Advanced Research and Development of Clean Energy Technologies within CNRS

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1. Introduction

The prospects for sustainable development depend on a sustainable, secure and competitive energy supply with reduced environmental impact, both locally and globally. The energy problem is part of a complex framework that must respond to several major challenges: guaranteeing access to energy for all at an affordable cost, being part of climate change mitigation and adaptation, preserving human health and the environment and providing a sustainable energy mix. Thus, the strong growth of demand expected by 2030 at the global level should be satisfied by a wide diversification of energy sources, by increasing production and the integration of non-fossil energy into the network, in particular to control greenhouse gas emissions or to limit reliance on feedstocks that are irregularly distributed and inherently limited. To meet the needs of diversification of supply and major climate issues, the 21st century will therefore be that of the energy transition.

Since signature of Paris agreement of COP 21, France has adopted several policies to tackle these challenges such as the energy transition for green growth (LTECV)[1] and the National Low Carbon Strategy (SNBC), among others. The goal is to guide technological and societal choices towards the objectives and to support the research and development effort (R & D) which is necessary for the continuous improvement of existing offers and the development of new options. This resulted in the launch in 2016 of a National Energy Research Strategy (SNRE), by the Ministries of research, Environment and Sustainability, and industry. This SNRE act aims at identifying the R & D stakes and the scientific barriers to overcome at different time scales and throughout the energy innovation chain to enable the achievement of the objectives of the LTECV policy plan in France, while at the same time inscribing this R&D in a broader international perspective.

France is also committed to several European R&D energy policies which focus on the systemic issues posed by tomorrow's energy challenges related to new modes of production of energy (variable and distributed sources of renewable energy), consumption (energy efficiency at industry and building levels...), transport (e-vehicule, smart grids…), and storage (batteries, hydrogen…).

2. R&D activities related to clean energy technology

CNRS, the National Centre for Scientific Research, is the largest research organization in France and in Europe. Its mission is to develop fundamental and generic knowledge in all scientific disciplines, and to bring out concepts that are breaking down and can lead to innovative products and services. CNRS has registred the Energy Transition among the six societal challenges for the period 2019-2023.Thus, more than 4000 full time researchers working within 250 CNRS-

[1] *Among the objectives: Reduce greenhouse gas emissions by a factor 4 between 1990 and 2050 ; Reduce the primary energy consumption of fossil fuels by 30% in 2030 compared to the 2012 reference; Increase the share of renewable energies to 23% and 32% of final energy consumption in 2020 in 2030, respectively; Set the share of nuclear power in electricity production to 50% by 2025.*

Universities joint labs over the whole country and abroad, are currently developing activities on topics related to energy. The main research themes of the researchers concern development of renewable energies (mainly biomass, solar and marine), flexibility of systems for the integration of renewable energies, energy storage including production and utilization of hydrogen energy carriers, decentralization and multi-scale governance of energy systems, improvement of nuclear energy production and safety, societal and economical aspects related to energy production and use, etc.

CNRS has also established strong collaborations with industry through several joint labs, such as with TOTAL, EDF, Air Liquide to mention some. The research topics concern photovoltaics, grid network and hydrogen production, respectively.

3. Specific research activities in renewable energies, next generation energy management system with batteries, hydrogen, CCUS, and related technologies

To mitigate the problem of global warming, decarbonisation of the energy sector is mandatory. It can be provided by using universal Renewable Energy Sources (RES) such as biomass, solar, and marine energies. Activities at CNRS labs dealing with biomass (wood, dedicated crops, vegetable waste), are mainly focusing on 2nd et 3 generation of biofuels produced by biological (ethanol) or thermochemical methods. As for solar energy, most of the R&D is concentrated on photovoltaics to develop either new materials based on abundant elements (e.g. metallic oxides …), advanced solar cells concepts (e.g. hot carrier solar cells, up/down shift converting layers…) or novel device architectures (e.g. 2T or 4T tandem cells). The aim is to develop high-efficient solar cells at low cost.

On the other hand, the energy transition requires the development of efficient energy storage and conversion technologies to manage the intermittent nature of the RES and ensure the matching between clean energy production and its consumption. Electricity and hydrogen are energy vectors particularly adapted to this task. They can be stored by electrochemical (batteries, supercapacitors) and physico-chemical (compressed gas and hydride materials) means, respectively. They have complementary discharge time-scales and energy densities and can be converted from one into another using fuel cells. Some CNRS teams have great and worldwide expertise in batteries and supercapacitors with the aim to develop new generation (Na batteries…). As for hydrogen, the challenges are the development of equipment for an efficient production of hydrogen by electrolysis (preferably at high temperature using “unused” heat), production of carbon-free hydrogen from renewable energy resources such as by electrolyzing water using electricity generated from solar or wind power, a breakthrough for the 3rd generation of PEM batteries for mobility and for innovative storage means (solid as well as organic liquids) and the understanding of degradation and aging phenomena.
In the topic of grid integration, CNRS is working on how connected multi-scaled grids are enable effective development and utilization of renewable-based distributed energy resources while optimizing quick energy transfer from distributed energy sources to variety of load centres (fluctuating, local and regional). The rationale behind it is a potential reduction in the need for investment in additional power generating stations.

Within CNRS, a total of 4500 full time equivalent staff work on the field of energy overall. Although all fields of energy are concerned, ranging from nuclear to storage, distribution and transports, renewable energy is the main focus of CNRS research on energy, with a total of nearly 1700 staff working on renewable energy research at CNRS.

4. International collaboration
4-1 International alliance/networking development

CNRS has a clear and ambitious international collaboration strategy as witnessed by the numerous international cooperation tools[2] that are offered to build and/or strengthen high level collaborations with leading institutes laboratories or Universities over the world. The most important and visible instrument for international cooperation of CNRS worldwide is probably the International Research Laboratories (IRLs) such as LIMMS in Japan. Such IRLs are located in a foreign country, and have facilities where researchers, students, postdocs, and support staff from CNRS and the foreign partner' institution are working together on well-defined topics. The Director of the IRLs is jointly named by CNRS and the foreign partner institution(s). The IRLs have a duration of five years and can be reconducted.

Other international cooperation tools are the *International Research Projects (IRP)* which are collaborative research schemes between one or more CNRS laboratories and one or two laboratories from foreign countries. The purpose is to strengthen previously-established collaboration through short- and medium-term scientific exchange, in addition to organising working meetings or seminars, developing joint research activity including field research, and supervising students. These programmes have usually a duration of five years. Another tool is the *International Research Network (IRN)* dedicated to structuring international research networks with a focus on a common theme or research infrastructure. It promotes the organisation of international workshops and seminars, as well as thematic schools organised by the network partners in France and abroad. It lasts for five years. There is also the International Emerging Actions (IEA) tool dedicated to exploring new topics and partnerships at the international level through PI-to-PI projects. The actions are usually short-term mobility of scientists, the organisation of working meetings, and the initiation of early-stage joint research works for shared scientific projects. Such projects are funded for a duration of two years.

It should be added that around 55,000 short visits (conferences, stays…) and secondments are also carried out by the CNRS fellowships over the world each year. More important, over 200 researchers (including secondments) perform research in foreign institutions for durations of one year or more. As a result, over half of the organization's publications are joint publications with international partners witnessing the CNRS' international vitality.

CNRS is also a major player in the development of the European research area and thus an important contributor to the European integration process. These last years, CNRS' researchers have participated to more than 1250 EU projects, and about the fourth of them are dealing with energy. CNRS also took an active part in the International Cooperation projects (INCO) launched by the EU commission. Last but not least, CNRS is participating to the European Interest Group (EIG) CONCERT-Japan which is a multilateral joint funding initiative between Japanese JST and European partners. In 2017, this program was focusing on "Efficient Energy Storage and Distribution" ».

Finally, researchers from the Humanities and Social Sciences department of CNRS are also involved in understanding and bringing solutions to issues which are emerging with the energy transition. Besides the commitment issue to new technologies (hydrogen for instance), they address the anthropological, sociological, political and economic aspects brought by the changes

[2] *https://international.cnrs.fr/en/cooperer-a-l-international/*

during usages: new consumption trends (consum'actor' citizens), new mobility, new markets, policies, multilevel managements, in addition to protection of privacy, availability of energy to all...

4-2 International joint R&D activities

It is worth saying that a high number of projects are carried out with European partners thanks to the bilateral and European commission on Clean and Sustainable Energy programmes. Yet, CNRS has used the tools mentioned above to fund, totally or partially, several joints projects dealing with the development of innovative clean energy technologies involving many foreign partners originating from North and Western Africa, North America (USA, Canada), Asia (Japan, Taiwan, China, India, Singapore), and Australia.

To mention some, there is IRP-ATLAS "Associated Trans-Mediterranean Laboratories for Applications in Solar Energy," with Morocco **(2017-2021)**, which is a formal structured international laboratory collaboration created by CNRS, Georgia Tech, and Moroccan education (MESRSFC) and research (CNRST) entities for international collaborations. This lab will allow for scientific synergies in photovoltaics, energy efficiency, and provides resources for the exchange of students and researchers, and a platform for building joint projects funded by companies and by public sources. There is also IRP NEXTPV (2016-2024) is an International Joint Laboratory on next generation of photovoltaic cells, operated by the French CNRS, University of Bordeaux and the Research Centre for Advanced Science and Technology (RCAST), The University of Tokyo. It aims at developing High efficiency solar cells concepts and devices based on III-V heterostructures, hot carriers solar cells and intermediate bands solar cells as well as Organic and Hybrid Solar cells. There also the French-SINgaporean network on renewable enERGIEs (SINERGIE), an international research network (IRN) resulting from a CNRS - NTU joint initiative. It has been formally established in 2017 for 5 years and covers a wide range of topics: Smart Grids and Power systems, Energy storage, Wind and Marine Energies, Photovoltaics and Green and smart buildings. The last IRN under finale signature is the French-Australian research network on Conversion and Energy Storage for stand-alone & maritime applications (FACES) which involves several CNRS labs, UNSW, University of South Australia and Deakin University. The scientific program of this program is focusing in two main research axes, namely electrochemical storage and hydrogen conversion. For the Electrochemical storage part, it is intended to design new electrode materials and electrolytes for lithium-ion batteries to their upscale, taking into account the Australian local mining and development of new battery and supercapacitor chemistries for energy storage, and to work on Prototyping, reliability, aging, management and safety tests. As for the hydrogen conversion topic, the IRN will address the chemical hydrogen storage related to on-board hydrogen production, will study the reversible hydrogen storage aspect and End-use of hydrogen and fuel cells, and finally to set a plan for system integration which includes architecture, energy management, design methodologies, etc.

As for nuclear, many international collaborations exist contributing to increase the safety of current reactors, to develop innovative reactors (SMR - "Small Modular Reactor", 4th generation reactors) and knowledge in the field of storage and dismantling. These collaborations are carried out with several countries (Russia, China, Japan, United States, ...), as well as with many European Member States within the framework of the programs supported by the European Commission. Last but not least, CNRS is involved in the international ITER project to demonstrate the feasibility of using thermonuclear fusion in the longer term.

5. Future perspectives (beyond 2030)

Mastering the energy mix by 2050 and beyond is an important international challenge that leads to major research and specific equipment needs. The energy systems of the future, in whatever form, require large investments, major research and development (R & D) with a strong need for dedicated research infrastructures. It also involves managing uncertainties (prices, geostrategic considerations, learning curves of different technologies, behaviour of actors, etc.) to make the decisions that are the least costly in the long term.

In this context, CNRS will pursue its R&D activities in the field of clean and sustainable energy by developing renewable energies (RES) and its storage, by mobilizing bio-sourced materials (for example wood in construction), by encouraging controlled and less polluting mobility, by offering solutions for energy savings in all sectors, especially industry, buildings, transport, and by developing the circular economy, via ecodesign, reuse and recycling. Among the topics, there is the development of new and efficient materials for energy for which many challenges emerge (need for new generations of lighter, more insulating, more resistant materials, possibly working in extreme conditions, to cover the needs of transport, building, storage and conversion of energy, etc.). storage of electricity in electrochemical form is an important axis of future R&D at CNRS to examine the new technologies of high-performance batteries (stored energy density, load / discharge cycles) and supercapacitors with opportunities for industrialization. Other R & D topics related to storage will concern for example the production of hydrogen by electrolysis but put in a broader perspective related to the multiple uses of hydrogen in several sectors, and performing materials for thermal storage. The numerous existing international collaborations in the different sectors of energy will be continued and strengthen and other are planned (India on photovoltaics, Australia on solar energy…)

It should be noticed that the major scientific issues, and particularly for the energy sector, pose the challenge of having experimental means and research tools at the forefront of scientific and technological knowledge. Observation, measurement, storage and sharing of data imply large instruments carrying technical capabilities beyond the existing and integrating interdisciplinary porosity source of innovation. These tools are the conditions for future discoveries as well as the product of the latest scientific and technological advances.

The existing very large infrastructures in the field of energy are five so far (ECCSEL, FR Solaris, Sophira, Theorem and West), covering different themes and all are the "French nodes" of future or existing European and international collaborations.

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• University qualifications:
- ◊ Habilitation à diriger des recherches, Université de Paris-Sud (1993)
- ◊ PhD, Université Paris Diderot (1985)
- ◊ Agrégation de Mathématiques (1982)

• Professional career
- ◊ From February 2019, on leave at CNRS
  - ∗ President and CEO
- ◊ From August 2006 to January 2018, on leave at Inria, Institut National de Recherche en Informatique et Automatique
  - ∗ From October 2014, President and CEO
  - ∗ From September 2010 to September 2014, deputy CEO
  - ∗ From August 2006 to August 2010, Director of the research center of Paris - Rocquencourt
- ◊ From January 2004 to July 2006, on leave at CNRS, the French national center of research
  - ∗ From September 2004 to Januray 2006, Regional Director for West South of France
  - ∗ In 2004, Director of the Information and Communication Technologies and Sciences department
- ◊ From 1994 to 2003, Full professor at ENS Paris-Saclay (formerly ENS de Cachan)
  - ∗ From November 2001 to December 2003, Deputy director of the directorate of research of French ministry of research, in charge of mathematics and in- formation and communication sciences
  - ∗ From October 1995 to October 2001, Director of the department of computer science of ENS Paris-Saclay

◊ After a PhD on formal languages theory, my researchs have focused on the study of models, mainly based on transition systems, for parallel and timed processes. As the years go, specification and verification of such systems become one of the main motivations of my studies.

◊ My research activities have been the subject of about fifty international publications among which 5 books, 17 journal articles and 26 conferences with proceedings and program committees. I advised 8 PhD students.

* Distinctions
- Chevalier de la légion d'honneur
- Officier de l'ordre national du mérite