Energy4Climate (E4C) Interdisciplinary Center

White Book

Energy and Climate: Research perspectives

E4C INTERDISCIPLINARY CENTER

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Foreword by Eric Labaye, President of École Polytechnique and Institut Polytechnique de Paris

"Global warming is speeding up. While the last report published by the IPCC offers a quite worrying perspective, we believe there is still hope if we use one of our greatest powers: scientific knowledge. In order to address one of the biggest challenges that humanity has ever had to encounter, research and innovation have the potential to bring solutions to reverse the trend. As scientists, as the leaders of today and tomorrow, it is our responsibility to help solve this issue.

It is with that goal in mind that Institut Polytechnique de Paris, composed of École Polytechnique, ENSTA Paris, ENSAE Paris, Telecom Paris, and Telecom SudParis created, in partnership with École des Ponts, its interdisciplinary center in energy and climate, E4C. With the support of the School's Future Investment Program Research University (EUR) and of our partners, CNRS, CEA, EDF, TotalEnergies, we share common concerns and ambitions: among them, we are convinced that solutions to climate change are scientific, transcending political divisions.

On the occasion of its 225th anniversary in 2019 and the organization of its international scientific symposium, École Polytechnique asserted its determination to place sustainable development at the core of its actions, in education, research and innovation. That major event sent out a strong message: the necessary adaptations of humanity facing climate change and the increasing scarcity of natural resources constitute a priority for all. And institutions of higher education need to take part in it. As we took this commitment and with the development of Institut Polytechnique de Paris, we were able to develop the EUR in energy and climate, which scaled up the E4C Center and designed programs specialized in sustainable development that fit younger generations' aspirations.

The publication of this white book of our E4C Center is a great testimony of the achievements we have made for the past two years, a token of our success. In order to meet Paris Agreement goals, the E4C Center's research is organized in 8 "Research Actions" grouped into 4 major pillars: reduce greenhouse gases in the atmosphere, reduce energy consumption, deploy renewable energies, and determine sustainability of climate policies. We are thrilled to present to you the many projects that our teams of researchers are developing, united by the same ambition: to reach the highest level of expertise in order to ensure energy transition. I would like to pay tribute to the excellence of our research staff as well as thank our partners, who are actively contributing to these accomplishments.

Throughout this white book, you will therefore be able to discover for instance how we are working to reduce greenhouse gases in the atmosphere, thanks to a demonstrator in the campus lake to produce biofuel from the CO_2 contained in the water. You will also read about the actions we are undertaking to help our campus achieve carbon neutrality, thanks to a smart building with an app that allows students to control their energy consumption remotely. You will also learn how to quantify energies extracted from natural resources and to project them at different timescales. Regarding climate policies, you will get a snapshot of how our researchers work to reveal energy sufficiency models, practices, mechanisms and dynamics, by combining various theoretical lenses. Those are only examples of the many promising projects led by E4C.

I hope you will enjoy reading this white book as much as I did, that you will learn about new technologies and ways of thinking and, perhaps, get inspired by them. It will also hopefully help you understand how committed Institut Polytechnique de Paris and École des Ponts are to training tomorrow's engineers and innovators, those who will be building the sustainable model that the world so urgently needs."

(September 22nd 2021)

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Context

The interdisciplinary Energy4Climate Center (E4C) launched in June 2019 by the Institut Polytechnique de Paris and the École des Ponts ParisTech is involved in the energy transition through research, training and innovation.

Humanity is facing a climate challenge of unprecedented magnitude and whose human origin is no longer in doubt. Keeping global warming below the 2 °C limit requires the development of appropriate solutions.

About 30 laboratories are working within E4C on four transversal themes to reduce greenhouse gas emissions, improve energy efficiency, deploy renewable energy distribution and evaluate public policies.
The center's activities are developed by its researchers in conjunction with industrial players. They combine social and economic sciences, materials sciences and engineering, applied mathematics, computer science and geophysics. The center develops instrumental platforms, models for energy forecasting and forecasting, and a data center.

Training the next generation of energy players is also a priority for E4C. It offers Masters degrees, 5-year PhD tracks, an entrepreneurship program for students wishing to create a start-up and an international student challenge.

During the year 2020-2021, the E4C center worked on its white book. In total, about 135 researchers and engineers contributed to this document, led by 35 coordinators, the steering committee, the training liaison group and the heads of the Research Actions and the E4C Datahub. Together, they have developed a plan for scientific work, training support and development of technological and experimental platforms.

This **Energy4Climate Interdisciplinary Center's White Book, *Energy and Climate: Research perspectives*** is meant to be spread to introduce E4C's research work and encourage partnership with industrial actors, academic institutions, innovation forerunners.

E4C INTERDISCIPLINARY CENTER

Governance

The E4C center's governance supports its research and training activities thanks to inter-laboratory collaboration, thus ensuring scientific and societal integrity, research activities' relevance and training and teaching in progress. This prevents conflicts of interest and guarantees teaching and research independence and their responsibility towards society.

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Executive committe members:

- Jordi BADOSA (technical director)
- Patricia CRIFO (science deputy director)
- Didier DALMAZZONE (science deputy director)
- Philippe DROBINSKI (director)
- Nathalie GIRARD (operation director)
- Celine GUIVARCH (science deputy director)
- Michel MAROT (science deputy director)
- Gérard MEMMI (science deputy director)
- Daniel SUCHET (science deputy director)

Governance bodies

Four governance bodies ensure the E4C center's exemplary nature of partnership.

- Scientific committee: composed of climate, environment or energy experts from outside E4C. They meet once a year for external opinions and recommendations on E4C's broad scientific orientation and its parteneships.
- Supervisory committee: composed of E4C center's director and a representative from each founding member, this council is the decision-making body of E4C. They meet once a year and they are in charge of E4C center's major strategic orientations and major development decisions, such as approving new research institutions or new sponsors.
- Council of sponsors: composed a representative from each sponsor. They meet once a year to discuss progress and progress recommendations if necessary.

- E4C executive committee (CODIR for *Comité de direction*): composed of E4C center's director, technical director, operation director and 6 scientific deputy directors. They meet once a month to steer the different E4C activities and the supervisory committee's decisions follow-up. They also drive E4C's strategy and general interest issues based on Scientific committee's recommendations and E4C's budget… Twice a year, the CODIR is extended to all E4C's laboratory's directors and chairs of research and education departments to form the CODIR+

The E4C center's organization is illustrated on figure 1.

The E4C center has defined ethical partnership and sponsorship charters to supervise fundraising. These charters are tools to clarify internal and external processes but they have no contract value. There are three major commitments:

1. E4C center's research focuses on decarbonizing the energy sector. A scientific framework shared between E4C and a partner must be developed explicitly and be connected to E4C center's research without guaranteeing the overall actions of the partner's activity.
2. E4C center's scientific expertise must be disseminated to the partner. Partnerships' framework must therefore include managers' and employees' training obligation on climate and energy transition issues.
3. Scientific framework developed with the partner can lead to teaching offer in E4C supervising higher education establishment's courses. The content of these courses is the responsibility of latter institutions.

Interactions with E4C laboratories

The laboratories composing the E4C center are*:

- CEREA: Centre d'Enseignement et de Recherche en Environnement Atmosphérique
- CERMICS: Centre d'Enseignement et de Recherche en Mathématiques et Calcul Scientifique
- CIRED: Centre International de Recherche sur l'Environnement et le Développement
- CMAP: Centre de Mathématiques Appliquées
- CREST: Centre de Recherche en Économie et Statistique
- HM&Co: Hydrologie Météorologie et Complexité
- I^3: Institut Interdisciplinaire de l'Innovation
- IMSIA: Institut Des Sciences de la Mécanique et Applications Industrielles
- IPSL: Institut Pierre Simon Laplace

* The laboratories that are partners of the École Universitaire de Recherche (EUR)

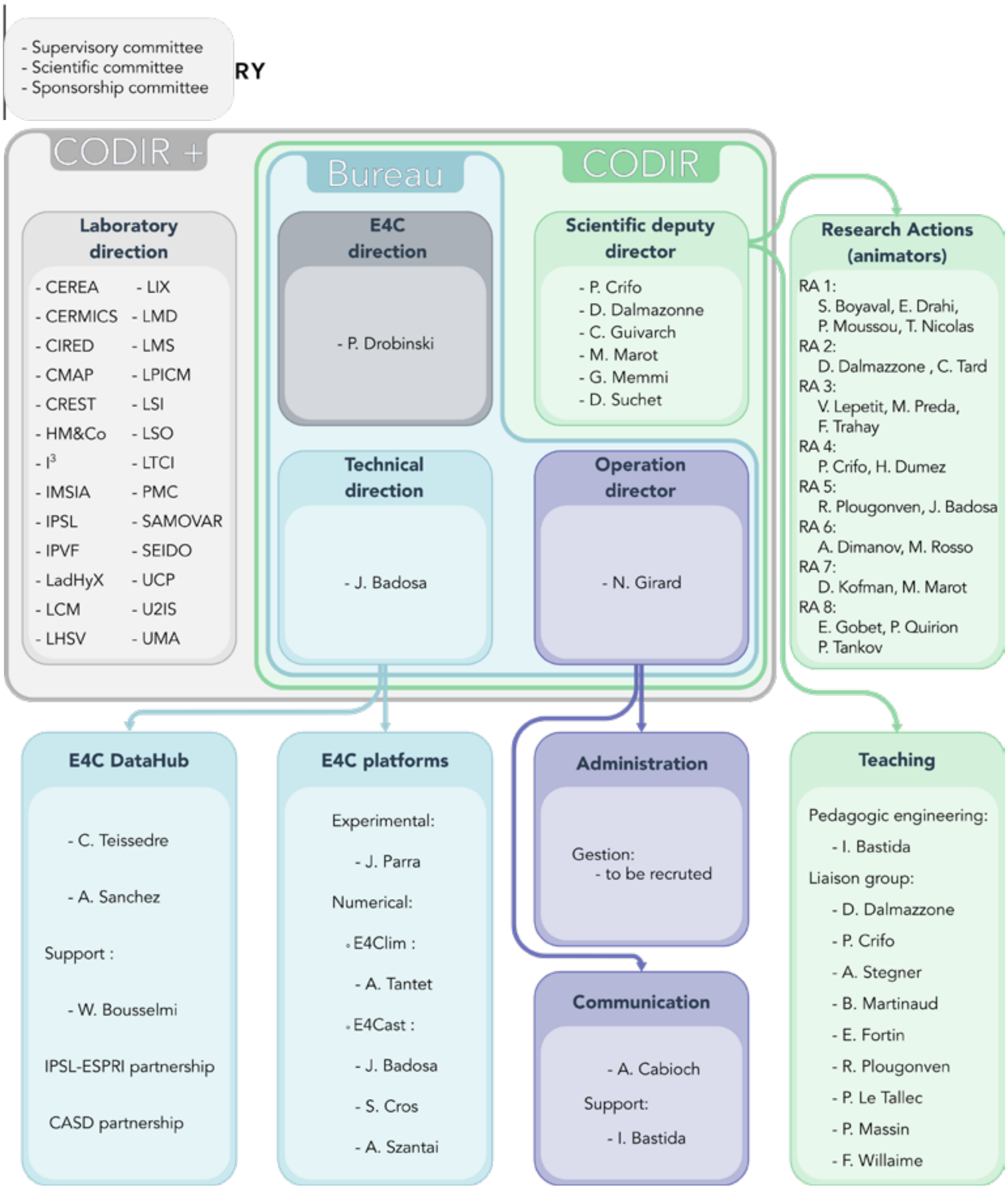

Figure 1. E4C organisation (2021)

- IPVF: Institut Photovoltaïque d'Île de France
- LadHyX: Laboratoire d'Hydrodynamique de l'École Polytechnique
- LCM: Laboratoire de Chimie Moléculaire
- LHSV: Laboratoire d'Hydraulique Saint-Venant
- LIX : Laboratoire d'Informatique de l'École Polytechnique
- LMD : Laboratoire de Météorologie Dynamique
- LMS : Laboratoire de Mécanique des Solides
- LPICM : Laboratoire de Physique des Interfaces et des Couches Minces
- LSI : Laboratoire des Solides Irradiés
- LSO : Laboratoire de Synthèse Organique
- LTCI : Laboratoire Traitement et Communication de l'Information
- PMC : laboratoire de Physique de la Matière Condensée
- SAMOVAR : Services Repartis, Architectures, Modélisation, Validation, Administration Des Réseaux

- SEIDO : Laboratoire de cyber-sécurité et internet des objets
- UCP: Unité Chimie et Procédés
- U2IS: Unité d'Informatique et d'Ingénierie des Systèmes
- UMA: Unité de Mathématiques Appliquées

In addition to the 26 laboratories forming the core group of the E4C EUR project, associate laboratories are part of the E4C center.

- CPHT: Centre de Physique Théorique
- LIGM: Laboratoire d'Informatique Gaspard Monge
- LPP: Laboratoire de Physique des Plasmas
- NAVIER

The E4C center is a federation of research laboratories interacting in a win-win approach. These laboratories bring their expertise for energy transition interdisciplinary research and their human and technical resources. In return, the E4C center supports their collaborative research by bringing an innovative and transversal research program on the energy transition and disruptive and technological platforms. The E4C center also brings a communication action on energy transition giving visibility to laboratories' activities and a science-society link promoted on energy transition. The E4C center brings support to IP Paris and École des Ponts climate and energy education tracks in interaction with IPSL-CGS (EUR). Finally, the E4C center brings resources to the labs:

- based on regular internal calls: travels, internships
- through internal seed funds to go to external calls: equipments, flagship projects
- through more targeted fund raising in a combined top-down/bottom-up approach: PhD and post-docs in relation with the research actions work plan
- through open calls École des Ponts/IP Paris E4C PhD grants

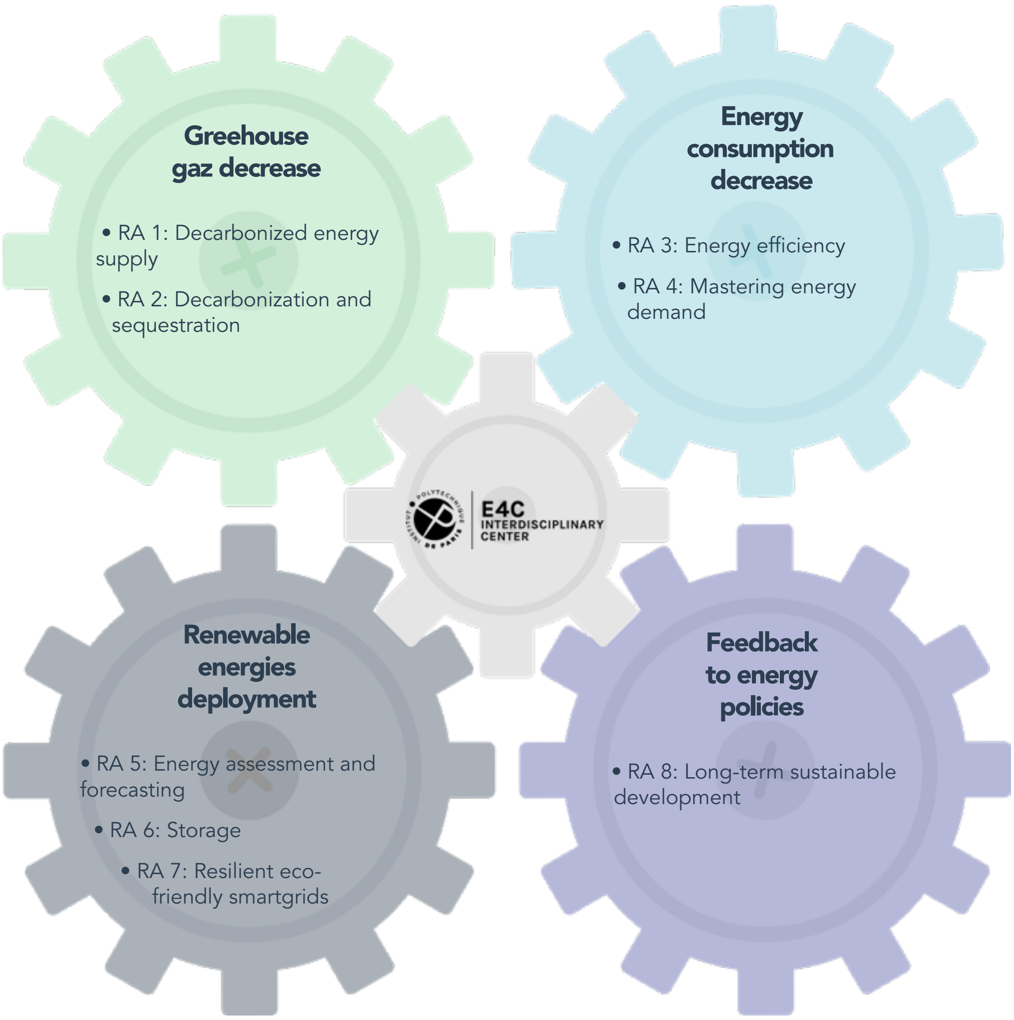

Figure 2. E4C research actions

Research

Introduction

The E4C center's ambition is to reach the highest level of excellence among world leaders in climate and energy sciences through an interdisciplinary approach involving different fields from social and economic sciences to materials sciences and from engineering, applied mathematics and computer science to geophysics.
E4C aims to meet the challenges of energy public policies, allowing a systemic analysis of the obstacles to climate change mitigation and energy transition and to provide the necessary expertise in support of public policies. The research carried out in E4C is organized around 8 research axes called "research actions" aiming at:

1. reducing greenhouse gases (GHG) in the atmosphere
2. reducing energy consumption
3. deploying renewable energies
4. determining sustainability of technical propositions

(see figure 2)

Climate change and mitigation

Since the pre-industrial era, the world temperature has raised by 1.25 °C due to anthropogenic greenhouse gas emissions. This global warming has accelerated since the 1980's and has emphasized natural temperature variability.
Since the pre-industrial era, atmospheric CO_2 concentration has increased from 300 to 415 parts per million (ppm)*. From geological time scales point of view, today's age is characterized by oil production and an increase of atmospheric greenhouse gases. This induces a radiative forcing of the order of 5 W/m² [1]. This evolution is hard to predict since the trajectory depends largely on worldwide nations' actions to reduce greenhouse gases emissions. Using demographic and socio-economic assumptions converted into GHG emissions, several scenarios have been produced to represent future possibilities for prospective purpose[2] as shown on figure 3. These scenarios then were converted into radiative forcing, meaning the modification of Earth's radiative balance. Going from 2.6 W/m² to 8.5 W/m², these radiative forcing could result in warming between 1 °C and 4

* Before the industrial era, the CO_2 concentration oscillated between 180 and 300 parts per million, following the Milankovitch cycle of about 100,000 years.

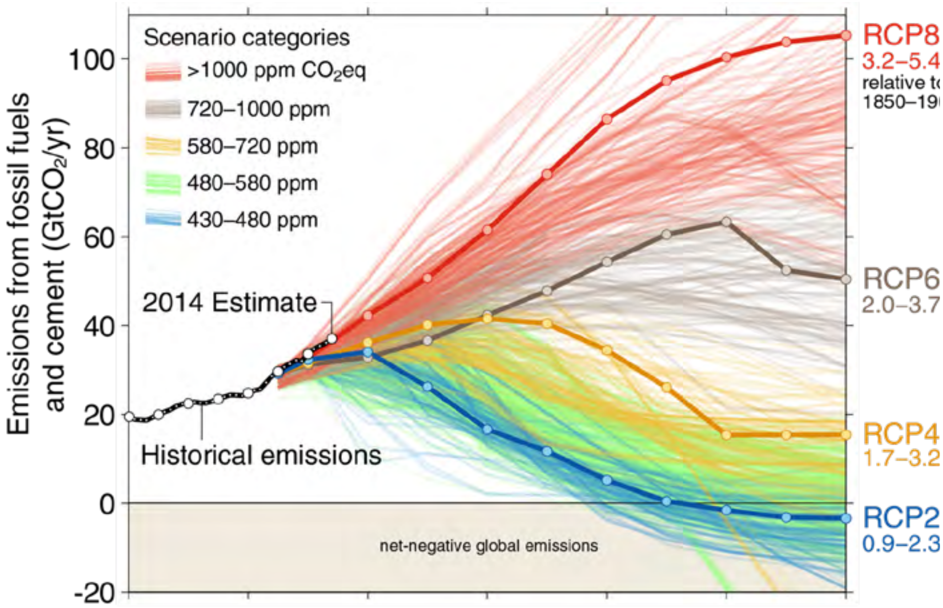

Figure 3. The colored lines correspond to the Representative Concentration Pathways (RCP) of cement and fossil fuels' emissions (Gt CO2/yr). The IPCC Group 5 has published over 1000 scenarios that are represented here and that are defined on CO2-eq concentration levels (ppm) for the year 2100. The 2014 estimation is shown on the red RCP 8.5 pathway. Source: Fuss et al. (2014)

°C.

Paris Agreement's second Article expresses the parties' commitment to limit global average temperature below + 2 °C compared to the pre-industrial era, as show on figure 4. This "acceptable" 2 °C limit was set in Copenhagen in 2009 during the COP15, where the Paris Agreement was negotiated. This threshold was suggested referring to a past period when this temperature could have been reached without causing a climatic disaster, but it was also chosen in terms of risks. Indeed, concerning water stress, an additional half billion people would be threatened by water shortages. Floods would endanger three times more people, while fish stocks would decrease considerably. The 2 °C limit is not absolute but if exceeded, it would increase climate risk bifurcation due to non-linear positive feedbacks leading to potential dramatic consequences.

To achieve the long-term temperature goal defined by Article 2, Nations aim to reach a global greenhouse gas emission peak as quick as possible as defined in Article 4. This is so balance between anthropogenic emissions sources and sinks is reached by the second half of this century, as shown on figure 5.

To limit global warming below 2 °C, it is necessary to reduce carbon dioxide (CO_2)

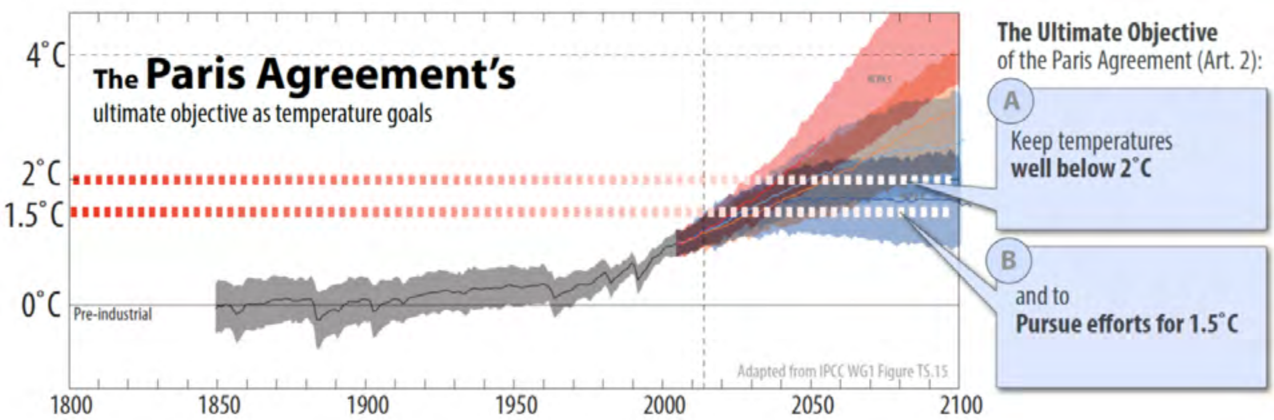

Figure 4. The Paris Agreement's ultimate objective as temperature goals (article 2).

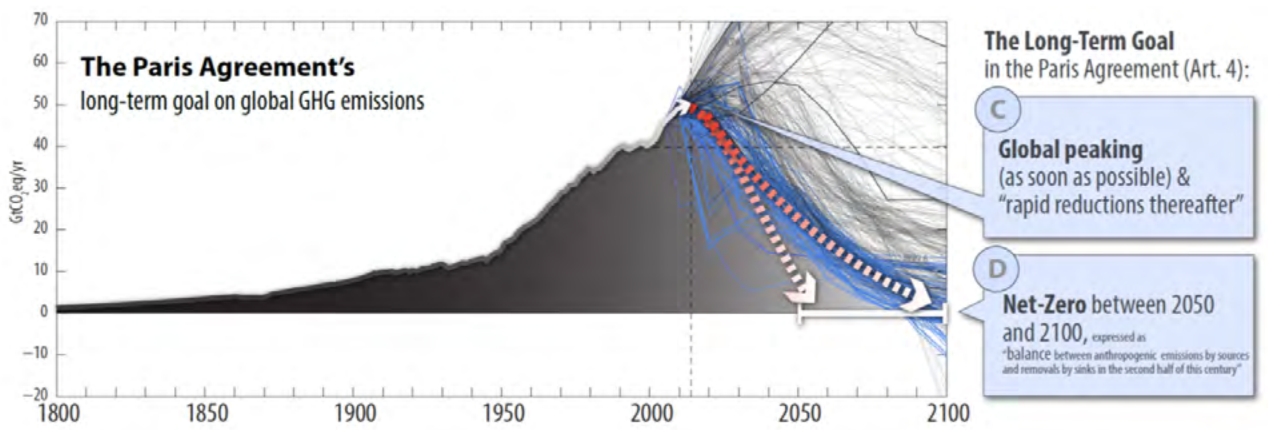

Figure 5. The Paris Agreement's long-term goal on global GHG emissions (article 4).

emissions by 50 % between 2050 and 2100. To analyze global CO_2 emission's evolution, Kaya's equation puts CO_2 emissions in relation with demographic, economic and energetic parameters[3]. Global CO_2 emissions' calculation results in the product of population, Gross domestic product (GDP) per capita, energy intensity and carbon content of consumed energy, as shown below. This equation helps simulating global CO_2 emissions regarding public policies to fight global warming.

To match the 50 % reduction of CO_2 emissions between 2050 and 2100, considering a demographic growth of 35 %[4], an average GDP growth of 3 %[5] per year and an economy energetic intensity decrease of 10 % per decade, the energy carbon content should decrease by 75 % in 40 years. This reflects the importance of today's challenge that must be addressed regarding energy transition, a radical transformation towards carbon-free energy production. Nevertheless, to match that CO_2 emission reduction, sharing the burden between the different parameters of Kaya's equation (shown bellow) is key. For instance, in Western Europe, three economic sectors produce CO_2: electric power production, transportation and heating.

Transition pathways to low-carbon energy technologies

$$\underbrace{CO_2}_{CO_2\text{ emissions}} = \underbrace{\frac{CO_2}{TOE}}_{\substack{\text{Carbon content}\\ \text{of energy}}} \times \underbrace{\frac{TOE}{GDP}}_{\substack{\text{Energy intensity}\\ \text{of the economy}}} \times \underbrace{\frac{GDP}{POP}}_{\substack{\text{Gross domestic}\\ \text{product per capita}}} \times \underbrace{POP}_{\text{Population}}$$

with:

- CO_2: global anthropogenic CO_2 emissions,
- POP: world population,
- GDP: world gross domestic product,
- TOE: wolrd primary energy consumption

To understand the different issues, it is important to keep in mind the energy production systems' carbon footprint. The energy supply systems' carbon footprint, according to the 2011 IPCC special report on renewable energies and climate mitigation[6], is shown in the table 1 below and is expressed in gCO_2eq/kWh*. This shows the carbon footprint difference between low-carbon technologies and fossil energy technologies. In median value, photovoltaic (PV) technologies emit 10 times less CO_2 than gas. In the low-carbon technologies, nuclear energy is distinguished from renewable energies.Despite the urgency of shifting from fossil fuels toward a carbon-neutral economy, post-fossil technologies are not fully operational. Nuclear fusion is not available and may never be. Conventional nuclear fission, including fuel cycles optimized Generation IV, could be part of the solution, even if it raises public acceptance issues. All over the world, dams produce a lot of electricity, but a large part of the resource is already exploited[7], and their impact on the biosphere is far from negligible[8]. Biomass is mostly limited by forests' regeneration rates, that is why it can hardly be considered carbon neutral[9]. Hydrogen is simply an energy vector, which impact depends on the primary energy source. Finally, even if solar and wind energy have impressively developed over the last two decades, exponentially reducing their costs and strongly increasing their implementation growth rate and their electricity production, their business model still depends on very favorable tax policies in Western countries or on complex subventions such as the "Accès Régulé à l'Electricité Nucléaire Historique" law (Arenh) in France. Solar and wind energy also come with limitations that R&D will overcome. For instance, intermittency is one of the limitations. Indeed, concerning energy production, capacity factor is a major issue. Latter factor measures the production plant running frequency at rated power. In the USA, among the energy sources producing electricity in 2016, nuclear had the highest capacity factor (92 %), it was twice as large as coal (48 %) or natural gas (57 %) plants and almost three times more frequent than wind (35 %) and solar (25 %) plants[10]. Renewable energy sources' variability and intermittency are serious issues for their massive deployment and integration to the grid.

Energy storage systems aim to buffer short-term fluctuations from renewable energy sources. For instance, compared to photovoltaic production, solar plants include heat storage, doubling its capacity factor. Buffered renewable energies storage systems are therefore a pathway to investigate technologically and economically[11]. However, electricity storage problems can not be tackled solely by batteries, aside from the sheer number of batteries required. Indeed, electricity needs to be stored on very disparate

* The values cover the source's full life, from material and fuel mining through construction to operation and waste management. Progress in efficiency, leading to CO_2eq reductions since the time of publication, have not been included.

		min.	median	max.
Currently commercially available technologies	Coal - PC	740	820	910
	Biomass - Cofiring with coal	620	740	890
	Gas - combined cycle	410	490	650
	Biomass dedicated	130	230	420
	Solar Pv - utility scale	18	48	180
	Solar PV - roof top	26	41	60
	Geothermal	6.0	38	79
	Concentration solar power	8.8	27	63
	Hydropower	1.0	24	2200
	Wind offshore	8.0	12	35
	Nuclear	3.7	12	110
	Wind onshore	7.0	11	56
Pre-commercial technologies	CCS – coal - PC	190	220	250
	CCS – coal - IGCC	170	200	230
	CCS – gas – combined cycle	94	170	340
	CCS – coal - oxyfuel	100	160	200
	Ocean (tidal and wave)	5.6	17	28

Figure 6. CO2 equivalent life cycle from selected electricity supply technologies. Arranged by decreasing median (gCO2eq/kWh) values. Source: IPCC 2014

time scales, from hours to years. Furthermore, for every unit of electricity produced (kWh), solar and wind energy require more steel, concrete**, rare metals*** or rare earths than fossil or nuclear energy[12]. Finally, for every kWh of electricity produced, the surface needed is several orders of magnitude larger than classical electricity production methods[13], which is problematic knowing that land use change is a biodiversity loss factor.

Climate change's impact on renewable energy sources and low-carbon energy supply is also at stake. To date, 98 % of global electricity is generated by hydropower and thermoelectric power[14]. These technologies strongly depend on water availability and water temperature which has a critical role in thermoelectric power generation cooling.

** Wind energy essentially

*** Solar energy needs more silver essentially

Climate change and its consequences on water resource will therefore affect energy production while energy demand will continue to increase with economic development and global population growth. Worldwide, between 2040 and 2069, hydropower plants' and thermoelectric power plants' usable capacity will respectively decrease by 61 to 74 % and by 81 to 86 %[15]. Building heating and cooling energy demand is also changing with global warming. From 1941-1960 to 1981-2000, continental energy demand for heating and cooling went from less than 10 % to more than 10 %. The energy demand increasing trends for cooling are more pronounced than the decreasing trends for heating[16]. However, global warming impact's quantification on future energy demand is still uncertain, although it is a key for accurate energy planning. Concerning solar and wind energy resources, this impact should be marginal, less than 5 % of losses, if global warming is limited to 2 °C. However, beyond 2 °C, the impact should rapidly deteriorate solar and wind resource in some regions[17].

Renewable energy source integration

To reach sustainable low-emission development, many countries are establishing ambitious renewable energy objectives for their electricity supply. Solar and wind are more variable and uncertain than conventional energy sources, that is why meeting those objectives will involve power system planning and operation changes. Developing efficient ways to deliver variable renewable energy to the grid is called grid integration. Robust integration methods maximize variable renewable energies cost-effectiveness

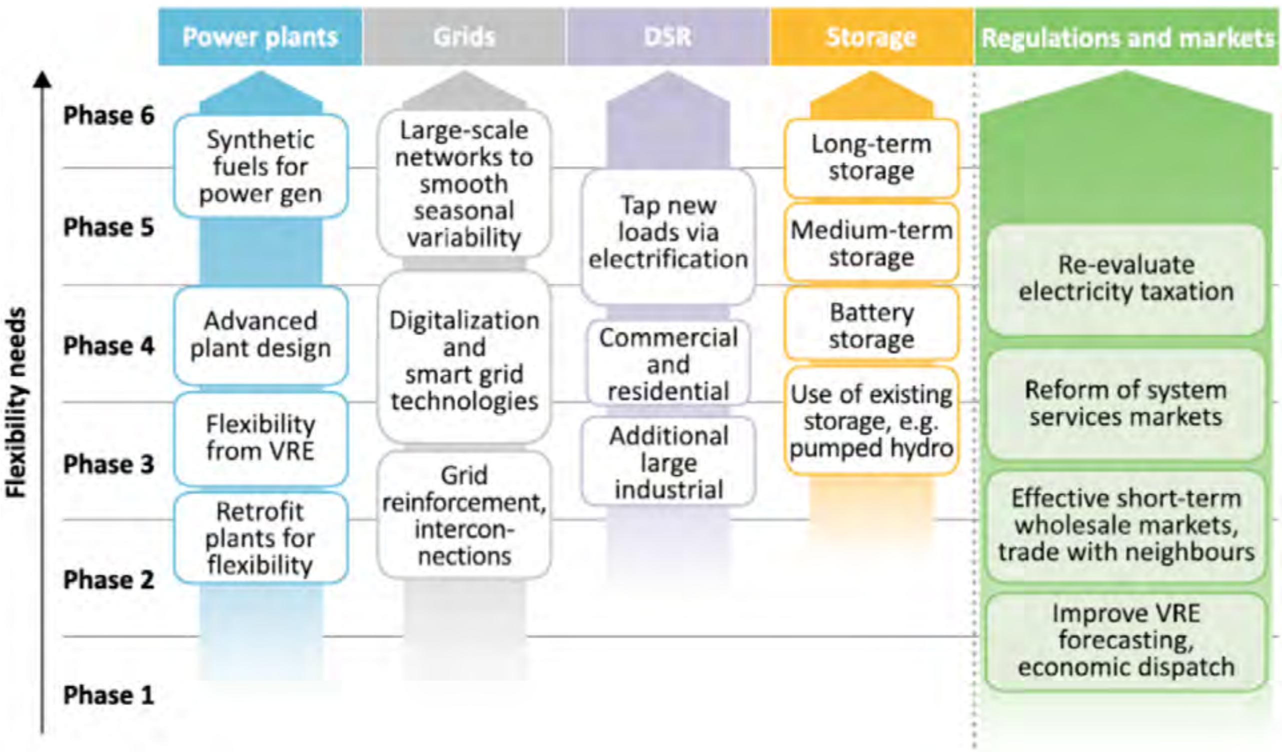

Figure 7. Flexibility options for different phases of renewable energy integration. Source: IEA (2018)

when they are incorporated into the power system while maintaining or even increasing system stability and reliability. Grid integration spans many issues such as[18, 19, 20]:

- new renewable energy generation
- new transmission
- increased system flexibility
- planned high renewable energy future

Increasing the variable energy production share in the network is not simple. Network sophistication can be divided into six phases depending on the variable energy source share in the network .

At first, renewable's low penetration is not an issue for the network. Then, conventional control systems like thermal power plants and hydropower are sufficient to integrate variable energies sources without network transformation. Next, investments must be made for network transformation to make it smarter and more flexible for supply-demand balance management with a much more variable net energy demand. This flexibility refers to strengthening storage facilities, decreasing or erasing hourly modulated consumption, early warning systems. Massive collection and real time processing of energy consumption and production data in a more sophisticated energy management system are also part of this step. Then, structural surpluses appear and other sectors' electrification becomes relevant.

Finally, seasonal deficit periods are bridged, non-electric applications are supplied and synthetic fuels emerge.

The last two steps are mandatory for a 100 % renewable energy mix.

The different phases' flexibility options for renewable energy integration are shown on figure 7. Flexibility resources can mitigate renewable energy integration challenges in different phases and allow more renewable energies integration to the system.

Figure 8 shows the grid's evolving

Figure 8. Smartgrid's architecture

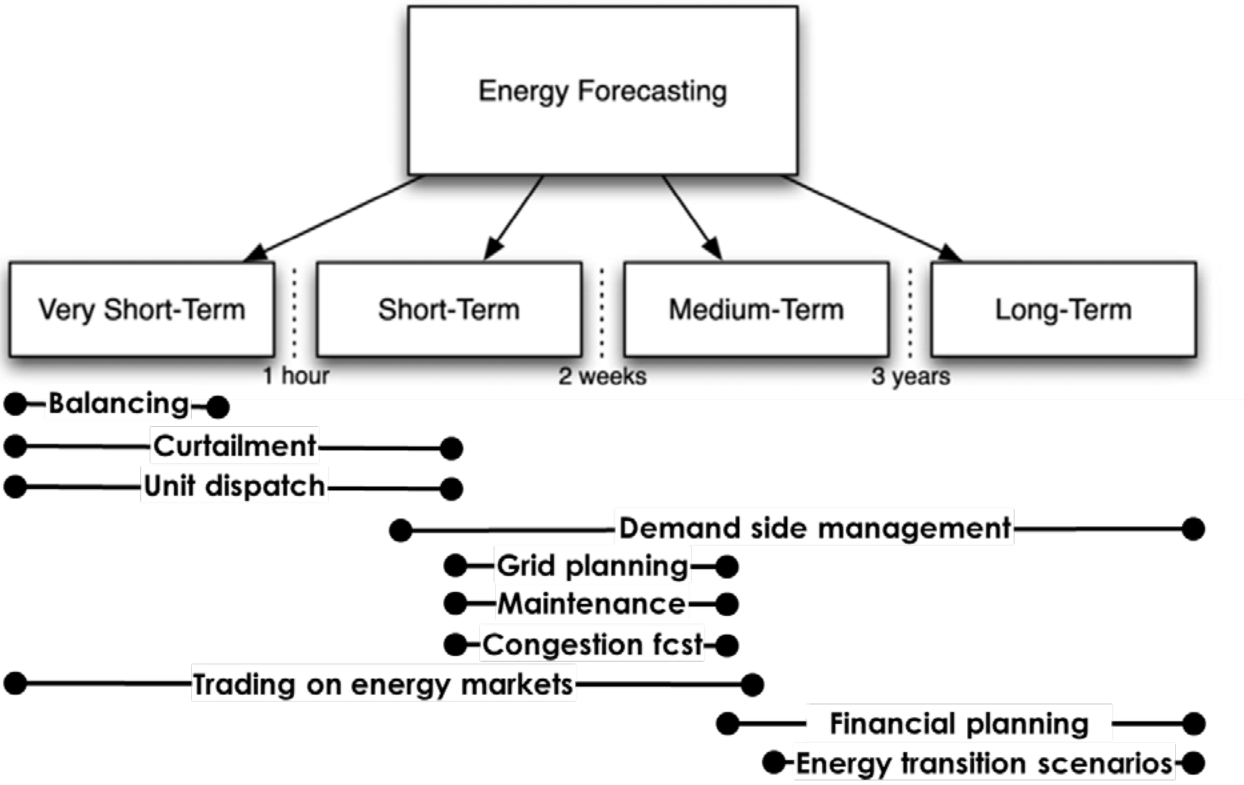

Figure 9. Energy forecasting needs at various time scales

architecture and the different players that can provide many network services, including generation, transmission and distribution and advanced new services requiring strong coordination[21, 22, 23, 24]. New service providers, including aggregators, emerge. Subscribers become clients and optionally prosumers (contraction of energy producer and consumer). Energy, mainly renewable, can be injected in any segment, including locally like residential premises. Meters becomes smart meters, able to monitor different data types and with a data channel that enables data exchange, information control and/or messages. Nevertheless, this may exacerbate cybersecurity issues. Consequently, a new architecture level appears: the business layer, that enables level agreements with advanced service models, business models and service provision. New paradigms become possible, like dynamic pricing approaches and possibility for prosumers to participate to the energy market. Operation and management have evolved to integrate new paradigms, like Internet of Things (IoT), for technology chain continuous and dense real-time monitoring, enabling those mechanism distant control. Transport network operation (TSO) and distribution network operation (DSO) concepts are more clearly identified, as well as their interfaces[25].

Some systems are initially programmed to face demand variability only. For these systems, renewable energy production variability may cause local power shortages due to renewable energies low-capacity credit, to transmissions increased congestions or to energy over production, causing curtailment. Today, part of these issues can be mitigated by accurate energy demand and supply forecast, at different timescales[26, 27, 28, 29] as shown on figure 9. Nevertheless, those issues still must always be compensated by ancillary services on different frequencies[30, 31, 32]. These issues are key to elaborate an optimal energy mix, with high renewable energy sources penetration[33, 34, 35, 36, 37]. Demand-response mechanisms also can compensate energy supply variability[38].

E4C center infrastructures in support of Research Actions

The E4C center develops technological and experimental platforms and a dedicated climate and energy datahub with significant industrial sponsors' and partners' support. All these means help the E4C center conduct its research, train its students and professionals. Technological and experimental platforms and E4C's datahub are presented on figure 10.

The E4C center also develops energy prospective models (E4Clim) to address optimal energy mix scenarios based on renewable energies, in a climate change context. Renewable energy production and energy consumption forecasting models are also being developed to support smartgrids management.

Finally, the E4C datahub is being developed to allow an easy access to climate and

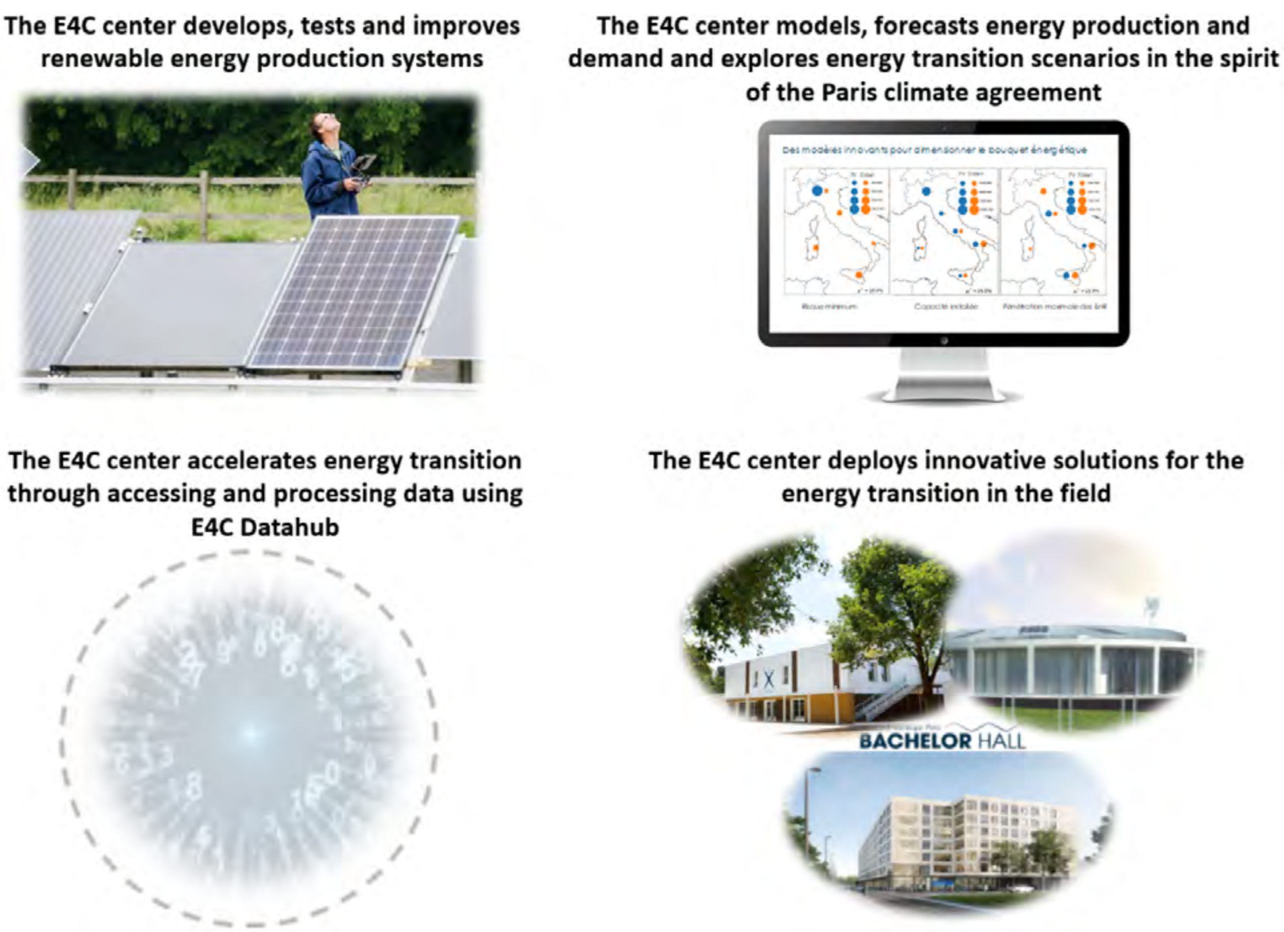

Figure 10. The E4C center's infrastructure development strategic axes to accelerate and demonstrate energy transition

energy data and to provide a service to data producers and users to accelerate energy transition through data access.
All these technology platforms also support E4C hands-on teaching training.

E4C Research Actions

The work program of the E4C center's 8 Research Actions is briefly described hereafter. Strong interactions are foreseen between the various Research Actions within the 4 groups containing the RA as presented on figure 2 and between these groups.
On figure 11, interactions between the different E4C Research Actions (RA) are represented by connections. This figure helps represent the interdisciplinary dimension of the E4C center.

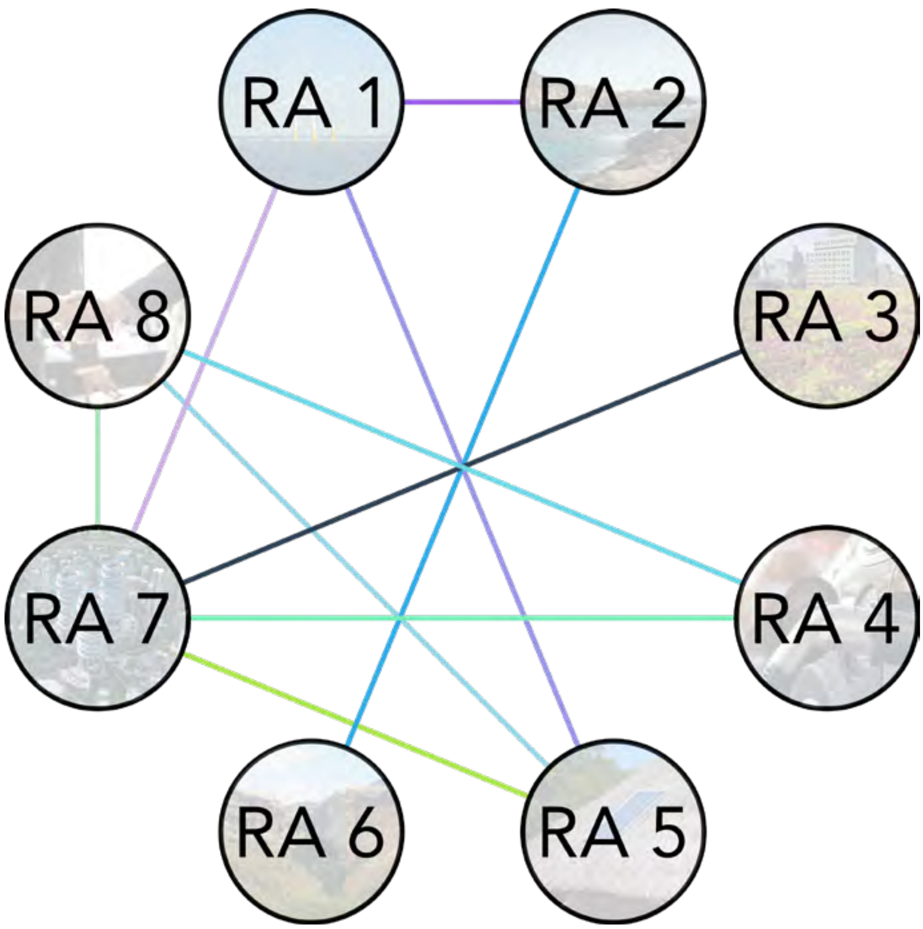

Figure 11. E4C's Research Actions' interactions

1 Decarbonized energy supply

Objectives:

- Improve new decarbonated energy conversion concepts
- Improve fluide-structure interactions in electricity producing technologies
- Improve reliability and performances of power facilities

Decarbonized energy supply

To keep global warming below the 2 °C limit, developing low-carbon technologies and renewable energies is primordial. Achieving this goal will need the improvement of low-carbon energy conversion, in other words: picking up energy available around us and converting it into exploitable energy, electricity among others. Nuclear, wind and solar energy are common low-carbon ways to convert energy (heat, wind and light) into electricity. But solar energy can also be converted into an energy like H_2 or fuel. Wave energy is also being investigated to convert kinetic energy into electricity. One issue is that almost every power generation facility is subject to fluid-structure interactions. The problem with fluid-structure interactions is the vibrations induced by turbulent flows, which limit the mechanical stability of industrial facilities. Even solar farms can undergo vibrations under the effect of gusts of wind, especially in the downstream wake of panels. Another well-known example is turbines, which convert the kinetic energy of a fluid (air or water) flow into electricity. Structural integrity and durability are major concerns for all types of power generation facilities, both for safety and economic sustainability reasons. A key factor here is the fact that the power generation issues are very similar to the ones met in other industrial fields, provided that the materials are identical. For instance, fatigue life prediction of rails under the load of passing trains is very similar to the one associated to cycles of pressurizing and depressurizing inside power plant vessels.

Processes and technology for energy conversion

Developing new photovoltaic (PV) technologies will allow better conversion of solar energy into electric energy. This research is based on new materials and their integration into devices thanks to characterization techniques. Thin film PV (perovskite) are very promising to develop more efficient and cheaper devices. They can also be used in combination with crystalline silicon solar cells to boost their efficiency and reduce cost per watt peak of PV system. In addition to PV technology, solar energy is investigated to produce fuel. To achieve this, hydrogen production and CO_2 conversion using decarbonized energy is the key. Solar energy is a serious candidate for this, but so is

biomass.
The future decarbonized electricity mix might also include nuclear energy. Producing energy from nuclear fusion on Earth is very challenging. The matter must be in plasma state thanks to high temperature and confined by strong magnetic fields to keep the edge temperature cold enough to comply with the vessel walls. The minimization of energy losses due to turbulence and the control of plasma instabilities require a deep understanding of processes at play, using experiment, theory and modelling. Finally, another energy conversion will be investigated: wave energy. Among other marine resources like tides and streams, waves are a promising renewable energy source in the ocean. However, it still must be efficiently converted. Numerical studies are relevant for ongoing proofs of concept.

Turbulent loading, structural dynamics and fluid-structure interactions

Electricity production relies on mastering fluid-structure interactions. These interactions can be between free-surface waves and a floating device like offshore wind turbine or offshore PV panels, or between turbulent flows and immersed structures like turbines or cables on the seafloor. Operations in extreme conditions need to be assessed through models to be developed or improved, based on experiments and simulations Thermal effects need to be carefully included, for steam generators or floating PV.
"Digital twins" also help improving not only the reliability of a facility, but its performance too. The approach could be fruitful for many different structures producing electricity in turbulent loading conditions.
Structural integrity of steam generators is compromised by "fluidelastic instability" which is still only partly understood. To reduce these vibrations, flow velocity is limited, with direct effects on the power produced. Understanding it and determining the range of flow velocities where it happens is primordial.
Five reference experiments* in fluid-structure interactions will be used to test state-of-the-art numerical approaches. It will lead to recommendations for future users in the field of fluid structure interactions for power generation.

Reliability, sustainability and performances

Thanks to PV energy, price drops as the cumulative shipped volume doubles (in Watt), which explains the massive growth of this field. To keep on reducing cost per W_p**

* Within the framework of the European project Viking (hosted by Nugenia)

** Watt peak

improving PV efficiency is key. To evaluate the real performance of a new technology but also to ensure its reliability, outdoor testing and precise weather monitoring are needed. Both allow to monitor and analyze the performance of a PV system at 3 timescales: short (15 min to 6 h), medium (days to months) and long (over PV's lifetime). This is necessary for operation and maintenance strategy and differentiating from aging but also to evaluate the full PV system energy production over the years (to assess the return on investment) and to anticipate weather-related degradation.

Another major safety issue is crack propagation in stainless steel. This phenomenon is closely related with the material construction process, namely its initial state that generates residual stress distribution within the structure. Crack propagation has recently been put forward as potential reason for reduced lifetime of towers of wind turbines. Understanding and predicting the influence of residual stress on the initiation of existing cracks or more generally on crack propagation is, therefore, primordial.

Additive manufacturing may be a factor for cost reductions in the future of power generation, contributing to the economic sustainability of some traditional or emergent sectors. The challenge consists in controlling the manufacturing process to produce components identical to the ones obtained through classical processes.

Other interdisciplinary projects are being considered

Agrivoltaics is under investigation: specific panels and systems synergy between PV systems and plants could be studied in collaboration with INRAE*, for example, specific panels and systems could be developed to improve agriculture yield or protect crops from environment and climate change while providing new spaces for PV systems deployment.

All the technological solutions studied above need to be assessed using Life Cycle Analysis and a special care will be given to their carbon footprint.

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2 Decarbonization and sequestration

Objectives:

- Improve CO_2 sensing using semiconductor metal oxides
- Assessing CO_2 geological storage feasibility
- Using plasma for CO_2 conversion and valorization
- Synthesizing fuel from seawater CO_2

Decarbonization and sequestration

It is well known that greenhouse gases, namely carbon dioxide (CO_2), are increasingly abundant in our atmosphere due to human activity and are responsible for climate change. In order to reach greenhouse gas (GHG) reduction, finding cheaper and sustainable ways to sequester CO_2 is essential. Different topics are explored to achieve this goal. First, sensing CO_2 is the prior condition to capture it, therefore optically activated technics using metal oxides (such as TiO_2) will be explored. Then, deep geologic storage of CO_2 will help mitigate the impact of anthropogenic CO_2 emissions: it is estimated that the practical capacity of deep geologic storage represents 3,900 Gt of CO_2 which is the triple of the demand of CO_2 storage. Although, gas leaks are the main risk threatening this topic. On the other hand, instead of sequestering it, converting CO_2 into molecules of interest will also help mitigating the impact of anthropogenic emissions. Indeed, rather than producing new GHG gases, E4C research explore the reusability of carbon dioxide as raw material for new energy sources. For instance, plasma will help induce chemical reactivity of CO_2 into different molecules able to return energy as fuel.

Another topic exploits the high concentration of carbon dioxide in seawater, which is 125 times higher than the atmospheric concentration, to combine it with dihydrogen (H_2), thus producing synthetic fuels.

Gas sensing using semiconductor metal oxides

Modelling semiconducting metal oxides and surfaces, could be important to understand and explain adsorption process(es) and the consequent optical response of the system at play during photocatalysis. The optical response could be investigated with E4C laboratories who have developed an expertise on the subject.

TiO_2 is an example of a semiconducting metal oxide. The binary titanium/oxygen system consists of various stable oxides that are used in a wide range of applications. TiO_2 exists in three different phases: rutile, anatase and brookite. Anatase TiO_2 is an interesting material in gas sensing applications due to its chemical stability.

Surface defects, and in particular oxygen vacancies and charges trapped therein,

play an important role in the reactivity of metal oxide surface. However, it is not well understood how optical properties of surfaces are modified by such defects, nor is the additional effect of the presence of a gas at the surface in gas-sensing applications.
The temperature favours the photocatalysis, and thus vibrations are expected to play an important role in the process. However, in some models, the importance of charge transfer is also emphasized. Among scientific questions worth investigating are the effect of the presence of a gas molecule on the electronic surface states, on the defect-induced electronic states, as well as the effect of temperature on the electronic states caused by the electron-phonon coupling.

Impact of discontinuities on the integrity of underground CO_2 storage

Deep geological storage is a topic with two major questions: what will be the cement/rock and the cement/casing interfaces behavior during storage? And how will faults be reactivated during storage?
In order to assess probable CO_2 leakage, a detailed analysis of cement/rock and cement/casing interfaces integrity requires numerical simulations considering thermo-hydro-chemo-mechanical couplings, and reactive transport phenomena. Such simulations require knowledge of the constitutive laws of the components of the system, namely cement, rock mass, and the cement/rock and cement/casing interfaces, as well as their possible evolution due to degradation by CO_2. Experimentally, direct measurement of the bonding between the cement and the rock or the casing will be carried out by performing bending experiments on composite specimens. These tests will allow to study a situation of rupture of the interface close to crack propagation.
At a larger scale, beyond injection wells, CO_2 migration can affect the mechanical stability of defects that go through the reservoir and the caprock. This issue will be addressed based on numerical modelling of coupled processes to assess the seismic risk induced by CO_2 injection. Different numerical tools have been developed to simulate fracture propagation thanks to, among others, water waste storage which causes similar problems or the Texan database of injections and micro-seismic events.

Using non-equilibrium plasma discharges for CO_2 conversion

Non-Thermal Plasmas (NTPs) are very weakly ionized gases in which a few highly energetic electrons transfer energy efficiently to molecules to induce chemical reactivity while keeping relatively low gas temperature, allowing chemistry far from thermo-dynamical equilibrium. Different kinds of NTPs can be obtained and are studied for CO_2 reduction and conversion into added value molecules.

Plasma can be used as electrodes to assist electrolysis cells where CO_2 reduction occurs. Positioning the plasma above the liquid will allow conversion of gaseous CO_2 into highly soluble carbonaceous molecules. This process can convert intermittent electrical energy (produced by wind or solar panels) into chemical energy.

But plasma can also promote asymmetric vibration in CO_2 molecules. When the density of vibrationally excited molecule is high enough while remaining at room temperature, it can lead to CO_2 dissociation into carbon monoxide (CO) and oxygen (O). It can also lead to CO_2 reactions with H_2, H_2O (water) or CH_4 (methane), producing a wide range of molecules like ethanol or methanol among others. However, the selectivity in the products being formed must be controlled and coupling of plasma with catalytic material can be envisioned.

Nanosecond discharges are also being investigated for methanol production. This approach for CO_2 dissociation uses fast gas heating: 2000 K during tens of nanoseconds, providing temperature needed for chemistry. Among others, the development of the discharge at elevated pressures in mixtures of a given composition is studied.

Synthetic fuel from seawater CO_2

This project intends to demonstrate that a synthetic fuel (namely methanol) could be produced from CO_2 dissolved in seawater using "photovoltaic-powered solar methanol island" (figure 12). The interest of extracting CO_2 from seawater rather than its direct capture in the atmosphere is simply due to the large difference in concentration (99 gCO_2/m^3 in the ocean vs. 0.79 gCO_2/m^3 in the atmosphere). To summarize this approach, the CO_2 extracted from seawater would be combined in a reactor with H_2 – produced from electrolysis of desalinated seawater – to give methanol. The energy required for the different processes would be generated by photovoltaic solar panels. Those devices would be integrated on a floating island located in specific region of the world where insolation and water depth are optimal, with low probability of hurricanes. Achieving this view would require skills in chemistry, mechanics, engineering and physics, together with expertise in meteorology and dynamics of atmospheric processes. This project will end up with a demonstrator on École Polytechnique's lake and its modularity will allow the test of different tool developed from different laboratories.

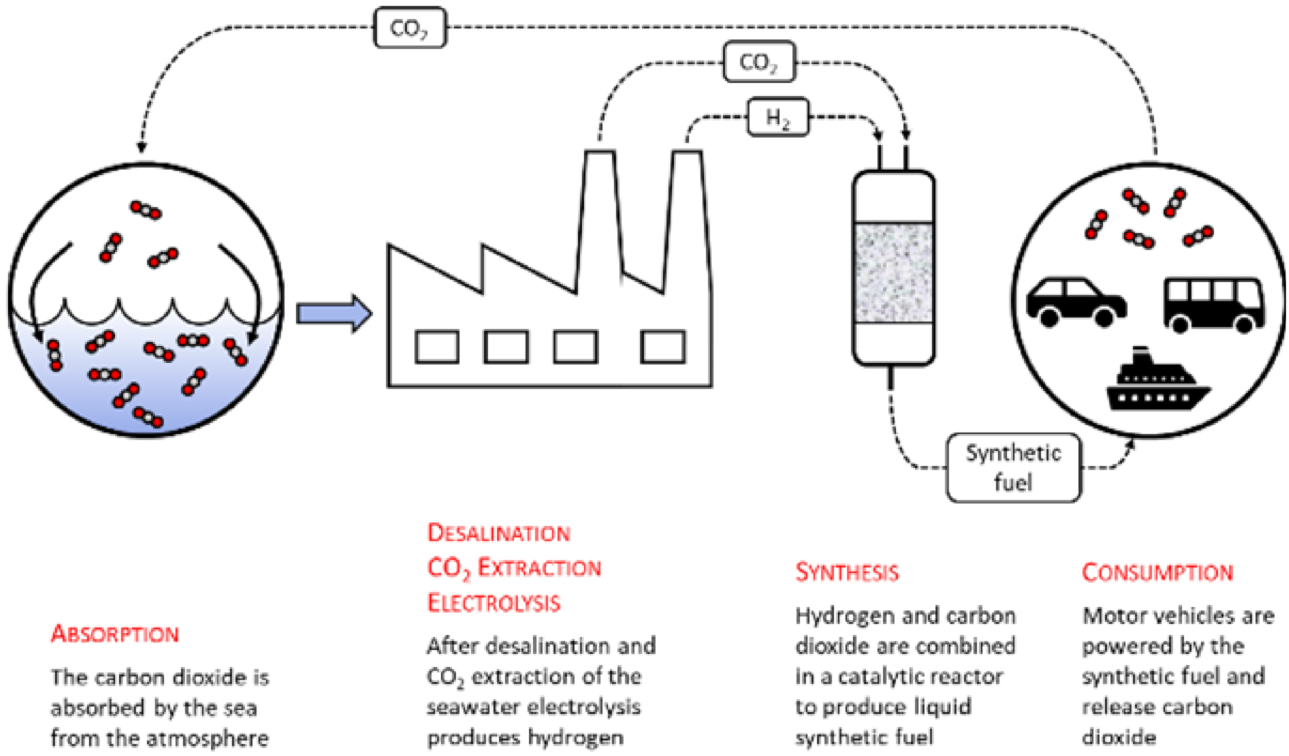

Figure 12. Principle of synthetic fuel production from seawater CO_2

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3 Energy efficiency

Objectives:

- Reduce energy consumption of data analytics
- Ensure new services, quality of service, and sustainable business models
- Use connected devices to reduce buildings' energy consumption

Energy efficiency

This Research Action aims at evaluating, predicting, estimating and suggesting optimization solutions for energy consumption and efficiency while respecting the quality of service and the comfort of users and applications.
Firstly, data analytics applications consume a lot of energy, due to recent changes in internet services' usage leading to a huge amount of data generated and stored in data centers. Processing these big data and training artificial intelligence (AI) models require powerful computers. Reducing the consumption of these computers is thus important.
Secondly, new generation of services are more and more modular and distributed over different internet layers. Analyzing the energy efficiency at different levels of distributed systems (system, middleware and service levels) should help reduce their consumption.
Finally, proposing intelligent solutions to control and optimize energy consumption related to contextual and predicted information is necessary to complete existing approaches for living spaces energy consumption optimization.
Therefore, the energy consumption reduction of these Information and Communication Technologies (ICT) considers a holistic and systemic approach, covering both device and device intercommunication. Specifically, it works on reducing the energy consumption of data centers and high-power devices, of networks and of low-power terminals (computers, smartphones) and embedded systems. It also works on increasing the lifetime of high-power and low-power devices relying on batteries and optimizing of the system (prioritizing and adapting device functionality to reduce the overall consumption). It is estimated that ICT are responsible for 4 % of the world greenhouse gas (GHG) emissions, and their energy consumption increases by 9 % each year. These emissions are mainly due to the production of terminals and their energy consumption also including data centers and networks, making this Research Action crucial.

Energy efficiency of High-Performance Data Analytics

Measuring the power consumption of models executing on various hardware platforms is the first step to understand the energy consumption of machine learning applications. The measured data could then be used to model other machine learning applications' energy consumption and highlight parameters affecting applications' power consumption and their performance. This could lead to recommendations on how to implement machine learning with a limited power consumption without degrading its performance. Another approach is to compress existing models that big technological compagnies use and target different downstream tasks. The process, called pruning, helps to remove unnecessary parameters like weights, heads and layers. This makes existing models smaller and faster. It also reduces their energy consumption.

Energy efficiency in new/next generation distributed systems

E4C laboratories focus on slices' allocation and their virtual function placement. This could be seen as the allocation of a virtual graph into a physical graph. In that case, problems appear when the graph size increases. E4C researchers aim at developing new AI based algorithms to design resource allocation and management policies that consider both performance and energy consumption.
Internet of things (IoT) system architectures consist in two elements: IoT devices and sensor networks. This kind of system must include efficient filtering mechanisms to control energy consumption of IoT devices and application devices. These filtering mechanisms consist in limiting data exchange flows. E4C researchers work on:

- event-based architectures to filter data flow and dissemination,
- software leveraging artifacts to filter data through APIs controls,
- energy patterns defining models to control data flowing through data exchange components,
- IoT application end-to-end energy consumption estimation to assess the average consumption of different IoT scenarios and filtering mechanisms.

Finally, E4C specialists offer to provide software architects with guidelines to consider energy efficiency and resource efficiency. Indeed, these parameters have direct effect on environmental sustainability and environmental quality of service characteristics.

Energy efficient spaces

E4C researchers work on designing appropriate models of buildings including constant and variable data. This includes room capacity, current occupancy or temperature preference. Part of the challenge is to associate information with various forms (WiFi APs, Bluetooth beacons, video cameras…) to the IoT devices used to gather them. Another part of the challenge is to translate users' temperature preferences into commands for heating, ventilation, and air conditioning (HVAC) systems, and which HVAC zones to activate according to users' presence. Of course, dealing with users' different temperature preferences is also challenging. To leverage this, users can also be advised on room utilization to occupy those that already are at the right temperature rather than those that must be heated or cooled down.

Another E4C project plans to optimize energy performance and large building comfort, air quality and hygiene using new end-to-end methodology. To do so, a metamodel is to be constructed based on a Transformer network trained using a dataset sampled with a simulation program (TRNSSYS). The metamodel will then be calibrated with optimization algorithms and real sensor data. Finally, a multi-objective optimization procedure will set optimal setting to minimize energy loads and maintain comfort temperature and air quality.

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- Laboratoire SAMOVAR (Services répartis, architecture modélisation validation administration de réseaux)

4 Mastering energy demand

Objectives:

- Analyze consumption flexibility through different lenses
- Explore energy sufficiency
- Understand and manage flexibility on demand-side
- Study the feasibility of sustainable cooling systems
- Study economic viability of technologic leapfrogging in emerging countries

Mastering energy demand

This Research Action focuses on mastering energy demand in the future at the macro, meso and micro levels.

Today, energy transition often appears as the substitution of high-carbon energies by low-carbon energies. This transition is only possible if the demand is mastered too. To do so, two dimensions will be explored: flexibility and sobriety.

Flexibility refers to the change of individual behaviors. Nevertheless, they are difficult to pin-point by nature, and are governed by a set of habits, standards and constraints, which are often difficult to observe in practice. The need to change practices is consensual, but the actions to be taken are complex to define.

Flexibility also refers to matching energy consumption to renewable electricity production (among others) as it is non-storable, intermittent and non-controllable. Demand-Side-Management (DSM) is a central challenge, giving consumers a new role to play.

Sobriety roughly refers to limiting energy usage by reducing consumption needs or adopting practices requiring less energy. Sobriety development faces many obstacles such as behavioral changes and understanding its factors is primordial.

The Research Action also focuses on particular challenges in certain regions of the world: the issue of avoiding detrimental, self-reinforcing feedback loops in adaptation to global warming through air conditioning will be addressed in relation to Africa, where AC is expected to spread dramatically.

Finally, energy plays a crucial role in facilitating the access to essential services, such as electricity, water, and mobility in developing cities in India and East Africa. These services are impacted by provision discontinuity, which opens an avenue to private operators proposing alternative services to partially fill the gap between the end-users' demand and the unreliable public service. The development of leapfrogging technologies and systems will be examined within the field of Information and Communication Technologies for Development (ICT-D).

Consumption flexibility: from carbon tax to local experiments

People tend to overestimate their losses due to carbon tax, despite information they are provided with. This response, allegedly caused by psychological costs, reflects one's choice of social identification. This provides explanation for new identity formation caused by carbon taxes, like the Yellow vest, and latter policy's failure. This example shows the impact that energy prices' change can have on identification models and how it can lead to carbon taxes' failure. E4C researchers want to examine these factors.
Secondly, E4C laboratories also want to study the impact of carbon regulations on extractive sector compagnies' theoretical value and countries with fossil resource's wealth using data on large deposits' ownership in the world.
Thirdly, E4C researchers wish to analyze the role of local initiatives for new low-carbon technologies' diffusion, mainly in mobility sector, not only households' energy consumption. The goal is to identify different administrative layers respective influence on low carbon technologies deployment and analyze policies optimal articulation at different levels.
Another aspect concerns pollution control coordination between upstream (power sector) and downstream (electric mobility). The goal is to understand the effort optimal allocation, the transition sequence (which sector begins or ends its transition first or last) and the coordination of policies (taxes and subsidy).
A fourth project will run experiments on consumption flexibility in a smart building on campus. This research is very promising to link implemented incentives and behavior changes, using devices for live visualization of water or energy consumption.

Exploring energy sufficiency

E4C research is exploring energy sufficiency at three levels:

- Sufficiency consumption behaviors at an individual level
- Community experimentations of transition and sufficiency at a collective level
- Practices and devices to manage energy sufficiency at an institutional level

E4C scientists will aim at revealing energy sufficiency models, practices, mechanisms and dynamics, by combining various theoretical lenses and using both qualitative and qualitative methods.

Flexibility in demand-side-management: institutional logics, management tools and prosumers

The demand flexibility is seen by energy players as an improvement target for the production/consumption balance, as well as a response to intermittent renewable energies. However, what is its place in consumers' vision of behaviors expected?
The first part aims in better understanding this vision to identify brakes and levers for demand flexibility.

- What are the representations/beliefs that consumers have of expected behaviors ?
- Which medium/tools conveyed these beliefs?
- What is the place of flexibility in these representations/beliefs ?

The second part aims to evaluate management and information devices on consumers' beliefs/representations and on their ability to make their uses more flexible.

Pathways to sustainable cooling in the developing world

E4C laboratories explore a way to avoid detrimental, self-reinforcing feedback loops in adaptation to global warming through air conditioning (AC). This issue will be addressed in relation to Africa, where AC is expected to spread dramatically. Big data will be collected on a pan-African e-commerce platform to study how the availability and affordability of energy efficient AC varies across seasons and during heat waves.

Leapfrogging energy services and payment systems for a better access to electricity

E4C laboratories aim at understanding the economic viability of companies like Janajal that use electric rickshaws to provide drinkable water to low-income households. Latter people live in areas where the installation of a fix water ATM kiosk was not justified, so these Indian companies developed a mobile water ATM built on e-rickshaws that accept different ways of payment adapted to users' capacity (prepaid cards, digital wallets, unified payment interface, coins).
E4C researchers also aim at understanding the way prepayment system implementation modifies users' consumption patterns, and how it made services more perennial.
Mobile money has massively emerged in East Africa over the last decade, and it is now a common way of payment for everyday purchased in the region. That is why even

electricity can be prepaid in countries like Tanzania or Zanzibar. Users prepay their electricity supply service through mobile money systems.

Finally, E4C specialists aim at studying island territories energy production and consumption practices. Indeed, those geographically remote lands face several problems highlighting the need to accelerate measures in favor of energy transition: the additional cost of fossil resources importation, their predicted scarcity, the island states infrastructure developing deficiency, the population financial insecurity and the lack of electricity in some isolated areas within the islands (cirques, valleys, remote villages).

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5 Energy assessment and forecasting

Objectives:

- Assess more accurately energy resource, supply and demand
- Forecast supply and demand at different timescales
- Differentiate natural and climate change induced resource variability

Energy assessment and forecasting

Solar and wind energy are variable in time, and spatially diffuse. Forecasts of these renewable resources are available but come with uncertainty. Dealing with this uncertainty in decision-making processes calls for tight interdisciplinary collaboration between applied mathematicians, climate scientists and economists.

Before forecasting the availability of renewable energies, the first vital step for their development is the assessment of the resources. This requires both information on the geophysical variables which determine the potential energy extracted, and a good knowledge of the technologies used for the extraction. E4C research focuses on the estimation of the potential for solar PV on roofs and on the fine-scale assessment of the wind resource for a given site. In addition to that, the human partitioning of space also must be explored, for it conditions the demand and the way some sectors are supplied.

Now, a fundamental requirement is to maintain the balance between supply and demand in the electric grid. This implies the development of tools and methodologies to forecast both supply and demand on an extended range of timescales, from minutes to seasons, using different resources (from observation to multi-model ensembles of numerical weather predictions).

Finally, it is primordial to anticipate evolutions and risks with climate change. Indeed, renewable energies are set to vary, naturally and due to anthropogenic reasons, form the year to the decade scale. These evolutions need to be considered in the energy transition which calls for rapid and profound changes in our systems and infrastructures. Latter changes require huge investments, therefore the anticipation of natural and anthropogenic climate change is important.

Resource and supply assessment

For a given site, the fraction of energy that can be extracted from the natural potential will depend on the technology adaptation and its deployment to the site and resource. Photovoltaic (PV) systems are being developed in big PV plants or small building scale systems. Latter systems are interesting for self-consumption applications. However, this rooftop production potential depends on several parameters:

- solar resource of the region
- the geometric characteristics of the rooftop (tilt, orientation)
- the obstacles that could cause shading effects on the panels (rooftop objects, surrounding buildings, trees and the orography of the place)

Potential evaluation of many urban rooftops requires treating geolocalised information and geophysical data to infer solar resource.

Regarding wind farms, the extraction of energy by wind turbines decelerates the flow and generates turbulence. These impacts on the flow decrease the efficiency of energy extraction. In other words: a wind turbine positioned behind another will be less efficient than the one in front of it. Finer modelling of these effects will contribute to improved planning of wind farm installations.

Finally, the energy supply must be investigated at the scale of administrative regions (or sub-domains) for it is more relevant than local data. The prospective adequacy of a power system often relies on data for a few electric regions and system operators often provide energy data at these scales while local information from local producers remains too sparse and not sufficiently representative.

Supply and demand forecast

Managing the energy system or grid needs forecasting to ensure supply-demand balance and stability, and to optimize the use of energy at lowest cost. Forecasts are usually needed to know in advance supply and demand, during the day (nowcasting) or at day-ahead (short-term) in order to make decisions that can have implication on different sites from production, demand or storage, and might be motivated for trading on energy markets, unit dispatch, grid planning, maintenance, congestion forecast or others. This research is articulated around two questions:

- What is the best way to forecast (supply or demand) given the available information at different scales and time horizons?
- How reliable is a forecast, that is, which is the uncertainty related to a given forecast and what does it depend on?

Forecasts are also valuable on longer time scales, such as sub-seasonal and seasonal scales. Indeed, a major part of energy variability comes from meteorological variability: temperature's fluctuations affect energy demand for heating in winter, and air-conditioning in summer. As renewables increasingly penetrate the energy mix, meteorological variability also crucially affects energy production. For horizons from two weeks to several months, forecasts can not be deterministic, they are probabilistic and based on ensembles. E4C laboratories aim at bridging the gap between the climate community and energy sector stakeholders, by revisiting and improving each step of sub-seasonal to seasonal forecasts, providing tools tailored for decision-making processes in the energy sector.

Anticipating evolution and risks with climate change

E4C laboratories aim at answering several questions:

- What are the risks due to the natural variability of climate for investments in renewable energies?
- How will climate change affect the potential for different renewable energies in a given region?
- How will climate change, economic activity and changing lifestyles affect demand on regional scales?
- How will climate change threaten the resilience of energy networks?
- What are the prospects for breakthrough innovations relying on renewable resources?

Investments in energy timescales go from the decade to a few decades, whereas assessment of renewable energies resources only takes a few years. Moreover, atmospheric circulation varies naturally on a wide range of timescales, even regardless of climate change. A key issue is therefore to sort out this natural variability from the possible changes expected from climate projections.

The uncertainty for climate evolution, coming in part from uncertainty on mitigation choices in coming years, makes projections difficult.

E4C laboratories focus on untangling natural variability effects on energy infrastructures and renewable resources, mainly interannual variability.

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6 Storage

Objectives:

- Use geologic structures to store energy
- Improve hydrogen production and storage
- Increase battery capacity and cyclability
- Investigate metallic foams to improve salts’ thermal energy storage

Storage

Energy storage has become a major issue, due to the intermittency of renewable energies and the necessary adaptation of the balance between electric production and its consumption. Energy storage is also an important area of improvement for cleaner means of transport such as electric vehicles. Depending on the application, different properties are required: large scale storage facilities for power leveling, or large power and energy densities for the electric vehicle. In all cases 4 key points need to be considered:

- *good cyclability (possibility of large number of storage and recovery cycles),*
- *a high efficiency (ratio between the recovered and the stored energy),*
- *the recyclability of the storage system after its end of life,*
- *and its safety.*

Within the E4C framework, different topics are investigated to match these issues. Firstly, geological storage is a major interest because of its massive capacity. The energy storage potential is very broad (compressed air, hydrocarbons, hydrogen), and can also be used for CO_2 long-term storage. Though, it is important to understand the reservoir rocks' mechanical behavior to ensure the integrity of the storage facilities.

Secondly, hydrogen is one of the promising means of energy production and storage, a possible substitute for hydrocarbons; however, different issues still require research efforts.

Thirdly, batteries are the best-known way to store energy, but they need improvement in terms of capacity, cycling rate and lifetime to meet the requirements of large-scale energy storage and electric vehicles. For example, alloying lithium with various metals or semiconductors should improve the energy density of batteries. However rapid degradation of cycling properties currently limits their practical use.

Finally, thermal energy storage also must be investigated, especially in Northern countries, where heating can represent a large part of households' bill. Exploiting the thermochemical potential of reversible chemical reactions, is among the most promising techniques for thermal energy storage.

Geological storage

Deep underground storage can present many advantages. It can for instance store energy under the form of compressed air in carbonate reservoir rocks such as depleted reservoir or saline aquifers. But it can also store CO_2. Nevertheless, if those techniques

can bring short term solution what about long-term evolution? It is imperative to understand mechanical properties of carbonaceous rocks using *in situ* measurements to foresee the evolution of these reservoirs and ensure its integrity.
Deep underground storage can also allow the storage of hydrogen. Massive storage in salt cavities is one of the keys of future hydrogen economy. Once again, it is primordial to understand thermomechanical behaviour and sealing properties of these cavities. Experimental measurements and numerical modelling will help assess the evolution of the cave during its use and after its abandonment.

Hydrogen – production and storage

A first research deals with the direct production of hydrogen in water using solar light, by combining catalysts with tandem solar cells. The main issue concerns the efficiency of this process compared to systems providing separate functionalities – solar cells providing electric power and electrolysis converting the electricity into the hydrogen by water splitting.
A second research concerns anode materials to produce hydrogen and oxygen by electrolysis of sea water, a clean and sustainable way to produce "green" hydrogen. However, impurities present in sea water can greatly affect the performances of the catalysts used for improving the efficiency of hydrogen production. It is thus crucial to propose solutions to protect electrocatalysts at the anode and the cathode against impurities. The research aims at the development of protective overlayers and the synthesis of nanostructured catalysts covered by a protective shell (Core-shell particles).

Batteries

This large topic covers many reseaches to improve energy storage. Indeed, many ways of improving lithium-ion batteries' (LIB) energy density are being investigated. For instance, using aluminum (Al) based negative electrodes is being studied by E4C laboratories. Some laboratories are also assessing the improvement of pure silicon's cyclability using methylated silicon while others are developing a predictive simulation based on physical modeling and experimental characterization to refine existing models for intercalation of lithium (Li) ions in lamellar materials. In the frame of NanoMADE-3E Initiative*, LIB based on nanomaterials are being investigated to produce lithium-ion batteries with silicon and sulfur electrodes. The construction of a nanospectroscopy platform will be used for LIB studies. E4C laboratories aim to understand the influence of mechanics and electrochemistry influence on the kinetics of transformation phase during lithiation and delithiation of electrodes. Finally, the E4C laboratories study the structural and electronic

* Eco-aware and Efficient Nano -MAterials, nano-DEvices and Engineering

properties of cathode material to correlate their electrochemical properties with their microscopic properties.

Thermal energy storage

Exploiting the thermochemical potential of reversible chemical reactions, is among the most promising techniques for thermal energy storage. Exothermic hydration reactions of salts are particularly interesting in terms of cost and environmental harmlessness. Yet, the storage capacity of these salts depends on their specific surface, in other words: their porosity. Latter suffers reduction upon hydration cycling. Experimental developments are needed to overcome the physicochemical evolution of the system.

E4C laboratories work on thermochemical reactions to store energy. Based on hydration reaction of hydrophilic materials, this method still needs improvement on materials cycle stability and medium storage capacity. Soon enough, E4C researchers will come with a solution for this issue (patent pending).

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- Laboratoire Navier (NAVIER)
- Laboratoire de Physique de la matière condensée (PMC)
- Unité chimie et procédés (UCP)

7 Resilient eco-friendly smartgrids

Objectives:

- Design better power allocation algorithm
- Test and validate latter algorithms in real-life conditions
- Design efficient communication systems between smartgrid's components
- Insure users' data privacy and security
- Design mechanisms for massive deployment of smartgrids

Resilient eco-friendly smartgrid

Energy digital transformation led to new concept emergence, namely smartgrids that enable massive renewable energy deployment and global energy efficiency by connecting different factors. But with this new concept, new service paradigms, new business models and new architectures emerged too, related with infrastructure continuous and real time monitoring capacity or consumers and prosumers behavior. In this context, new technologies potential leveraging raised many challenges that this Research Action aims at solving.*

Firstly, E4C laboratories want to design stochastic optimizing algorithms, focusing on the context's uncertainty in which smartgrids evolve, contributing to their resilience. These algorithms will then be tested in real condition.

Methods of co-simulation will be developed by information and communication systems design to validate smartgrids operations, contributing to its resilience.

Since metering is crucial for the smart grid, an IoT infrastructure for advanced metering and control will be designed, set up and tested.

In addition to these tools, E4C laboratories aim at developing advanced artificial intelligence (AI) learning-based methods to detect anomalies. Concerning privacy issues, methods allowing distribution of calculation without exchanging data based on secure multi party computation are to be developed. Privacy is a major issue, given that smartgrid operations are based on collected data providing private information.

Finally, E4C researchers work on advanced mechanisms for massive smartgrid deployment, using a holistic scope, combining technical, social and economic approaches.

Design of stochastic optimization algorithms

E4C laboratories focus on mathematical formulations and resolution methods to address optimal power allocation in new energy systems. Indeed, relying on renewable energies introduces variability and uncertainty in the production, in addition to demand uncertainty. Therefore, electricity network management must be assured by optimization strategies, to find the best possible use of the different means of energy production given uncertain forecasts.

* Contraction of producer and consumer

This topic relies on demand and energy production statistical models provided by E4C laboratories, and algorithms should be tested experimentally or using real smartgrids (see following topic). Although, many questions are to be solved:

- What are the best algorithms to optimize small scale micro-grid involving renewable energies and storage capacity?
- How can energy production uncertainty meet demand uncertainty on a countrywide scale, at different time horizons?
- How to geographically distribute renewable energy productions to optimize energy mix on a country or international scale?

These questions will require sophisticated mathematical approaches to determine, in a complex system, with only limited possibilities of training from past examples, the preferred strategies.

Testing and validating EMS control algorithms in real conditions

E4C center built the Nanogrid Research Laboratory (NRLab) in 2016 to implement, test and compare different energy management systems (EMS) algorithms. This real-life, real-time small-scale platform allows easier evaluation than those exploiting historical data and provides meaningful results.
For instance, the NRLab has tested a collection of EMS algorithms, achieving the highest economic gains when tested with a typical PV-battery microgrid and using data collected by industrial energy company in 70 different sites.

Information and communication system design

E4C laboratories propose research contributions to develop different systems to manage the smartgrid. These systems include an information system able to manage information, an industrial supervision system able to control the electrical network and a telecommunication system able to transmit information between all elements of the system.
The design of smartgrid information system requires simulation approaches to compare different possibilities. However, these simulations need heterogeneous models corresponding to electrical, information processing and telecommunication domains that must be linked to detect influences on one another and identify emerging behaviors. A model-driven approach allows code generation to ensure consistency between domains.
While simulation is a powerful tool to study different communication networks in a scalable way, it still has limitations facing cyber-physical systems because of the

unpredictability of the physical world. Simulation tools will allow researchers to combine the scalability of software simulation and the reality of field tests.
E4C researchers also propose to tackle the complexity of a smart grid system through a model-driven engineering (MDE) approach and to decompose it into different views. One of the advantages of MDE is to deliver executable models generated using software engineering tooling.
Finally, E4C researchers will work on improving Internet of Things (IoT) infrastructure, to improve the environment perception and human activities, to facilitate decision-making process quicker and to help students to learn how network communication systems work.

Security and privacy issues

Security of information system is important for smartgrid resilience. The ability to detect intrusions is vital for cyber-physical systems operation: any leak may lead to human casualties. However, security measures may cause collateral damage in case of false positive. Partitioning the smartgrid may reduce these effects by restricting security measures to sub-systems, although it may also increase computation. E4C laboratories want to use IoT federated learning that distributes anomaly detection to the edge to smartgrids.
Designing methods to detect suspicious traffic during exploitation in operational phase requires nominal reference traffic traces, although traffic is encrypted so that it is not possible to rely on the traffic content to analyze its threat-level (contrary to the traffic shape). E4C specialists wish to augment datasets from real users using generative models to increase its volume and diversity. Key challenges appear on generated data's realism validation and anomaly detection in dynamic setting.
Energy and consumption data are valuable information that can improve energy optimization and prediction if exploited by energy providers. However, this kind of data is also considered as personal identifying data that must protected. Secure Multiparty Computation (MPC) has proven its efficiency in data computing and security even if it still needs improvement before being deployed to smartgrids, to ensure system resilience for instance. The adoption of data conditional disclosure principle, statistical disclosure control methods and consumption data perturbation with noise are being investigated.

Massive deployment of local renewable energy sources and storage, a joint technical, social and economic approach

It is known that existing grids' architectures are not designed for enabling a massive deployment of local energy generation and of local storage. Moreover, costs induced by local energy and storage deployment are limiting the potential impact of those technologies. That is why E4C laboratories work on designing smartgrids' advanced mechanisms for efficient local generation and local consumption matching, modulated by local storage and including innovative demand-side management mechanisms. In addition to that, new economic collaborative investments and business models highly incentive the required investments and create new channels of value and revenue creation.

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- Laboratoire d'informatique de l'École polytechnique (LIX)
- Laboratoire de météorologie dynamique (LMD)
- Laboratoire traitement et communication de l'information (LTCI)
- Laboratoire SAMOVAR (Services répartis, architecture modélisation validation administration de réseaux)

8 Long-term sustainable development

Objectives:

- Model long-term power system evolution and resilience to climate change
- Study the relevance, social feasibility and sustainability of the proposed energy transition solutions
- Model long-term consumption habits
- Study cities and buildings' role in the energy transition
- Assess compagnies' decarbonization, low-carbon financing and responsible investments
- Develop environmental impact and climate risk measurement tools
- Use artificial intelligence to reinforce tools

Long-term sustainable development

The objective of this Research Action is to focus on long-term sustainable development questions and energy system evolution, in other words: the economy transition to a carbon-free system. This issue will be studied through different questions:

- *Sustainable long-term evolution of the energy system: how can new systems be modeled and adapted to new prosumers ? Decentralized management also raises questions of resilience, reliability, viability and efficiency.*
- *Prospective models for the development of low-carbon public policy: how can climate change mitigation public policies be reconciled with their social impact? The yellow vest crisis showed that neglecting the connection between these factors was a mistake. The social feasibility of a solution can only be studied through its consequences on CO2 emissions, households' income, employment and living conditions in general.*
- *Long-term energy demand modeling: what is the impact of physical, socio-economic and climatic factors on consumption?*
- *Role of cities and buildings in the energy transition: how will existing cities be re-imagined and converted into low carbon connected hubs to face the future technological, environmental and social changes?*
- *Financing the energy transition: how can finance become more responsible and accomplish its multiple roles? It involves financing household energy transition investments, promoting real economy greening, facilitating energy transition infrastructure financing, protecting investors from climate risks and guaranteeing them an acceptable level of return under the sustainability constraint.*
- *Measuring the risks associated to energy transition and the environmental impact of economic activities: is it possible to align measures based on integrated modeling scenario while considering their associated uncertainty?*
- *Data and artificial intelligence (AI) issues: can AI integrate data for climate risk and impact analysis? Can AI use physical assets to quantify their vulnerability? Can AI analyze available data to build risk and impact indices?*

Long-term power system evolution, resilience and reliability

E4C specialists want to analyse the threat that physical hazard represents to nuclear plants and general decarbonization process. To do so, *ad hoc* modelling tools will be created for random uncertainty by quantifying risk. Furthermore, this modelling needs to consider several mechanisms to incorporate a component of random uncertainty:

- Impact of temperature and drought on plant cooling
- Impact of climate change on hydropower electricity production
- Impact of increasing weather variations on solar and wind electricity production
- Meteorological variables modelling using temporal and multi-site statistics
- Climate change impact on electricity consumption

At the same time, E4C collaborates to understand future European electric market dynamics through game theorical modelling to propose optimal market design and policies that ensure economic sustainability. This modelling will also help to understand potential users' and energy suppliers' behavior, network security and CO_2 emission evolutions.

This will allow market mechanisms optimal designs and optimal policies to achieve CO_2 emission specific objectives.

Relevance, efficiency, social feasibility, economic viability and sustainability of energy transition solutions

E4C collaboration aims at producing an economic analysis of energy systems primarily based on renewable energies. This E4C research will address several questions:

- What is the optimal local distribution of wind turbines and photovoltaic panels, considering the spatial and temporal correlations of wind and sun, and the electricity transmission network?
- How to consider the imperfect weather forecasts in the optimization of an electrical system?
- How will climate change and decadal variations impact such an energy system by changing winds, cloudiness, temperatures and therefore the efficiency of solar panels, precipitation and therefore hydroelectric production?

Long-term consumption modeling

The evolution of energy consumption is notoriously difficult to predict: it is systematically overestimated in French official forecasts. The difficulty comes from the fact that energy consumption is influenced by climate's evolution, international situation and technological and lifestyle changes. However, long-term greenhouse gas emission forecast requires modeling the energy consumption evolution, but also its distribution between different energy sources and energy carriers. A better long-term consumption modeling involves explicitly representing the physical, socio-economic and climatic determinants of this consumption. For example, as far as heating energy is concerned, the number of households, heated surface, winter temperatures, household income, renovations' price and performance and energy prices are needed to model. Regarding transportation energy, the density of cities, the prices of different fuel types and vehicles, the various public policies are necessary.

There are many interactions between socio-economic and climatic variables: heating and cooling are influenced by temperature (and humidity) but contribute to global warming, both global and local; urban density reduces CO2 emissions but aggravates the urban heat island effect.

E4C laboratories will study these interactions, as well as the influence of information technologies (in particular on the level of demand and its flexibility), and the couplings between sectors, which are likely to develop through conversions between energy vectors (in particular from electricity, the so-called power-to-X).

Role of cities and buildings in the energy transition

Two E4C researches aim at producing an economic evaluation of climate plans and sustainable finance strategies at local level.

The first E4C research evaluates the synergies between public policies. Indeed, many studies evaluate measures' impact separately while only few studies consider the wide picture and the interactions both positive and negative between those measures. More specifically, E4C researchers want to study how the carbon neutrality measures interact with each other depending on the policy sector such as transport or energy and on the type of measure.

The second E4C research involves integrated city modeling. E4C researchers aim at developing a modeling platform that considers various users and energy suppliers to study long-term mobility behaviors, both residential and transportation. The modeling platform will progressively be extended to integrate various informations such as residential mobility or household energy behaviors. Ultimately, these integrated transport land-use and environment (ITLUE) models will allow cities energy and ecological transition scenarios evaluation.

Decarbonization of companies, low-carbon economy financing and responsible investments

Finance has many responsibilities to achieve ecological transition.
Firstly, financing households' energy transition investments through green consumer credit to encourage them to adopt greener behavior. E4C laboratories want to analyze the credit's dynamics for green investments like housing energy renovation. They also want to analyze economic instruments supporting households and SMEs.
Secondly, promoting real economy greening. To achieve this, policies excluding polluting compagnies and lowering green compagnies capital cost are necessary. To assess responsible investment impact, E4C researchers will measure investment decisions' impact on business practices.
Thirdly, facilitating energy transition infrastructure financing. Precise quantification of investors' financial risk in renewable energy projects is primordial. E4C center will focus on wind farm projects and public support policies' cost to make these projects sustainable, as shown on figure 13.
Fourthly, protecting investors from climate risk and ensuring them financial system stability regarding transition risks. On this subject, E4C specialists will study how transition risks are considered in investment decisions.
Finally, guaranteeing investors an acceptable level of return under sustainability constraints. Usual portfolio management methodologies are obsolete in green investment scenario. To compensate it, machine learning techniques are interesting to categorize the immense available data and integrate it in strategies' construction.

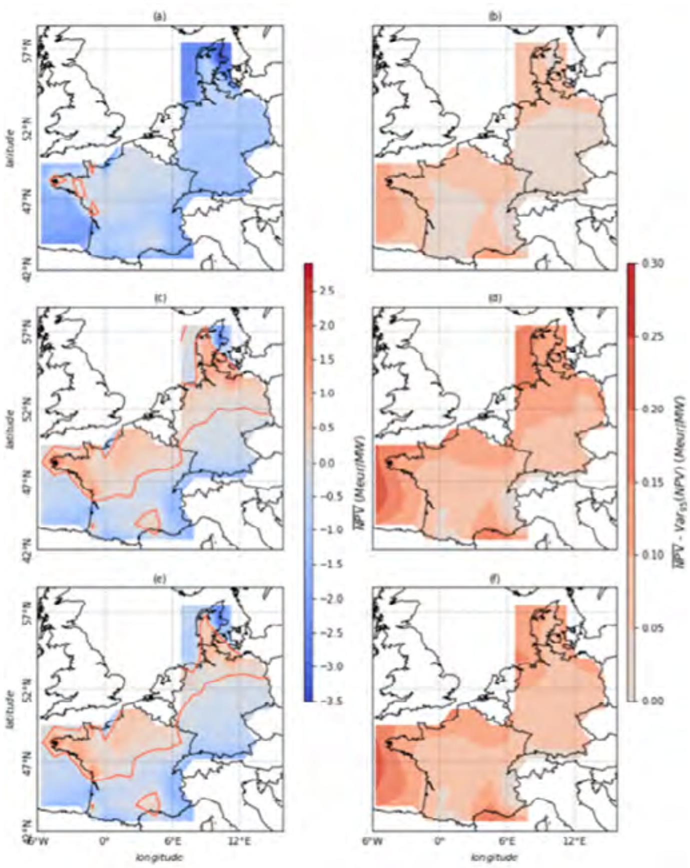

Figure 13. Expected revenues (left) and risks (right) of wind farms under present climate without subsidy (top), with feed-in tariff (middle) and with feed-in premium (bottom)

Measures of environmental impact, climate risk and alignment with the objectives of the Paris

accord

E4C laboratories have two objectives: developing a forward-looking scenario data incorporation standard methodology under carbon constraints and producing energy sector financing projects risk associated analysis tool.

On one side, a project aims at providing risk-sharing instruments development tools for low-carbon transition sectors to increase the effect of public action on private capital inflow for this transition. The ultimate objective is to develop risk measures in energy transition projects so their cost will decrease by reducing risk premium and assess risk-sharing instruments' cost.

On the other side, a robust and open-source methodology is being developed. The objectives are:

- Computing uncertainty measures of key parameters from information contained in existing databases, poorly exploited, on the prospective scenarios produced by the integrated models
- Constructing a risk matrix associated with the financing of projects in low-carbon energy sectors

The ambition is to create an open-source analysis model, robust, accessible and adapted to various economic and geographic contexts, capable of facilitating the redirection of financial flows towards low-carbon assets.

Data and artificial intelligence issues

E4C center works on AI based techniques to produce and process data answering these questions:

- How to integrate data into the E4C datahub for climate risk and impact analysis
- How to estimate damage by measuring physical assets' vulnerability using damage functions or impacts observation based adaptive methodology?
- How to construct risk and impact indexes from available data by correlating them with asset data allowing attribution of observed impacts to specific entities and classifying them to identify the most discriminating indicators in terms of investment impact?

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- Centre de recherche en économie et statistique (CREST)
- Laboratoire de météorologie dynamique (LMD)
- Laboratoire SAMOVAR (Services répartis, architecture modélisation validation administration de réseaux)

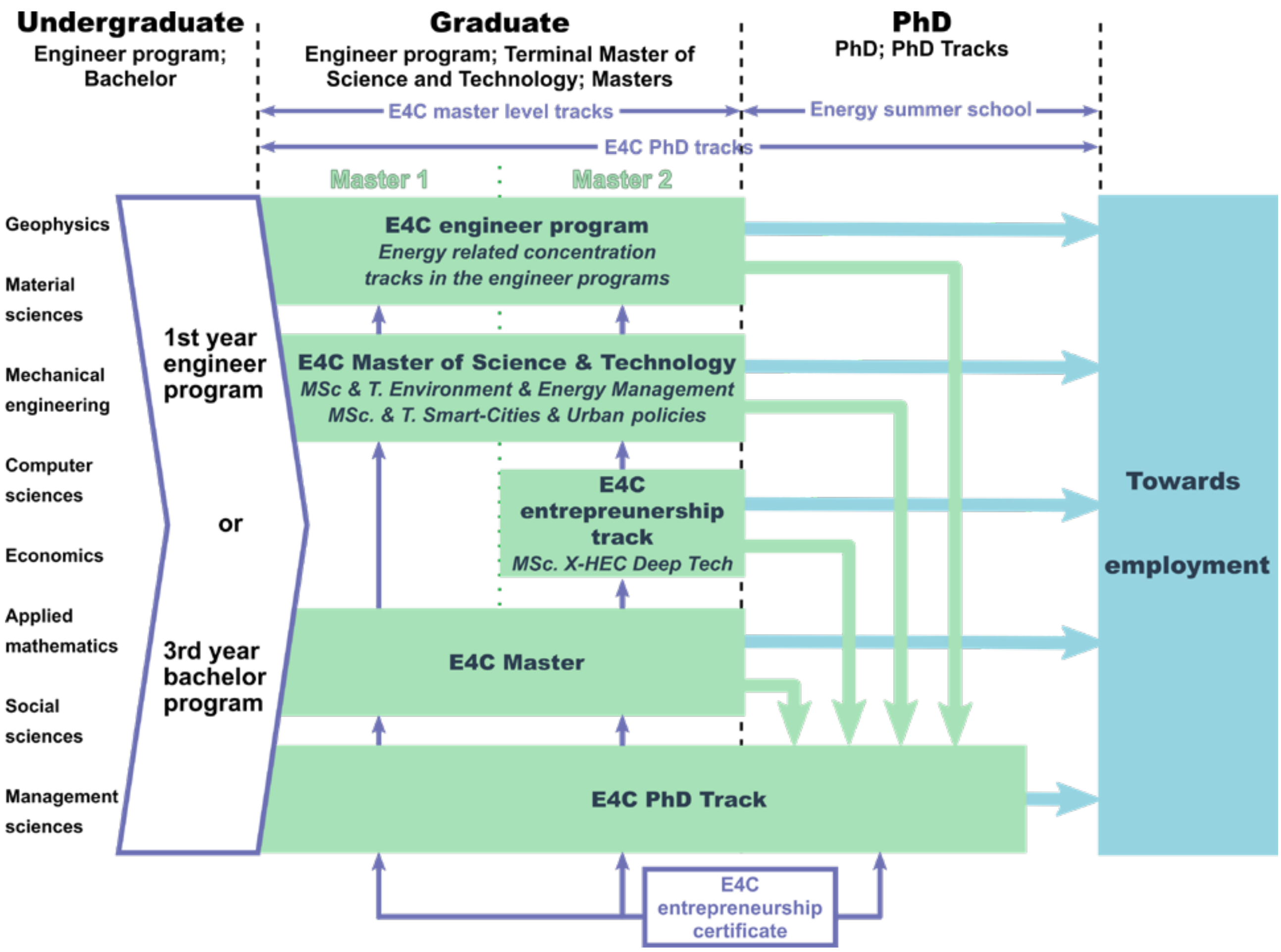

Figure 14. E4C training course

Education

Education program

Thanks to its national and international research programs of excellence, the E4C center offers an international interdisciplinary training in the energy field aiming to give students high level skills and knowledge for the socio-economic and professional world (academic research, private compagnies R&D, entrepreneurship…).
From master to doctorate, E4C teaching program is based on three pillars:

- Interdisciplinary education, key in energy transition field
- Entrepreneurship skills development, crucial for energy transition deployment as global solutions are absent
- Employability in a booming industry, PhD students executive training and alumni network mobilization

About 5 % of the best graduate students are selected in a 5-year energy field PhD track to recruit best students at an early stage to support E4C's research actions.
The whole teaching program has a strong international dimension: international students selection, students and teachers mobility, summer school, double degree coupled with leading international institutions. Figure 14 shows E4C's education programs.
The E4C teaching program is built on Institut Polytechnique de Paris and Ecole des Ponts' main strengths. Its strong international visibility offers students strategic climate and energy disciplines technical expertise and a deep understanding of climate change and energy transition issues.
Researchers are very involved in various E4C tracks, facilitating interaction with students. Unique E4C experimental infrastructures have been developed for energy research and innovation and immersive hands-on projects, reinforcing education and research links.
The E4C center also supports 12 Master internships per year and 4 Master grants for PhD tracks, favoring direct research-based education. Energy transition related summer schools are organized for PhD students and promotes students' and experts' interactions.

International interdisciplinary E4C masters

Engineer track

The six E4C center's founding schools have famous engineering pathways with a concentration track in third year (corresponding to second year of Master). The engineer cycles offer several environment and energy related specialized courses: Energies of the 21st century (Ecole Polytechnique), Production and energy management and Offshore energies (both ENSTA Paris). These courses are characterized by major mechanical engineering and physics backgrounds. All these students come from the 2nd year of engineer programs.

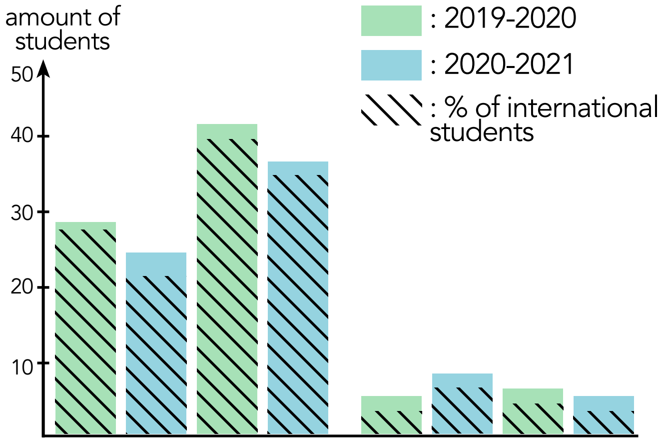

Figure 15. Student proportion of STEEM and SCUP programs

Masters of science

The Masters of Science and Technology (MScT) mainly target foreign bachelor or first year master students. The MScT were developed to enhance international attractiveness and visibility by selecting the best international students for a professional training. This training is remunerated, dispensed in English and balanced between technical and managerial training. The MScT Environment and Energy Management (STEEM), Smart Cities and Urban Policies (SCUP) train for private compagnies employment. The E4C center supports MScT students grants. The figure 15 shows the number of students and percentage of international students of STEEM and SCUP first and second years for 2019-2020 and 2020-2021.

Master of science and technology

Two Masters of Science (MSc) constitute natural initial trainings for PhD tracks: Energy transition at local scale (Ecole des Ponts) and Science and Technology for Energy (Institut Polytechnique de Paris). Latter program was created with the E4C center to lead to the E4C PhD track program (further detailed). The first year of this MSc program provides advanced scientific and technological knowledge to students about physics, engineering, applied

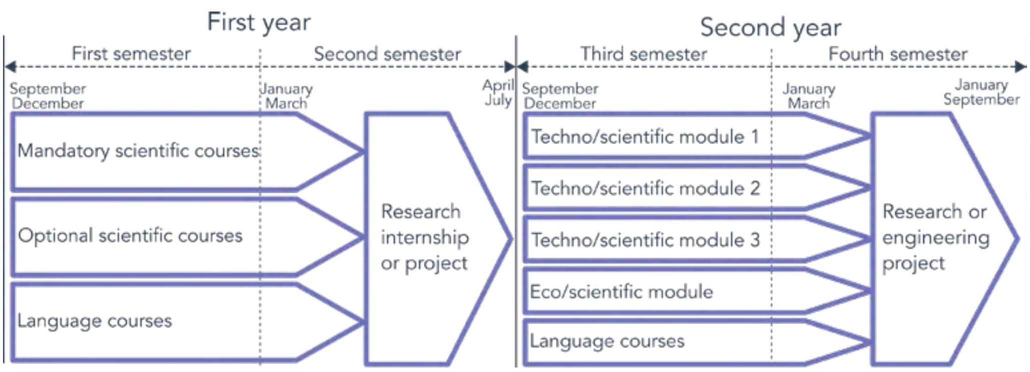

Figure 16. E4C MSc Science and Technology for Energy two years' organization

mathematics and network management. On the MSc second year of program, students choose specialization among following majors: Clean energy production, energy infrastructure management or optimizing energy utilizations. MSc Science and Technology for Energy's structure is shown on figure 16.

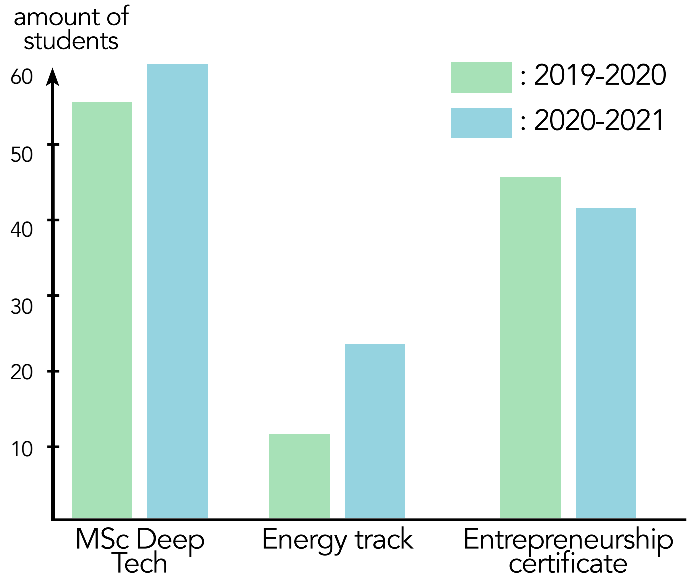

Figure 17. Student proportion of MSc Deep Tech, Energy track and Entrepreneurship certificate

International entrepreneurship pathways

Innovating in the energy sector is fundamental to elaborate and test new solutions as part of a global strategy to mitigate climate change. The E4C entrepreneurship energy track includes 2 pathways for masters and PhD:

- A one-year intense full-time training on Deep Tech Venture at Master 2 level
- An entrepreneurship certificate compatible with a full-time scientific track at Master 1 or 2 level, or even PhD

These two tracks were created soon after the E4C center's creation and figure 17 shows the last two years evolution of students.

E4C track of the msc deep tech

Since 2019, the E4C center offers a specific energy track as part of the MSc Deep Tech and aims to develop a world class entrepreneurial program on Deep Tech Ventures, dispensed in English. Students are admitted after an E4C Master 1 and 2. Figure 18 shows this track's structure.

The objective is to identify a scientific project related to students' startup projects by the end of the year. Business courses, researchers', experts' and startups' conferences and opportunity search are also included in the first term. It also includes two project modules, one related to startup creation and the other to scale up. One month

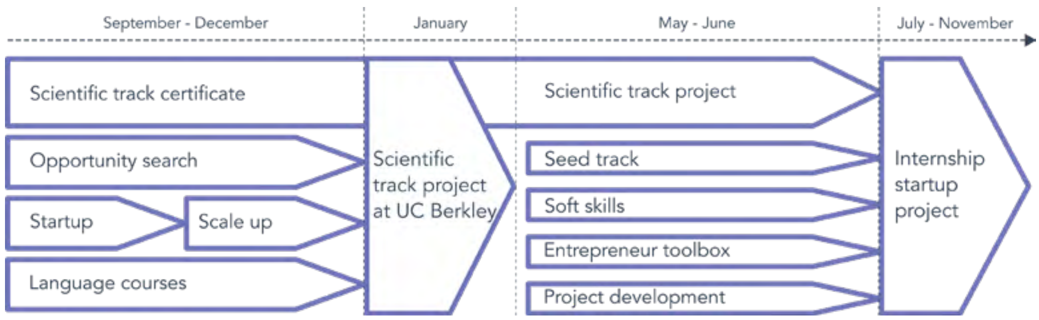

Figure 18. E4C entrepreneurship track in MSc Deep Venture

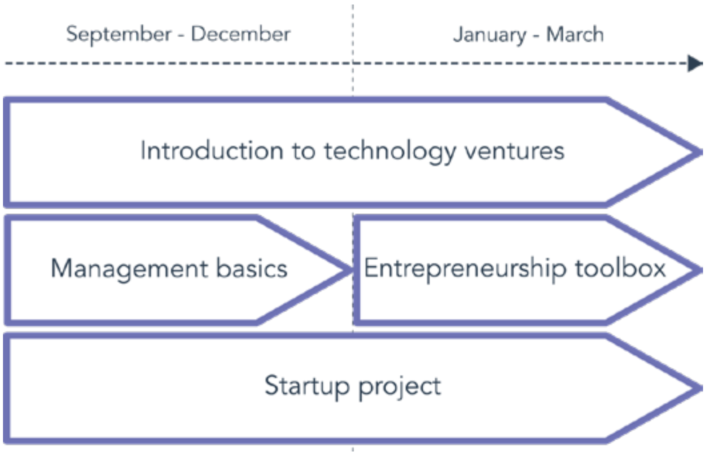

Figure 19. E4C entrepreneurship certificate

of the E4C track is held at Berkeley University and includes scientific projects work, scientific courses, an immersion in the Silicon Valley, and a field work on the student's startup project. The five-month internship is dedicated to the startup project, including the possibility to work in partner universities: Berkeley (USA), Tokyo Tech (Japan), NTUST and NCTU (Taiwan), Kaist (Korea) and EuroTech (Europe).

E4C Entrepreneurship certificate

The objectives are to develop a solid entrepreneurship culture among E4C Master students, to motivate future entrepreneurs among PhD and perhaps stimulate opportunity search and identification among laboratories. The course is dispensed in English and is shared between 120 hours of class activity and 80 hours of project work. Attending student already are registered in E4C Master 1, a concentration track or a PhD. Certificate structure is shown on figure 19.

Introduction to Technology Ventures exposes the entrepreneurial process key steps, including opportunity assessment, innovation territories exploration, business plan writing and also technology transfer specificities. Management Basics is an online course, while Entrepreneurship Toolbox is a course dispensed through workshops and it addresses design thinking, fablab prototyping, Venture Capital related business model design… Finally, in the Startup Project, students work in teams on a startup project related to their scientific background.

PhD Tracks

Within the E4C center's framework, a five-year program leading to a PhD degree in the energy transition field is offered by Institut Polytechnique de Paris. This PhD track trains excellence students for careers in leading academic institutions or top compagnies worldwide. The dedicated committee selects the best applications and the selected students engage into a five-year PhD track. Master's and PhD's candidate's selection take place at the same time. Selected students access a variety of courses and they design their own education program within all E4C master tracks. If a PhD student does not wish to pursue a thesis work, he/she can join one of the E4C masters track. The five-year PhD track's selectiveness contributes to its attractiveness. In 2020-2021, three students were selected for the E4C PhD track, one of them was recruited in Master 1, the other two were selected in Master 2. Once selected, a dedicated mentor coached them to elaborate a research program and to identify which laboratory and PhD advisor were most relevant. Every year, three E4C PhD track grants are provided by IP Paris' doctoral school.

E4C
Learn more about E4C education programs

E4C educational media library

This interdisciplinary catalog provides E4C cursus with learning approaches and tools with different learning levels as described in the Revised Bloom's taxonomy: new ways to reinforce learning basic levels (remembrance and evaluation) and fill specific actions for learning upper levels (application, analysis, evaluation and creation). In addition to e-learning resources such as MOOCs and SPOCs, online tools are available like serious games and jupyter-notebook exercises that dynamize amphitheater sessions. This catalog promotes immersive field demonstrations about weather and energy monitoring using SIRTA* experimental platform. Such field demonstrations also allow hands-on studies on weather forcings on wind and solar energy with real-time and past measurement analysis, learning-by-doing projects to practice measurements and characterization techniques. Existing expertise and laboratory facilities let students create, develop and test new concepts in real-life environmental conditions while in their cursus projects like wind turbine prototypes or new generation photovoltaic mini-modules. As for microgrids, smart-buildings demonstrators and e-mobility are prepared to host projects about data analysis, performance evaluation and new algorithms development. Latter algorithms can be implemented and evaluated in the Nanogrid Research Laboratory (NRLab) under controlled and safe conditions.

Education inreach and outreach are both E4C center's missions, with pedagogical resources available for teacher's exchange dynamization, new learning tool design and complementing existing ones. Pedagogical innovation relies on learning tools improvement and their diversification, technologically but also in their content. Learner's motivation and quality of learning improve with learning tools diversification (videos, inversed classroom, serious games, lab experiments, field trips, etc). As long as interdisciplinary topics are concerned, media libraries are of major importance for teachers exchanges. That is why, the E4C center, in collaboration with IPSL**, is building

* Site instrumental de recherche par télédétection atmosphérique

** Institut Pierre-Simon Laplace

an education library with different learning tools:

- Short video tutorials for different topics
- Data sets with study cases that can be used as study case analysis project for students
- Experimental teaching materials that can be consulted and reproduced by teacher
- Serious games
- Set of jupyter-notebooks for data analysis, with first E4C examples on-going development.

This first online open-source E4C book is designed for professors and can be partly made available for graduate and postgraduate students. An outreach version will be developed for general public to make them aware and help them understand links between energy and climate.

Learn more about E4C educational media library

E4C International summer school on energy

Every year, the Advanced Technology and Higher Education Network (ATHENS) hosts several Master and PhD thematic schools, with participants coming from 15 European partner universities. Existing themes include Photovoltaic Solar Energy week hosts 25 students and is co-organized by different IP Paris laboratories. The E4C center supports innovative training installations for the Fluid Dynamic for a Sustainable Environment summer school, in collaboration with Cambridge University. In addition to these pre-existing activities, the E4C center also organizes an interdisciplinary summer school which topics changes every year. The first E4C summer school in July 2021 had smartbuildings as theme.

Learn more about E4C summer school

E4C international student challenge

Every year, the E4C center organizes an international student challenge mobilizing teams from different schools and universities to reflect on energy transition major challenges and to deal with climate mitigation questions in the energy sector.

The E4C center student challenge theme for the year 2019-2020 was "Imagine a carbon-neutral city" and it brought together 106 students in 18 groups. A total of 10 institutions from various backgrounds took part in the challenge: the 5 schools of the Institut Polytechnique de Paris (École Polytechnique, ENSTA Paris, ENSAE Paris, Télécom Paris, Télécom Sud Paris), the École des Ponts and the institutions of the Alliance program

(École Polytechnique, Sciences Po. Paris, Columbia University). The candidates have shown great imagination and innovation in proposing projects for a carbon-free city. The challenge also allowed them to mobilize the knowledge acquired in their training to submit a project that is realistic and feasible. Yves Bréchet chaired the jury, composed of Thierry Braine-Bonnaire, David Fraboulet, Bernard Niclot, Thierry Sudret and François Bertiere. The latter selected and rewarded two winning projects. The first winning project «Metr'Eau'Pole», submitted by Paula Charles, Loraine Coste, Camille Plessis, Victor de Bretagne, Thomas Rousselet, Martin Vaz (École Polytechnique) and Charlotte Hacot (Sciences Po), mentored by Gilles BORDIER (CEA), proposes to use wastewater to produce thermal energy using heat exchangers and mechanical energy using turbines. The second winning project "Waste not, want not" submitted by Benny Bertagnini, Erifili Draklellis, Jonas Goldman, Kristin Klein (Columbia University), mentored by Juan Francisco Saldarriaga (Columbia University), proposes to produce a biofuel using biogas to generate electricity in Paris wastewater treatment plants.

For the 2020-2021 edition of the E4C student challenge, the theme is "Achieving net-zero carbon emissions by 2050: local-scale actions". In order to keep global warming below 1.5 degrees, achieving carbon neutrality by 2050 is essential. Given the effort required, reaching this goal involves profound changes in our lifestyles. The challenge consists in analyzing what this means, in practice, in a given perimeter (a company, a campus, a city, a field of activity …). The teams must define and quantify what carbon neutrality means at this scale, what are the viable solutions to achieve it and what is required in terms of investment or organization. For the 2020-2021 E4C student challenge, the group of participating insitutions in 2019-2020 was enlarged to the HEC business school and the Eurotech program (DTU, École Polytechique, EPFL, Technion, TU/e, TUM). For the second edition, 85 students compete in 15 teams from 18 institutions of 6 countries. 11 teams are composed of students from various institutions and 4 teams mix French and International institutions.

E4C

[Learn more about E4C Student Challenge]

E4C activities for student employability

To promote student employability, three strategies are used: industries involvement in E4C education programs, PhD executive training and alumni network interaction.

Alumni network mobilization and industry involvement

To promote interactions between students and energy-related professionals, a large

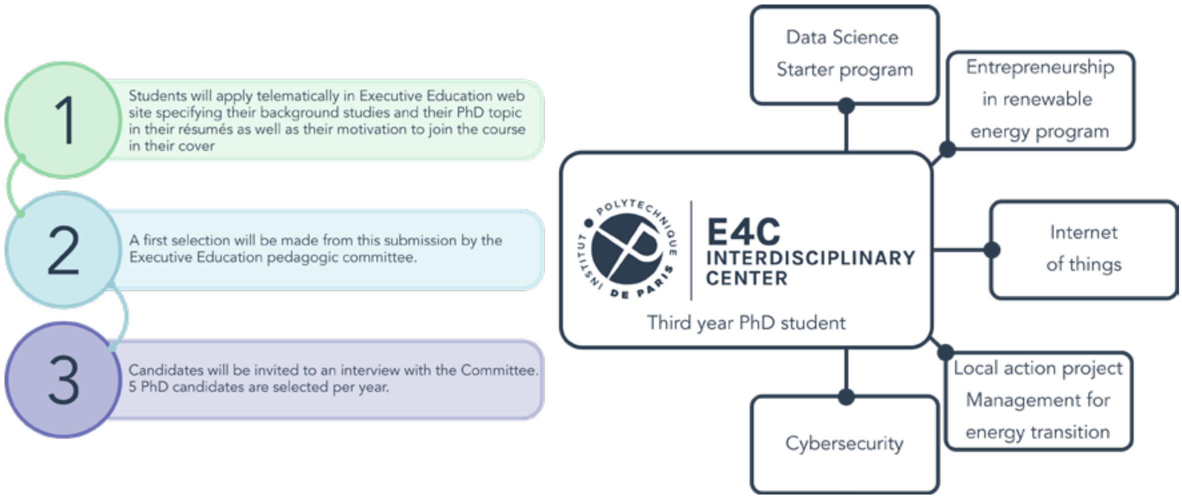

Figure 20. Executive training of 2nd and 3rd year PhD candidates

alumni network, composed of 63,000 alumni from IP Paris and École des Ponts, allows dialogue and meetings. Moreover, strong connection between IP Paris, École des Pont and the socio-economic sector like public agencies also promotes interactions with students, mainly Master 2 and PhD students, during conferences organized by the E4C center.

The monthly Coriolis conference program already existed before E4C and is now ensured by the center. In addition to Coriolis conferences, similar conferences were organized in 2021 by the E4C education group at ENSTA Paris, ENSAE Paris and École des Ponts.

Executive training for PhD candidates

The E4C center proposes to give access to some selected PhD to students with clear professional energy-related project so they can develop skills thanks to executive training. Each year, the center finances grants up to € 25,000 to support, partially or fully, PhD candidate registrations to executive training sessions. The first executive training projects call is planned for the year 2021 and will be sent to IP Paris and École des Ponts doctoral schools. The E4C executive committee selects the projects submitted by E4C PhD candidates. Students are offered an executive training within an executive environment. PhD candidates can choose training programs from any executive training center, nevertheless, it is worth emphasizing that IP Paris and École des Ponts have executive education centers where science, technology and design thinking meet with business. The call will focus on certifying programs that provide energy transition related skills, indispensable for further industrial or business career orientation, as shown on figure 20.

Learn more about Coriolis Conferences

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All the online information about E4C trainings, conferences and pedagogical tools are here:

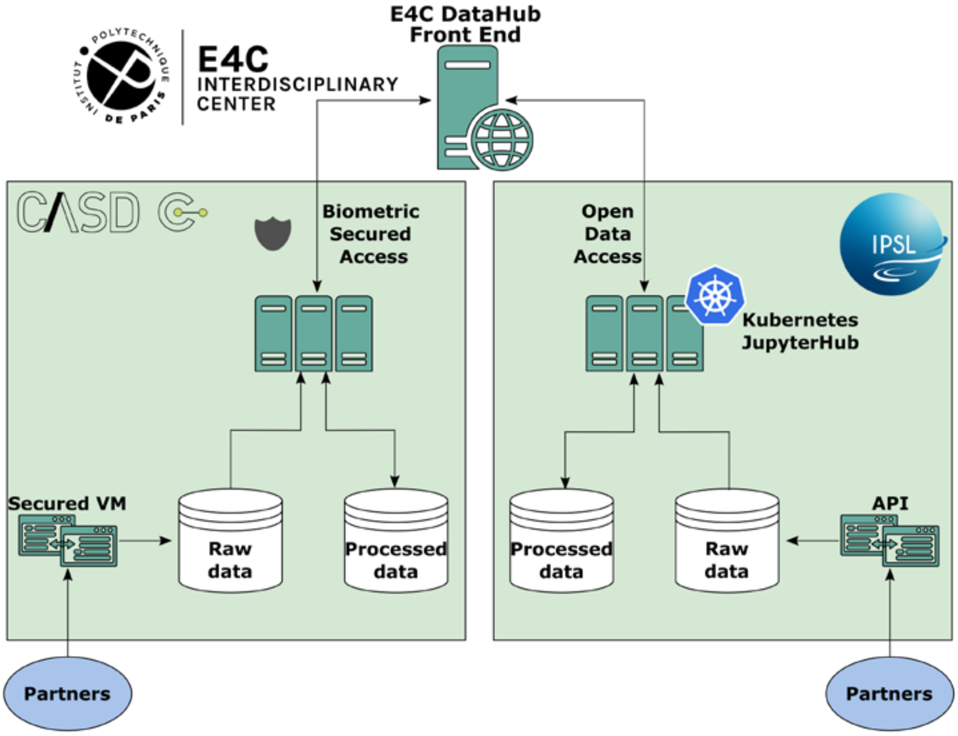

Figure 21. E4C datahub infrastructure

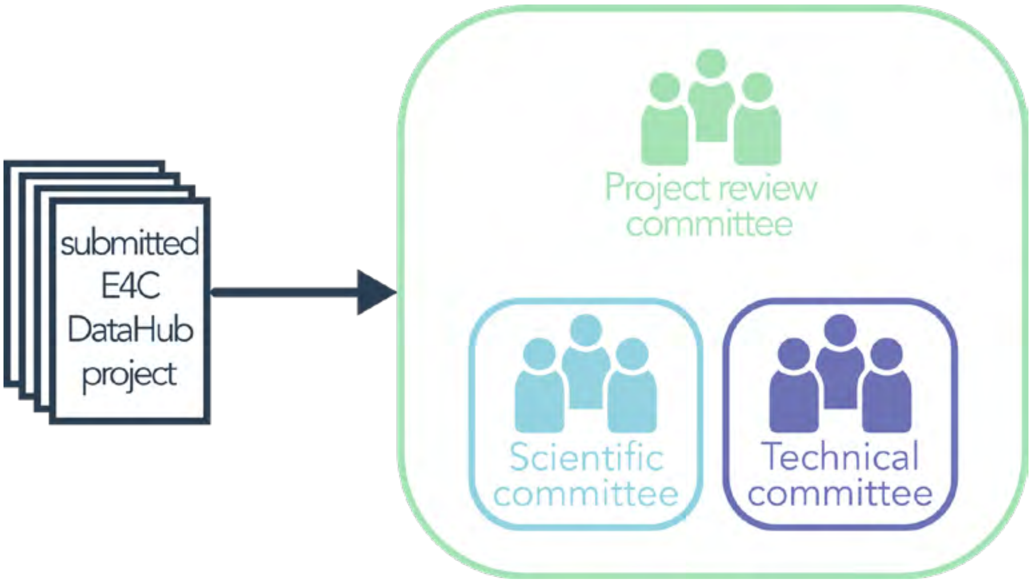

Figure 22. E4C Datahub project submission process. Once a year, the users' committee meet with those who submitted a project

E4C datahub infrastructure

The E4C DataHub is a digital platform for easy access to energy and climate data.
The E4C DataHub offers a project-driven approach. Producers or users of data can submit projects on the web interface: **https://www.e4c.ip-paris.fr/#/fr/datahub/submission/introduction**.
All submitted projects will be evaluated on the scientific and technical aspects.
Using a web interface, the E4C DataHub provides a service to data producers and users by focusing on two pillars:

To submit a project on the E4C DataHub

- Service to users:
  - Definition of project framework
  - Establishing contact with the competent actors (institutional or producers)
  - Legal, technical, economic or human assistance
  - Follow-up in the collaboration with the actors
  - Valorization of the results (publication, communication actions)
- Data processing:
  - Collection and integration of data in the E4C DataHub catalog
  - Data matching if needed
  - Making the data available
  - Provision of necessary platforms
  - Protection of sensitive data

To process the data, the E4C DataHub can rely on two partner infrastructures as shown

72

on figure 21:

- The CASD (Centre d'Accès Sécurisé aux Données) for sensitive data, requiring a maximum level of security
- The ESPRI mesocenter (Ensemble de Services Pour la Recherche IPSL) for all data that does not require maximum confidentiality and security

The E4C DataHub also combines HPC computing resources, high-capacity storage and very high-speed interconnection networks with GENCI's centers.

The E4C DataHub guarantees data continuity and follows the FAIR (Findable, Accessible, Interoperable and Reusable) principles. The governance of the E4C DataHub follows the "data producer" and "data user" charters and is composed of a project review committee made up of a scientific committee and a technical committee that evaluate submitted projects as shown on figure 22. A user committee gathers all the DataHub actors, once a year, to evaluate the innovations to be brought to the service.

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E4C DataHub partners:

- Centre d'Accès Sécurisé aux Données (CASD)
- Ensemble de Services Pour la Recherche IPSL (ESPRI)

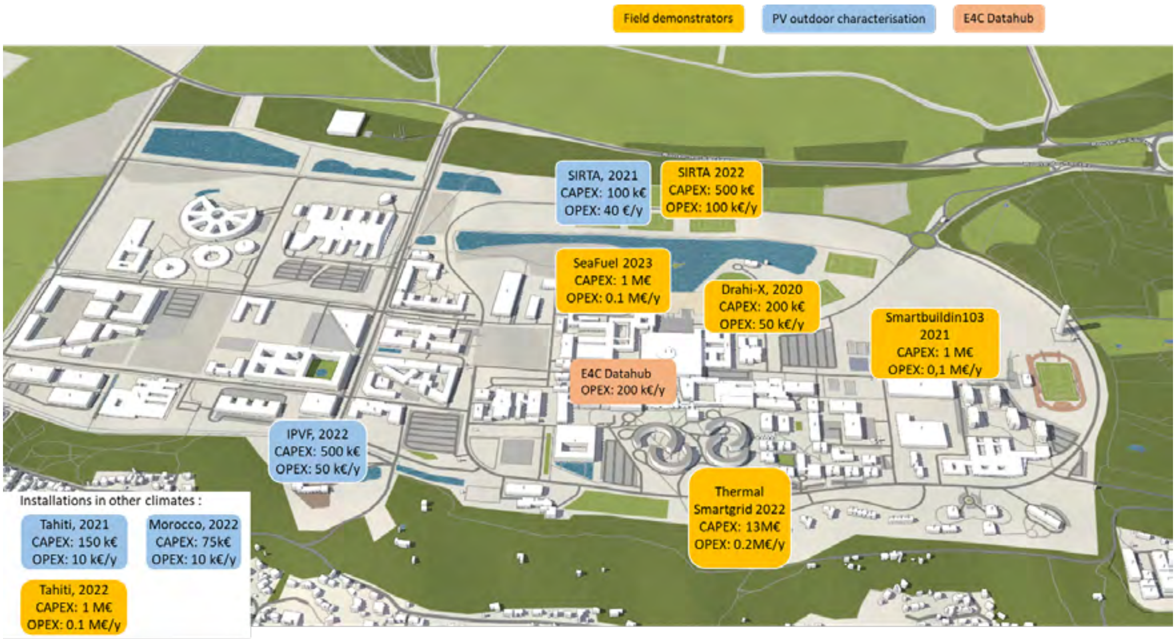

Figure 23. Technological platforms deployment roadmap

Figure 24. Photovoltaic test bench installed on the SIRTA climate observatory operated by IPSL allowing simultaneous measurement of photovoltaic production and the weather variables affecting it

E4C technological and experimental platforms

The E4C center's ambition is to develop demonstrators in collaboration with startups, small or large compagnies to research on large-scale energy transition solution implementation. Demonstrators are mainly developed on IP Paris campus but also in foreign countries such as French Polynesia or Morocco. Moreover, demonstrators should also be extended to École des Ponts campus. To date, photovoltaic (PV) outdoor characterization platforms and smartgrids constitute the E4C center's demonstrators. An on-going project described in "Synthetic fuel from seawater CO_2", page 29 and consisting in extracting dissolved CO_2 from seawater to produce fuel should allow a new E4C demonstrator to be build on École Polytechnique's lake. Figure 23 show platforms deployment roadmap. Finally, the E4C datahub also appears on the roadmap as technological infrastructure deployment.

Photovoltaic test bench

Photovoltaic strongly depends on panels' exposition conditions: lighting, temperature, dirtiness, shading, water forms (rain, snow, dew, frost) and environment. That is why, PV panels test benches were installed in real condition at SIRTA climate observatory operated by IPSL in close collaboration with GeePs* and LIMSI**.
Latter PV panels are shown on figure 24. A similar platform is settled in the University of French Polynesia, in Tahiti to assess tropical environment impact on PV production. Gathered measurements allow mathematical models development.

* Group of electrical engineering – Paris

** Computer Science Laboratory for Mechanics and Engineering Sciences

Smartgrids

Smart Nanogrid Research Laboratory (NRLab)

Collaborating with GeePs and LIMSI, the E4C center has developed an intelligent nanogrid designed to model complex smart-building-like system operations through production, storage and consumption. This Nanogrid Research Laboratory, or NRLab, is composed of a PV panel, a wind turbine, a secondary energy source and two types of batterie. System's power consumption is established with a programmable charge. This charge reads and imposes real-time power consumption of the Drahi-X Novation Center building on a 1:100 scale, as shown on figure 25.

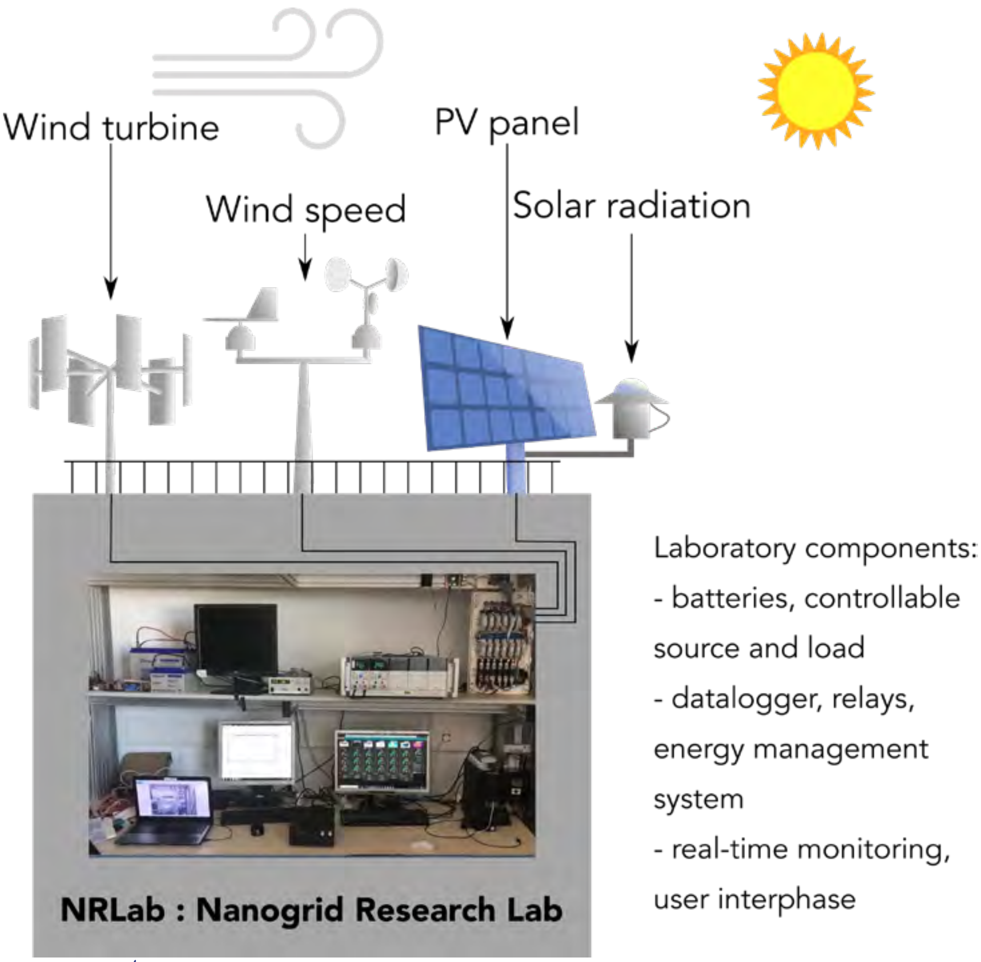

Figure 25. Figure of the NRLab with its indoor and outdoor components.

E4C Smartbuildings

Buildings are responsible for 44 % of the French energy consumption, according to the ADEME*. Many challenges require building to become involved energy actors:

- Environmental challenges: reduce energy's carbon footprint
- Energy challenges: decentralize energy production using renewable energy sources
- Communication challenges: increase connected objects and AI use to process large volumes of data

* Agence de l'Environnement et de la Maîtrise de l'Energie

A framework regulates individual and collective self-consumption in France**. In this context, the E4C center develops smartbuilding demonstrators, composed of three electric smartgrids and one thermal smartgrid.


Figure 26. Roof of the Drahi-X Novation Center building at the École Polytechnique with the photovoltaic farm made up of panels of 6 different technologies

These demonstrators aim to optimize building-provided services, related to carbon footprint, energy bill or indoor well-being. One of the electric smartgrids, located in the Drahi-X Novation center building, Ecole Polytechnique's incubator, was developed in collaboration with five startups***, the European Commission of Ile de France region support and an industry: TotalEnergies.

PV panels are shown on figure 26.

Connected electricity meters give a high-resolution counting of many variables:

Figure 27. Electric vehicle charging and discharging terminal

- all electrical uses
- PV production
- electrochemical battery storage capacity
- electric exchange between a shared electric vehicle and the grid, via the charging/discharging terminal, as shown on figure 27.

Drahi-X Novation Center users are involved in smartgrid operation using a communication system providing messages informing real-time energy use within the building and its self-management capacity. Two other buildings are equipped with an electric smartgrid: the SIRTA building and the "Smartbuilding 103" residential building, shown on figure 23. Latter building accommodates up to

** Law No. 2017-227 of 24 February 2017

*** DotVision, Elum Energy, CLEM, Luceor and Evolution Energie

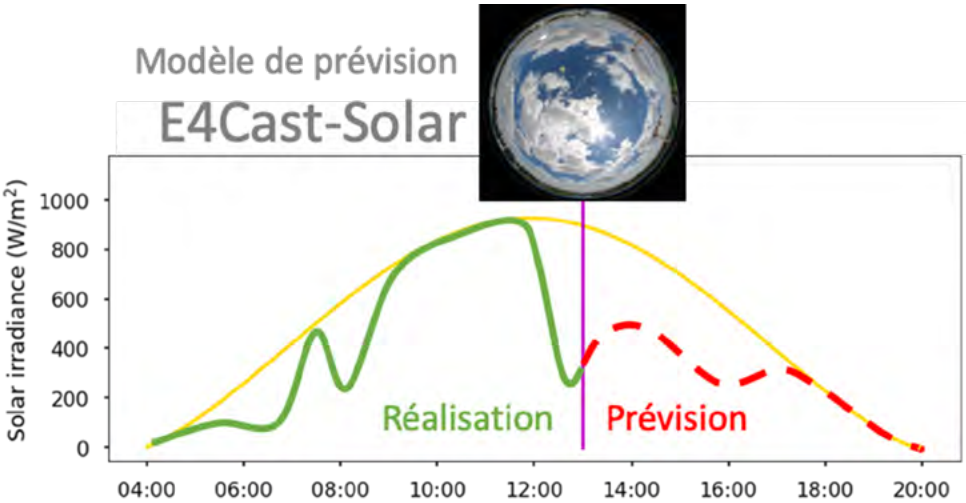

Figure 28. Forecasting principle of solar resource forecast for photovoltaic production

480 students. A thermal smartgrid project is undergoing on a residential project on campus combining solar thermal heating system, heat pump and underground storage system for seasonal recovery and cold or hot air injection inside the building.

Integrated models

E4Cast: energy supply and demand forecasting methods

E4Cast is a set of methods to anticipate renewable energy production, such as wind, hydroelectric and solar. It also helps to anticipate electric consumption, depending on weather and climate conditions. E4Cast-wind and E4Cast-solar have been developed for this purpose and have been tested on wind and PV farms for application integration in the electric market, but also for local storage tank system management support or network operator decision support. To reach these goals, E4Cast forecast scales go from a few minutes to days. Seasonal scale is also needed to assess production and consumption trends, as well as to plan energy production systems availability. E4Cast methods combine physical approaches, from digital time modelling outputs and local or satellite observations, with statistical approaches and AI, as shown on figure 28.

E4Clim: platform for modelling optimal energy mix with high

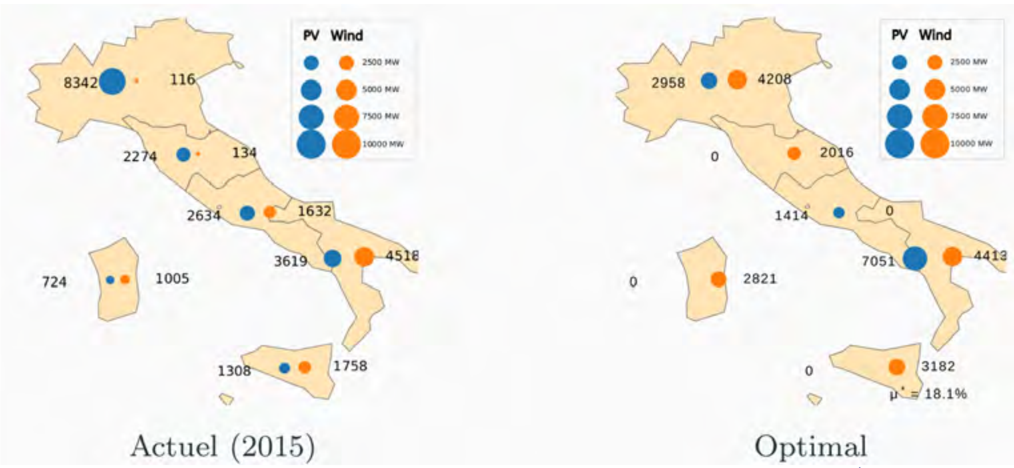

Figure 29. Wind / solar photovoltaic energy mix installed in 2015 in Italy and optimized using the E4Clim model

Download E4Clim software

penetration of renewable energies

E4Clim is a free Python software that integrates flexibility need associated with renewable energies for regional energy packages development. It is a flexible and extensible tool for researchers and engineers but also for educational and popularization purposes. The software enables renewable energy deployment strategies' evaluation and optimization, to assess those new technologies impact and their climate variability and to conduct sensitivity studies. It optimizes energy mixes based on energy variables estimations from climate and energy data. A first application to the Italian PV-wind package is shown on figure 29.

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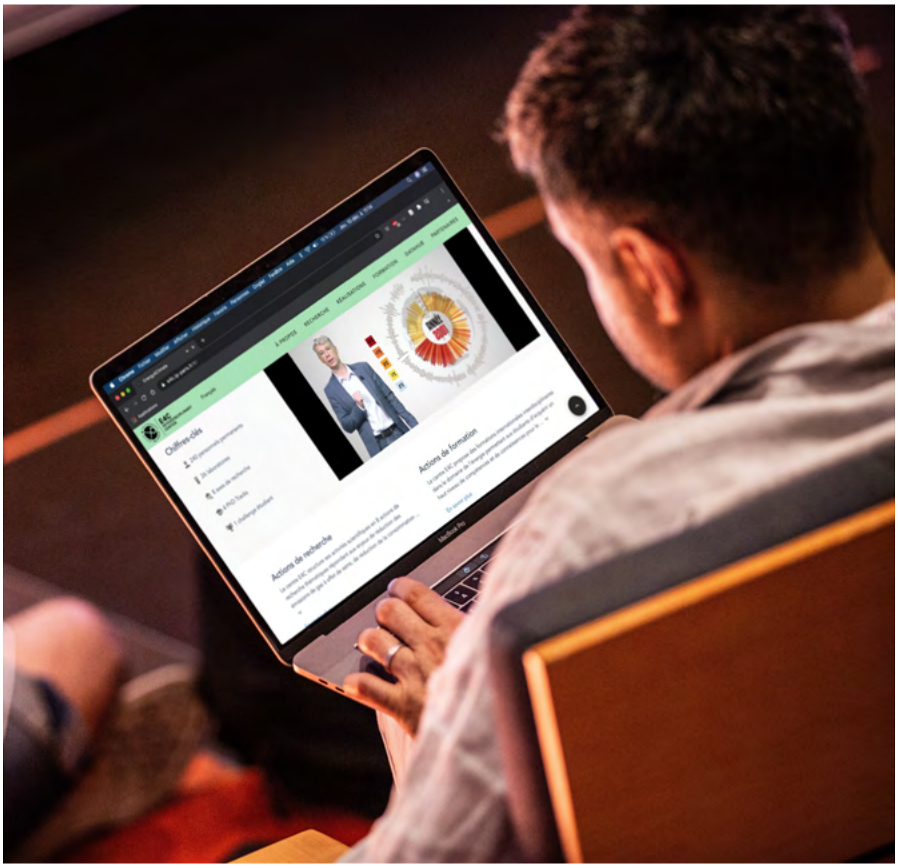

E4C communication and outreach

The E4C center is relatively recent but extremely involved in today's energy challenges. Therefore, it is essential to communicate about its actions, goals, projects, achievements… to develop its visibility, involve its scientific community, create new collaborations and projects.
The E4C center's communication is based on two specific objectives. The E4C center aims to define and deploy a communication action on energy transition to increase the center's visibility and to promote science-society links on energy transition. The E4C center also aims to attract French and foreign students in elite multidisciplinary E4C training courses.

Communication tools

The first E4C communication tool is its website. Indeed, the internet has an increasing importance in French people daily life: 90 % of them use the internet[39] and 7 out of 10 French people are connected every day[40]. Moreover, the advantage of the website is that it can be consulted by everyone, whereas social networks require Internet users to create an account. Furthermore, the website frees from the constraints in terms of use or distribution algorithms, which increases visibility. But its online presence also allows the E4C center to establish a trust relationship with users, since 56 % of Internet users do not trust an organization without a website[41]. This creates a community around the E4C center. Finally, the E4C center offers qualitative content on its website positioning the center as a reference in the field of energy transition.
Thus, the website is the center's showcase: it presents the interdisciplinary center as well as the laboratories, the demonstrators and the work carried out by the researchers, the upcoming events such as conferences, student challenges or summer schools.
In order to multiply contact entries and visibility, E4C is also present on the social network LinkedIn. Its presence on this network of professionals also allows the center to showcase its achievements and consolidate the relationship of trust with Internet users. In addition, it also improves the referencing of the interdisciplinary center. Publications on social networks allows the center to communicate in a different way, to relay its activities

and news and above all to redirect to its website.
To keep in touch with its collaborators and to build loyalty among the users of the net, E4C distributes two newsletters, one internal and one external. Increasing traffic towards the website, it improves the center's referencing, while highlighting its achievements and accomplishments. Bimonthly or four-monthly newsletters deal with current topics on the website and remind users of the key events to which the E4C center contributes, such as the Fête de la Science.
Since the end of 2020, the E4C center has its own playlist on the YouTube channel of the Institut Polytechnique de Paris. Videos have several advantages: they catch the eye of the Internet user, animate social networks, make announcements, include external interlocutors in interviews... and introduce the E4C center because, as the saying goes: a picture is worth a thousand words. In addition, videos can be used to broaden the range of educational tools, with educational capsules for example, or to promote and capitalize on past or future events such as the Student Challenges.
In addition to videos, visual supports are also used, as they facilitate attention, comprehension and memorization. Indeed, explanatory or illustrative, the images arouse emotions, provoke the identification or the commitment of the Internet users. Above all: images save time by delivering information more quickly.
Finally, how can all these digital media be brought together and made easily accessible? The E4C center is experimenting it with QR code. Indeed, the public is increasingly digital: individuals consult their cell phone more than fifty times a day[42]. The QR code allows us to quickly provide them (QR is the abbreviation of "Quick response") with information about the E4C center identity, its activities and its presence on social networks.

Communication actions

The E4C center's visibility relies on making the research projects, results and E4C researchers' publications accessible to the scientific community, students and the general public. To do this, online publications of various media are possible: articles on current events and laboratories' achievement. Portraits of researchers are also considered, as the human aspect of research should not be neglected. Conferences are also a way to have a look on the state of the art in the discipline of energy transition. On this point, the training of doctoral students and researchers in mediation would make it possible to make them actors of their own visibility. In addition, as there are already many internet users, articles on the E4C website could increase the visibility of the laboratories' activities. Finally, to regularly disseminate the achievements of the laboratories, newsletters are tools to periodically send updates on current activities to a database of recipients.

Promotion of science-society links

The promotion of links between society and science is a major issue, particularly on the energy transition. Indeed, the general public is not always comfortable with this hot subject or does not master all its aspects. Popularization and dialogue are needed. To this end, visits of the platforms can be open to the general public in order to demystify the place where research and researchers are carried out. The meeting with scientists can also take place during conferences. However, to reduce the solemn and magisterial dimensions of the conferences, evening debates are a solution. To reach a younger audience, interventions in schools and turnkey workshops can be imagined. Participation in public events and the production of popular media (exhibitions, videos, activities, etc.) are good ways to reach a curious public.

Attraction of French and foreign students

To attract the best students, it is important to support the attractiveness of the E4C center's courses and laboratories. As for the first objective described, it is necessary to capitalize on the activities of the laboratories to make them attractive. In addition to this, visits to the platforms for students and workshops with researchers and measurement equipment are solutions to make the research projects concrete and generate vocations among students.

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Follow E4C on their different social media available here:

Publications and patents

E4C publications

2021

Alonzo, B., Concettini, S., Creti, A., Drobinski, P., & Tankov, P. (2021). Wind farm revenues in Western Europe in present and future climate. Available at SSRN.

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* The *Conseil de l'Europe* of Europe awarded the North-South 2020 prize to the MedECC for its first assessment report entitled « Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future ». This prize rewards public personalities and for the first time organisations for their commitment to the protection of humanrights and North-South solidarity. For this work, five laboratories of the E4C center (Energy4Climate) – LMD, LIX, I3, CREST, CIRED as well as the IPSL (Institut Pierre-Simon Laplace) have contributed. Édouard Civel, Vincent Boucher, Robert Vautard, all three were the lead author of the Energy chapter, under the coordination of Philippe Drobinski were rewarded as lead authors. In addition, Anna Creti, former member of the Department of Economics of the École Polytechnique, was also rewarded as lead author. The contibuting authors from the E4C laboratories are Alexis Tantet, Rémy Lapère, Thierre Brunelle.

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TREND-X (pre-E4C) publications

2020

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