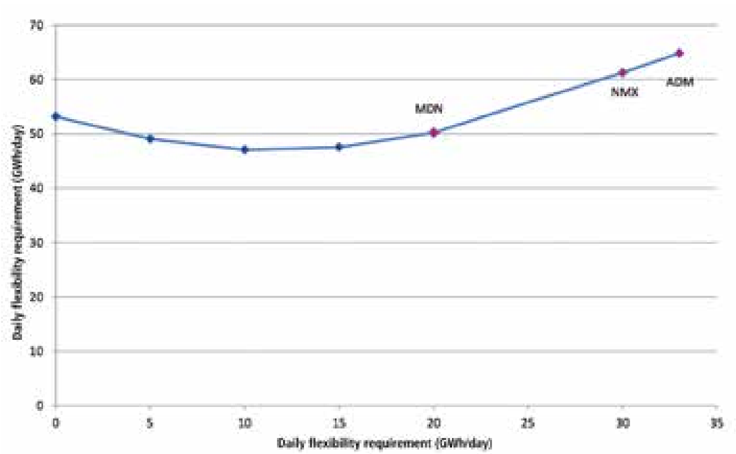
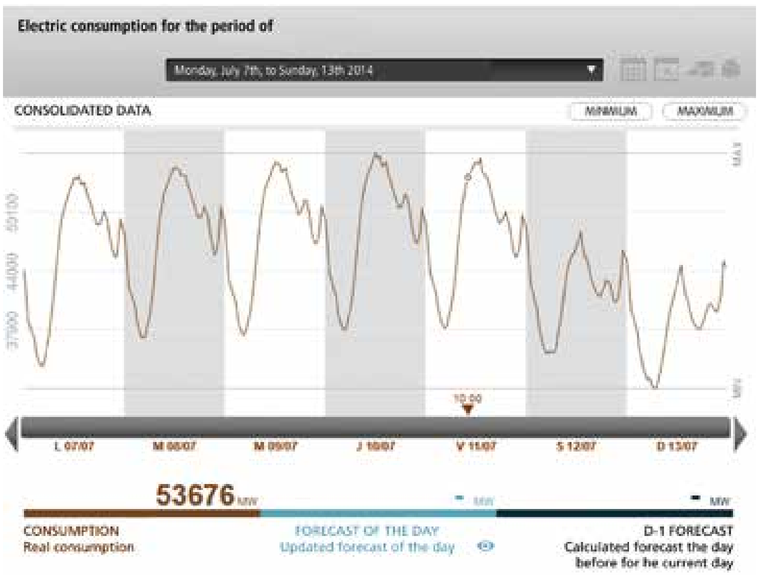


FIGURE 34 : DAILY FLEXIBILITY REQUIREMENT ACCORDING TO INSTALLED SOLAR CAPACITY. SOURCE: ADEME*

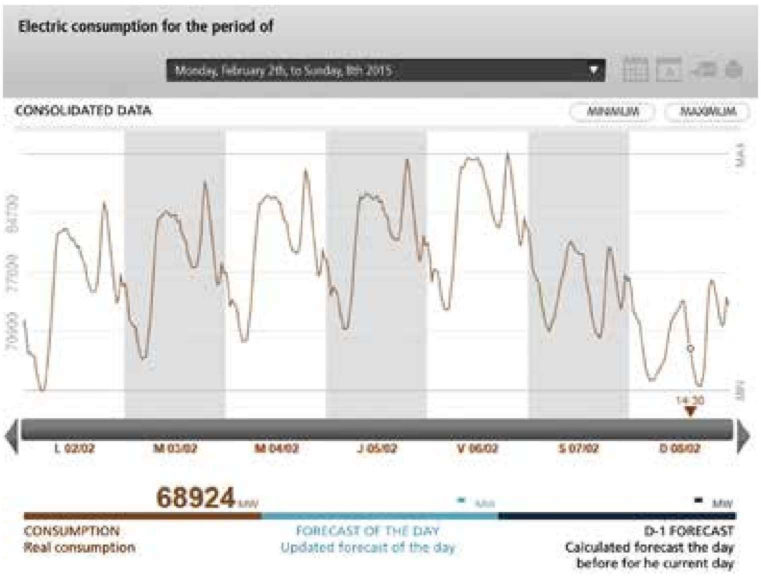
* (Ademe - DGCIS - ATEE, 2013) CITATION Ade13 \l 1036

▸ **FIGURE 35 :** VARIATION IN ELECTRICITY DEMAND OVER ONE WEEK AT THE RTE-FRANCE LEVEL IN SUMMER (A) AND IN WINTER (B) SOURCE RTE

A



B



Weekly fluctuations

The second factor of intermittency of photovoltaic systems is fluctuations from one day to the next or weekly fluctuations. There can be major variations from the maximum level of the photovoltaic production bell shown in *Figure 32*. This can therefore create management problems at the level of the electrical system. At present this variability exists at the consumption level, as shown by the example of a week in July 2014 and a week in February 2015 (see *Figure 35*).

In two days, the difference in power demand between the minimum power and maximum power can be from 20 to 30 GW with a variation in the average power of approximately 15 GW. The electrical system must therefore withstand an across-the-board increase in power demand. The same phenomenon can occur with photovoltaic systems, for other reasons, considering net demand. The latter can change from one day to the next due to a variation in the total photovoltaic production following changes in sunlight hours at the national level. These variations are not necessarily at the same times. On the other hand, photovoltaics cannot accentuate the preceding phenomenon significantly so long as it stays within penetration levels of approximately 20% to 25% of the maximum power demand. If this were the case, it would have to significantly increase the consumption peak and reduce the consumption trough. Now, it is at peak time that the photovoltaic system can produce, whereas at the time of the trough, it never produces. There is therefore in theory basically no significant impact of photovoltaics on the weekly flexibility requirement, at least so long as the installed photovoltaic capacity remains within proportions similar to standard consumption flexibilities.

This "dimensional" analysis is consistent with the studies performed internally by RTE for France. According to RTE's experts, the expansion of photovoltaic systems has no significant impact on the weekly flexibility requirement.

Seasonal intermittency

The last factor of variability is seasonal intermittency. This factor applies to the regions furthest north. For the "sunbelt" regions[47], insolation is far more regular throughout the year. Irradiance[48] can vary by a factor of 1 to 6 as in Germany, or a factor of 1 to 1.5 as in Mali [49]. This fact makes it possible to understand that the proportion of photovoltaics is not equivalent in all regions of the territory, and that in any case an electricity mix will always be necessary. The special feature of northern regions is that they have winters that are windier and with fewer sunlight hours, and summers that are less windy but with more sunlight hours. The complementary use of solar power and wind power is therefore appropriate to compensate for the disadvantage of photovoltaic power over the full year.

This overall analysis shows that current transmission systems are able to absorb 20-25% of photovoltaic power, i.e. 5% to 8% of the total consumption of an electricity system. As a reminder, at present photovoltaic power represents only slightly more than 1% of French consumption. There is therefore no particular problem at the level of national management of the electricity system, a fact that is corroborated by RTE. In Germany, on the other hand, photovoltaic power already accounts for 7% of consumption: its impact on the grid is starting to become perceptible. However, these difficulties are not necessarily insurmountable. On 20 March 2015, a partial eclipse of the sun affected Germany at around 10 o'clock in the morning. Photovoltaic production fell by 5 GW in 75 min. and then increased by 14 GW in 75 min., the equivalent of the start-up in 75 min. of 15 nuclear reactors of 900 MW capacity, without the grid collapsing or going outside its standard operating specifications. Here, the important factor for electricity system management is the variation in power over a short period and not the quantity of energy involved. Admittedly, PSPS's and thermal power stations[50] were able to compensate for this production shortfall, but, more importantly, this test showed the feasibility of maintaining the balance of a power grid despite very significant variations in the power of one of the system's means of production[51].

As mentioned by a recent EDF study[52], a system with significant intermittency may require far greater variations in conventional thermal facilities in addition to the system's storage facilities to provide major variations in production. However, the above example shows the possibility of managing significant variations through anticipation and smart consumption management.

Inclusion of photovoltaic power with regard to the distribution system

With regard to distribution systems, photovoltaics behaves differently. It expands less, and also the low-voltage power lines which will to the end consumer may be affected by an injection of electricity coming from small installations, whereas their management was initially planned only for draw-off.

The main problems are: congestion problems, with the need to strengthen the grid, and problems in keeping the voltage within margins defined by a voltage map[53]. These problems are not caused by all installations.

Congestion problems

For large-capacity installations, there is in theory no particular problem[54], because they are connected to the medium- or higher-voltage grid by dedicated infrastructure, like run-of-river hydropower plants in the past. There is therefore no grid impact.

For low -and medium- voltage installations, the situation is different. The first problem is related to the distribution of production capacity relative to electricity demand and grid density. On dense urban networks, whether for residential or service sector zones, the photovoltaic capacity could reach 100% of the consumption peak for the area[55]. On networks that are less dense, congestion constraints would limit to 20-30% of capacity the rate of penetration without strengthening the grid. At present, various examples show that small- and medium-capacity photovoltaic systems are expanding in zones of low density and often with a capacity far greater than local consumption peaks, which creates an extra cost. The typical example is an isolated farm installing 100 or 250 kW of photovoltaic capacity on a shed, i.e. the equivalent of the power for several dozen houses[56].

It is therefore necessary to deploy photovoltaic systems intelligently in relation to the consumption locations, to avoid having capacity constraints on the distribution system. The constraint of production density matching consumption density must therefore be verified, which is not necessarily the case where there are no incentives.

Compliance with the voltage map

Regarding the voltage map, the problem is mostly related to low-voltage lines. Even in the event of a good local match between photovoltaic production and consumption, there will always be current increases on lines devoted mainly to the supply of points of consumption. Current injection into a low-voltage network line tends to increase the voltage. Conversely, when current is drawn off, this tends to lower the voltage. For good resistance of the distribution system, the voltage must always remain within a reference range. In a configuration without photovoltaics, it is understandable that the voltage map will tend to maintain the voltage near the top of the range to cope with consumption peaks. If, in this system, one incorporates photovoltaics which will inject electricity

47- The "sunbelt" comprises the countries located between the two tropics which enjoy the best insolation on earth by comparison with the countries in the northern regions.

48- Irradiance is a measure of the power of solar radiation on the ground per unit area. This quantity is expressed in W/m^2.

49- (Anne Labouret and Michel Villoz, 2012)CITATION Ann12 \l 1036

50- Note that at that time of day (between 10.00 am and 11.15 am) and for a day without an eclipse, in the absence of photovoltaic solar power in the German energy mix, production would have been ensured by thermal power stations, because this corresponds to a consumption peak.

51- http://www.techniques-ingenieur.fr/actualite/technologies-de-l-energie-thematique_89428/eclipse-solaire-l-allemagne-passe-avec-succes-le-stress-test-de-sa-transition-energetique-article_293344/

52- (EDF - R&D Division, 2015)CITATION EDF15 \l 1036

53- The voltage map defines lower and upper bounds that the voltage in a distribution system must not exceed in order to maintain a standard quality of the electricity supplied to consumers connected to the grid.

54- (ERDF, 2013) CITATION ERD13 \l 1036

55-(CIRED - A. Minaud - C. Gaudin - L. Karsenti, 2013) CITATION CIR13 \l

56- Although, for photovoltaics, the maximum production capacities are added to one another, this is not the case for consumption, where time difference effects mean that the total power is far less than the sum of the individual power ratings. In France, there are about 30 million homes with a maximum electrical capacity of approximately 6 kVA, but the consumption peak is at most around 100 GW and not more than 180 GW (180 GW = approx. 30 million x 6 kVA).

with potentially large and rapid power fluctuations, this will tend to generate voltage peaks which could cause the voltage to go beyond its reference range, causing a local collapse in the network. This problem can be settled by changing the voltage map (which must be done in an organized manner), but above all by local regulation of the voltage based on appropriate management of photovoltaic installations' reactive power.

Therefore, constraints on photovoltaics exist, but they can be overcome by an improved match between production and consumption and by the implementation of new systems, the cost of which will remain marginal by comparison with the overall cost. A reactive power management system uses power electronics which costs less than an inverter. It currently represents about 10% of the cost of an installation. Combining this perspective with the capacity of the transmission grid to accept photovoltaic intermittency, 5% to 8% of electricity consumption could be produced by photovoltaic systems without excessive changes in the grid[57]. However, to go further and achieve the 20-25% levels underlying the prospects for development of photovoltaic systems from a purely economic and financial standpoint, additional measures would be needed.

Moreover, grid management in itself can improve the integration of intermittent renewable energies. According to some experts, the Danish grid manager enormously changed its grid management methods, making increased use of forecasts and with far greater involvement of the stakeholders in the very short-term management of their production. This made it possible to generate greater flexibility in grid management and hence greater reactivity to cope with rapid variations in the production of some types of power stations. In Denmark, it is of course wind power that is predominant and not photovoltaic power, but basically this changes nothing in the problem of intermittency, with regard to the power grid.

Likewise, via the services provided by their inverters, photovoltaic power plants can contribute to control of the electrical mains frequency. Apart from the additional remuneration for photovoltaic power farms (and hence an increase in their competitiveness), this can increase the grid's capacity for incorporating intermittent renewable energies. In France, Energy Pool proposes to photovoltaic power plants a participation in service systems as of 2016.

57- This does not include the connection of large-capacity installations, but as was the case for hydroelectric power stations or the Flamanville EPR, specific lines were built in each case to transport their production.

3.2 Consumption management

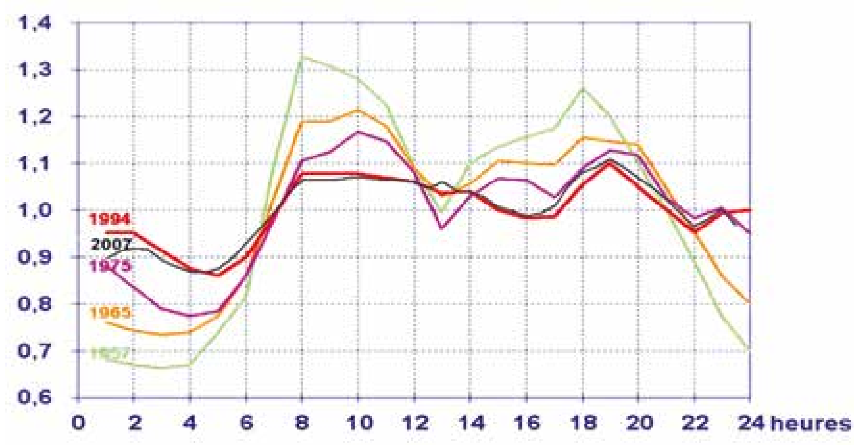
In the old electricity world, that of the grid as it has been developed since Edison's first electric power station in 1882, consumption is variable and it is production that adjusts. But, with photovoltaic power it is production which is variable. Therefore, consumption must now adapt to production.

In the paradigm of the "old world" stakeholders, this is inconceivable. Electricity is a basic commodity which must be able to be supplied securely at all times. But is electricity an end product consumed as such? In some ways, no. What is consumed are the services of electrical equipment: the possibility of telephoning, obtaining lighting by means of a lamp, having clean linen using a washing machine, having a pleasant temperature thanks to a radiator, etc. But, you don't necessarily want to phone or wash your linen at all times. Likewise, given the inertia of a housing unit (especially if it is well insulated), it is not necessary for a radiator to operate constantly. Therefore, there is clearly an intrinsic flexibility in the use of the various equipment.

A first observation: management can increase the proportion of photovoltaic electricity used by electrical equipment. The Ines organization carried out an experiment on electric cars. Without management, photovoltaic production accounted for 15-20% of the battery's electricity supply. With management – and taking into account operating constraints – the proportion of photovoltaic electricity injected into the battery increased to more than 75%. The same result could be expected on hot water cylinders now managed, in France, especially as a function of nuclear surpluses at night (resulting in low prices) or local constraints on the grid. This result is very interesting in allowing extensive development of photovoltaics. Without consumption management and with a large photovoltaic capacity, production peaks at midday could potentially exceed electricity consumption. Since it is possible to manage electricity uses and make them consume photovoltaic power for at least 75% of their needs, it is possible to consider actively absorbing these production peaks by distorting the gross consumption curve and making the consumption curve net of photovoltaic production compatible with the operation of the power grid. For refrigeration and heating uses, it is also possible to fairly easily increase the rate of penetration of photovoltaics up to 50% of the equipment's consumption.

The questions which then arise concern the technical feasibility and the proportion of electricity consumption which can be effectively managed.

In France, consumption management has existed for more than 50 years. It is implemented mainly via direct management of hot water cylinder consumption and through price structures providing incentives to consume in specific time slots. This management was and still is not very dynamic, because it aims mainly at managing the problem of electrical peaks in a fully manageable production system. While the objective is different from that for the incorporation of photovoltaics, the results are nevertheless impressive, as shown by *Figure 36*. The amplitude of power fluctuations in one day has been able to be divided by a factor of 4 in 50 years. However, this management is performed only on a specific segment of electrical uses which have increased sharply (heating, refrigerator, washing machine, electronics, etc.) and will continue to increase (electric car).



‣ **FIGURE 36 :** CHANGE IN THE DAILY PROFILE OF FRENCH ELECTRICITY CONSUMPTION FROM 1957 TO 2007 (TO COMPARE EACH YEAR, THE RATIO BETWEEN POWER DEMAND AND THE AVERAGE DAILY POWER HAS BEEN SHOWN ON THE VERTICAL AXIS). SOURCE: "RENDRE PLUS FLEXIBLES LES CONSOMMATIONS D'ÉLECTRICITÉ DANS LE RÉSIDENTIEL" ("MAKING RESIDENTIAL ELECTRICITY CONSUMPTION MORE FLEXIBLE"), THE SHIFT PROJECT 2015.

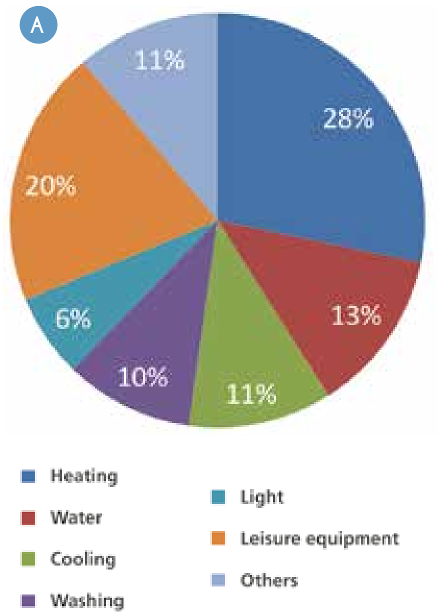
In 2015, the Shift Project think tank performed a detailed study of the flexibility potential of various residential electricity uses. For the type of uses identified, heating, domestic hot water (hot water cylinder) and domestic cooling account for over half of consumption. *Figure 37-b* shows that about 3 kW is flexible in homes, including 1.8 kW for hot water cylinders. The advantage of these power ratings is their potential for absorbing intermittent production peaks. At present, hot water cylinder management can reduce consumption peaks by 6 GW in the morning and 6 GW in the evening. With approximately 11 million electric hot water cylinders, the potential is in fact around 20 GW for a daily consumption of approximately 50 GWh. The electric hot water cylinders present in only 30% of homes would by themselves be able to meet the flexibility requirements of approximately 25 GW of photovoltaics (see above) [58]. If all homes were equipped with electric hot water cylinders, the manageable power would be tripled and the energy that could be shifted each day would be approximately 150 GWh, well above the 65 GW flexibility requirements of photovoltaics in France. The potential of this existing technology is therefore very substantial.

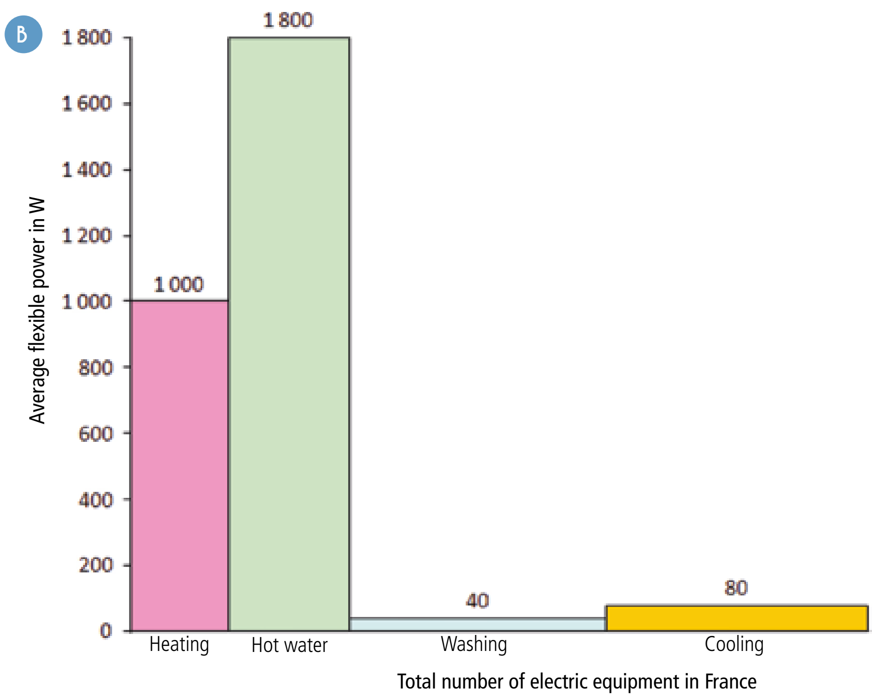
58- At present, only 80% of hot water cylinders are servo controlled, so that only 16 GW of flexibility is now operational, but there is nothing to prevent 100% servo control of hot water cylinders.

‣ **FIGURE 37 :**

Ⓐ BREAKDOWN OF ELECTRICITY CONSUMPTION IN THE RESIDENTIAL SECTOR IN FRANCE

Ⓑ AVERAGE FLEXIBLE CAPACITY IN THE RESIDENTIAL SECTOR. SOURCE: "RENDRE FLEXIBLES LES CONSOMMATIONS ÉLECTRIQUES DANS LE RÉSIDENTIEL" ("MAKING RESIDENTIAL ELECTRICITY CONSUMPTION MORE FLEXIBLE"), THE SHIFT PROJECT 2015.





This situation is not specific to France, even though France is characterized by a high rate of electrification of thermal applications. The following table shows the share of electricity in domestic hot water. There is therefore already great potential for using the above flexibilities on the global level.

The development of the electric vehicle will add even greater potential which could play a flexibility role over several days. With average travel distances of approximately 40-60 km and due to increased battery life (Tesla is already at 500 km[59]), batteries no longer have to be charged each day (see below for developments in electrochemical storage).

As more and more stakeholders are saying, all the technology for electricity consumption management exists and there is great potential. If this is not taking place at present, it is because of two reasons.

- The first is related to the fact that the rate of penetration of photovoltaics (and intermittent renewable energies in general) means this is not yet necessary.
- The second is that, at least in France, this management must emerge from its legacy of control by grid managers to shift to the level of management by private stakeholders. This also requires reviewing the tariff structures, which do not yet take into account the concept of excess intermittent renewable production.

Another reason put forward is the discomfort for consumers. The existing example of hot water cylinder management, but also the use of peak/off-peak rates or 'EJP' (peak-day load shedding)[60] tariffs with manual control by the consumer of the use of their clothes or dish washing machine, show that discomfort is a false reason.

Consumption management can be performed by shifting consumption to the appropriate time in the event of a production peak, but also by consumption shedding[61] in the event of a production trough. Voltalis, which has a diffuse load shedding technology, has performed experiments on electric heating management in Brittany in order to prevent blackouts due to the weakness of the grid and of production in this region. The results of these experiments show that (i) the diffuse load shedding solution makes it possible to control voltages on the power grid and prevent blackouts, and that (ii) consumers very readily accept rotating heating switch-offs for 20-30 min. and cumulative load shedding operations for up to about one hundred hours. Energy Pool has also developed a load shedding system at the industrial level to absorb production troughs via demand response schemes. The day of 5 April 2013 is fairly eloquent regarding current capacity and future possibilities. On that day, with two hours' prior notice, Energy Pool found 500 MW of load shedding from 24 industrial plants for a total volume of about 1.8 GWh over a maximum period of 4h. The magnitude of the decline shows that it is already possible to "manage" the electricity consumption of industry depending on the electricity system's needs. At present, Energy Pool has 1200 MW of capacity subject to load shedding with industrial consumers that can be activated within 2 hours. This capacity was placed on alert 5 times in 2015.

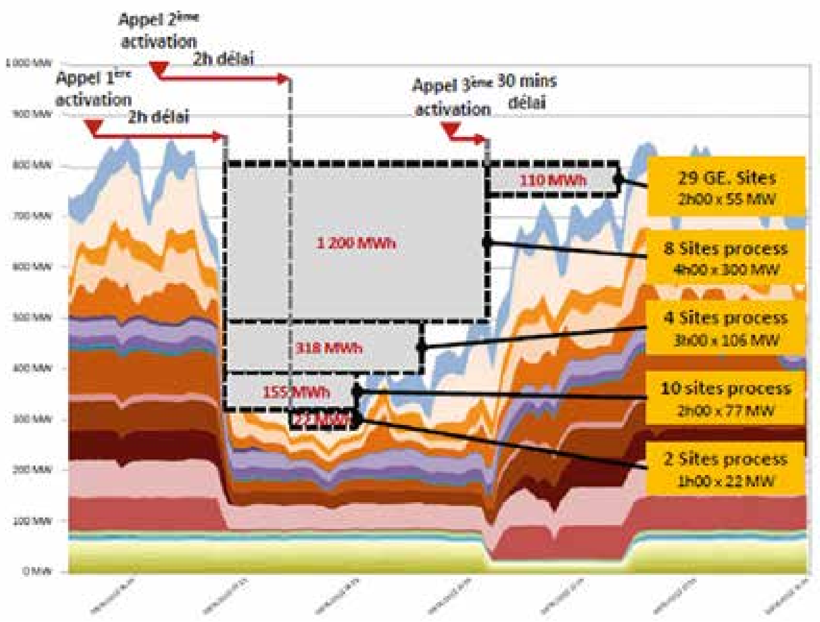
Another flexibility problem has been mentioned earlier, the problem of inter-seasonal flexibility which depends

FIGURE 38 : SHARE OF ELECTRIC DOMESTIC HOT WATER IN RESIDENTIAL ELECTRICITY CONSUMPTION IN VARIOUS COUNTRIES OF THE WORLD, "TECHNOLOGY ROADMAP - ENERGY STORAGE", IEA, 2014

2010	*Electricity use for water heating (TWh)*	*Share of residential electricity use (%)*
European Union	93	22
Germany	23	27
France	20	43
Italy	7.4	25
United Kingdom	6.1	9
Spain	5.8	11
Belgium	3.3	29
Czech Republic	2.9	31
Netherlands	2.1	13
Ireland	1.8	34
Austria	1.8	21
Sweden	1.8	20
Finland	1	19
Greece	1.3	38
United States in 2005	123	20

Source: Enerdata (2011), Odyssee, the Europe Energy Efficiency Project, (database), Grenoble, France, http://enerdata.net/enerdatauk/solutions/data-management/odyssee.php and EIA (Energy Information Administration) (2013), Annual Energy Outlook, Washington, D.C.

FIGURE 39 : LOAD SHEDDING PERFORMED BY ENERGY POOL ON MORE THAN 500 MW IN 2013.



59- http://www.teslamotors.com/fr_FR/models

60- EJP = effacement jour de pointe (peak-day load shedding). This is a special tariff with several price levels (day/night differential, and some days are very expensive to reduce consumption on those days).

61- Load shedding involves asking stakeholders (private buyers or businesses) to stop their energy consumption voluntarily or automatically. This action could be remunerated.

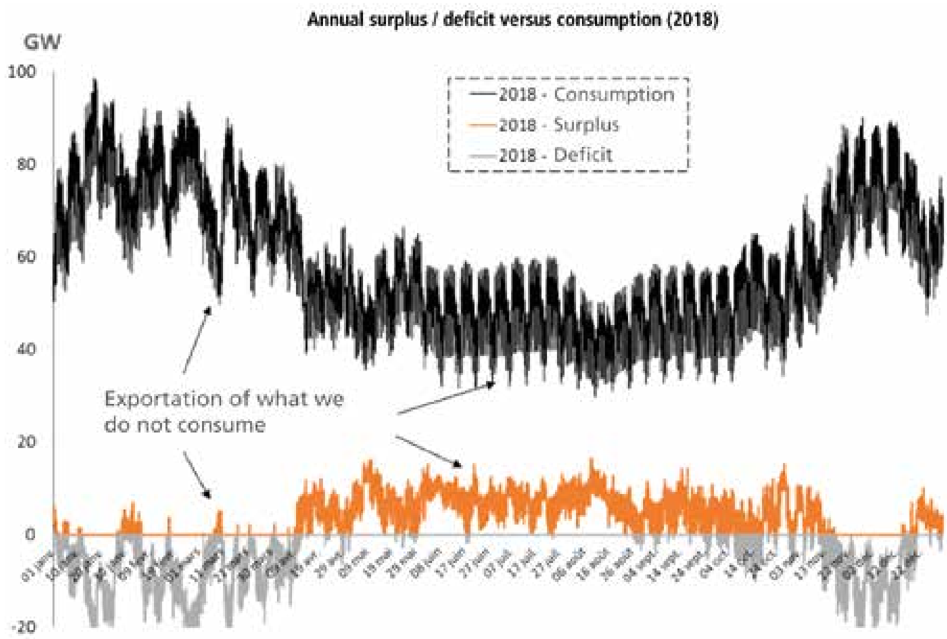


FIGURE 40 : COMPARISON OF FRANCE'S ELECTRICITY CONSUMPTION AND PRODUCTION SURPLUSES/DEFICITS IN 2018 DUE IN PARTICULAR TO THE STRONG PENETRATION OF PHOTOVOLTAIC/ WIND-POWER INTERMITTENT ENERGIES. SOURCE: "FLEXI-CONSOMMATEURS" THINK TANK.

on latitude. This problem, which is practically non-existent in some countries, is significant in northern latitudes. On the face of it, this difficulty in the development of photovoltaics is not easy to manage. While postponing the filling of a hot water cylinder until midday instead of the evening will not impact the use of hot water by the consumer, shifting consumption from winter to summer is not obvious. The only types of consumption which can be adjusted over the year are those of industries capable of storing their production.

Energy Pool has reflected with manufacturers on this question within the framework of the "Flexi-consumer" think tank. The think tank's findings show that, according to the figures from RTE, the problem of seasonal variations in photovoltaic production will be perceptible as of 2018. This analysis naturally takes into account the electricity mix and not merely photovoltaic power. In summer, however, wind power, the other intermittent energy, produces less than in winter. It is therefore clearly photovoltaic power that is the main intermittent energy generating potential surpluses in summer relative to winter, especially since, in regions such as France, summer represents a trough in consumption from an overall annual view of electricity consumption.

Figure 40 shows two things:

- In summer there is a fairly stable production surplus (NB: the scale of the graph could be deceptive, since on a small time scale there can be major variations leading to a far smaller surplus than what appears on the graph).
- There is a tendency to have deficits in winter, but with far larger variations than in summer.

Such a situation might seem insurmountable and represent a major curb on the expansion of photovoltaics. However, the manufacturers in the "flexi-consumer" think tank, after analysis, have reached the conclusion that there was an economic benefit from shifting large volumes of their industrial production and hence their electricity consumption to summer while maintaining flexibility, and, on the other hand, increasing their flexibility in winter when the situation is more chaotic[62]. This is technically feasible for these manufacturers[63] (one of the members of the think tank rightly pointed out that the curve in *Figure 40* corresponded to the curve of concrete production, for example).

62- There could be question marks concerning the social acceptability of an increase in the workload in summertime. No study has been performed, but between being able to spread their holiday leave over the entire summer season and being forced to take leave during the annual shutdown which generally takes place in early August, right in the peak holiday season (hence peak costs), some could favorably view an increase in the workload in summer.

63- This does not apply only to small industries, but to large industrial firms such as cement and steel producers, i.e. industries carrying out complex industrial processes.

IS THERMAL REGULATION RT 2012 WELL DESIGNED?

Thermal Regulation RT 2012 implicitly combatted electric heating and domestic hot water on the grounds that they required the start-up of gas- or coal-fired electric power stations. Without wanting to enter this controversy, it is clear that flexibility requirements at the consumption level to absorb the intermittency of photovoltaic power and effectively flexible uses (in particular for heating and domestic hot water) require a rethink of RT 2012. For example, it is far more appropriate to power a hot water cylinder with photovoltaic electricity than with gas. The same holds for heating. It would therefore be useful to rethink the RT 2012 approach in light of prospective changes in the electricity mix.

It is also financially feasible provided one promote service systems associated with constant modulation of their consumption and take into account the fact that these manufacturers would absorb a large quantity of intermittent electricity having a zero marginal cost.

Demand management, whether by forcing consumption at specific times or by consumption shedding during production troughs, is therefore now not only feasible but, what's more, already implemented. It is also more widely distributable, both in France and throughout the world. It is one lever available to start supporting the grid with a view to an increase in the share of photovoltaics, but also to go beyond the 5-8% of photovoltaic production that a mature grid can absorb (without requiring preliminary changes). One of the major obstacles to the deployment of consumption management is often the fact that certain stakeholders do not want to change, because that would jeopardize their historical business model. The slow pace of change in the regulations to allow economic exploitation of this management (changes in consumption profiles, changes in hot water cylinder controls, etc.) is also a problem. Admittedly, there will also be a capital cost for implementation of the management equipment, but it will be marginal, since the present cost of the products needed (which, moreover, are far from prohibitive) will fall steeply given the potential size of the market.

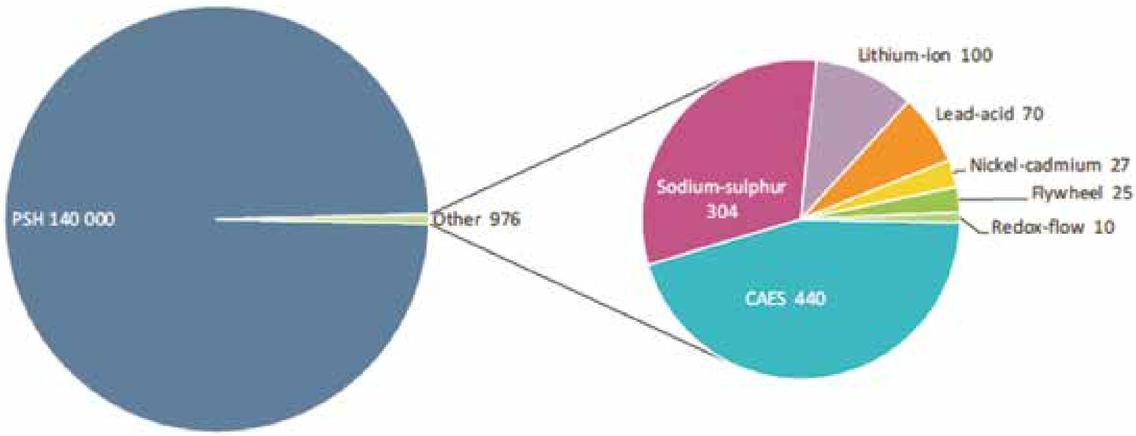
3.3 Storage, a new revolution?

Given the increasing potential for adapting electricity consumption to production and grid characteristics, it is already possible to foresee significant growth in photovoltaics worldwide. At the same time, developments in storage, and especially electrochemical storage, could radically change the approach to standby facilities to cope with intermittent production such as photovoltaic power.

This study focuses on electrochemical storage in particular, because it is one of the storage processes which benefits from technical and economic trends promising improvements similar to those in photovoltaics and electronics in general. Moreover, it is a storage technology which can be located anywhere, unlike PSPS's[64], for example. Finally, after analyzing this technology, it could be less insignificant than was thought just three or four years ago.

64- PSPS = Pumped Storage Power Station. These systems consist of two lakes at different altitudes connected to one another. To store electricity, water is pumped from the lower lake to the higher lake. To remove it from storage, water flows via a turbine from the higher lake to the lower lake. In France, there is 4 GW in active PSPS capacity. This capacity is at present used mainly to absorb surplus nuclear production at night or in periods of low consumption. Their operation is evolving, but this was clearly the primary reason for their construction, due to the relative inflexibility of nuclear power.

▸ **FIGURE 41 :** BREAKDOWN OF STORAGE FACILITIES WORLDWIDE ACCORDING TO INSTALLED CAPACITY IN MW (PSH = PUMPED-STORAGE HYDROELECTRICITY, CAES = COMPRESSED AIR ENERGY STORAGE) (INTERNATIONAL ENERGY AGENCY, 2014)CITATION AGE141 \L 1036



Source: IEA analysis and EPRI (Electric Power Research Institute) (2010), "Electrical Energy Storage Technology Options", Report, EPRI, Palo Alto, California.

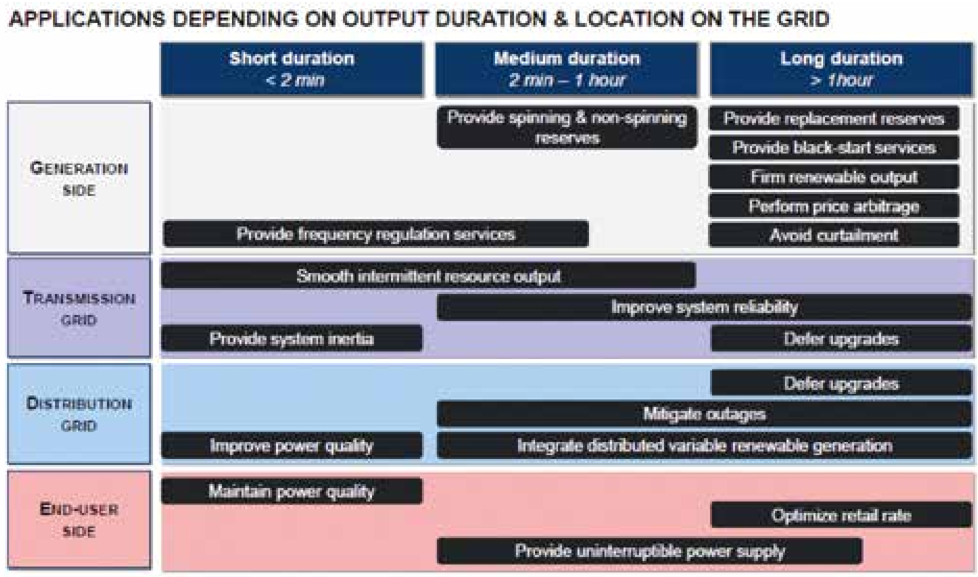


FIGURE 42 : ELECTRICITY STORAGE APPLICATIONS (INTERNATIONAL ENERGY AGENCY, 2014)CITATION AGE141 \L 1036.

3.3.1 The various storage technologies

Electricity is difficult to store, and is always stored in an indirect form:

- Gravity storage using hydroelectric reservoir dams, PSPS's;
- Mechanical storage using compressed air;
- Electrochemical storage using batteries;
- Chemical storage using power-to-gas.

At present, gravity storage using water is by far the majority technique used worldwide.

Moreover, storage can meet very different requirements depending on the aspects to be addressed. In its Technology Roadmap on storage, the IEA lists the various characteristics of the types of storage.

Batteries in the broadest sense – electrochemical storage facilities – cover the following main technologies: lead-acid battery, Li-ion battery, sodium-sulfur battery, sodium-ion battery, flow battery, zinc battery.

These technologies can meet short-term storage requirements (a few days at most) at the demand level (production transfer) and at the production level (smoothing of the intermittent production curve to prevent excessive variations in the power produced, service system role for frequency control)[65]. Battery characteristics can meet nearly all the constraints of intermittency of photovoltaic production, except for interseasonal storage[66].

One aspect seldom pointed out is the density of energy, i.e. the quantity of energy that can be stored per unit volume. Although, in a centralized electricity system, this is a secondary issue, in a decentralized approach in which local constraints generated by the intermittency of photovoltaic production facilities must be faced, it is no longer necessarily trivial. As emphasized by Jean-Marie Tarascon, Professor at the Collège de France, electrochemical storage, and in particular lithium batteries, has a very high energy density compared with storage in dams (since PSPS's are always presented as the ultimate storage system). For example, to store 10 kWh, the daily average consumption of a home in a developed country (excluding heating), you need:

- 500 g of lithium battery which fits in a 130 x 86 x 18 cm Tesla Powerwall;
- Or you must raise 3700 cu.m of water (i.e. about forty residential swimming pools) by one meter.

Electrochemical storage could therefore, depending on developments regarding its competitiveness in particular, provide an answer to local intermittency constraints.

65- (International Electrotechnical Commission, 2011) CITATION Intl1 \l 1036

66- Flow batteries could play this role.

3.3.2 Technical and economic prospects for batteries

The important technical and economic factors for a battery are as follows.

- The capital cost. Unlike electricity production facilities for which the relevant capital cost is the number of dollars or euros per unit power (W, kW, GW), for a battery the important thing is the number of dollars or euros per unit quantity of electricity that can be stored (Wh, kWh, MWh).
- For stationary use, the other important factor is the battery's durability, characterized by the number of charge and discharge cycles. Over time, a battery which could store 10 kWh will only be able to store 8 kWh (maximum lifetime for a mobile application) due to deterioration of the battery's component parts (electrodes and electrolytes [67]). Moreover, the number of cycles that can be performed depends on the depth of charge/discharge[68], as illustrated by *Figure 43*.

Component parts of a battery

A battery is formed of:

- Elementary cells containing the basic storage elements: cathode, anode, electrolyte and separator;
- A pack of cells determining the battery's total storage capacity;
- The overall system with electronic components.

Most of the cost (about 70%) is due to the cells/packs part in which lies the main issue with batteries: how to ensure the best possible density for the best capital and operating costs.

67- A battery consists of a cathode from which the current leaves, an anode where the current enters, and an electrolyte for ion exchange, allowing either the storage of electricity or its removal from storage.

68- The depth of discharge is the percentage of the total quantity of stored electricity which is discharged.

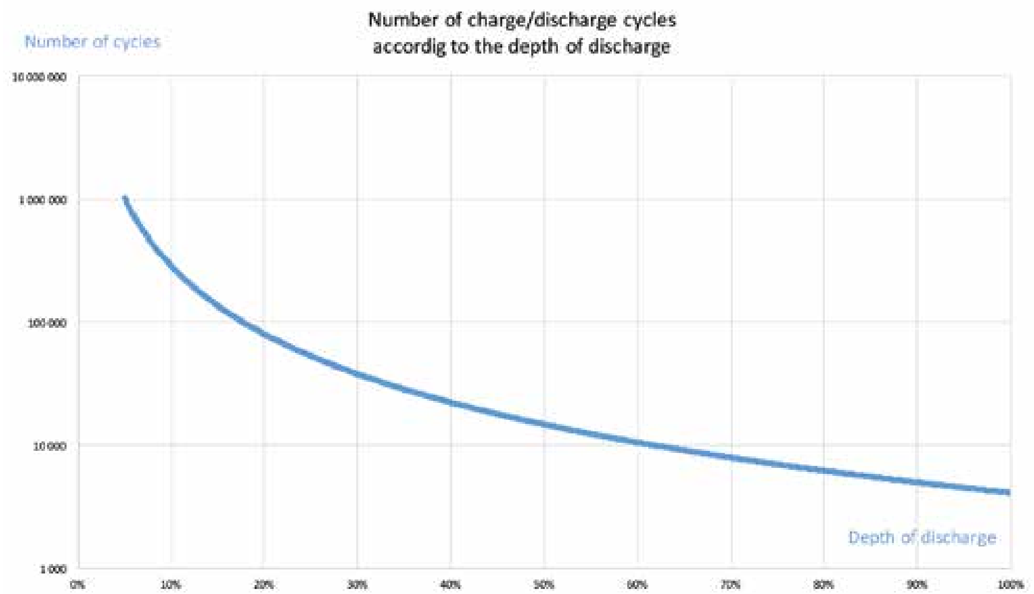
Historical trend in battery costs

Electrochemical storage has similar characteristics to photovoltaics in terms of the underlying physics and cost drivers. There is the same learning curve in terms of cost per kWh stored as for photovoltaics, as shown by *Figure 44* relating to the Li-ion battery market for electric vehicles.

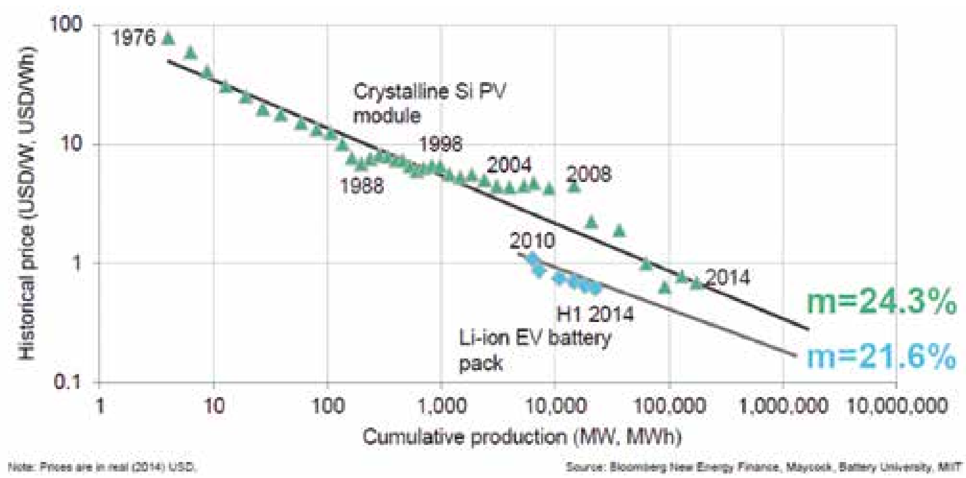
Winfried Hoffmann (see *Figure 45*) has a slightly different curve, with a similar trend for the cost of the cells alone. This is the more important curve for our report, because the battery pack for stationary use is not identical to that for on-board use in an electric vehicle where there are greater space and weight constraints.

The advantage of electrochemical storage is that its learning curve does not depend solely on direct use for the electrical system. It also benefits from momentum in the electric vehicle market:

‣ FIGURE 43 : NUMBER OF CHARGE/DISCHARGE CYCLES THAT CAN BE PERFORMED WITH THE BEST BATTERIES ON THE MARKET ACCORDING TO THE DEPTH OF DISCHARGE, SAFT PUBLIC DATA. ILLUSTRATION: FONDATION NICOLAS HULOT.



‣ FIGURE 44 : CHANGES IN THE COST OF THE LI-ION BATTERY PACK FOR ELECTRIC VEHICLES COMPARED WITH THAT FOR CRYSTALLINE SILICON PHOTOVOLTAIC MODULES. SOURCE: BNEF, 2014.



the cell production process is the same, only the end packaging differs depending on the use.

Like for photovoltaics, but undoubtedly in a more pronounced manner, there is a divergence entered the perceived cost of the batteries and the actual cost reached. The 2015 reports of the IRENA or the IEA on storage technologies and batteries estimate the capital cost at around US$600-800 per kWh, or even more. However, the current cost is rather US$300-350 per kWh for the lithium technology in light of data provided notably by Tesla and LG Chem. The company EOS even announces US$160-200 per kWh for batteries based on the zinc technology, production of which is expected to begin in 2016.

This divergence can be explained by the fact that the batteries' electronic fundamentals confer on them a speed of innovation faster than the time for analysis by the conventional energy world. So long as batteries were expensive, their market and their impact remained anecdotal. The continuous rapid improvement in the cost of this equipment has resulted in practically an on-off dynamic: in a very short period of time, these technologies could cease being relatively invisible and could have a major impact on the electricity system.

Outlook for changes in the capital cost

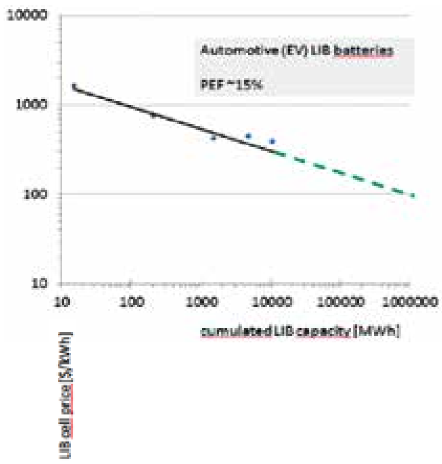
Electrochemical storage and its applications (for mobile systems in particular) are the subject of intensive research. Like for photovoltaics, the possibility of using the potential of physics at the micro and nano levels points to further very significant prospects for improvement. Conversely, gravity storage using water, the PSPS, is based on a tried and tested macroscopic technology for which no radical change is foreseeable.

To reduce battery costs, several factors are looked at.

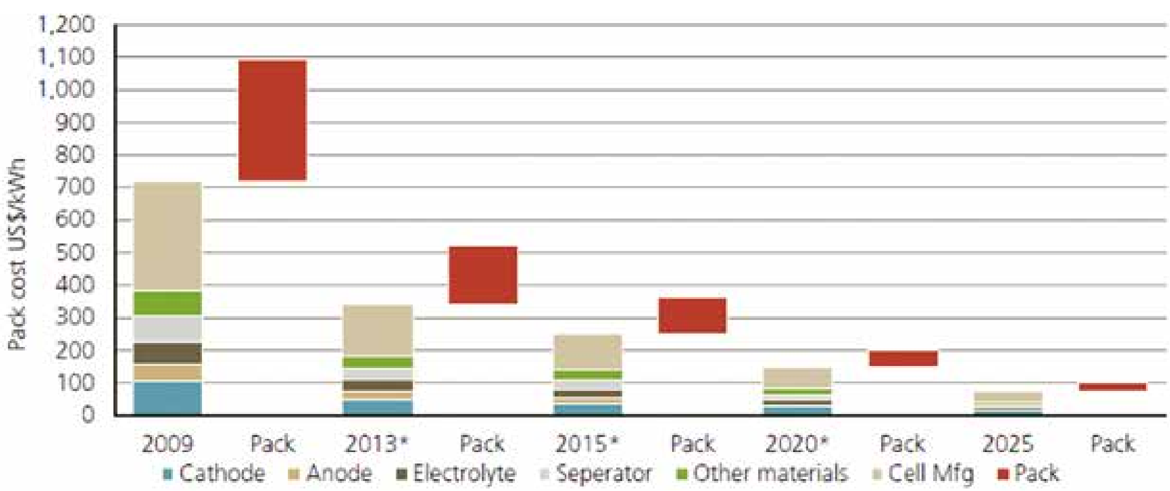
- An improvement in industrial processes via greater automation using all the inherent potential of the electronics and microelectronics industries.
- An improvement in energy density making it possible to reduce the quantity of active elements. For example, a Toyota research team announced in mid-2014 that it had succeeded in developing a lithium battery storing seven times more energy than a standard battery by changing the composition of the battery's cathode. If this breakthrough were confirmed and industrialized, it would entail significant prospects for a reduction in the capital cost of stored energy. Likewise, a research team from the Karlsruhe Institute of Technology has announced a new electrochemical storage concept making it possible to increase the energy density of a lithium battery (tested technology) by a factor of 7 [69]. This arrangement could also be extended to other battery concepts.
- An improvement in lithium extraction processes, notably by reducing energy consumption.

69- http://phys.org/news/2015-03-energy-density-lithium-storage-materials.html

▸ **FIGURE 45 :** CHANGES IN THE COST OF LITHIUM-ION CELLS. SOURCE: ASE-HOFFMANN



▸ **FIGURE 46 :** PPROSPECTS FOR CHANGES IN THE COST OF LITHIUM-ION BATTERIES. SOURCE: UBS.



▸ **FIGURE 47** : PROSPECTS FOR CHANGES IN THE COST OF LITHIUM-ION BATTERIES. ILLUSTRATION: FONDATION NICOLAS HULOT.

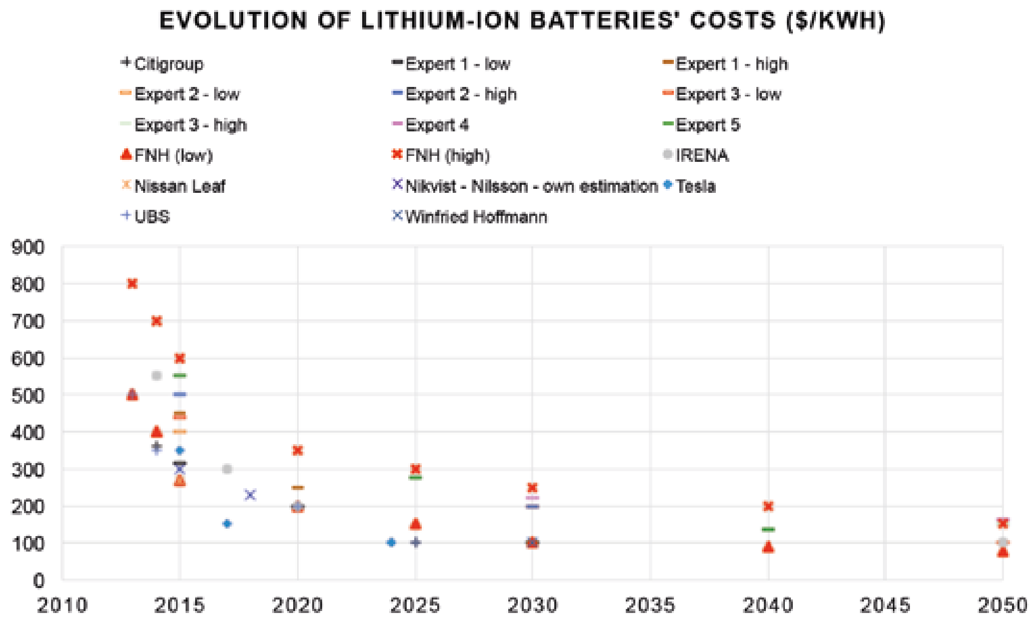


Figure 47 shows the prospects for changes in the capital cost of electrochemical storage (cost of the complete system excluding the inverter and installation).

The data currently available point to a rapid fall in the cost of batteries over the next 10-15 years, which will make them an important aspect of the electricity system[70].

Manufacturers and experts also mention other promising technologies, such as redox-flow technologies using liquid reagents, or technologies based on sodium, which is abundant and easy to access[71]. In light of current research and the demonstration phases completed, it may be imagined that in future technologies will merge, thereby accelerating the cost learning curve, shown above. For example, 24M, a spinoff company from MIT, has developed a lithium battery based on the flow-battery technology concept in which the electrodes are in suspension in a liquid and in a single block. 10,000 batteries have already been produced, US$50m has been raised and the 24M roadmap plans to reach US$100 per kWh for an equivalent or greater lifetime and use, and with better recyclability.

Likewise, some are wagering on the development of batteries based solely on sodium, as a substitute for lithium.

However, industrial developments are not expected until 5-10 years' time.

Ease of installation and space requirements will play an important role in the development of batteries used for stationary electricity storage (especially with a view to a decentralized use such as residential use). They could, effectively, impact the system's overall cost and the relative competitiveness of the various technologies.

Battery LCOE

To analyze in greater detail the competitiveness of electrochemical storage for the electricity system, notably with regard to photovoltaic intermittency management, we must look at the storage LCOE, i.e. the cost for each charge/discharge cycle.

The aim here is to analyze use of the batteries within the framework of coupling with a photovoltaic system. The costs presented above (see *Figure 47*) concern only the storage system. However, a battery must not only be installed but it is also necessary to convert its direct current into alternating current, like for photovoltaic panels.

At the time of the release of Tesla's Powerwall, some said that the cost announced by the producer (US$3500 for 10 kWh of storage) was deceptively low because it took into account neither the inverter nor the installation cost.

Regarding the inverter, if a battery is inserted in an existing photovoltaic system, the latter will have a single inverter making it impossible to also manage conversion of the battery current. A second inverter will therefore be necessary. On the other hand, in the case of a new installation, it will be possible to use hybrid inverters capable of managing a "PV + battery + connection to the grid" system for an extra cost at present of approximately 10% compared with a standard inverter. For a system such as the Tesla Powerwall, the extra cost would be approximately US$50, to be compared with a cost of US$3500 for a 10 kWh battery.

As regards installation, whether it be performed on a centralized location (connected to the electricity grid) or in a residential context, its extra cost is small. Like for the inverters of industrial plants, a centralized storage system arrives in complete modules. The only costs are civil engineering and connection. These costs are in no way similar to those for installation of the photovoltaic part which produces electricity and which is far more labor-intensive, whether for a ground-based system or a residential installation. In the latter case, the labor for installation of a battery consists mainly of fastening the battery to the floor or a wall and connecting it to the inverter. This work performed as part of a new installation will have only a marginal impact on the overall cost. To take the residential example, fastening to the wall and connecting to the inverter a Powerwall type battery will require at most half a day's work more than what is needed to install an electric radiator. Assuming

70- See below, regarding the storage LCOE

71- These technologies will be interesting mainly for stationary storage due to the volume that they occupy. Indeed, their market will be less vast than that for batteries that can be used for electric vehicles, and hence a smaller scale effect.

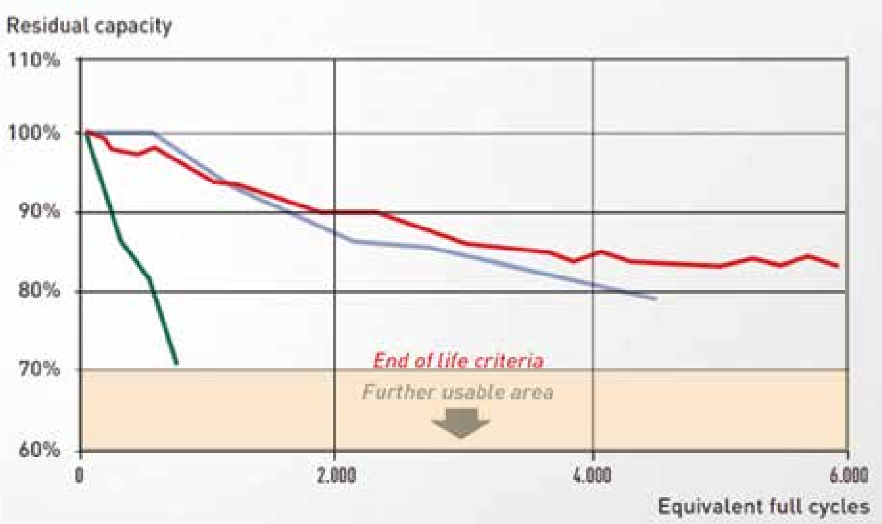


FIGURE 48 : CHANGE IN RESIDUAL CHARGE DEPENDING ON THE NUMBER OF CHARGE/DISCHARGE OPERATIONS (IN RED: SAFT BATTERY WITH 60% DISCHARGE / IN BLUE: SAFT BATTERY WITH 100% DISCHARGE / IN GREEN: BATTERY FROM OTHER MANUFACTURERS). SOURCE: SAFT.

ANALYSIS: THE GRAPH SHOWS THAT CURRENT TECHNOLOGIES MAKE IT POSSIBLE TO ACHIEVE 4000 CHARGE/DISCHARGE CYCLES FOR A BATTERY, I.E. ABOUT 10-12 YEARS OF DAILY USE. ON THE OTHER HAND, IT IS CLEAR THAT BY COMPARISON WITH THE 80% LIMIT TO RESIDUAL STORAGE CAPACITY, THERE REMAINS A LARGE REGION OF BATTERY USE (FROM 80% TO 60% OF RESIDUAL STORAGE CAPACITY).

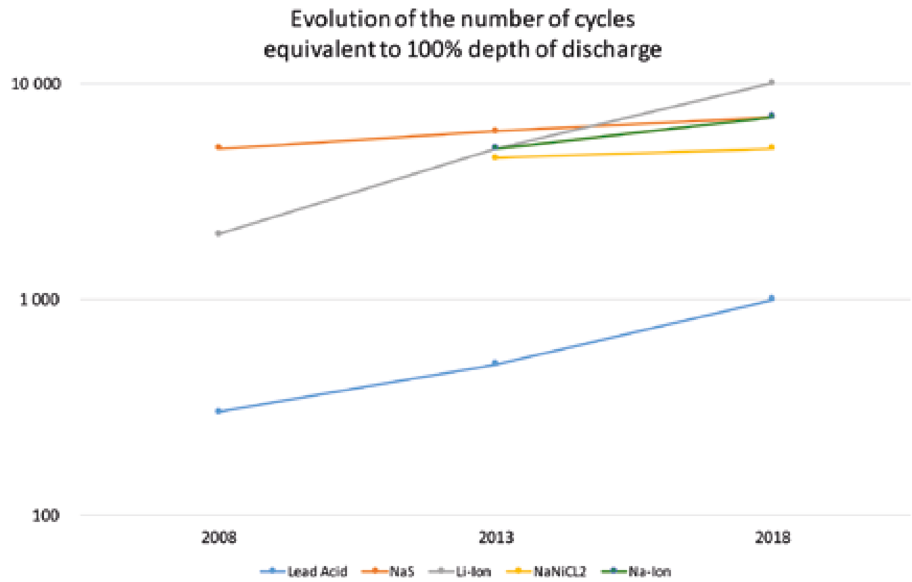


FIGURE 49 : PROSPECTS FOR CHANGE IN THE NUMBER OF CHARGE/DISCHARGE CYCLES AT 100% DISCHARGE FOR VARIOUS BATTERY TECHNOLOGIES. SOURCE: IEA (INTERNATIONAL ENERGY AGENCY, ENERGY TECHNOLOGY PERSPECTIVES 2015)CITATION AGE15 \L 1036 .

an overall cost of US$50 an hour, that makes US$200 extra cost. The extra cost of "installation + inverter" is therefore approximately 10% of the capital cost of the battery for a residential location. It will undoubtedly be less for a centralized production facility.

Another important factor is the number of charge/discharge cycles that the battery can perform. At present, a battery can perform about 4000 cycles at 100% discharge, which corresponds to about ten years' operation. After that time, the maximum quantity of energy stored corresponds to 80% of the initial quantity. Increasing the number of cycles is an important area of research. According to some manufacturers, it is even a major area ahead of reducing capital costs. This is the case, in particular, for Saft, whose photovoltaic storage battery technologies achieve 6000 cycles at 100% depth of discharge according to the online documentation. A transition to 6000-7000 cycles within the next 5-10 years is a development foreseen by numerous specialists and manufacturers.

The IEA, generally fairly conservative in its forecasts concerning renewable energies and related technologies (and in this case concerning battery costs), is more optimistic than the stakeholders in the sector regarding improvements in the lifetime of lithium-ion batteries. It estimates that the batteries could reach 10,000 cycles on the 2018 horizon.

To determine the competitiveness of a battery, the first thing examined is the LCOE for daily use. *Figure 50* shows the LCOE for various stored energy costs.

By comparison with the PSPS, for which the LCOE is approximately US$100/MWh, we observe that the batteries very soon become competitive. In a 2015 report[72], Citigroup analyzed the competitiveness of battery storage according to the capital cost of storage. With a capital cost of US$250/kWh, local storage with photovoltaics is competitive in many countries (LCOE US$102/MWh). With a capital cost of US$150/kWh, it rules out electric power stations using fossil fuel energies in a back-up role (LCOE of US$65/MWh). These figures are consistent with the market analysis performed by EOS[73] on the North American region, as illustrated by *Figure 51*. For a capital cost of less than US$200 per kWh, battery storage provides a more competitive solution than a back-up with fossil-fueled thermal equipment.

Moreover, calculations show that if use is not limited to the number of cycles after which the residual storage capacity is 80% of the initial capacity (the standard end-of-life threshold for a battery used in an electric car), but if use is continued until 70%, giving slightly more than 7000 cycles, the LCOE can be reduced by 30% to 40%. Here we assume a linear degradation to 70% of the residual capacity, which is a reasonable initial approximation according to the experts[74]. Note that the lifetime improvement at a constant cost, i.e. maintaining a better residual capacity after a larger number of cycles (e.g. 7000), only marginally improves the LCOE of battery storage (5-10%) by comparison with a configuration in which storage is pushed up to 7000 cycles with a decline in residual capacity to 70%.

Finally, in addition to the development goals of competitiveness and durability of the batteries influencing their design, areas of research have focused on management of the battery. For example, Younicos, a German software company, has developed expertise in the optimi-

72- (Citigroup, 2015) CITATION Cit15 \l 1036

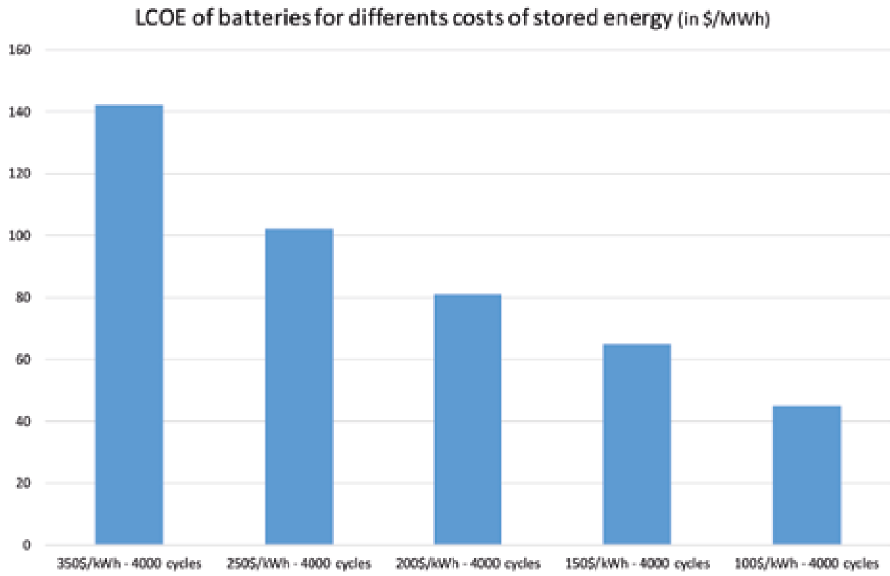
73- EOS is developing a battery system based not on lithium but on zinc. Production is set to begin in 2016. If its costs (US$160/kWh) are confirmed, its technology will be a market leader. It could compete with the lithium technology and be a driver for competition and innovation.

74- According to the experts, the deterioration is generally linear once the first cycles have been performed. On the other hand, when the battery's storage capacity deteriorates excessively and reaches the region of 50% of the initial storage capacity, accelerated degradation phenomena appear.

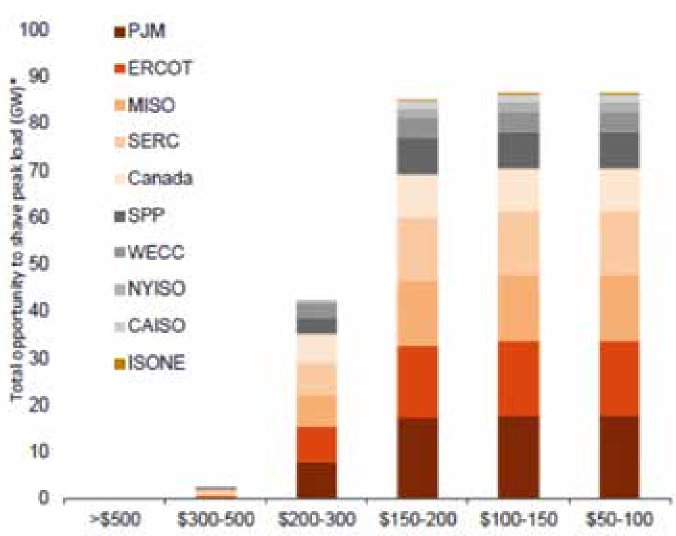
▸ **FIGURE 50 :** CHANGES IN THE LCOE OF A BATTERY DEPENDING ON ITS COST AND USE AT UP TO 80% OF ITS INITIAL STORAGE CAPACITY. CALCULATIONS: FONDATION NICOLAS HULOT*.

ANALYSIS: A BATTERY WHICH COSTS US$350 PER STORED KWH HAS AN LCOE OF US$142/MWH.

* We assume a 10% extra cost for the installation/inverter part by comparison with the capital cost of the battery alone, with a minimum of $150-200 for a 10 kWh battery. We assume a 5% WACC and a storable energy loss of 2% per year with a 93% inverter efficiency. The latter is count only once due to DC-DC storage between photovoltaic production and the battery. On the technical level, the battery is assumed to have a standard lifetime of 4000 cycles.



▸ **FIGURE 51 :** ADVISABILITY OF DEPLOYING ELECTROCHEMICAL STORAGE ACCORDING TO ITS COST IN THE NORTH AMERICAN REGION (THE ACRONYMS REFER TO THE VARIOUS ZONES OF THE NORTH AMERICAN ELECTRICITY SYSTEM). SOURCE: EOS/IHS.



zation of battery management (based on the sodium-sulfur technology) in order to improve their durability. The Younicos technology, closely watched by major battery manufacturers, would, according to Samsung[75], be able to extend the guarantee on its batteries up to 20 years (instead of 10 at present). This company has raised hundreds of millions of dollars, demonstrating the confidence in its technology, which must nevertheless be validated on the industrial level.

3.3.3 The energy and non-energy impacts of electrochemical storage

The energy impact

Like for photovoltaics, electrochemical storage raises the question of its sustainability from the perspective of the energy investment needed for the storage of this energy and for access to the commodities necessary for manufacture of the batteries (hence the issue of recyclability).

According to the experts, approximately 350-400 kWh of energy is needed to "produce" 1 kWh of battery storage (of the Lithium-ion, lead or Ni-MH type), with emissions of approximately 100-120 kg of CO2. The main source of this energy consumption and greenhouse gas emissions is the extraction and conversion of raw materials.

Before denouncing an ecological scandal, let us examine the figures rather more closely:

- 350-400 kWh for 1 kWh of storage is a lot. But this "1 kWh" of storage will be used several times, and more precisely 4000 times. So, manufacturing energy for each cycle falls to about 0.1 kWh[76] for 1 kWh stored and half less with a doubling of the number of cycles. Moreover, the transition from production costs of US$400-500/kWh, for an energy cost of kWh350-400/kWh of storage, at US$100/kWh, corresponds to an equivalent fall in energy consumption per kWh of storage. At first sight, US$100/kWh for 8000 cycles corresponds to 0.01 kWh/kWh of storage. Even doubled, to allow for indirect energy costs, this extra energy cost for a photovoltaic installation coupled to a storage system would merely reduce the EROI range of photovoltaics from 5-10 to 4.5-9.
- 100-120 kg of CO2 is also a lot. But, with 4000 cycles, the kWh stored in each cycle contains only an additional 0.03 kg of CO2 at present, and this level will merely decline with the decline in the energy necessary to manufacture the batteries.

Like for the photovoltaic part, not only are the current figures not disastrous, but they are also improving over time.

Moreover, faced with environmental constraints, it can be noted that companies working on battery development are taking this into account in designing new batteries. Here are a few examples:

- The firm 24M, already mentioned, took into account in developing its battery the need to reduce the quantities of energy involved in its manufacture, and above all to improve recycling, which, in general for mineral ores, can save the energy used for their extraction by a factor of 2 to 10[77].
- Researchers are also looking into the development of bio-inspired/bio-assisted synthesis methods making it possible to reduce the energy consumption involved in manufacturing the materials constituting a battery.

Material constraints

Like for the issue of the sustainability of massive deployment of photovoltaics, there are question marks concerning the availability of the materials used in batteries to allow their massive deployment.

In its 2015 study, the MIT examined this question in detail. Sodium-ion technologies pose no problem of supply. Technologies such as the EOS technology based on zinc cathodes also pose no problem. Regarding lithium, the picture is rather different, and this is the main battery technology at present. It is the technology that offers the best energy density (both for on-board electronic applications and for mobility, the space constraint is key).

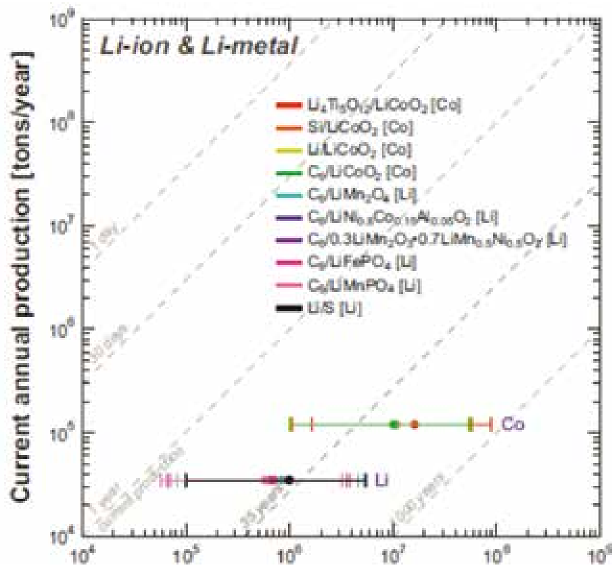
- For most of the technologies, 35 years of current production with current battery performances would be necessary to store every day 10%-15% of global electricity demand in 2050 according to the IEA's Perspectives (see *Figure 52*).
- The technologies using more cobalt, such as the LiCoO2 technology, are more problematic from a supply viewpoint.

75-https://www.greentechmedia.com/articles/read/younicos-wants-to-be-the-worlds-biggest-grid-battery-controller

76- Taking into account the deterioration of storage capacity over time.

77- UNEP, Metal Recycling, April 2013

▸ FIGURE 52 : YEARS OF PRODUCTION OF MATERIALS FOR THE LITHIUM BATTERY TECHNOLOGIES TO MEET 1% TO 55% OF PEAK DAILY REQUIREMENTS WORLDWIDE. SOURCE: MIT.



This data reflects the present situation considering the technologies currently deployed. It does not take into account research on improving energy density, or on technologies using more abundant materials. The boom in storage is evident from a resurgence of research in this area which points to significant changes.

The mining sector is also endeavoring to improve its technologies both from an environmental perspective and with a view to access to larger reserves. To take lithium, an Australian company, Cobre Technology, recently announced the development of a new technology consuming less energy for extracting lithium from micas. If this technology is confirmed, it could considerably expand lithium reserves[78].

Nevertheless, whatever the quantity of reserves, recycling remains the major process. According to some experts, the recycling constraints are not technical but merely economic. Recycling of battery component materials is already underway, and the increase in market size will assist this process. In Europe, the directive on waste electrical and electronic equipment[79] imposes certain levels of recycling. Other countries have adopted similar constraints to varying degrees. The tried and tested technologies for recycling of conventional acid batteries could easily be transposed to the recycling of lithium batteries, according to the UCSGS[80]. Bio-inspired/bio-sourced processes are also developing for concentrating rare or strategic metals found in water (aqueous mixture coming from recycling processes) or in soils, making it possible to concentrate nickel and cobalt, for example[81].

Some experts consider 2014 as a pivotal year in the development of electrochemical storage. This is undoubtedly due to the fact that batteries have reached a first threshold of profitability and hence visibility on the energy market, attracting attention in both scientific and financial circles. There is a boom in initiatives: Tesla is going into stationary storage, and Benz is doing likewise[82]. Many stakeholders are announcing large investments in battery production capacity. Tesla plans to have more than 35 GWh of production capacity in 2020, and the same holds for BYD, backed by Warren Buffet. This technology is currently entering the electricity system rapidly and with a major impact, like photovoltaics, due to the speed of its deployment and its pace of innovation similar to that of the electronics world, i.e. far faster than the pace of innovation for conventional facilities, which is measured in decades.

78- http://reneweconomy.com.au/2015/australian-company-says-new-process-could-bring-unlimited-lithium-supplies-29957

79- 2012/19/EU Directive

80- (USGS, Lithium Use in Batteries - circular 1371, 2012) CITATION USG12 \l 1036

81-(D. Larcher and J-M. Tarascon, 2014) CITATION DLa14 \l 1036

82- http://www.greencarreports.com/news/1098541_mercedes-follows-tesla-will-offer-home-energy-storage-batteries-too

4. ARE MANUFACTURERS PREPARED FOR THE POTENTIAL (R)EVOLUTIONS TO COME?

4.1 Photovoltaics is not THE solution, but an important solution to global energy issues

"Never put all your eggs in the same basket", the saying goes. The same applies for electricity. Technically, economically and rationally, photovoltaics could never be considered as THE technology. On the other hand, whereas many projections put its place at around 5% of global electricity consumption on the 2050 horizon, the above developments suggest rather a contribution of 20-25%.

The main conclusions so far are as follows.

- Electricity production based on photovoltaics is already competitive in many countries, and this can only increase due to the prospects for development, both economic and technical.
- The investment amounts needed to achieve a production representing 20-25% of electricity consumption are affordable.
- Mature grids can without any problem accept up to 8% of photovoltaic power.
- Then, consumption management can increase to 75% the rate of penetration of photovoltaics in half of the manageable residential consumption uses. It also makes it possible to manage a significant part of industrial consumption and hence increase the rate of penetration of photovoltaics in consumption.
- Finally, battery developments point to management of at least 10-15% of the world's daily consumption on the 2050 horizon, according to the IEA Perspectives.

These development perspectives for photovoltaics also open the way to the deployment of decentralized energy. Apart from the suitability (not excluding other storage technologies) of batteries at the centralized level, calculation of the production costs for a residential installation capable of storing about 50% of photovoltaic production at the level of a region such as southern France shows how quickly direct supply becomes competitive with supply via the grid.

Admittedly, this supply cannot be 100% based on photovoltaics with storage due to the annual variability of photovoltaics. However, current prices for the supply of electricity via the electricity grid are approximately €130/MWh, and can only increase over time because (i) renovation investments will be needed on the grids and (ii) the cost of the nuclear fleet can only increase, at least given the difference between the cost of new nuclear development (at least €100/MWh) and the old cost (approximately €45/MWh). A comparison with these prices shows that local management of part one's consumption and production has already reached economic equilibrium.

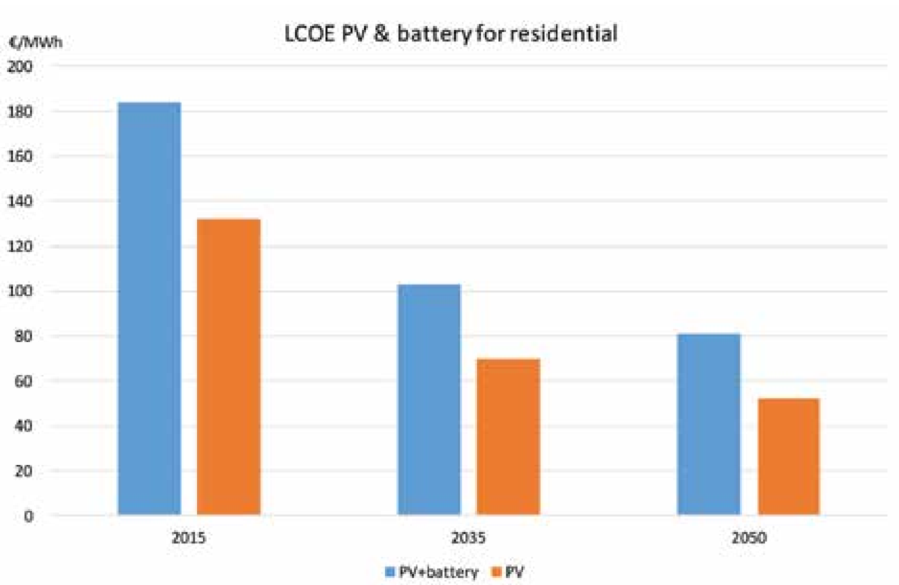
This trend, called "load defection"[83], is emphasized by a number of banks in reports published during the second half of 2014[84].

Moreover, recent reports by the MIT, the Fraunhofer Institute and the Rocky Mountain Institute all note the strong coming penetration of photovoltaics and batteries into the electricity mix, and a high proportion of load defection on a substantial fraction of electricity consumption.

83- This expression means that part of consumption and capacity is disconnected permanently from the power grid. There is therefore a decline in the energy and capacity connected to the grid.

84- Quotes taken notably from (Rocky Mountain Institute. 2015) CITATION Roc15 \l 1036.

▸ FIGURE 53 : LCOE OF A 9 KW INSTALLATION WITH OR WITHOUT STORAGE FOR AN INSOLATION OF 1350 KWH/KWP AND THE COST ASSUMPTIONS FOR THE SCENARIOS OUTLINED PREVIOUSLY IN THE REPORT (FIGURE 22). CALCULATIONS: FONDATION NICOLAS HULOT.



In this context, there are question marks concerning the future activity of stakeholders. Many firms which were not related to the electricity universe are penetrating this market, notably via the door of storage or photovoltaics. These are stakeholders in the world of electronics (Microsoft, Google etc.), or electric mobility (Mercedes Benz, Google). They are accustomed to a pace of innovation different from that conventionally seen in the electricity sector. They also have a different approach to the customer relationship, organization schemes and business models. Their advent with disruptive technologies could have a major impact for the traditional stakeholders, especially if these stakeholders do not take these developments into account in their industrial strategy sufficiently in advance.

In a note dated 20 August 2014[85] , UBS analyzed the risks posed by the development of photovoltaics, batteries and electric vehicles for a number of big utilities. In the note, UBS indicated the utilities negatively impacted by such development. EDF, Verbund, Engie and Fortum were among them, due to non-flexible assets locking up huge amounts of capital (nuclear power stations in the case of EDF) and facing increasing production costs. It must therefore be hoped that the conventional utilities, which historically have a growth strategy not focused on renewable energies in general and photovoltaics in particular, will all come to realize the changes in progress and reposition their financial capacity insofar as possible.

The prospects for the development of photovoltaics could nevertheless be curbed in certain respects by bad regulations. This is the case, in particular, for self-consumption and the issue of invoicing connection fees for such installations. If it is not economic rigor that prevails but a will to limit such a trend with all sorts of taxes (such as the tax on the sun planned by the Spanish government for self-consumption installations), there would be risks of seeing good solutions stifled on unjustifiable grounds. Such a threat is not imaginary. In the energy transition law enacted in France (host of the COP21 in December this year), it is said that “measures necessary for a controlled and secure development of installations designed to consume all or part of their electricity production, including in particular the definition of self-production and self-consumption conditions, and the conditions for subjecting these installations to a tariff for use of the public electricity distribution grids and the use of experiments” will have to be taken. If by ‘controlled’ is meant not adversely affecting conventional installations and stakeholders, this would then be in pure contradiction with what economic analysis dictates and what the issues related to COP21 require of us.

85- (UBS, 2014) CITATION UBS14 \l 1036

FIGURE 54 : IMPACT OF PV + STORAGE + ELECTRIC VEHICLE DEVELOPMENT FOR VARIOUS INTERNATIONAL UTILITIES. SOURCE AND CALCULATIONS: UBS.

Net earnings opportunity by compagny, 2025E (€m)

	E.ON	RWE	EDF	GDF	Enel	IBE	EDP	FUM	VER	CEZ	SSE	CNA
Value-add supply NOPAT	200	224	455	74	665	197	94	26	15	136	7	115
Smart grid NOPAT	310	217	756	0	953	305	146	0	0	208	7	0
Decentralised back-up power NOPAT	89	59	28	96	0	92	54	68	6	34	0	34
Conventional generation NOPAT at risk	-210	-322	-1,300	-350	0	-35	-35	-192	-206	-360	21	26
Total net opportunity	**389**	**178**	**-61**	**-179**	**1,618**	**559**	**259**	**-98**	**-185**	**18**	**106**	**175**
% of EPS 2016E	22%	17%	-1%	-6%	49%	24%	23%	-12%	-77%	2%	10%	14%

Source: UBS estimates

4.2 The sun, gold for the salvation of developing countries?

4.2.1 The electricity grid of tomorrow

As said previously, the electricity grid of tomorrow (in France and in mature countries) will not consist solely of photovoltaics or small power plants close to the consumption locations. Maintaining a national and even supranational grid has certain advantages for the security of electricity supply, but also for the integration of intermittent renewable energies.

On the other hand, a large portion of consumption will be managed locally, directly at the consumption locations. If it is designed intelligently, the grid will permit this local management of part of local consumption and capacity. This will reduce consumption and capacity with regard to the grid, as a consequence reducing the requirements and hence costs in terms of grid infrastructure. On the other hand, consumption locations will use the grid as a supplementary source of supply and as an insurance thanks to smart management of their consumption manageable by a decentralized storage facility. In this study, the FNH has not examined in detail this question of scenarios for the electricity grid of developed and developing countries, in a context of development of centralized and decentralized intermittent production facilities, centralized and decentralized storage facilities and consumption management/adaptation to the variability of production. The probably positive impact of these developments on investment in electricity transport infrastructure (in mature grids or in grids under construction) would deserve to be studied.

The view presented here is realistic in light of the technical and economic perspectives described previously. Moreover, it is the business model of a number of companies.

4.2.2 Photovoltaics: an immediate solution to significantly improve the life of billions of human beings

The prospects for development of photovoltaics and batteries represent a fantastic hope for developing countries and, in particular, the 20% of the world's population who still do not have access to electricity.

Regarding this, it should be remembered that what is important is not electricity in itself, but the services that it can provide: Moreover, it should be clearly understood that yesterday's grid with centralized means of production is different from tomorrow's grid with a large quantity of renewable energies, that could be centralized, but also decentralized as close as possible to consumption. This difference explains the difficulties faced at present by some developed countries in implementing their energy transition. This is the case for Germany, which has had to and still must not only reorganize its grid topology, but also the way in which it is managed.

Although Africa cruelly lacks electricity, it nevertheless has exceptional assets. It enjoys substantial, regular insolation and, since its electricity history has hardly been written, it can establish directly the electricity system of tomorrow based on centralized and decentralized renewable energies.

Given the current situation, the main challenges facing Africa are fairly simple in the short term.

- Lighting.
- Communication (in particular, mobile phones, which are a structural feature of the African economy, and access to knowledge via internet).
- Healthcare, with hospital installations that can operate in satisfactory conditions of hygiene, having refrigeration areas and sewage treatment installations requiring pumping and filtration systems running on electricity.
- Crop irrigation.

Such services would be provided far more rapidly and efficiently by innovative solutions based on small photovoltaic installations coupled to storage with easily transportable backup thermal systems. Whereas several decades are needed to build an electricity grid, a few weeks are sufficient to set up a small system based on photovoltaic power and energy storage.

This local approach, according to a leopard-spot pattern, would then gradually lead to interconnection, but not necessarily as extensively as in the case of a centralized system. Above all, it could be deployed for a lower cost, involving the local populations and gradually developing an industrial fabric notably for management and maintenance of the installations.

A few examples:

- The establishment of a photovoltaic solar power system to pump water during the day (coupled with a water storage system to manage the sun's intermittency) would immediately provide a significant gain in terms of development for the most isolated populations without needing to pull power lines over thousands of kilometers.
- Providing a photovoltaic system and a battery to give lighting for several hours at night, allow mobile phone recharging during the day, and to use internet, would also be simple and significant in terms of improving living standards.

Moreover, this more modular electrification would allow populations to make use of electricity and improve their standard of living without necessarily radically changing their life style. They would be able to adapt the use of renewable energies to their perspective, which is not foreseeable in the case of centralized deployment plans which are inevitably approximate in their allowance for specific local features.

Certain initiatives, supported by large groups, should be highlighted and promoted. Schneider Electric is involved in a support program via the Energy Access Ventures Fund which aims to invest in African SMEs in order to provide Africans with electricity. An increase in this type of financial support would be extremely useful and effective for Africa. Likewise, the initiatives of EDF-Help and blueEnergy, in Ethiopia and Nicaragua, form part of a local approach making it possible to implement local electrification solutions directly and simply. If these initiatives are not supported and promoted as solutions, they will remain marginal by comparison with a more conventional and more centralized, hence less modular industrial deployment.

Shari Berenbach, chairman and CEO of the United States African Development Foundation[86], said the same thing at the end of 2014 in an interview with the Global Energy Initiative, saying that for many rural populations, the establishment of off-grid solutions was essential. She said she hoped that Africa would not repeat the errors of the United States, focused solely on the centralized grid[87].

86- http://www.usadf.gov

87- http://globalenergyinitiative.org/insights/200-interview-power-africa.html

EXAMPLE OF AFRICAN START-UPS/SMES OFFERING INNOVATIVE SOLUTIONS BASED ON DECENTRALIZED PHOTOVOLTAICS

Station Energy: A start-up which aims to bring electricity to the most disadvantaged regions of Africa using the qualities of photovoltaics while drawing inspiration from the local culture. The company has developed a multiservice kiosk concept inspired by African grocery stores and powered by solar energy. By bringing electricity to the most remote and least equipped non-electrified regions (in both rural and urban areas) of the continent, Station Energy generates activity: lighting, hire of batteries and refrigerated areas, access to Internet, trade, etc.

M-KoPa: This Kenyan start-up proposes to the 30 million Kenyans deprived of electricity and not connected to the national power grid the purchase of solar energy by the hour via a prepaid electricity system. Each M-Kopa kit allows customer homes to light 3 light bulbs, for the equivalent of about 43 euro cents per day. This budget allows the most precarious inhabitants to obtain access to lighting safely, abandoning the dangerous - and especially highly pollutant - oil lamps still used by millions of homes in Kenya and in Africa. Once equipped, each home can pay for its green electricity supply by the day, via M-Pesa, the mobile payment system which dominates the banking economy in Kenya. The level of 150,000 homes equipped has already been exceeded.

These two firms both share the same vision: using the malleability of photovoltaics to rapidly bring about an improvement in the living standards of African populations without going via substantial electricity infrastructure, and fitting in with the local culture.

5. CONCLUSION

Apart from tangible facts such as rapid improvements in photovoltaics, consumption management and electrochemical storage, reports from the university world, the financial world and the industrial world together reveal an underlying trend to improvement in the competitiveness of technologies related to photovoltaics and electrochemical storage. The simultaneous technical and economic development of these technologies is altering the prospects for the electricity systems of tomorrow.

A first effect can already be seen on two fronts, with the rapid deployment of small individual devices on one hand, and elsewhere in the construction of high-capacity power plants ordered by wealthy sunny countries. This trend also points to radical changes which will concern the developed countries' electricity systems. The big operators and managers of these systems, like the public authorities, must become aware of their potential for development, and facilitate it rather than ignore it or, even worse, combat it. Like it or not, some households, economic stakeholders and local authorities are thus acquiring a capacity for and an interest in becoming their own electricity producers. Those who do not make the transition soon enough will be badly positioned in the energy organization of tomorrow.

A scenario in which this deployment were to be implemented by ignoring or merely bypassing the current centralized electricity system would definitely not be optimal for society. Regarding this, the legislation which will supplement the Energy Transition Act in France will have a responsibility, in particular, for encouraging such a deployment within the framework of an adaptation of the national and European electricity systems.

The changes that this study glimpses for the near future therefore require a strengthening of public policies concerning decentralized production, electricity storage, consumption management, and tariff links with the grid. These disruptive changes will also, fortunately, result in easier access to electricity services for all those populations (billions of people) which are more or less deprived of them at present.

The COP21 which is to be held in Paris in December 2015 is an opportunity to raise awareness of these breakthroughs and to guide capital investment taking into account the outlook for development of electricity production and storage technologies that are both competitive, beneficial for the population and the climate, and compatible with our planet's material resources. It is also an opportunity to enable initiatives supporting electrification of the developing countries to take paths that are both short and effective. This is by no means a panacea which would eliminate the need to reduce energy consumption in the rich countries and change our way of envisaging energy, but it is one way for us to face up to the energy and climate challenges of our planet. Let's seize this opportunity!

6. BIBLIOGRAPHY

—
Ademe DGCIS ATEE.
(2013). Etude sur le potentiel du stockage d'énergies.

—
Ademe.
(2015). Produire de l'électricité grâce à l'énergie solaire.
(2015). Vers un mix électrique 100% renouvelable en 2050.

—
Agence Internationale de l'énergie.
(2014). Technology roadmap Energy Storage.
(2015). Energy Technology Perspectives 2015.
(2014). World Energy Outlook.

—
Anne Labouret et Michel Villoz.
(2012). Installations photovoltaïques. Dunod.

—
Bank, D.
(2015). FITT for investors Industry Solar.

—
Bloomber New Energy Finance.
(2015). New Energy Outlook 2015.

—
CEA Ines.
(2015). Solar Mobility : long term practical experience charging electrified cars with PV.

—
CIRED A. Minaud C. Gaudin L. Karsenti.
(2013). Analysis of the options to reduce the integratino costs of renewable geenration in the distribution networks.

—
Citigroup.
(2015). Investment Themes in 2015 Dealing with Divergence Storage Batteries : a Third Growth Market.

—
Colin P. Kelley, S. M.
(2015). Climate change in the Fertile Crescent and implications of the recent Syrian drought.

—
D. Larcher and J-M. Tarascon.
(2014). Towards greener and more sustainable batteries for electrical energy storage. Nature chemistry.

—
Deutsche Bank.
(2014). 2014 Outlook : Let the Second Rush Begin.

—
EDF Division R&D.
(2015). Technical and economic analysis of the european electricity system with 60% RES.

—
EPIA.
(2014). Global Market Outlook for Photovoltaics 2014-2018.

—
ERDF.
(2013). Fiche thématique SERRER n°2 bis.

—
Finance, B. N.
(2015). Bloomberg New Energy Finance Summit 2015.
(2015). Global trend in clean energy investment.

—
Fondation Nicolas Hulot.
(2011). L'énergie solaire photovoltaïque.

—
GIEC.
(2014). Climate change 2014, synthesis report, summary for policymakers.

—
Institut Fraunhofer Agora Energiewende.
(2015). Current and Futur Cost of Photovoltaics.

—
International Electrotechnical Commission.
(2011). Electrical Energy Storage White paper.

—
International Technology Roadmap for Photovoltaic.
(2015). ITRPV, rapport 2014, 6ème edition.

—
Jean-Claude Debeir Jean-Paul Déléage Daniel Hémery.
(2013). Une histoire de l'énergie. Flammarion.

—
MIT.
(2015). The Futur of Solar Energy.

—
Morgan Stanley.
(2014). Batteries + Distributed Generation May Be a Negative for Utilities.

—
Morgan Stanley.
(2014). Solar Power & Energy Storage.

—
NREL.
(2013). The impact of Wind and Solar on the Value of Energy Storage.

—
Pedro A. Prieto & Charles A.S. Hall.
(2013). Spain's Photovoltaic Revolution The Energy Return on Investment. Springer.

—
Project, T. S.
(2015). Rendre flexibles les consommations électriques dans le résidentiel.

—
Rocky Mountain Institute.
(2015). The economics of load defection.

—
RTE.
(2014). Panorama des énergies renouvelables.

—
UBS.
(2014). Will solar, batteries and electric cars re-shape the electricity system ?

—
USGS.
(2012). Lithium Use in Batteries circulaire 1371.
(2015). Mineral Commodities summaries 2015.

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