LES CAHIERS

Louis Bachelier

RESEARCH ON THE TRANSFORMATION AND DECARBONIZATION OF THE ELECTRICITY SYSTEM

WITH

René Aïd, Joseph Frédéric Bonnans, Alain Burtin, Ivar Ekeland and Pierre Gruet

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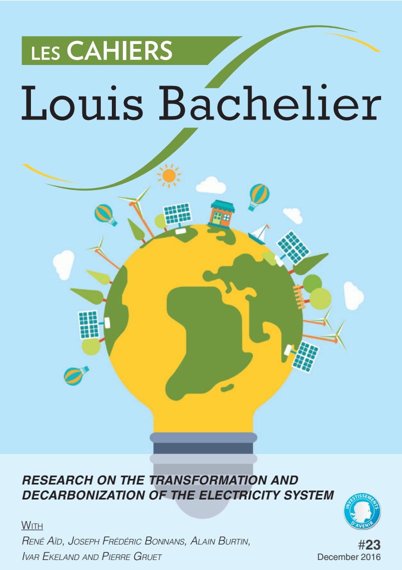

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EDITORIAL

Clémence ALASSEUR

Nizar TOUZI

The reality of global warming and the need to move towards an energy transition that reduces the consumption of fossil fuels (oil, coal, gas) has now achieved a global consensus.

The Paris Agreement, negotiated at COP21 in December 2015, has been ratified by more than 100 countries, enabling it to come into force at the beginning of November 2016. Its main objective is to hold the average global temperature rise to below 2°C at the end of the century, by reducing greenhouse gas emissions into the atmosphere.

In this context, in which the future of coming generations is at stake, renewable energy (wind, solar, hydropower), along with nuclear power, plays a major role in decarbonising electricity production. Today, these sources account for 23% of the world's energy mix and, if the Paris Agreement is adhered to, could be as high as 37% by 2040, according to the latest report by the International Energy Agency (IEA).

At the level of the European Union, the proportion of renewables in electricity production could be even higher, in the range of 45% to 60% by 2030. This ambitious objective is one of the priorities of the relevant authorities. The challenges, however, are immense, because this paradigm shift, linked to the development of green energy, entails financial, technological and operational constraints for energy companies. And this is where the contribution of research is vital.

As a long-established player in the electricity sector in France and abroad, the EDF Group is making major efforts in terms of scientific research, concretely illustrated by the Finance for Energy Markets Laboratory (FiME). Created in 2006, the FiME laboratory is today a Research Initiative of the Europlace Institute of Finance Foundation. It brings together a team of some thirty academic researchers and engineer-researchers from EDF R&D, specialised in particular in applied mathematics, economics and finance.

These varied profiles thus make it possible to link fundamental and applied research, a linkage indispensable for identifying and overcoming the many challenges of the electrical sector, already shaken up by the deregulation of recent years. This situation has given rise to many problems that research can answer. What pricing policy should be adopted in a competitive environment? How should an energy company manage variable demand? What buying/selling strategies in the wholesale markets should a producer deploy? How should the increased share of renewables, where production is irregular, be managed? And, above all, how can we gradually increase green energy and so reduce carbon emissions from the electrical system?

In this latest issue of the Cahiers Louis Bachelier, you will find answers to these questions from four recent scientific papers by FiME researchers, as well as an exclusive interview with the director of energy management programmes at EDF Research and Development.

Enjoy your reading!!

***Clémence ALASSEUR,** Director of the FIME research initiative and research engineer at EDF R&D*
*and **Nizar TOUZI**, Professor of Applied Mathematics at l'École Polytechnique*

PARTNERS

Electricity pricing: how are the current challenges best met?

The opening up to competition, the end of regulated tariffs and the development of renewable energies are transforming the electricity market. Ivar Ekeland and his co-authors address the question of how suppliers might construct new tariff packages adapted to these major changes.

Key points

- The modelling carried out by the researchers should allow electricity suppliers to establish tariff schedules that are better adapted to the needs of their potential customers and to the constraints linked to their different sources of production.
- This work also helps to understand and measure the impact of competing suppliers arriving in the market.
- For suppliers, it would then become possible to assess the cost of certain public service obligations, such as providing a basic service throughout the territory or offering special rates to those on income support.

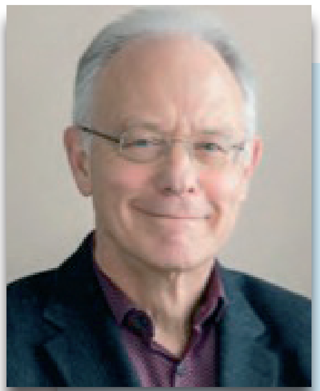
Based on an interview with Ivar Ekeland about his forthcoming paper *"Second-best tarification for a producer-provider of electricity"*, co-authored with Dylan Possamaï, Romuald Elie, Nicolas Hernández Santibáñez and Clémence Alasseur.

The selling price of electricity is currently one of the suppliers' most central concerns. Several factors, such as the opening up of markets, the end of regulated electricity tariffs, changes in power generation mixes, and especially the rapid development of renewables, are causing suppliers to rethink the pricing formulas offered to consumers. Smart meters, currently being deployed in Europe, are one of the tools that will enable innovative pricing to be introduced. But how can pricing proposals be adapted to the evolution of the energy mix? In other words, how can the various types of electricity production be taken into account? And what is the impact of other suppliers arriving in the market?

Taking account of competition and customer reaction

This type of problem already existed in the era of monopolies, but less acutely. Today, however, with the liberalization of markets, consumers are no longer as captive as they were in the past. They will sign a contract only if it meets their needs and is the most competitive offer available. The supplier must therefore take account of its customers' reaction to what it offers – not only their willingness to sign the contract, but also their level of consumption. The supplier needs also to make the tariffs it offers simple and easy to understand. They must be clearly visible on bills, rather than seeming to emerge out of nowhere. To this end, these four researchers have come up with a solution: *"Our work would enable electricity suppliers to establish pricing schedules that are better suited to the needs of their potential customers,"* says Ivar Ekeland, adding that the impact of the arrival of competing suppliers in the market

> *Electricity pricing gives rise to a new class of optimization problems, since customers have differing requirements that need to be met with specific tariffs.*



Ivar Ekeland

Ivar Ekeland has been a professor at (and president of) Université Paris-Dauphine and at the University of British Columbia (Vancouver). His research focuses on mathematics, finance and economics. His latest book, "*Le syndrome de la grenouille*", is concerned with climate change. He has received honorary doctorates from various universities and is a member of several academies.

Methodology

Ivar Ekeland and his co-authors have developed a model based on the economic theory of information asymmetry, and in particular the adverse selection principal-agent approach. In this type of model, the principal (the electricity supplier) offers a price schedule that varies according to the standing charge, the maximum power and the price per kilowatt hour consumed. Agents (consumers of electricity) are characterized as belonging to a specific "type", that is, a certain willingness to consume electricity at a given price. The principal does not know what particular type a given consumer belongs to, but knows only the distribution of types in the overall population – by means of surveys, for example. Of course, agents select a tariff only if its utility for them is greater than what they could get elsewhere, for example by turning to another supplier. In its optimization the principal must take into account the fact that only a proportion of consumers will subscribe to its offer. The principal's problem is then to construct a tariff schedule that will maximize its profit.

could also be understood and measured.

Pricing problems

Electricity pricing gives rise to a new class of optimization problems, since customers have differing requirements that need to be met with specific tariffs. An individual – who turns on the heating and uses her oven on returning from work – does not consume in the same way as a large firm that can shift some of its production to off-peak hours so as to take advantage of lower rates.

Just like a car insurer not knowing whether a prospective customer is a careful driver, the electricity supplier must establish a rate that will enable it to distinguish (or "discriminate between") customers according to how much electricity they consume. In the same way as the insurer offers a rate with a high excess and a low premium to attract cautious drivers (the reverse for others), the electricity provider prices on basis of the maximum usable power and the cost per megawatt hour.

> *"Unlike other commodities such as wheat or oil, electricity cannot (or can only to a small extent) be stored. Production must therefore closely match consumption at all times"*

Problems specific to electricity

While pricing in competitive environments is generally very complex, it is even more so in the case of electricity. In particular, suppliers must take into account the fact that the cost of production borne by the producer at any one time depends on customers' total consumption. Indeed, unlike other commodities such as wheat or oil, electricity cannot (or can only to a small extent) be stored. Production must therefore closely match consumption at all times. At peak periods, coal and gas-fired power stations can be used as well as nuclear energy and renewables. But the cost of instant production, which is much higher, increases the overall cost of production. In addition, renewables, such as wind and photovoltaic, operate intermittently, in accordance with weather conditions. *"Our model takes into account the constraints related to the different sources of energy production,"* Ivar Ekeland emphasizes.

Finally, it should be added that suppliers must take into account certain public service obligations, such as providing a minimum service throughout the territory and offering special rates for those on income support.

How can electricity demand volatility be reduced by means of pricing?

Because the reduction of greenhouse gas emissions necessarily involves increasing the share of renewables in the energy mix, the possibility for electricity suppliers of modulating demand becomes a key component of power systems management.

Key points

- The model can describe an optimal contract that reduces the volatility of an individual's electricity consumption.
- In the more realistic approximate version, where the price signal is sent by the electricity supplier, not continuously but at given times, the consumption smoothing effect occurs mainly at the start of the period.
- This work should allow new pricing schedules and new active demand management methods to be developed, that are better adapted to the generation constraints of renewables.

Based on the paper *"A principal agent model for pricing electricity demand volatility"*, by Nizar Touzi, René Aïd, and Dylan Possamaï, and on an interview with René Aïd.

The Paris Agreement on Climate Change, arising from COP21, seeks to limit global warming to two degrees Celsius between now and 2100. Achieving this goalwill necessarily involve decarbonising the economy.
To this end, electricity production needs to reduce its impact on the environment, given that it accounts for a third of the carbon emissions from fossil fuel combustion, according to the 2015 report by the International Energy Agency.

Intermittency of renewables

To reduce carbon emissions from electricity generation, nuclear power and renewable energy (primarily wind and solar) are the preferred modes of generation. Renewables, however, work only intermittently in time and space, as they are dependent on weather events (sunshine, wind, etc.).

Faced with this discontinuity of renewable electricity production, producers and suppliers need to have the wherewithal to modulate production and consumption. The three ways of doing so differ in terms of their benefits. *"First, physical storage capacity can be augmented by means of batteries, but these require considerable space and are entail high costs. Another solution is to use gas power plants, but these generate carbon emissions. Finally, changing consumption is a lever in which energy companies can invest, even though there is still insufficient information regarding this solution. Our work precisely concerns new techniques of active demand management"*, René Aïd says.

> *The optimal contract is able to reduce the volatility (or variation) of the customer's nominal consumption differences, while reducing the producer's costs*

Modulating electricity consumption by means of smart meters

Active management of electricity demand has existed for a number of years. Producers have applied differential pricing schedules depending on the day of the week and peak hours. These tariff incentives thus help reduce the power consumption of individual households, which are particularly responsive to price signals.
However, the results of this approach are still inadequately known and need to be refined. *"We consider it vital to improve communication with consumers,*

René Aïd

René Aïd is professor of economics at Université Paris-Dauphine. An engineer and then PhD in applied mathematics, he began his career at EDF R&D as a research engineer on optimization and enhancement models of electricity production assets. In 2006, he co-founded and became director of the Finance of Energy Markets Research Initiative, a joint laboratory involving Dauphine, EDF, the Ecole Polytechnique and CREST. In 2012, he was appointed head of the delegated department at EDF R&D, then in 2016 joined Université Paris-Dauphine. His research focuses on the management of financial risks in energy markets.

Methodology

Within the framework of a principal agent model involving an electricity producer (the principal) and a consumer (the agent), the researchers define an optimal contract, which minimizes the producer's production cost. In this type of model, the principal is unable to observe the agent's behaviour efforts. The model's solution for specifying the optimal contract is based on recent advances made by Jaksa Cvitanic (Caltech), Dylan Possamaï and Nizar Touzi. The optimal contract is then simulated numerically and compared with an approximate contract that is more realistic regarding the conditions for its practical application.

so as to reduce the time lag in the price signals being sent. In fact, producers need to further smooth out energy demand by encouraging consumers to shift their consumption forward or back in time, according to production constraints," René Aïd explains.

To do this, smart meters (such as France's Linky) need to be installed, so that power consumption modulation programmes can be deployed. In fact, this technology provides producers with extensive information related to consumption. With 45 million smart meters already installed – in Italy, Finland and Sweden – further investment of 45 billion euros is needed to reach the figure of 200 million smart meters in all 28 countries of the European Union.

A simple but effective model

Until such time as producers are able to use the data from such meters to develop modulation systems of electricity consumption at neighbourhood, commune or city levels, René Aïd, Dylan Possamaï and Nizar Touzi are seeking to establish, on the basis of a principal-agent model, what would be the best pricing schedules for achieving this goal of demand modulation. More specifically, they are looking at a situation where a producer (the principal) seeks to encourage a customer (the agent) to smooth out consumption over time.

Although a very simplified representation of reality, this model provides valuable insights for designing more realistic management systems that include a large number of consumers.

The model's basic assumptions are as follows:

- The electricity producer has a power plant with production costs not only depending on the level of production, but also on the movements upwards or downwards of this production.
- The producer only knows the customer's total consumption. He cannot observe the customer's actions and efforts to reduce or shift consumption.
- The consumer has a utility to consume and a cost to change his consumption in response to the producer's signals (effort, adaptation, time shift, etc.).

It is then a matter of finding the optimal contract that minimizes the producer's overall production costs and the payment to the consumer for smoothing out consumption.

Note that this model lies within contract theory, the research field for which Oliver Hart and Bengt Holmstöm have just been awarded the 2016 Nobel Prize for Economics.

Towards a more realistic model

Numerical simulations confirm that the optimal contract is indeed able to reduce volatility (or variation) of the customer's nominal consumption differences, while reducing the producer's costs.

However, the modelling was carried out on the assumption of a price signal in continuous time, which is not operational at a technical level.

To overcome this constraint, the researchers compared the optimal contract with an approximate contract that depends on consumption points at given moments (breakdown into consumption periods). *"With the approximate contract, the consumer reduces his volatility of consumption mainly at the start of the period. This allows the producer to reduce its costs. However, we need to further develop our work if we are to come up with a single and intelligible pricing system intended for a consumer population. The aim is to obtain a signal compatible with the modulation capabilities of local production without creating inconvenience for the consumer,"* René Aïd concludes.

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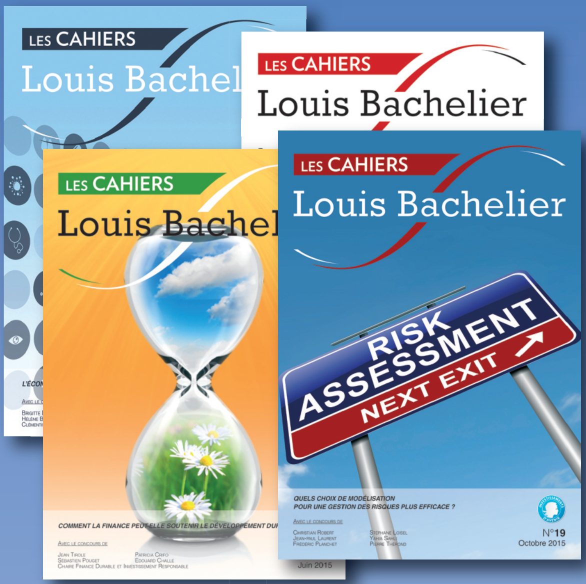

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How should producers behave in intraday electricity markets?

With the increasing share of renewables – which are inherently intermittent – in power generation, energy providers have to contend with an increasing degree of uncertainty. The intraday market for electricity is one of the means at their disposal to compensate for any unexpected shortfalls in production.

Key points

- In this model, the producer aims to find the best trading strategy in intraday electricity markets so as to minimize its physical and financial costs.
- The producer compares the costs of its means of production to the price of electricity in the intraday markets. It needs to be fully aware of their volatility and of its own impact on price rises and falls.
- It is in the producer's interest to smooth out its purchases in the intraday markets so as to reduce the impact of his own purchase or sales orders on the price and to take into account the most recent information on its production from renewables as well as forecasts of demand.

Based on the paper *"An optimal trading problem in intraday electricity markets"* by René Aïd, Pierre Gruet and Huyên Pham, and on an interview with Pierre Gruet.

While the level of nuclear or coal-fired electricity generation is largely controllable by energy providers, this is not the case for the level of production from renewable energy sources (solar and wind), which is subject to meteorological events (sunshine and wind speed).

The margin of error for forecasting the power generated by a wind farm may, for example, be as high as 20% of its installed capacity within a six-hour time period.

In general, taking account of this uncertainty is a growing problem for the sector's actors, in a context where the proportion of renewables in the French and European energy mix is steadily increasing.

Electricity producers also have to contend with the fact that electricity is difficult to store, which means they have to accurately match production with demand at all times, or be faced by financial penalties.

In order to reduce the gap between production and demand, producers have two main options. They can bring on stream additional thermal power plants (for example, gas or fuel oil) to increase supply, or they can purchase electricity in intraday markets. While both these solutions give rise to specific additional costs, the choice of the best strategy to adopt at any given time can be quite complex.

> *"Intraday markets offer an alternative for meeting electricity producers' temporary needs"*

Intraday electricity markets are indispensable levers

Because the costs of using a booster thermal plant can be very high, especially if it is not already in operation, intraday markets offer an alternative for meeting electricity producers' temporary needs. Exchanges for spot power trading, such Epex Spot in Paris, are open 24 hours a day, seven days a week. These markets operate on an auction basis between buyers and sellers. Spot prices are set daily at midday for next day delivery and the intraday markets then take over, enabling producers to continue trading. *"Intraday markets are a valuable adjustment variable for producers, who can use them to manage their production more flexibly, because they can buy or sell electricity as news comes in, for example, anticipation of ad-*

Pierre Gruet

Pierre Gruet is a research engineer at EDF R&D, working on prices modeling. He holds a PhD in applied mathematics from University Paris Diderot, bearing on statistical estimation and stochastic optimal control. He is also a fully qualified member of the French Institute of Actuaries, and holds the diploma of the École Nationale de la Statistique et de l'Administration Économique.

Methodology

The model involves three sources of uncertainties, namely residual demand, available thermal capacity and variation in electricity prices. Such price changes are the result of natural hazard, the impact of the first two uncertainties and the producer's actions in the market. The objective of the problem is to minimize the producer's expected costs in the presence of these three uncertainties. Its solution gives the producer, at every moment, the fraction of its residual demand that it must cover and how it should do so, either by purchases in the markets or by using its thermal production. This strategy also depends on the variables of the system, namely demand, purchases/sales already made on in the intraday markets, and the price quoted.

ditional demand, meteorological information, breakdowns, etc.," Pierre Gruet says.

A producer who decides to use the intraday market must also take account of phenomena specific to these markets, such as price volatility and the impact on the price of its own purchase or sale orders. This makes the trade-off decision between using more of its own means of production or trading in these markets more complex.

An original model for optimizing a producer's decisions

In order to better understand the effects of these choices and to facilitate the decision-making of an energy supplier confronted with this type of problem, René Aïd, Pierre Gruet and Huyên Pham have developed an original mathematical model that combines the financial techniques of optimal trading and the physical constraints of production management. This model variously takes into account the costs of financial penalties imposed on the producer in the event of an imbalance between supply and demand, the costs of producing non-renewable energy in thermal power plants and the costs involved in trading in the markets.

The researchers have also introduced an additional variable, namely the producer's random residual demand, which represents the consumption of its customers minus its production from renewables. And it is this residual demand that the energy supplier must meet through thermal production or market operations, or be liable to financial penalties. This residual demand is not fixed and may vary abruptly, for example in response to unforeseen weather events. Moreover, available thermal production can also vary due to a breakdown in a thermal power plant, obliging the producer to turn to the market. But in such a case, i.e. lack of production at time T, electricity prices on the intraday markets are then driven up, since all actors are informed of the shortage. *"We have sought to determine the strategy that a producer should adopt in the markets when there is a sudden peak of residual demand or an unexpected event in conventional thermal installations,"* Pierre Gruet explains.

In other words, should the producer immediately purchase the amount of electricity it needs or wait for prices to fall? This decision will depend partly on the producer's risk aversion. Above all, the model suggests that it will be in the producer's interest to smooth out its purchases over the day, as this strategy allows it to reduce its exposure to the markets and to adjust its purchases in accordance with the news it receives regarding its production of renewable energy, its expectations of electricity demand and the state of operation of its thermal power stations (all three of them random factors). On the other hand, if electricity prices in the markets are higher than its production costs, it makes sense for the producer to activate its thermal power plants. *"Our model addresses the problems of optimizing the production of energy companies. They can determine the best strategy to adopt in the markets while minimizing their costs,"* Pierre Gruet says.

Improving microgrid management

The management of microgrids - which make it possible to bring electricity production closer to consumers - gives rise to complex optimization problems. In particular, they must satisfy variable demand for electricity at least cost, making maximum use of renewable energy sources and possible storage equipment.

Key points

- The researchers have developed an original dynamic programming model that involves a stochastic approach. This can optimize the management of an isolated smart microgrid by assessing its demand for electricity.
- Through this stochastic model, the microgrid's electricity production is managed more efficiently, reducing the use of the diesel generator.
- The speed of calculation of the solution provided in this new model is higher than that obtained through a deterministic approach.

Based on the paper *"A Stochastic Continuous Time Model for Microgrid Energy Management"*, by Benjamin Heymann, Joseph Fréderic Bonnans, Francisco Silva and Guillermo Jimenez, and on an interview with Joseph Frédéric Bonnans.

The French Regulatory Commission of Energy defines "microgrids" as small-scale power grids that provide an energy supply (...) to a small number of consumers. They operate mainly through renewable energy sources (solar, wind, hydro), but also non-renewables (diesel generators) and to a lesser extent electric storage batteries. The management of these systems is carried out by means of computer programs.

They can, moreover, be connected to the main distribution grid to relieve it during periods of peak consumption or they can operate autonomously. With regard to the latter, microgrids are able to supply electricity more efficiently to remote areas, such as villages in developing countries.

A fast growing market

In addition to these characteristics, microgrids bring other economic and operational benefits, because the expansion of large conventional power grids and gas distribution networks entails significant investment, and storage costs, as well as technical constraints.

For all these reasons, microgrids are enjoying a worldwide expansion – a trend that is expected to increase in the coming years. A recent study by the US firm Navigant Research estimates that the electrical capacity of microgrids will, at the very least, amount to 7.6 gigawatts (GW) in 2024, compared with 1.4 GW in 2015.

> *"The researchers have extended their previous work, based on a deterministic model, by developing a dynamic stochastic model new to the literature"*

However, the deployment and operation of these microgrids create specific needs for the sector's actors and various stakeholders (the public authorities and consumers). In particular, how should the functioning of these installations be optimised to take account of the variable demand for electricity?

A model to improve the management of an existing microgrid

To answer these questions, the four researchers (Benjamin Heymann, Joseph Fréderic Bonnans, Francisco Silva, Guillermo Jimenez) analysed an isolated microgrid located in the Atacama desert in northern Chile, that supplies electricity to the village of Huatacondo.

The grid consists of solar panels, wind turbines, a batte-

Joseph Frédéric Bonnans

A graduate of the École Centrale Paris and PhD in Engineering from the University of Technology of Compiègne, Joseph-Frédéric Bonnans is a senior researcher at the French National Institute for Research in Computer Science and Control (INRIA) and leader of the COMMANDS team, researching dynamic optimization, at the Centre for Applied Mathematics, École Polytechnique.

Methodology

The model involves three sources of uncertainties, namely residual demand, available thermal capacity and variation in electricity prices. Such price changes are the result of natural hazard, the impact of the first two uncertainties and the producer's actions in the market. The objective of the problem is to minimize the producer's expected costs in the presence of these three uncertainties. Its solution gives the producer, at every moment, the fraction of its residual demand that it must cover and how it should do so, either by purchases in the markets or by using its thermal production. This strategy also depends on the variables of the system, namely demand, purchases/sales already made on in the intraday markets, and the price quoted.

ry energy storage system and a diesel generator powered by fuel oil. Using these various parameters, the researchers developed a model that enables demand to be met more effectively. In other words, the model optimizes the use of the different sources of electricity production, in accordance with their specific constraints.

The researchers thus took account of the villagers' variable demand and the microgrid's different energy sources of energy, primarily solar panels that generate most of the energy, with a peak at noon, along with wind turbines, whose operation is subject to weather conditions. A battery is used to store surplus renewable energy and to offset increased demand, though it has a limited lifespan. Finally, there's a generator powered by fuel oil (producing CO_2 emissions), which consumes more when it starts up.

A dynamic and innovative stochastic model

Alongside these parameters, the researchers were able to access data from the electricity produced from the solar panel. *"The production of solar energy was easily predictable, since our experiment was conducted in an arid desert. However, we were faced with two major problems. First, modelling the variability of electricity demand. And second, as much as possible limiting the use of the generator, which runs on fuel oil and has a high operating cost,"* Joseph Frédéric Bonnans says.

To solve these problems, the researchers have extended their previous work, based on a deterministic model, by developing a dynamic stochastic model new to the literature. From a methodological standpoint, this new, more realistic and operational model involves discrete variables (battery on/off) and continuous variables (battery charge level), as well as stochastic differential equations. Technically, the model has a structure suitable for dynamic programming, which opens after discretization on a semi-Lagrangian algorithm. By applying to the latter an ad hoc method of minimization of the Hamiltonian, which is also new, the researchers were able to simplify the numerical calculations. *"Our stochastic dynamic programming model estimates electricity demand and the cost of using the generator through an algorithm, which makes it possible to optimize the management of an isolated microgrid. Moreover, the speed of calculation of the solution by our stochastic algorithm is higher than that obtained by a deterministic approach in continuous time,"* Joseph Frédéric Bonnans says.

In practice, the model makes it possible to envisage more efficient management of the resources of this Chilean village, and thus would give them a better energy autonomy.

Important potential applications

While the results of this research are highly encouraging, they nevertheless need to be taken further in order to deal with more refined extensions. The tracks envisaged include in particular the modelling of battery aging, that is to say, estimation of the battery's lifetime as a function of its use. In addition, understanding and managing a smart microgrid would eventually allow this new model to be extended to a set of microgrids that would be connected to a main grid. Research in this area thus more than ever needs to continue.

“Competition is not uniform across the various means of production”

While the energy transition, based on a reduction in carbon emissions, is gradually taking off, it nevertheless requires significant efforts in terms of research and development (R&D).

To get an overview of the research carried out by EDF, Alain Burtin – director of energy management programmes at EDF R&D – details his priorities. In the capacity of his job, he is in charge of research issues linked to the optimization of the various means of electricity production, interactions with financial energy markets and the development of low-carbon power systems that will go hand in hand with the further development of renewables. He is also Vice-President of the European Smart Energy Demand Coalition (SEDC).

Could you briefly describe EDF’s R&D department?

At EDF, research and development involves than 2,000 people at ten sites around the world. This international openness allows us to have a global vision of energy problems and to consider different points of view. In 2015, the group had an R&D budget of 560 million euros.

What does the FIME laboratory – which celebrated its tenth anniversary this year – bring to EDF?

This research initiative of excellence is a very good bridge between the academic and industrial worlds on issues at the interface between finance and energy. For example, FIME has developed numerical models and methods to further identify the mechanisms of energy markets, focussing on the characteristics of financial products specific to electricity.

What are the current priority areas of research for EDF?

Our R&D is currently focussing on three main areas. First, the development of innovative energy services, which are major challenges for consumers. Indeed, the development of new information technologies and the rapid growth of the Internet of things, together with remotely controllable equipment such as the Linky meter, will enable us to experiment with new services for our customers and to monitor their consumption more accurately. These upcoming improvements are consistent with the energy transition, because they will lead to greater awareness among customers and therefore better use of electricity. Our aim is to go beyond simply supplying electricity and to contribute to a more efficient use of energy.

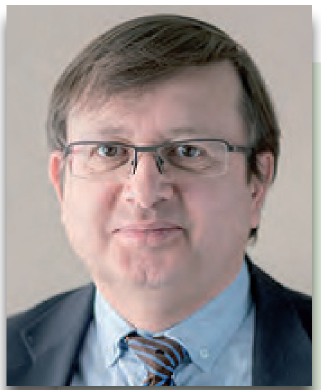
Secondly, we are particularly interested in the development of tomorrow’s power systems, which will include more renewable energy sources such as wind and solar. However, these decentralized forms of power generation, which fall short of meeting the total need for electricity, have to interact with the main traditional networks. The latter are of fundamental importance because they can store some of the electricity generated by decentralized renewables, and share them and reduce costs while benefitting from synergies with conventional centralized nuclear and hydraulic power generation, which are also low-carbon. The strengthening of these networks and their management is therefore decisive for the efficient integration of renewables into electrical systems. As a result, the increased use of power electronics, particularly for connecting renewables to networks, reduces their inertia and requires the development of more efficient frequency and voltage regulation, so as not to jeopardize the security of networks. This issue entails reviewing protection plans and grid equipment in order to increase the integration thresholds of renewables into electrical systems.

> *“The encounter between the academic and operational spheres has been an inspiration for developing a number of tools for the Group’s various departments”*

Thirdly, we are working on the consolidation and development of various low-carbon power generation technologies such nuclear and renewables, as well as on the development of efficient electricity uses (electric vehicles, heat pumps, etc.). A specific research programme is devoted to energy storage, particularly of electricity by means of batteries. This technology is still very expensive, but it has potential for significant cost reductions.

How can the proportion of renewable energy be increased in the energy mix in France and more generally in Europe?

At present, renewable energies amount to 18% of the French electricity mix, including hydroelectricity, the production of which is not intermittent. Wind and solar have become competitive energy sources in recent years. They therefore have a real place in the electricity markets of the world and of Europe, the latter having made a major decision in encouraging their development. In the European context, where the potential of hydropower is widely exploited, wind and solar are the



Alain Burtin

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two main sources of electricity that need to be developed in order to meet the renewable energy objectives of the European 2030 Climate and Energy Package.

It should not be forgotten, moreover, that the share of renewables in the energy mix is also expected to increase for the production of heat. The multi-annual energy programme, the decree for which has just been published, proposes a set of measures to speed up the development of electricity-generating renewables and of renewable heat production in France.

Achieving the European 2030 targets would bring the share of renewables in the European electricity mix to 45%. Doing so is conceivable within the framework of the large interconnected European network, since the capacity for integrating renewables into this grid is higher than that of national systems taken separately. In 2015, EDF R&D published a study simulating the consequences for the European electricity system of a rise to 60% of renewables in total electricity production, which goes further than the targets set for 2030. This high-end scenario appears to be achievable, though major challenges will need to be overcome.

For example?

The integration of wind and photovoltaic energies into the electrical system raises the twofold question of managing intermittency at the local level in distribution networks (high and low voltages) and managing the impact of the variability of renewables on the supply-demand balance across the interconnected European system. Given that electricity is not stored and that supply and demand have to be balanced at all times, it will be necessary to adapt the electricity system and develop new flexibility levers in addition to the existing levers, particularly by making renewables contribute to this flexibility.

The pace and development thresholds of intermittent renewables needs to be optimized in order to adapt electrical systems to these new challenges. As I mentioned earlier, the adaptation of the networks and of the system in general to renewable energies is a major problem, because when the proportion of renewables is high, the requirements from supplementary forms of production, particularly thermal power stations, are higher. In terms of the evolution of the production mix, the contribution of nuclear power will be needed to reduce expected CO_2 emissions in Europe within the 2030 timeframe, while thermal backup is likely to remain permanently necessary to ensure power supply security.

How about investment requirements?

One of the main challenges is to find a compromise between the temporal trajectory needed to reduce CO_2 emissions and sustainability at a technical and financial level. The capital-intensive nature of our sector calls for a rethinking of market structures in order to create incentives to invest. It must be said that today there is a real problem of consistency in regulation. Competition between the different forms of production is not uniform. Thus electricity generated from renewable energy is paid for by long-term purchase obligation contracts, while demand does not increase at the same rate. Under these conditions, short-term market prices do not regulate longer-term investments. The low price of CO_2 in the EU ETS market simply adds to the market's lack of effectiveness in guiding investment decisions and consumption in the medium and long term. This situation prevents us knowing clearly what additional capacities will be needed in the future. The debate on the ground rules of electricity markets is on-going and needs to be settled.

What if we look beyond 2030?

The mix options after 2030 will no doubt call for further changes, hence the importance of carrying out research. It is important not to discard any technology in principle, for it is within this perspective that we set up scenarios and intensively monitor technologies. Nor should we forget the many partnerships we have with start-ups in order to avoid missing important innovations.

Find Alain Burtin's full interview on www.louisbachelier.org

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