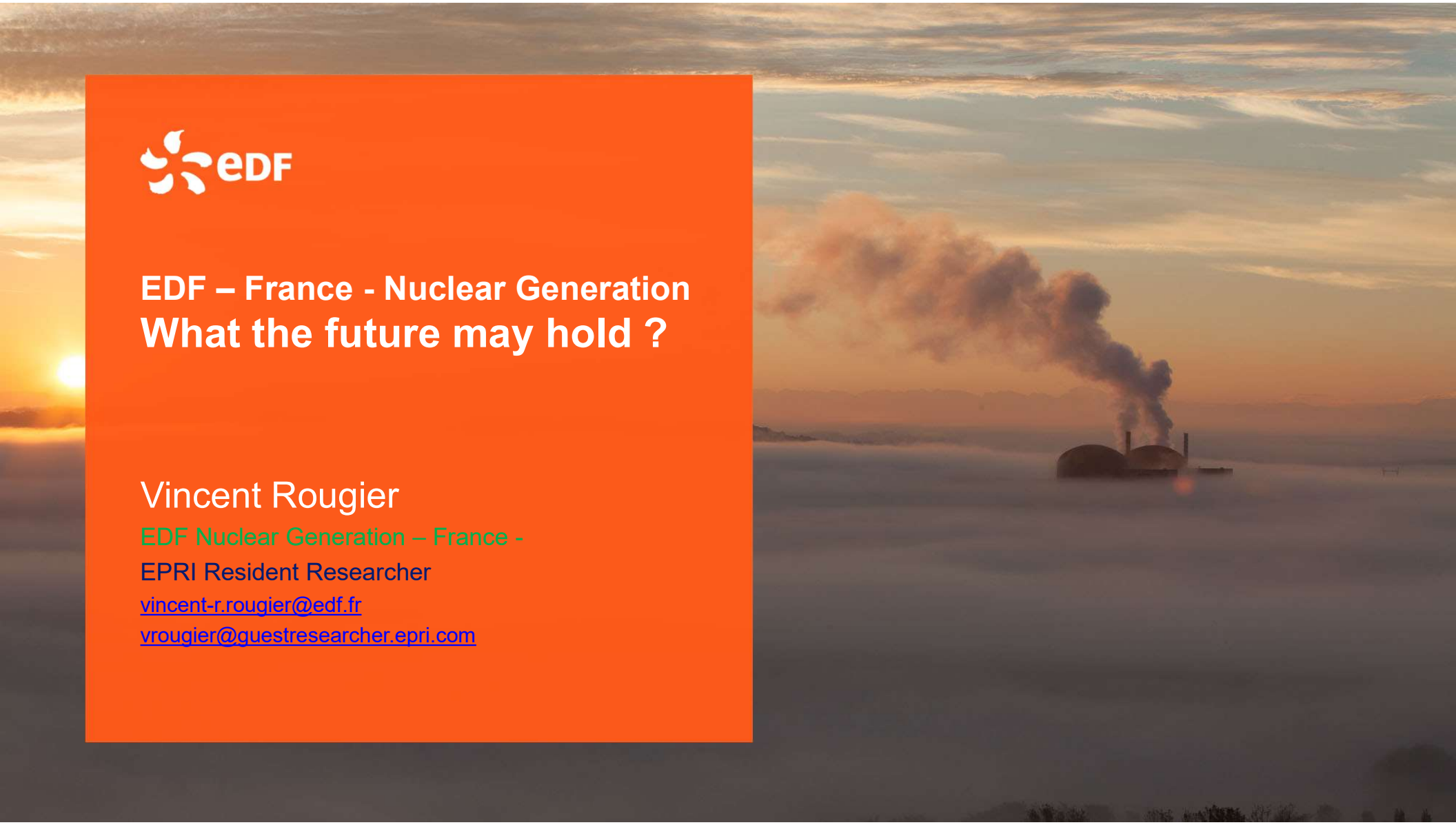

EDF – France - Nuclear Generation
What the future may hold ?

Vincent Rougier

EDF Nuclear Generation – France -

EPRI Resident Researcher

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- The values indicated in the slides are given for illustrative purposes.

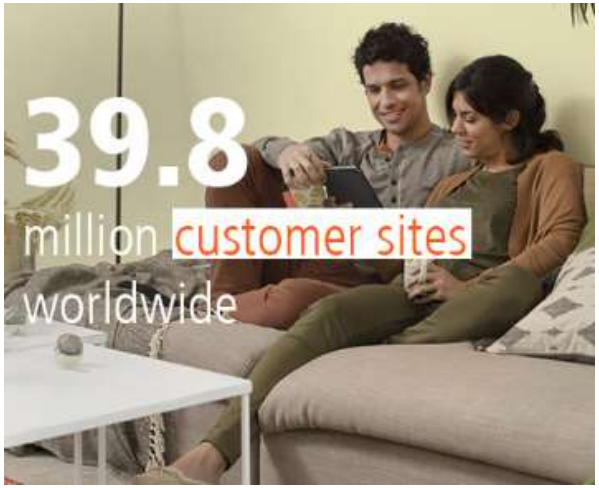
Agenda

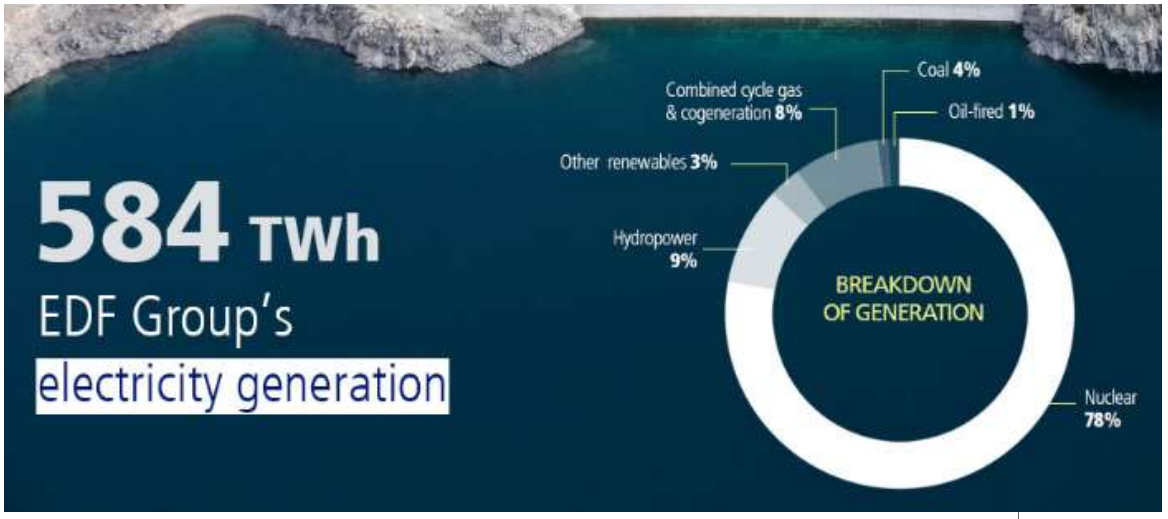
1. EDF in the world and in France
2. The « Grand Carenage » renovation plan
3. Main orientations of EDF R&D
4. The future will be digital
5. The future will be flexible
6. Advanced reactors & new builds
7. Conclusion & Questions

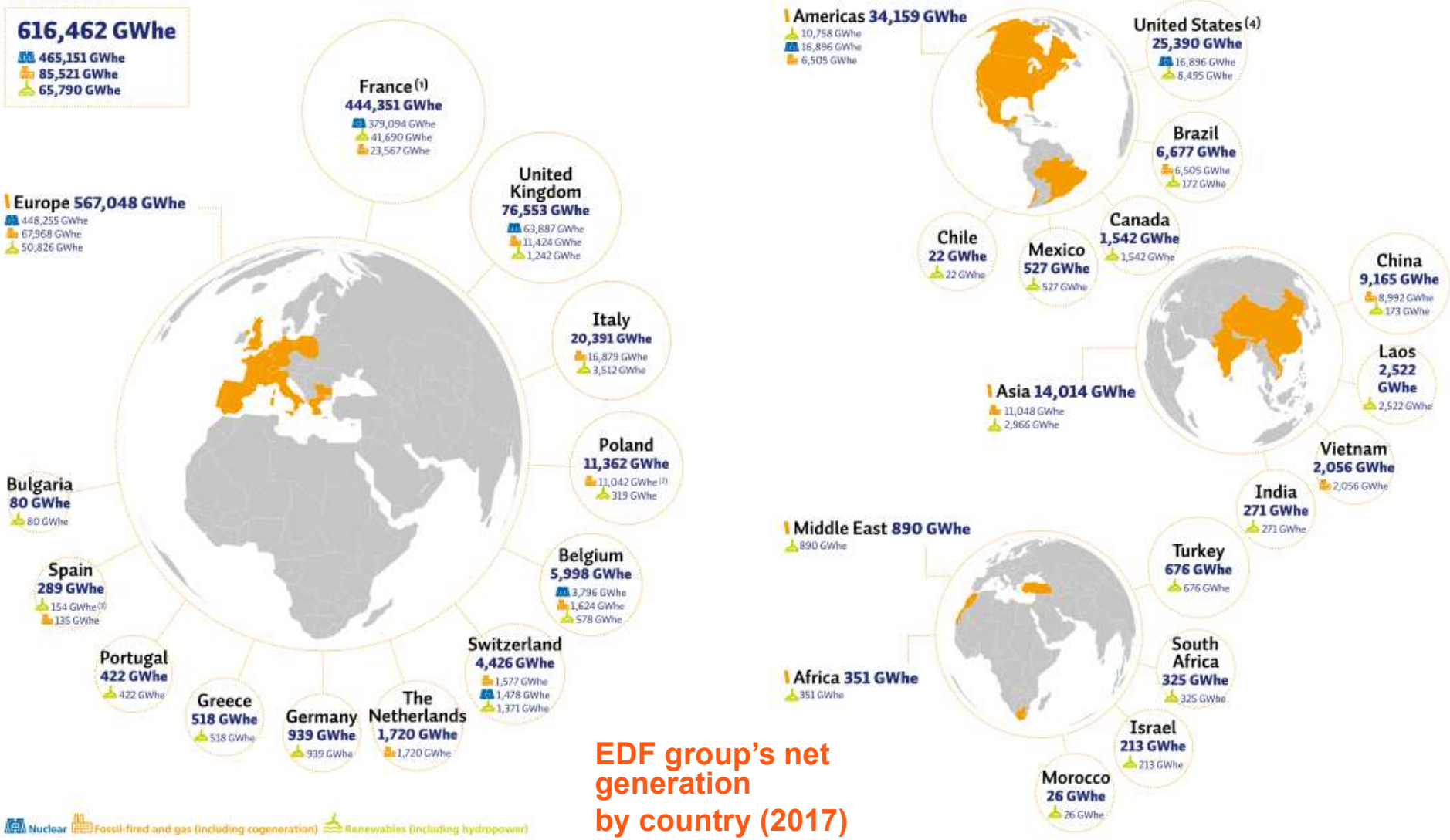
1

1.1 EDF in the world

EDF at a glance

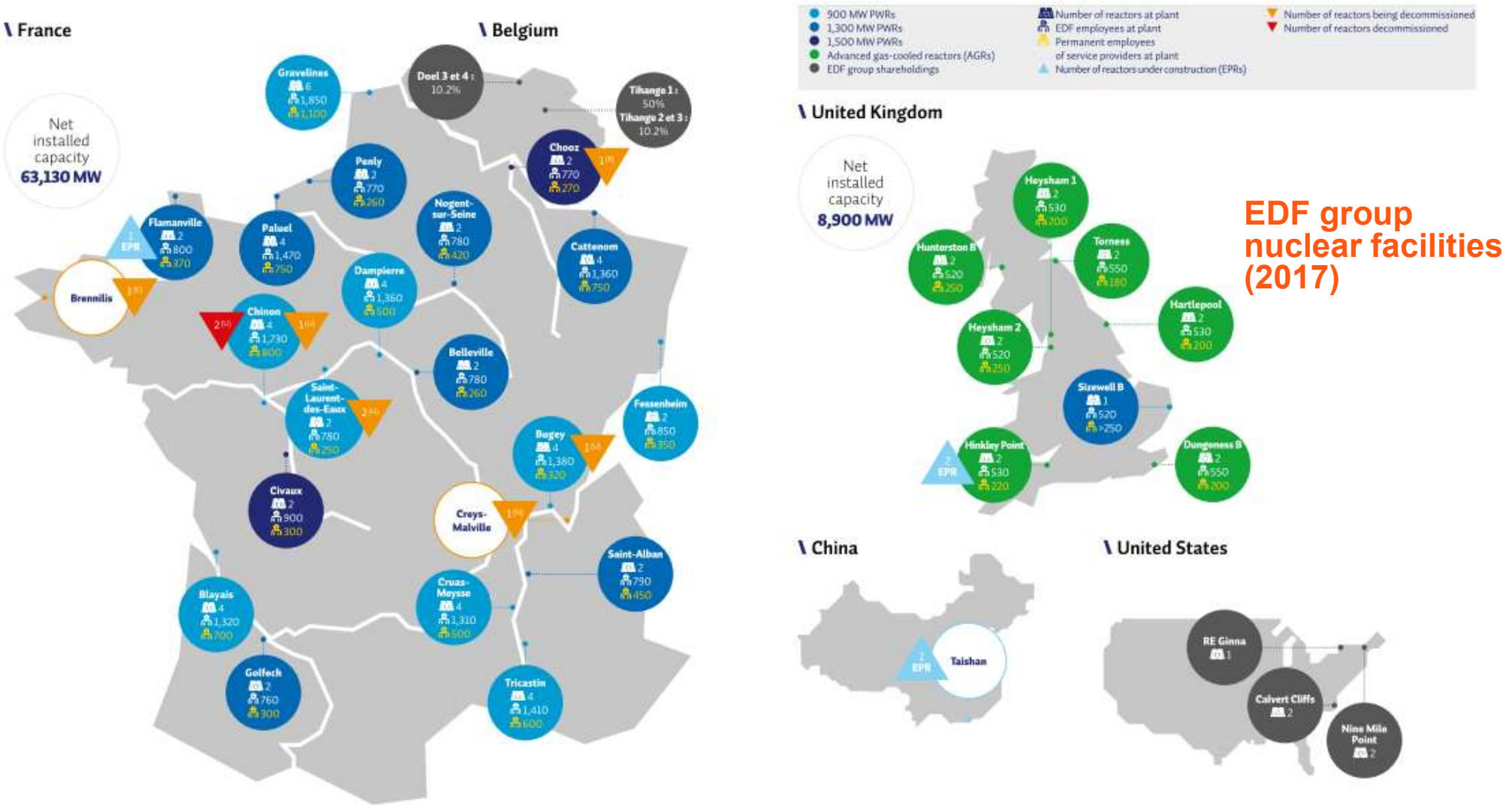






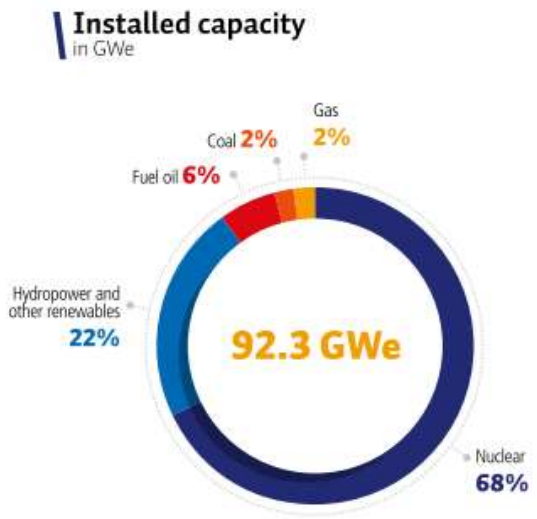
EDF group's net generation by country (2017)

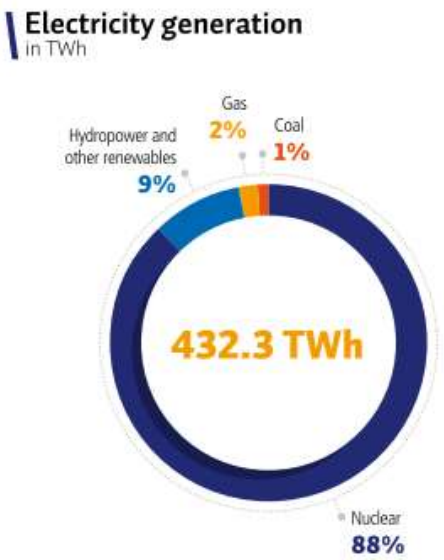
EDF group nuclear facilities (2017)

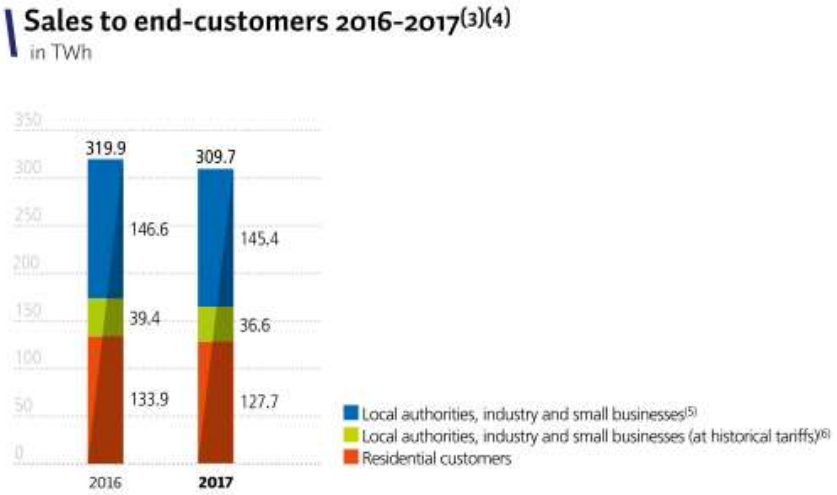


1.2 EDF in France

EDF Generation in France (2017)







AGE PYRAMID of the French NPP reactors (French NPP fleet as at end 2016; by date of first criticality; power per reactor)

Date of 1st criticality									Global power
1977	Fessenheim 1	Fessenheim 2							1,800 MWe
1978	Bugey 2	Bugey 3							1,800 MWe
1979	Bugey 4	Bugey 5							1,800 MWe
1980	Tricastin 1	Gravelines 1	Tricastin 2	Tricastin 3	Gravelines 2	Dampierre 1	Gravelines 3	Saint-Laurent B1	7,200 MWe
1981	Dampierre 2	Saint-Laurent B2	Blayais 1	Dampierre 3	Tricastin 4	Gravelines 4	Dampierre 4		6,300 MWe
1982	Blayais 2	Chinon B1							1,800 MWe
1983	Cruas 1	Blayais 4	Blayais 3	Chinon B2					3,600 MWe
1984	Cruas 3	Paluel 1	Cruas 2	Paluel 2	Gravelines 5	Cruas 4			6,200 MWe
1985	Saint-Alban 1	Paluel 3	Gravelines 6	Flamanville 1					4,800 MWe
1986	Paluel 4	Saint-Alban 2	Flamanville 2	Chinon B3	Cattenom 1				6,100 MWe
1987	Cattenom 2	Nogent 1	Belleville 1	Chinon B4					4,800 MWe
1988	Belleville 2	Nogent 2							2,600 MWe
1990	Cattenom 3	Penly 1	Golfech 1						3,900 MWe
1991	Cattenom 4								1,300 MWe
1992	Penly 2								1,300 MWe
1993	Golfech 2								1,300 MWe
1996	Chooz B1								1,450 MWe
1997	Chooz B2	Civaux 1							2,900 MWe
1999	Civaux 2								1,450 MWe

● 900 MWe ● 1,300 MWe ● 1,450 MWe

- **The French nuclear fleet:**
  - 19 nuclear power plants
  - 58 pressurized water reactors in operation
  - Standardized fleet: 34 x 900 Mwe
    20 x 1300 Mwe
    4 x 1450 Mwe
  - \+ under construction 1 x 1650 Mwe

EDF's nuclear fleet approaching the age of 40

2

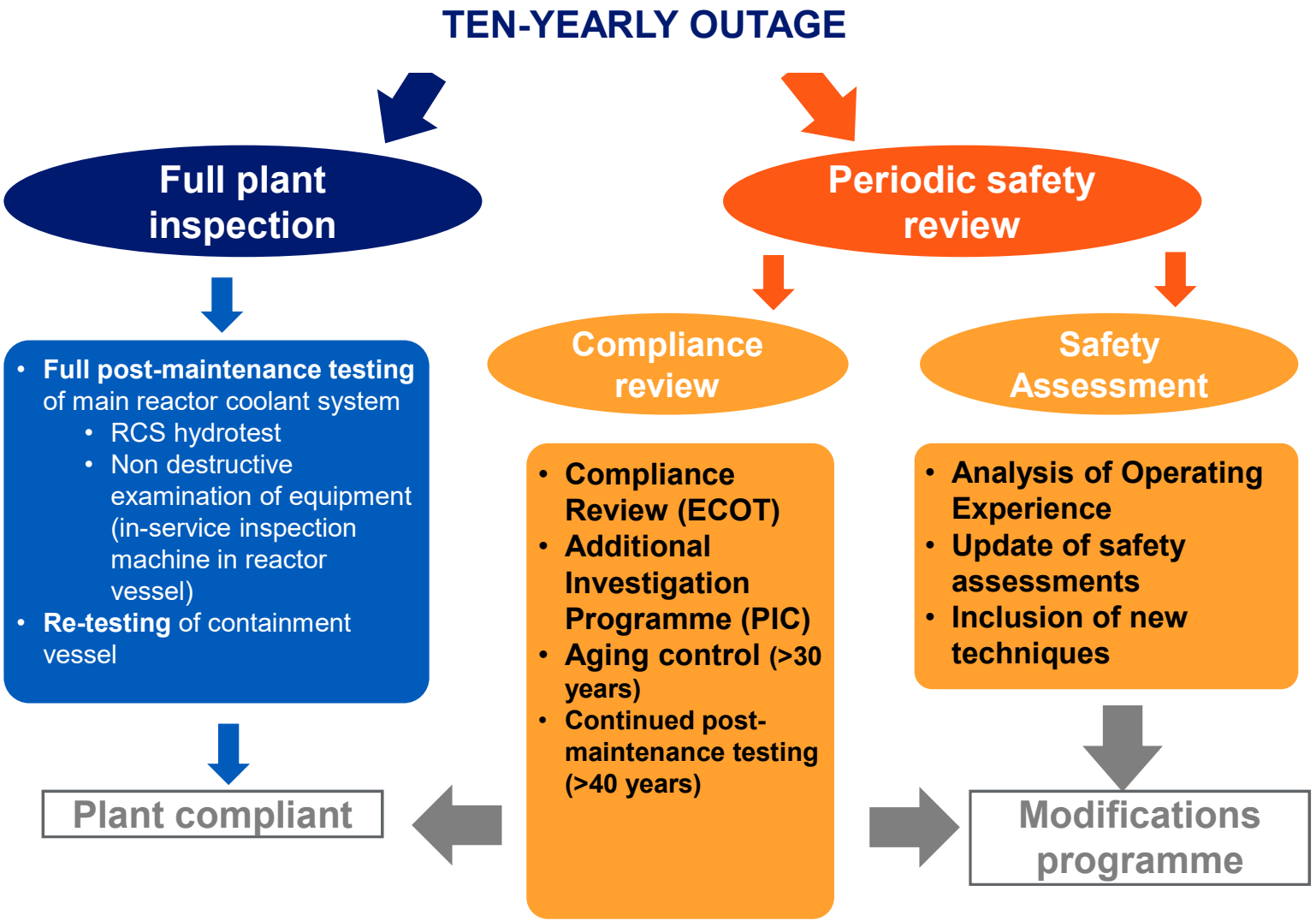
The « Grand Carenage » renovation plan

FLEET LIFE EXTENSION: AN ECONOMICALLY BALANCED OPTION

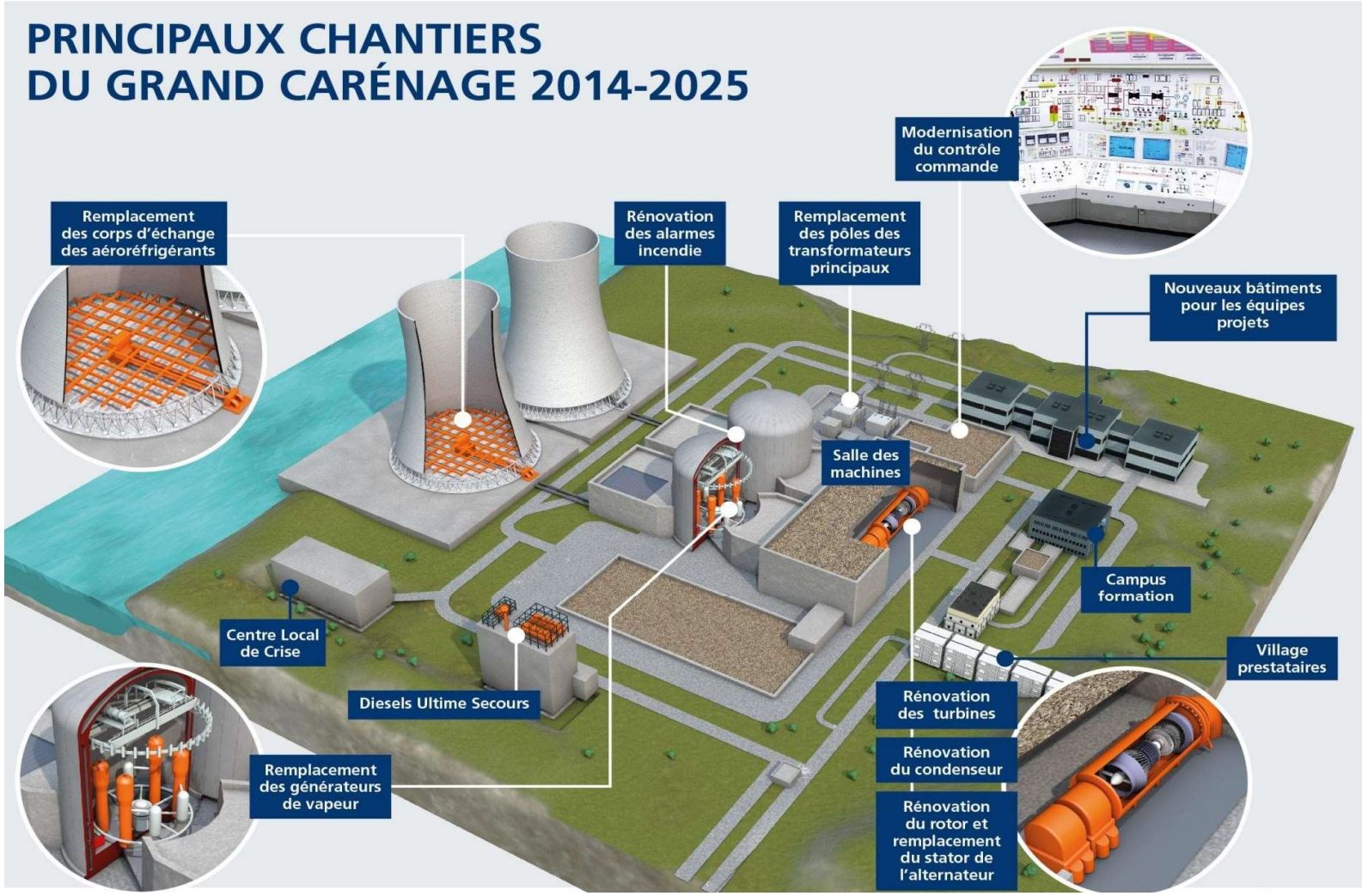
- **First reactors reaching the age of 40**

- **Fleet's lifespan:**
  - No technical or regulatory limitation
  - Every ten years a specific authorization must be granted by the regulator

- **Advantages for the country**
  - Preservation of competitive energy prices
  - Cost per MWh are much lower than in alternative scenarios


TEN-YEARLY OUTAGE
Full plant inspection
Periodic safety review
Compliance review
Safety Assessment
• Full post-maintenance testing of main reactor coolant system
• RCS hydrotest
• Non destructive examination of equipment (in-service inspection machine in reactor vessel)
• Re-testing of containment vessel
• Compliance Review (ECOT)
• Additional Investigation Programme (PIC)
• Aging control (>30 years)
• Continued post-maintenance testing (>40 years)
• Analysis of Operating Experience
• Update of safety assessments
• Inclusion of new techniques
Plant compliant
Modifications programme

PRINCIPAUX CHANTIERS DU GRAND CARÉNAGE 2014-2025



FLEET LIFE EXTENSION: IMPACT ON THE ECONOMY

- In terms of workload, Grand Carénage is **comparable to nuclear new build**
- **Significant economic stimulation**
- **110 000 direct and indirect jobs**
- Over **3000 additional workers involved** in the peak of activities at a single site

Cost of the Grand Carenage Program 2014-2025 : € 45 Bds

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R&D involvement in the Grand Carenage

An approach that involves EDF R&D teams

- An example of R&D: VERCORS mock-up, laboratory conducting studies into the aging of containment vessels

A 1/3 scale mock-up of reactor containments in the 1300 MW series, subjected to accelerated aging

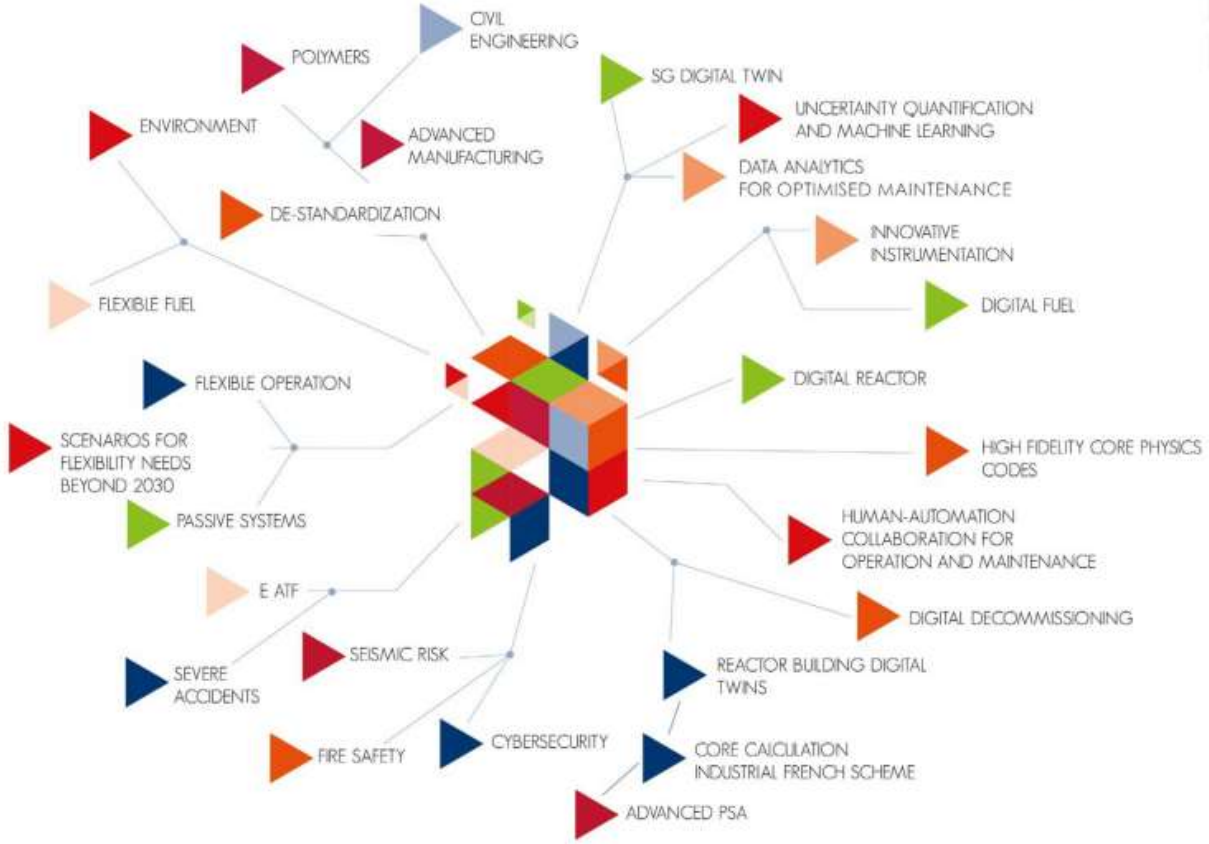
3

Main orientations of EDF R&D for the nuclear sector

Nuclear of the Future Initiatives

A set of technological bricks :

- Safety continuous improvement (fuel, seism, fire , cyber)
- Digital transition, AI and Data Analytics for Operation
- New solutions for manufacturing and repair
- Flexibility ENR / NUC beyond 2040



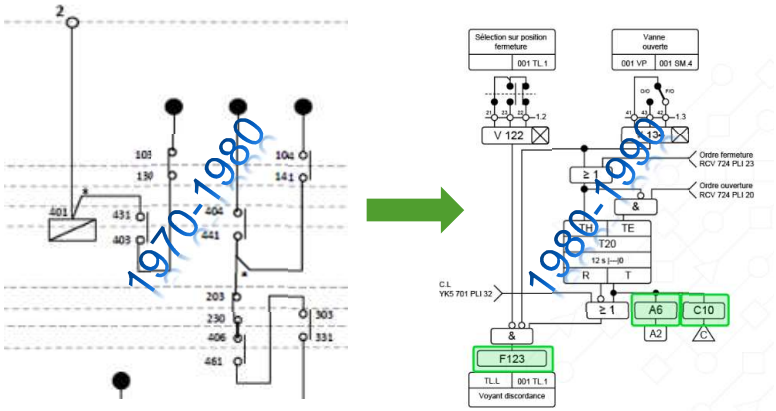
4

The future will be digital

4.1 Evolution of Control Systems Design at EDF NPPs

Evolution of Control Systems Design at EDF NPPs

900 MW CP0/CPY – All analog technology



1300 MW P4/P'4– Mix of analog & digital technology

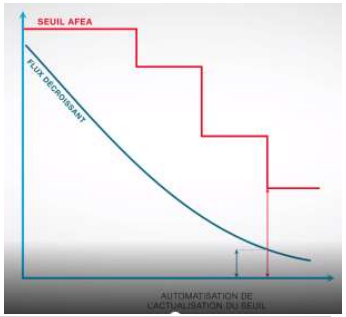
1450 Mwe N4 – Almost all digital

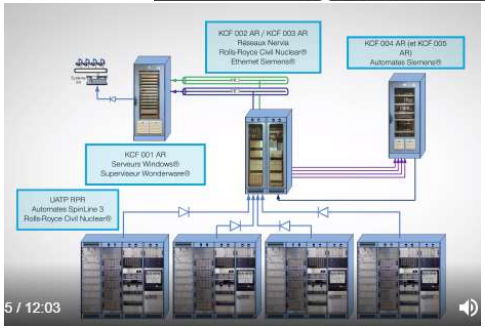
EDF

Evolution of Control Systems Design at EDF NPPs

- **During the 3rd 10-year visit of the 1300 MW (VD3-1300), P4/P'4 design, an important upgrade is implemented on the digital I&C control systems :**

- Started in 2016 on PAL and to be achieved on the 20 reactors of the 1300 MW fleet, the improvements are related to the Neutron instrumentation, reactor protection, and Rod control systems. Included in the design changes :
  - Transition from analog multibloc technology to digital SPINLINE technology
  - New network connections, for ex. implementation of a maintenance network with interfaces at various locations
  - New functions & alarms, improving troubleshooting, automation and control
  - Implementation of digital recorders in the CR, and display of new information
  - New connectivity hardware consisting of copper & optic fiber
  - New system for logic control and improved calculations
  - Ex : Automated reset of the neutron flux thresholds during shutdown and startup operations
  - Ex : Automation of the periodic tests of the RPN (NIS) system and improved software for diagnosis
  - The new system is modular for implementation of future functions
  - Cyber-security features included (one-way transmission, coded specific usb keys, etc…)





Evolution of Control Systems Design at EDF NPPs

- **For the training and testing of the new systems, a “digital control room & simulator” has been developed :**

- Principles of the SDCN :

  - Initially designed for training in the scope of the 1300 MW I&C Digital Upgrade
  - First fully digital PWR CR in France
  - Mostly designed with available commercial technology and devices
  - Fully configurable : adaptable to various plant configurations (following major modifications for example)

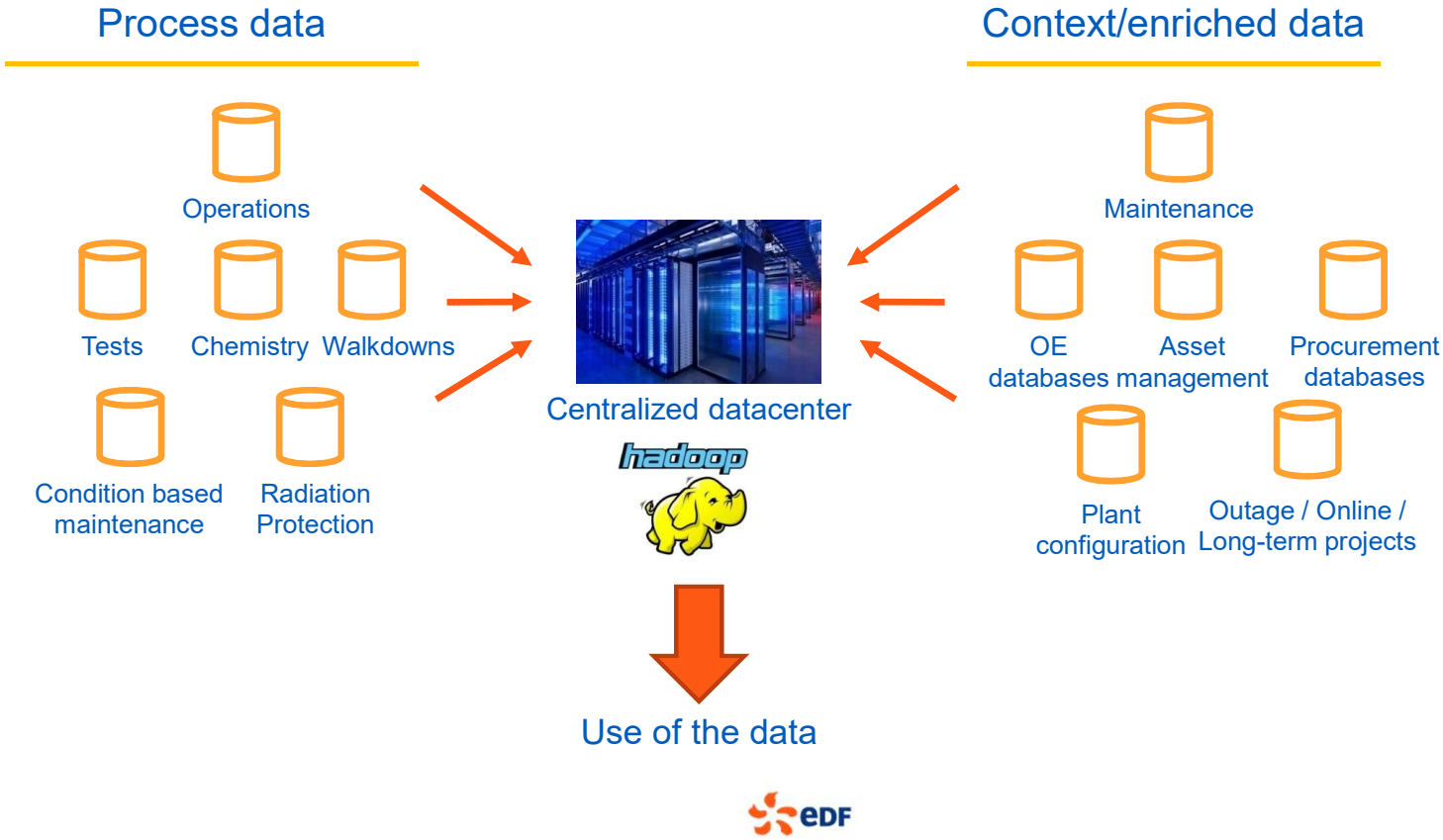
4

The future will be digital

4.2 The uses of data for operating reactors

The uses of data

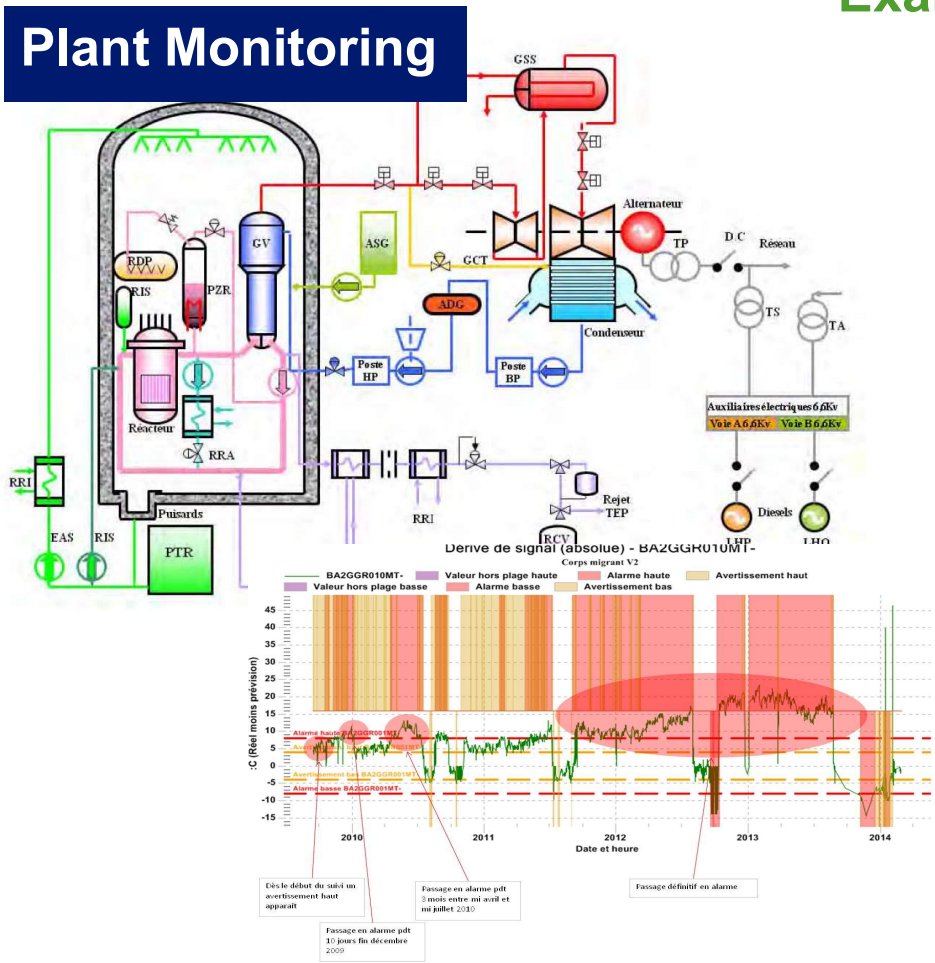
Since the mid 2000's, EDF is building its data lake, dedicated to nuclear generation



The uses of data

Examples

Plant Monitoring



EDF electronic Work Packages

DRT

Dossier de Réalisation de Travaux

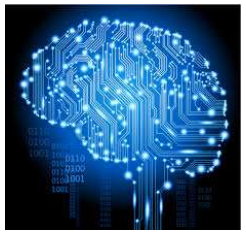
EDF

The uses of data
Examples

Data Analytics Factory for generation

DAP Lab
Field: Producers and Engineers

IDée
Field : Trading on B2B, B2C markets



SoData
Field: Energy market

IA Field
Field : ChatBot, Virtual Assistant…

R&D
Field: Upstream on any business

A team of data engineers, scientists & analysts, mixed with subject matter experts

- **Clustering and mutualization** of data science skills / business / technological from **Production business**, **R&D business** or **Information Systems business**,
- **Secured Data Governance**
- **Capitalization** of the results and **reuse** of the deliverables, between producers and between business.
- **Centralization of multi-trade's data** within a data lake

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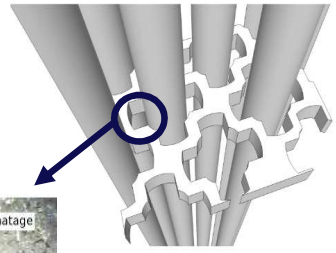
Data Analytics Factory for generation

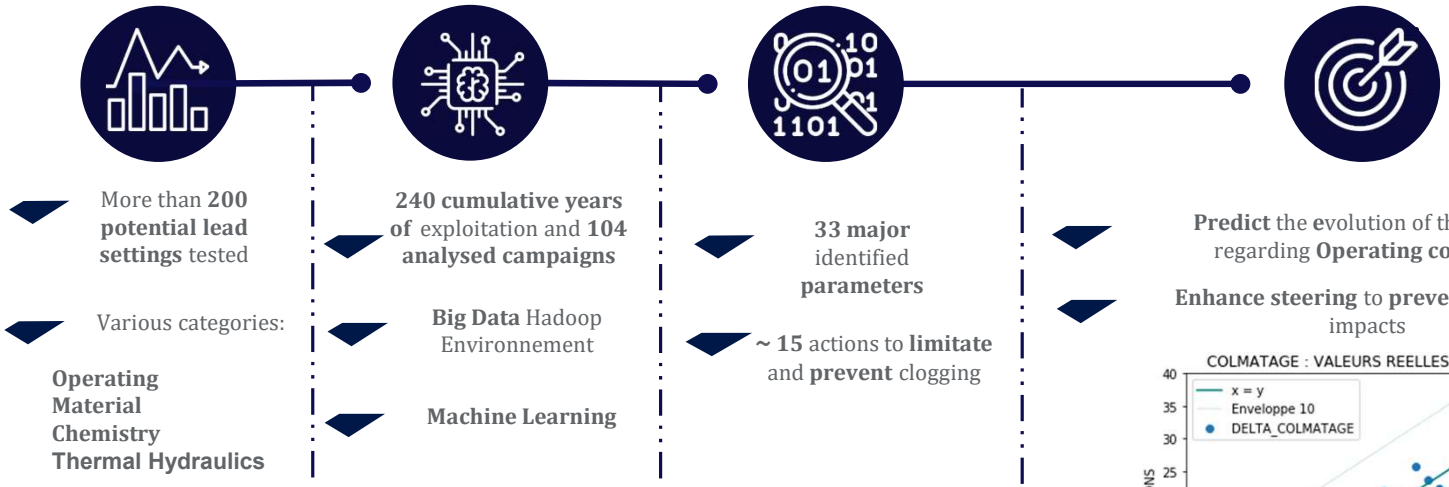
Example - SG clogging data analysis

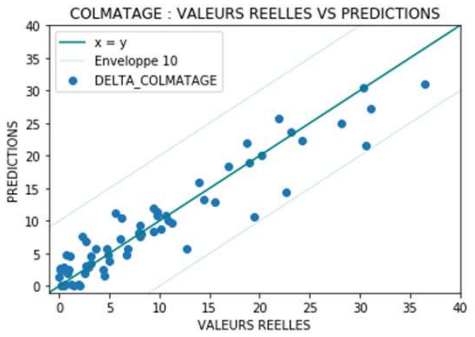


Needs :

- Identify the main influencing parameters controling the evolution of the clogging
- Anticipate maintenance

The uses of data
Examples



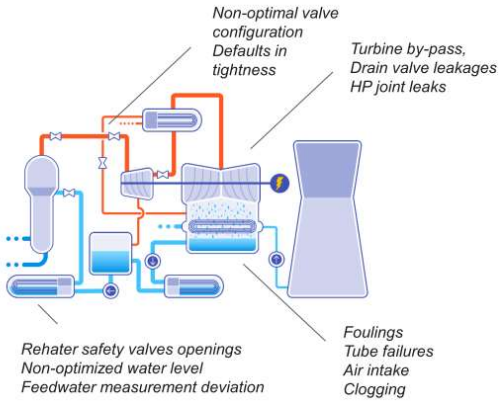


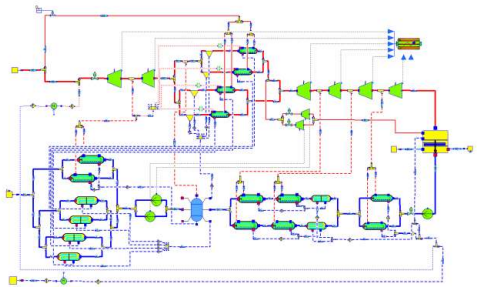
AI Diagnosis for Maintenance teams

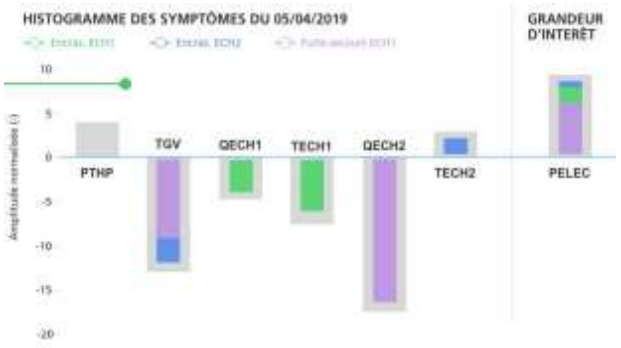
metroscope
GROUPE EDF

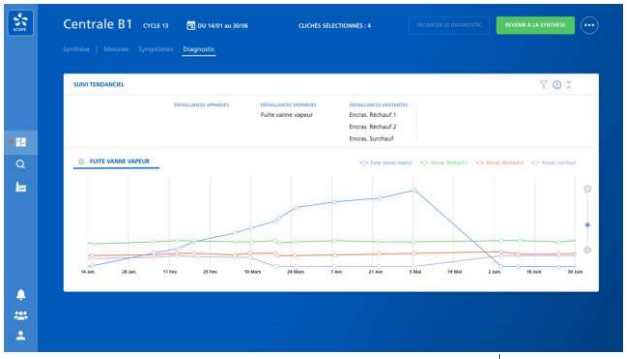
The Metroscope™ tool is planned to be used for all of the reactors in operation in France

> METROSCOPE engine is powered by Markov Chain, just like Google page rank!









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4

The future will be digital

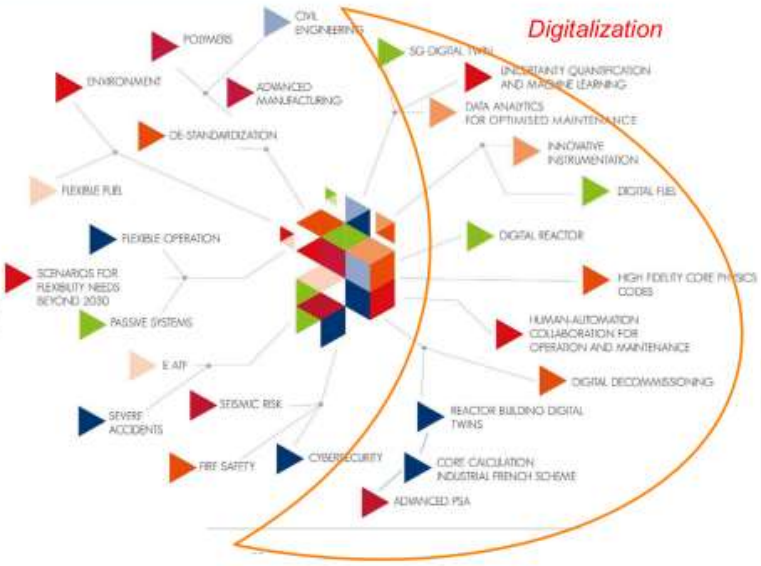
4.3 R&D for the future

EDF R&D strategy for digital transition

Nuclear of the Future Initiatives

A set of technological bricks :

- Safety continuous improvement (fuel, seism, fire , cyber)
- Digital transition, AI and Data Analytics for Operation
- New solutions for manufacturing and repair
- Flexibility ENR / NUC beyond 2030



Reactor building digital twin for outage preparation

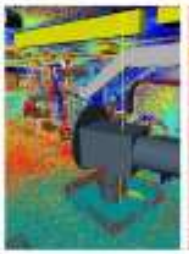
360° photos : automated localisation of areas and equipments

Scans : direct measurement of clearance

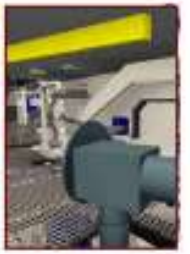
CAD : object reconstruction and plant walk-down

1025 photos
450 million pixels

1086 scans
40 billions dots



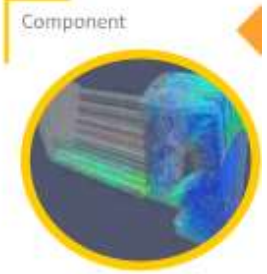
precision 2 cm

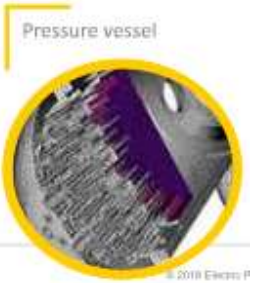


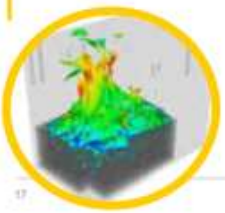
EDF R&D strategy for digital transition

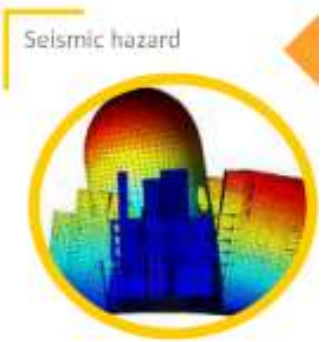
Digital solutions for O&M

Technological building blocks









5

The future will be flexible

5.1 FPO at the EDF French PWRs

Flexible Operation of nuclear plants at EDF: a long story

- The first French NPP originally designed for base load
- Early 80's, decision taken to improve NPPs Load Following capabilities, leading to studies, modifications and administrative authorizations
- Modifications implemented :
  - mechanical design : surge line, spray line, charging line
  - pressurizer control loops
  - control rod drive mechanisms
  - introduction of a new core control mode (grey mode)
- Flexible Operation has been successfully implemented at EDF NPPS for 35 years with manageable impacts

What is Plant Flexibility ?

Power variations recorded in June 2013 at a French 1300 MW NPP

5

The future will be flexible

5.2 The French & European governmental policies

In France, new policy priorities have been issued on Jan 2019 "the Pluriannual Planification For Energy"

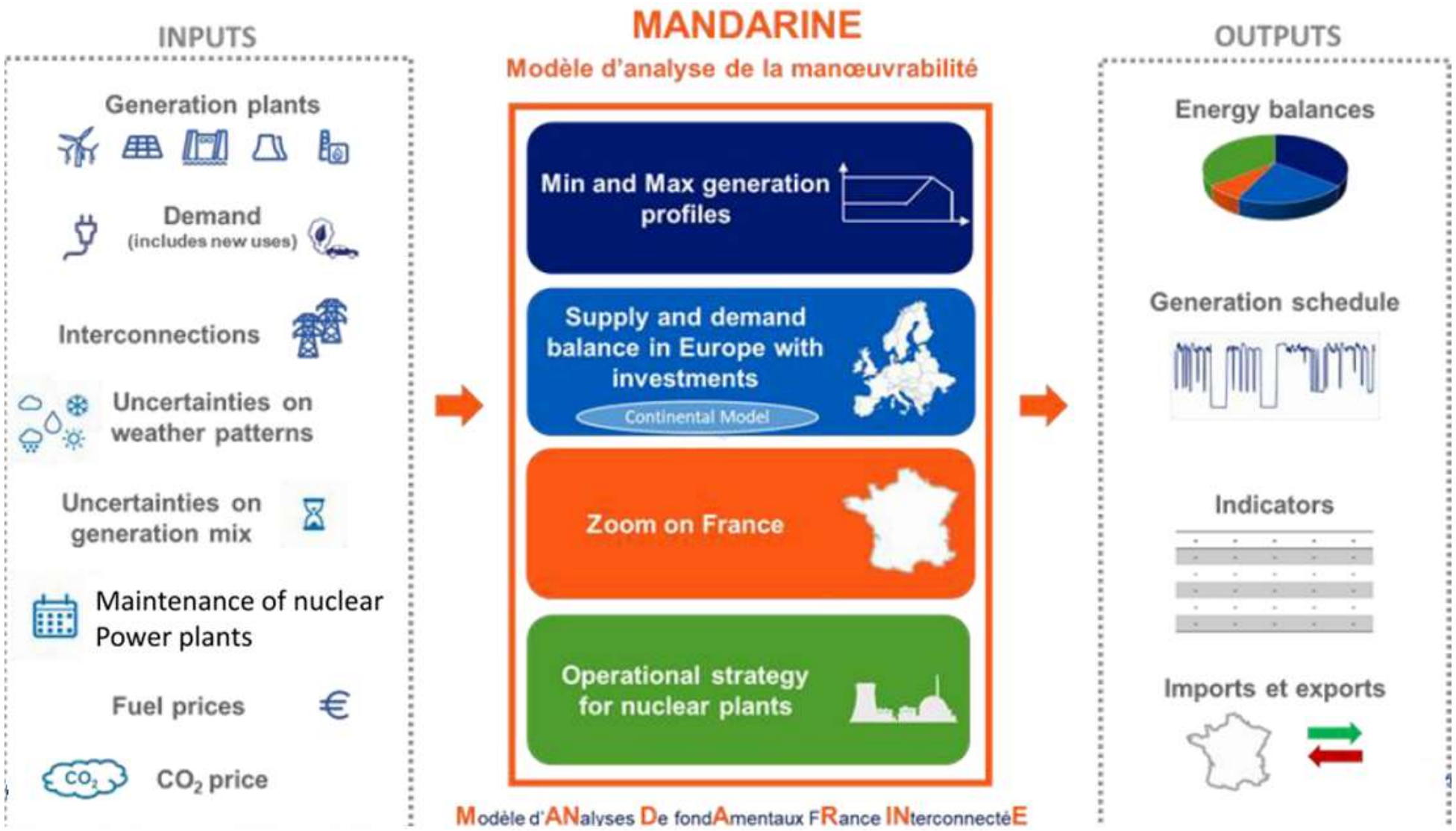
►French Government key points integrated in "PPE 2019-2028"

- France must decarbonize its economy as per its climate goal commitments:
  - Reducing drastically the consumption of fossil fuels through low CO2 electrification of end uses
  - No new thermal fossil plants (coal, gas) in the French Mix.
  - Closing by 2022 last coal plants or convert them to biomass.
  - Contribute to get a significant CO2 price in Europe.
  - Develop the use of electricity in transport and building (vehicles, Heat Pump ,smart grids)
- Energy efficiency must be accelerated particularly in buildings
- Build a new energy mix based on pragmatic objectives:
  - 40% renewable share by 2030: X 3 onshore wind by 2030, X 5 for PV.
  - a balanced energy mix of 50 % nuclear 50 % renewable by 2035.

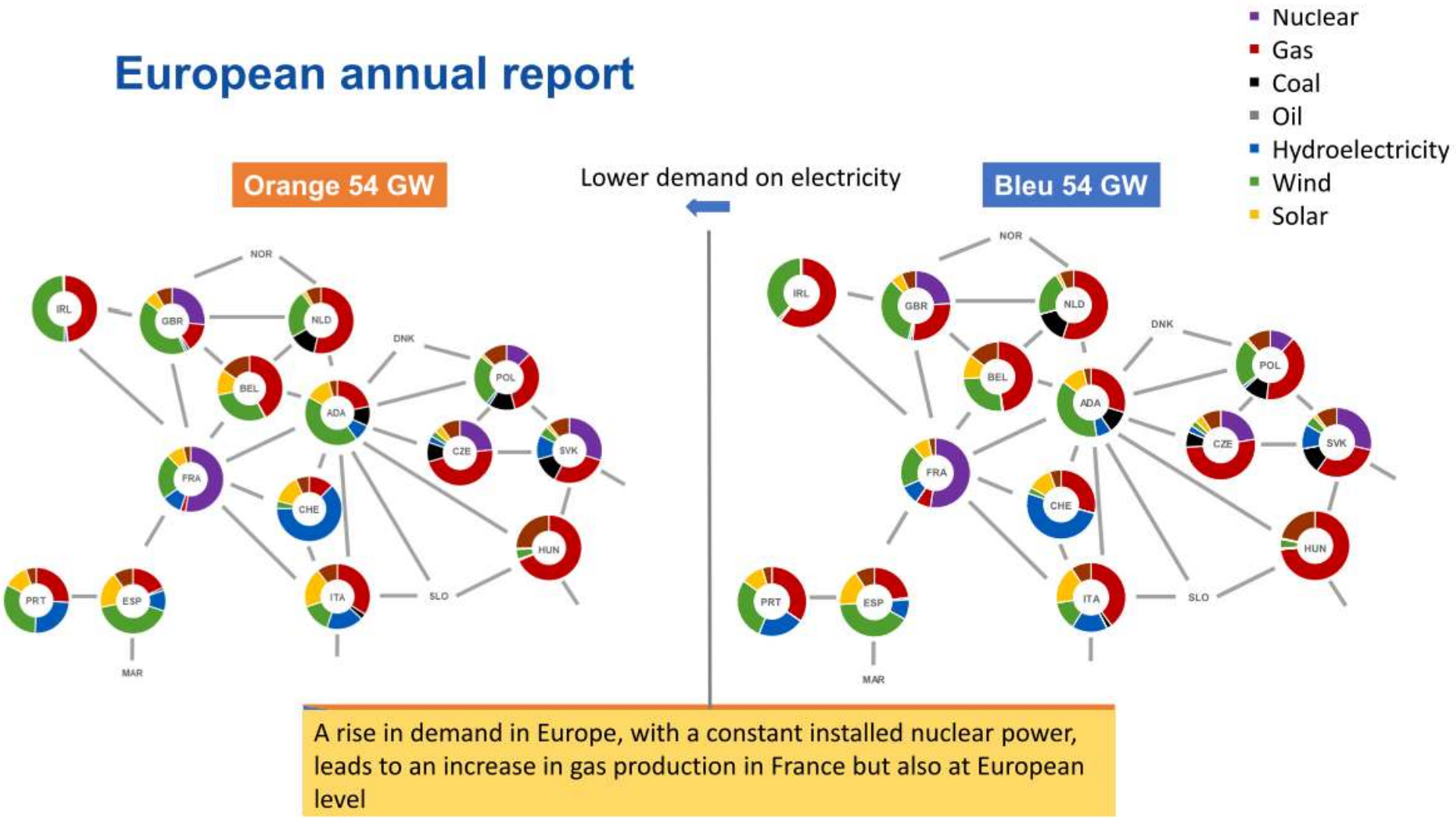
5

The future will be flexible

5.3 The increase in renewables, an opportunity for nuclear Generation ?


INPUTS
Generation plants
Demand
(includes new uses)
Interconnections
Uncertainties on weather patterns
Uncertainties on generation mix
Maintenance of nuclear Power plants
Fuel prices
CO_2 price
MANDARINE
Modèle d'analyse de la manœuvrabilité
Min and Max generation profiles
Supply and demand balance in Europe with investments
Continental Model
Zoom on France
Operational strategy for nuclear plants
Modèle d'ANalyses De fondAmentaux FRance INterconnectéE
OUTPUTS
Energy balances
Generation schedule
Indicators
Imports et exports

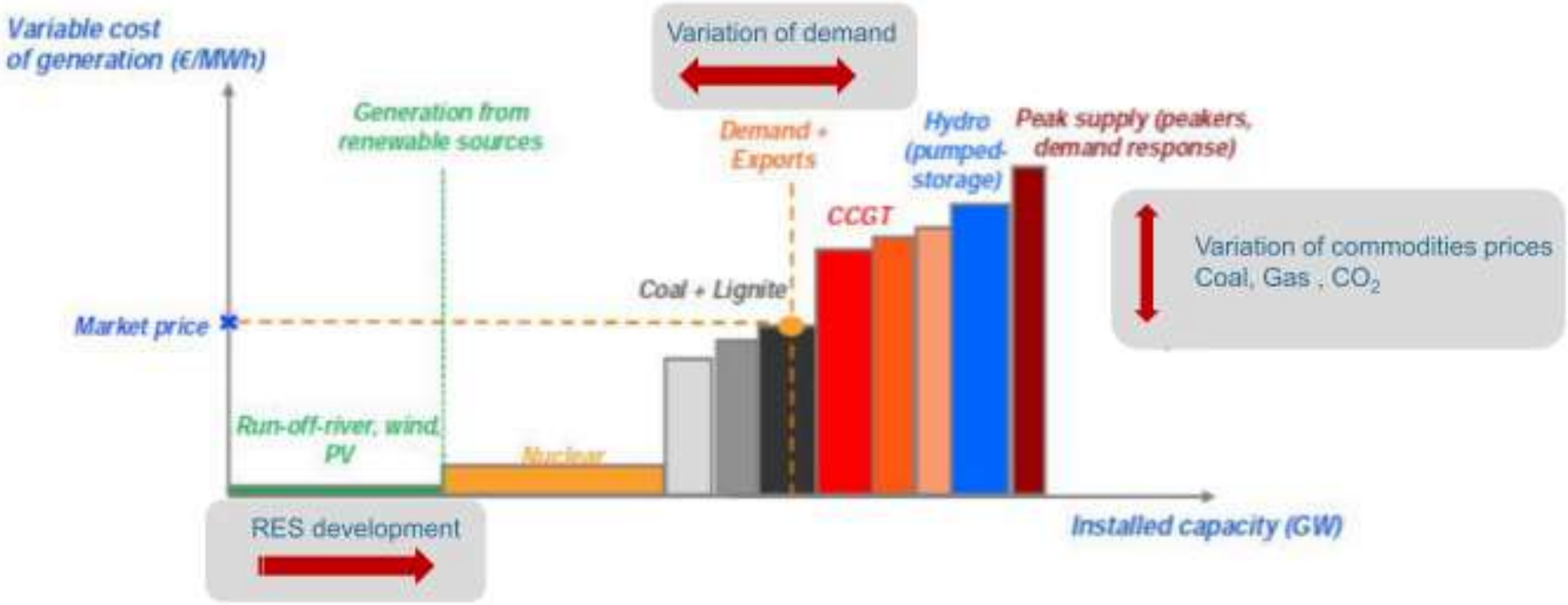
European annual report



A rise in demand in Europe, with a constant installed nuclear power, leads to an increase in gas production in France but also at European level

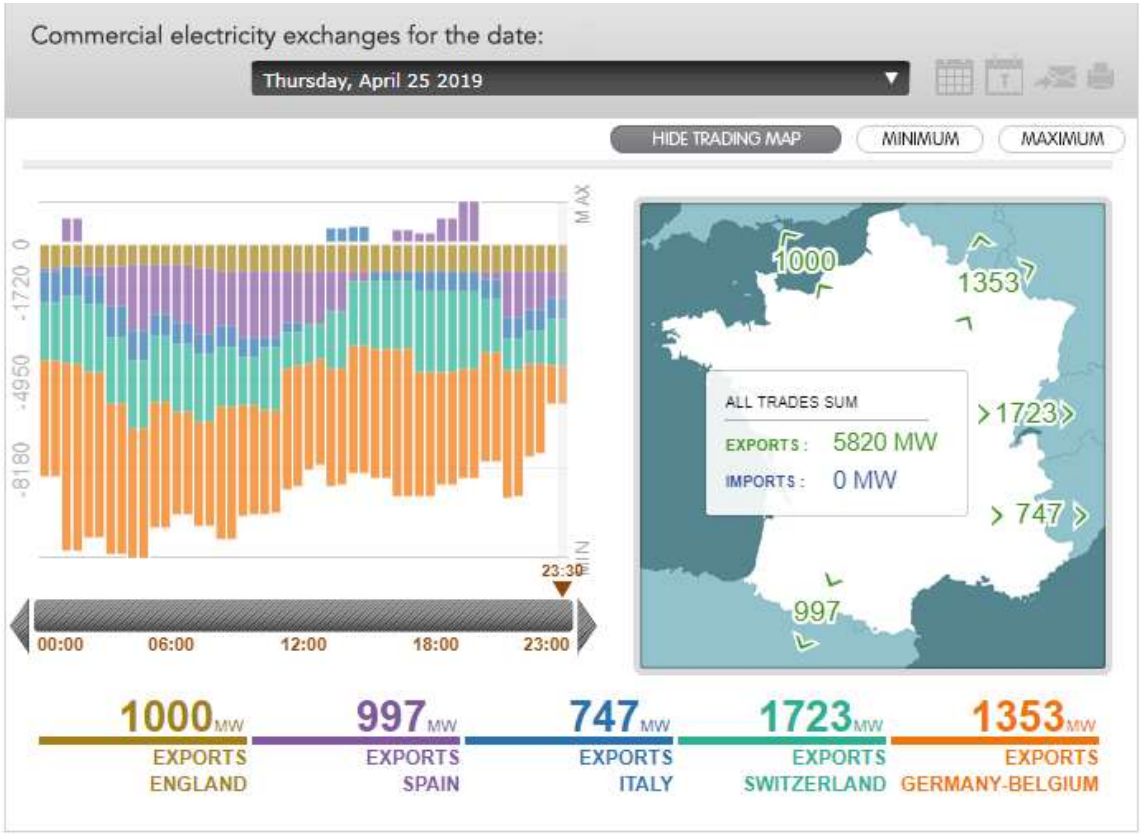
Flexible Operation at EDF

Market Price setting and merit order



The increase in renewables, an opportunity for nuclear Generation ?

https://www.rte-france.com/en/eco2mix/eco2mix-echanges-commerciaux-en



6

New builds & advanced nuclear

EDF New builds : EPR & EPR2

Potential future projects :

- Additional EPRs in France (no decision before 2021)
- UK/Sizewell C
- India/Jaitapur

Strategic Contract for the Nuclear Sector (CSFN)

Contrat stratégique de la
Filière Nucléaire
2019-2022

Mid-term

- **Recycling of plutonium in PWR using MOX2** type of fuels containing both Pu recycling rods and enriched uranium rods (Corail) or rods containing both (MIX)
- R&D plan to be implemented with the target to introduce a test assembly in reactor by 2025 horizon.

Short term :

- Guarantee a production rate in line with the needs of the nuclear fleet
- **Prepare the moxing of part of the 1300 MWe reactors fleet**

Long term :

- **Conduct an R&D program on the Generation IV and closure of the fuel cycle,** including sodium FNR reactors and corresponding cycle plants.
- **R&D programme will capitalize on the learnings of the Astrid and includes :**

- a simulation program, using new digital know-how (e.g. digital twin)

- an experimental program

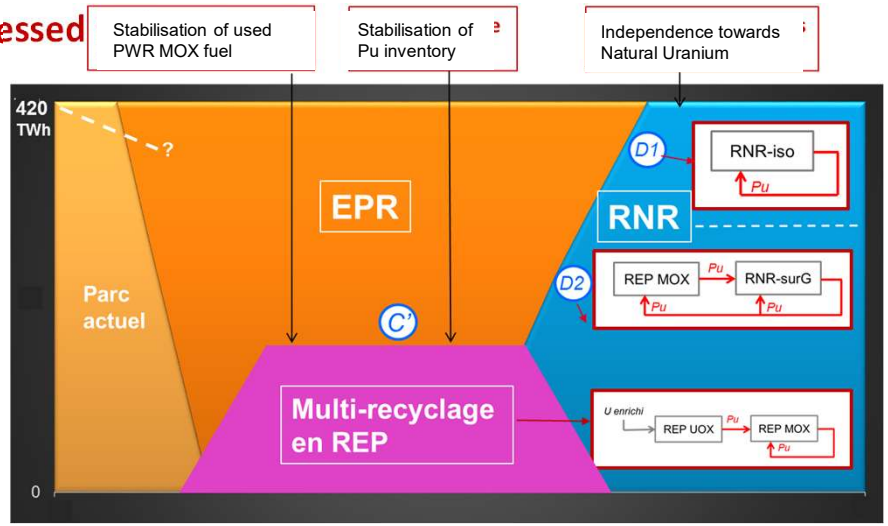
Plutonium Multi-recycling in PWR

Multi-recycling in PWR study program

- An R&D program under construction between CEA and industrials EdF, Framatome and ORANO
- Global vision of a possible industrial cycle has to be built
- Issues for industrial deployment have to be integrated into the different stages of scenario studies

Scientific and Technical challenges to be adressed

- Adaptation of reactors
- Neutronics
- Radioprotection
- Impact on cycle plants (La Hague and Mélox)
- Impact on deep geological disposal facility (Art. 51 of the PNGMDR)



Merci / Thank You

Conclusion :

- The French nuclear fleet is undergoing a massive renovation program to ensure the continuing of operations
- The digital transition (‘Plant modernization’) is on track
- The strategic context has changed with the French government plans
- But this context is now secured, some difficult decisions will have to be made but the path is clear
- In this context, Flexibility of nuclear reactors is an opportunity and a competitive advantage
- For new builds and advanced nuclear, a strategy is defined but a lot of uncertainties remain.

8

Appendixes

French strategy for climate and energy / Multiannual Energy Program (PPE)

Main measures :

- The Government has set the target of achieving a 50% share of nuclear power in the electricity mix by 2035. The objective set in the Energy Law will be modified accordingly.
- Achieving this goal will mean the closure of 14 NPPs (900 MW reactors), including the 2 Fessenheim reactors.
- The plant shutdown schedule will meet the 5th decennial visit schedule of the concerned reactors, with the exception of 2 reactors that will close in the second period of the PPE, in 2027 and 2028, provided the security of supply of the country is ensured.
- If certain conditions related to the electricity price and the evolution of the electricity market at European level are fulfilled, the shutdown of two additional reactors could occur by 2025-2026, on the basis of a decision to be made in 2023.
- The Government will identify sites that will be subject to these closures, based on a proposal to be built by EDF. Except for a few possible cases, the decrease of the nuclear fleet will not lead to the complete closure of any nuclear site.
- **The strategy of treatment and recycling of nuclear fuel will be preserved over the PPE period and beyond, until the 2040's horizon. To this end, a certain number of 1300 MW reactors will be moxed and studies will be conducted for the deployment of the multi-recycling of fuels in the current reactors.**

Strategic Contract for the Nuclear Sector (CSFN)

Contrat stratégique de la Filière Nucléaire
2019-2022

Axis 1: Employment, skills and training

Axis 2: Digital transformation

The aim is to structure the supply chain and the innovation approach in the nuclear sector through digital technology.

Axis 3: Ecological transformation, R&D and tools for the future

- **Promote a circular economy within the nuclear industry.**

Recycling spent fuel is a major element of the strategy for ensuring sustainability of Nuclear Energy.

- **Define the reactors and tools for the future.**

We must conceive the "Nuclear Plant of the Future" with EDF, CEA and Framatome and develop a French technology SMR model launching in 2019 the preliminary design phase of the reactor.

Axis 4: International matters

The closing of the fuel cycle : Gen. IV reactors and cycle

	R&D programs objectives
Future Reactors	■ Consolidation of technical knowledge on sodium FNRs and R&D basis to maintain skills and further develop 4th advanced generation technologies (reactors and cycle plants) ■ Actions for the development of SFR technologies and, ultimately, qualification of industrial components (using simulation tools and experimental facilities, e.g. JHR reactor) ■ Sketch studies and R&D assessment of other FNR technologies, in particular MSR-FNR with identification of challenges (salts, corrosion / durability, online processing, safety) ■ Construction of a "small FNR reactor", for demonstration or experimental purpose, at an horizon compatible with the industrial needs (horizon of the 2nd half of the XXI century)
Cycle Back-end	■ Used fuel reprocessing: advanced processes and technologies for recycling in FNR ■ MOX manufacturing for FNR: industrial manufacturing capacity ■ Development of a multi-recycling process for uranium and plutonium (CORAIL/MIX) ■ Assessment of the consequences of U and Pu multi-recycling on Pu flow and Minor Actinides inventory, in particular in respect to the deep geological disposal
International	■ Development of collaborations with partners, in particular Europe, USA, Japan, Russia…