

LEAD FAST REACTOR SUSTAINABILITY

Presented by;

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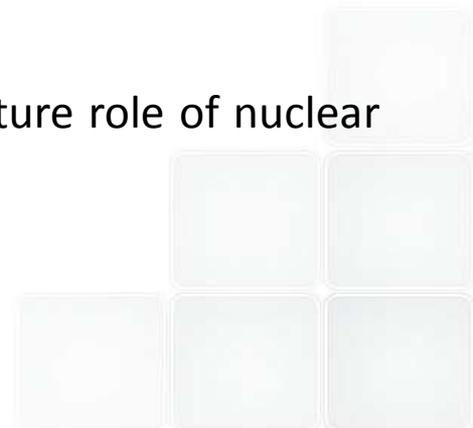
L. Mansani, Ansaldo Nucleare



- ❖ Introduction, the sustainability concept
- ❖ Environmental sustainability
- ❖ Economical sustainability
- ❖ The ALFRED Demonstrator
- ❖ The Falcon consortium

The path from current nuclear systems to **Generation IV** systems is described in a 2002 Roadmap Report entitled “*A technology Roadmap for Generation IV Nuclear Energy Systems*” which:

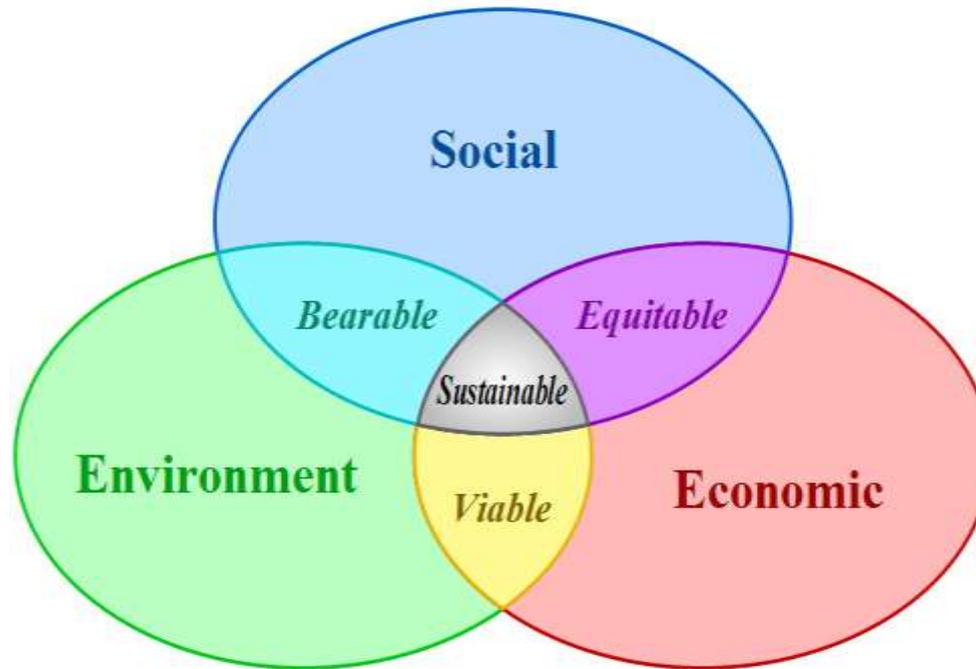
- defines challenging technology goals for Generation IV nuclear energy systems in four areas:
 - ✓ **sustainability,**
 - ✓ **economics,**
 - ✓ **safety and reliability, and**
 - ✓ **proliferation resistance and physical protection.**
- identifies six systems known as Generation IV to enhance the future role of nuclear energy;



THE SUSTAINABILITY CONCEPT

Sustainability has been largely debated in various frameworks. In the nuclear field, the former meaning of this concept was mainly related to **fuel cycle aspects**, and particularly to what concerns the **uranium resources** duration and **spent fuel accumulation** with respect to a foreseen world reactor fleet.

IAEA has developed a comprehensive definition



Venn Diagram Of Sustainable Development At The Confluence Of Its Three Constituent Aspects

The need for energy will increase in the future and, the natural resources will decrease, even if much more gradually than foreseen by catastrophist, hopefully compensated by the technological evolution in several fields;

Anyhow the sustainability concept is becoming more and more central.

**Are our Generation IV fast reactors
more sustainable**

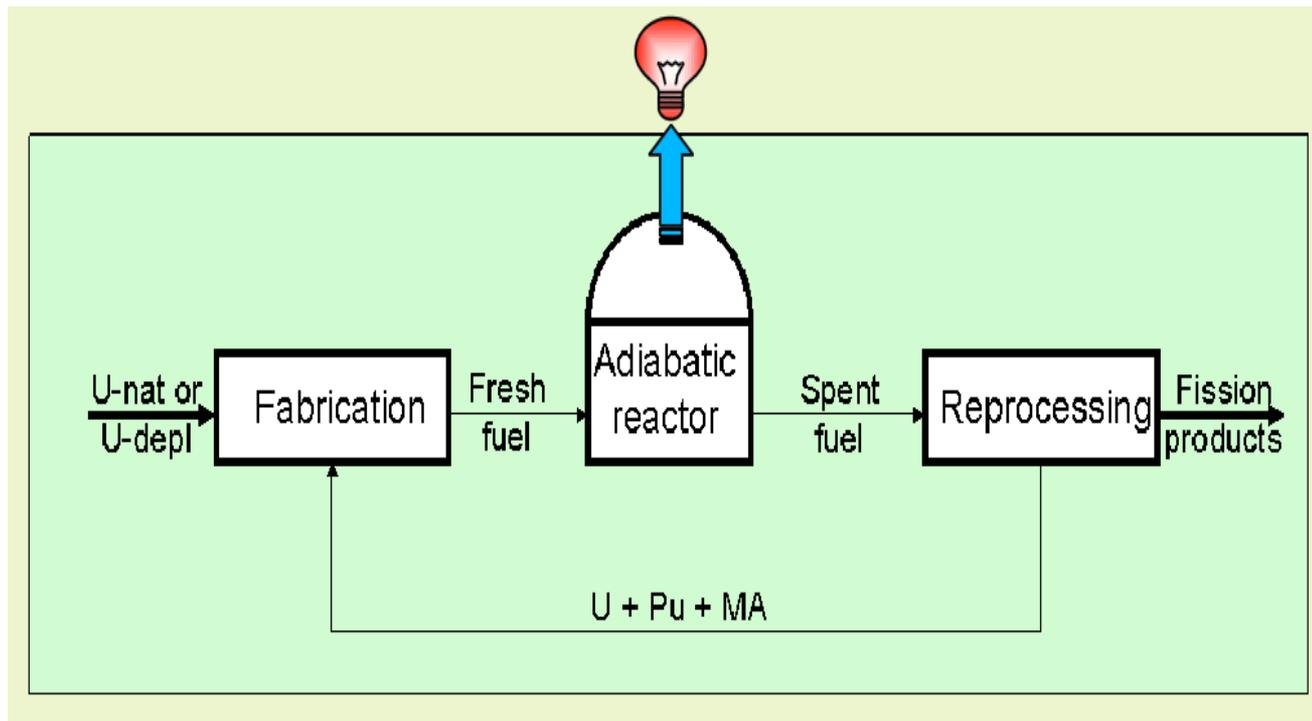


ENVIRONMENTAL SUSTAINABILITY: FUEL CYCLE

Fast reactors can use the fuel intrinsic energy content much more efficiently than thermal reactors, leading to a significant extension of the natural resources duration, being, in any possible configuration, of the order of thousands years. The energy content that can be extracted from the same amount of fresh fuel, with respect to a Gen-III reactor, is around two orders of magnitude larger, decreasing consequently the ore and the repository impact of the same amount.

In addition the lead fast reactor is potentially particularly friendly from the environmental point of view and this is due to physical refrigerant properties.

The lead low absorption and scattering cross-sections leave the designer the degree of freedom required to look for the best core configuration aiming at the most effective implementation of a closed fuel cycle.



Fuel Composition During Different Phases Of The Adiabatic LFR Fuel Cycle. The Steps Are:

Before Irradiation (**BI**)

After Cooling (**AC**),

After Re-fabrication (**AF**)

Fuel Discharge (**FD**),

After Reprocessing (**AR**)

	Time [y]	Am [%]	Cm [%]	Np [%]	MA [%]	Pu [%]	U [%]	FP [%]
BI	0	1.02	0.16	0.11	1.29	18.15	80.56	0.00
FD	5	0.81	0.22	0.11	1.14	18.53	74.85	5.48
AC	10	0.96	0.17	0.11	1.24	18.40	74.88	5.48
AR	11.5	1.00	0.16	0.11	1.27	18.34	74.82	0.00
AF	12.5	1.02	0.16	0.11	1.29	18.15	80.56	0.00

Wastes volumes: comparison with fossile fuels



0.012 kg/TWh of MA and 0.227 kg/TWh of Pu

Only reprocessing losses

LWR in standard open cycle, nominally 3.0 and 26.1 kg/TWh of MA and Pu **(factor 100)**

The fission products (no geological deposit needed), are 10^6 kg/TWh

The CO₂ produced per TWh is ranging from $0.5 \cdot 10^9$ kg for a natural gas plant up to around $1.0 \cdot 10^9$ kg for a coal plant

Just to give an order of magnitude if 25% of 2013 Italian electricity consumption (317 TWh) would be produced by LFRs, 950 g of MA and 18 kg of Pu would go to final disposal every year.

The total volume of these elements is around 1 liter.

the CO₂ (greenhouse effect also asphyxiant gas) to be stored for a comparable power plant fleet, fed with fossil fuels are around $40-80 \cdot 10^9$ kg.

In terms of **volume**, at 25°C, 1 atm, it ranges between **22.5 and 45 km³**.

The gas can be compressed with energy consumption and overall efficiency decreased

CO₂ Compressed up to liquefaction reduces volume to about 10^8 m³.

Wastes storage, for fossil fueled systems, are usually not considered,

Ashes and/or other combustion gases are not accounted.

- ◆ Upgrading the safety level of NPPs with traditional-type reactors, (in which potential energy is stored in large amounts) requires increasing the number of safety systems and defense-in-depth barriers.
- ◆ **We have to understand that such measures can only reduce the probability of severe accidents and mitigate the consequences, but cannot eliminate them when there is large potential energy.**
- ◆ **Reactors, in which the potential energy is accumulated in coolant in great amounts and can be released in an event of tightness failure in the primary circuit and destruction of protective barriers, can lead to large radioactivity release.**



STORED POTENTIAL ENERGY FOR DIFFERENT COOLANTS

Coolant	Water	Sodium	Lead, Lead-bismuth
Parameters	P = 16 MPa T = 300 °C	T = 500 °C	T = 500 °C
Maximal potential energy, GJ/m³, including:	~ 21,9	~ 10	~ 1,09
Thermal energy	~ 0,90	~ 0,6	~ 1,09
<i>including compression potential energy</i>	~ 0,15	None	None
Potential chemical energy of interaction	With zirconium ~ 11,4	With water 5,1 With air 9,3	None
Potential chemical energy of interaction of released hydrogen with air	~ 9,6	~ 4,3	None

From ICAPP 2011, Paper 11465

Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters

G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev

Lead environmental impact

-needed extracion energy with ore 6% enrichment (current value),
Imperial Smelting process, not considering co-extraction

600 MWe reactor, lead 10.000 t, 25 GWh, less than 0.1%, not relevant

CO₂ produced (considering coal plant, 35% efficiency) 2 kg_{CO₂}/kg Pb

600 MWe reactor **10 g CO₂/kWh** (8-45 g/kWh overall balance)

Lead availability

Current (1999) lead production 6.2 Mt (+around 3 Mt recycled).

10 reactors/year=0.1 Mt , not relevant

Lead can be recycled continuously

The only raw material input needed for the fuel cycle is depleted uranium, largely available at zero energy consumption.

EFFICIENT USE OF ENERGY: EROI



EROI (Energy Return On energy Investment) is a very effective environmental sustainability indicator, unexplainably underused (efficient use of energy).

The nuclear power plants have been usually assigned for net energy revenue ranging in between 10 and 50 meaning that on the overall plant cycle the net energy production is from 10 times to 80 times the energy needed for plant construction, operation and maintenance, full fuel cycle, decommissioning and waste maintenance.

Large differences come from the ore grade assumptions and different enrichment technologies; as an example, diffusion is highly energy expensive (EROI average around 15), while centrifugation is much efficient (EROI more than 40).

Life cycle analysis for Vattenfall's Environmental Product Declaration for its 3090 MWe Forsmark power plant for 2002.lower-grade ores, or EROI is 74.

Output over
40 years,
299 TWh
3324 PJ

Mining	5.5
Conversion	4.1
Enrichment	23.1
Fuel fabrication	1.2
Plant operation	1.1
Build & decommission plant	4.1
Waste management	4.3
TOTAL	43.4 PJ

EROI = 74
For lead reactors
at least double
Larger than a
hydropower plant

the input energy turns out to be 1.35% of output

ECONOMICAL ESTIMATION

The nuclear economic sustainability has to be fairly evaluated in comparison with other type of sources showing comparable characteristics, i.e. dispatchable and CO₂ free; also for these systems, such as hydroelectricity, geothermic, fossil fuel with CSS and biomass, economic estimations are affected by many possible uncertainties, due, for example, to:

- Forecasts on fuel cost;
- Carbon Sequestration and Storage is still undefined in terms of technology to be adopted, costs and environmental impact;
- Forecast on load factor; the strong introduction of intermittent sources has driven the electrical mix toward the use of fast reacting systems - i.e. with good ability to change rapidly their power output - and has relegated some traditional sources to a minor role. Future sources have to be planned with such a capability and this brings about additional planning hardware and maintenance cost.

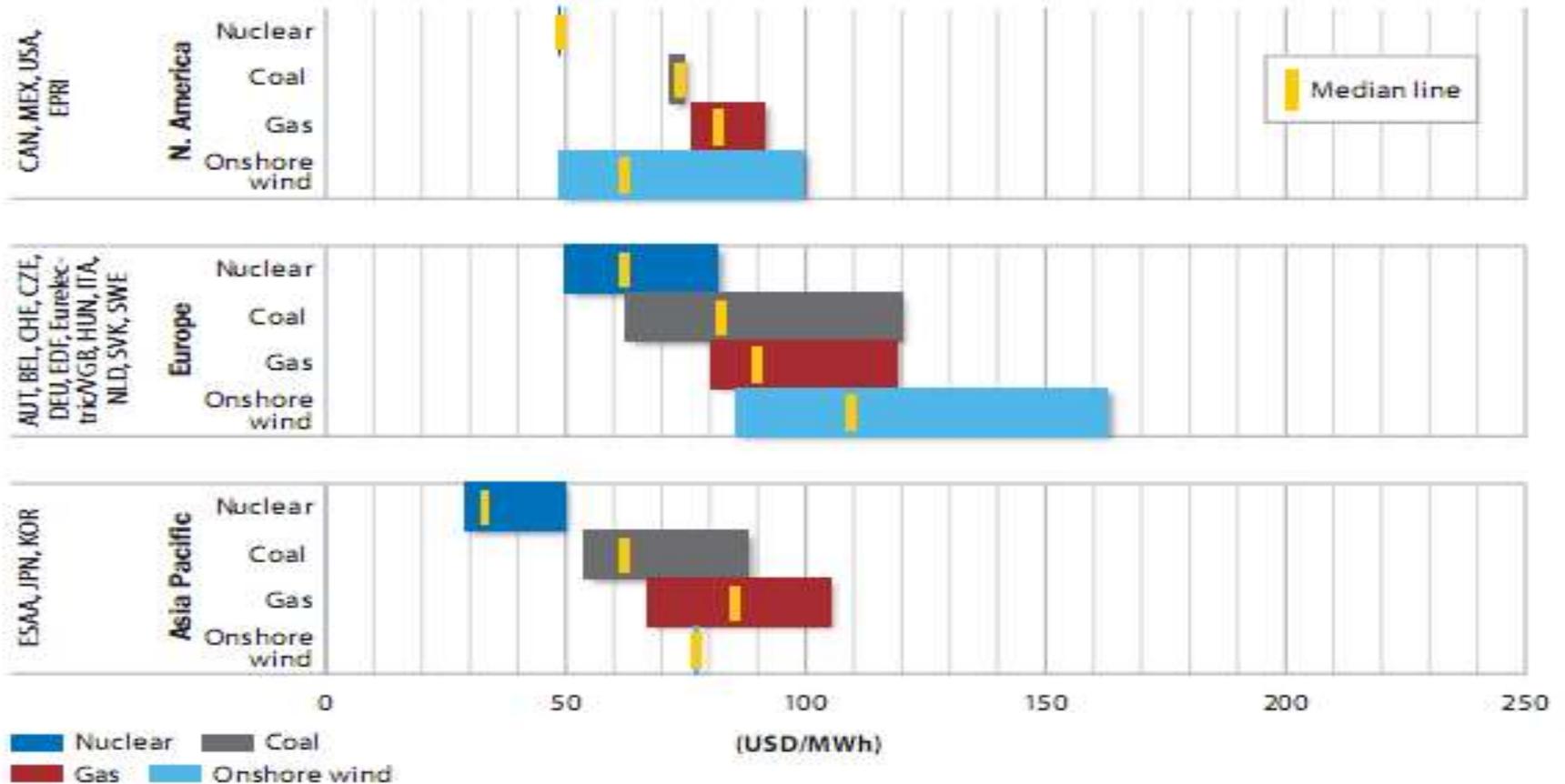
Cost item	Optimistic	Nominal	Pessimistic
R&D	-	-	-
Engineering, licensing & construction	3600 €/kWe	4100 €/kWe	4900 €/kWe
Engineering, licensing & construction (incl. 1 st core, D&D, contingencies)	4100 €/kWe	5200 €/kWe	6300 €/kWe
Operation & maintenance	81 €/kWe/a	110 €/kWe/a	143 €/kWe/a
Fuel cycle	4 €/MWh	8 €/MWh	19 €/MWh
Energy generation	22.5 €/MWh	37.5 €/MWh	69 €/MWh

Range
30 - 90 \$/MWh

ELECTRICITY GENERATION COSTS

Average price in the Italian electricity stock market was, during the year 2012, 75.5 €/MWh

(at 5% discount rate)



The Electricity Production Cost Are Quite Variable Across Different Countries.

Source: NEA: Projected Costs Of Generating Electricity: 2010 Edition

COST COMPARISON: CO₂ FREE DISPATCHABLE SOURCES



Elaboration on the basis of the IPCC III (2001), IV (2007) and V (2013) reports.

Data have been extracted in a complex framework in an attempt to give an extremely synthetic illustration of possible scenarios. The message is that, even if with some modifications along the subsequent reports, IPCC forecasts indicate a **relevant anomalous warming in a time frame of several decades**

IPCC Report	Short period (70-110 years) temperature increase [°C]
III, 2001	1.4-5.8°C
IV, 2007	1. 0-3.0 very probable
V, 2013	1.0-2.5 probable

The greenhouse gases emissions in terms of CO₂ equivalent (eq.) from nuclear energy, evaluated in Life Cycle Analysis, turns out to be only in the range of **8-45 g CO₂ eq./kWh**, the one of natural gas being in the range **422-548 g CO₂ eq./kWh**.

Cost analysis has to be performed among dispatchable CO₂ free sources

ECONOMIC SUSTAINABILITY



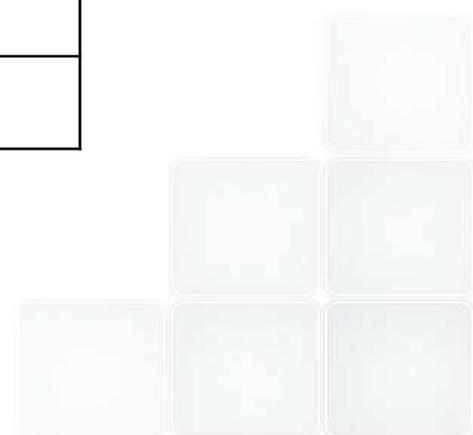
Levelised Costs For Electricity Production And Their Uncertainty Intervals, Plants Commissioning In 2025-30. Nuclear Is the most cheap and the most mature technology. Technology Specific Hurdle Rates Are Used. Source: Elaboration On The Basis Of Data From Department Of Energy&Climate Change (DECC). 1£=1.25€

Technology type	projects commissioning in 2025 €/MWh	projects commissioning in 2030 €/MWh
Nuclear FOAK/NOAK	95-125	85 -110
CCGT with post-combustion CCS-FOAK	120-180	120-145
CCGT with pre-combustion CCS-FOAK	140-180	135-180
COAL ASC with ammonia, FOAK	150 210	145 200
COAL IGCC with retro CCS, FOAK	125-180	125-180
BIOMASS with CCS	220-275	220-275
HYDROPOWER large- < MW	110-375	110-375

ECONOMIC SUSTAINABILITY

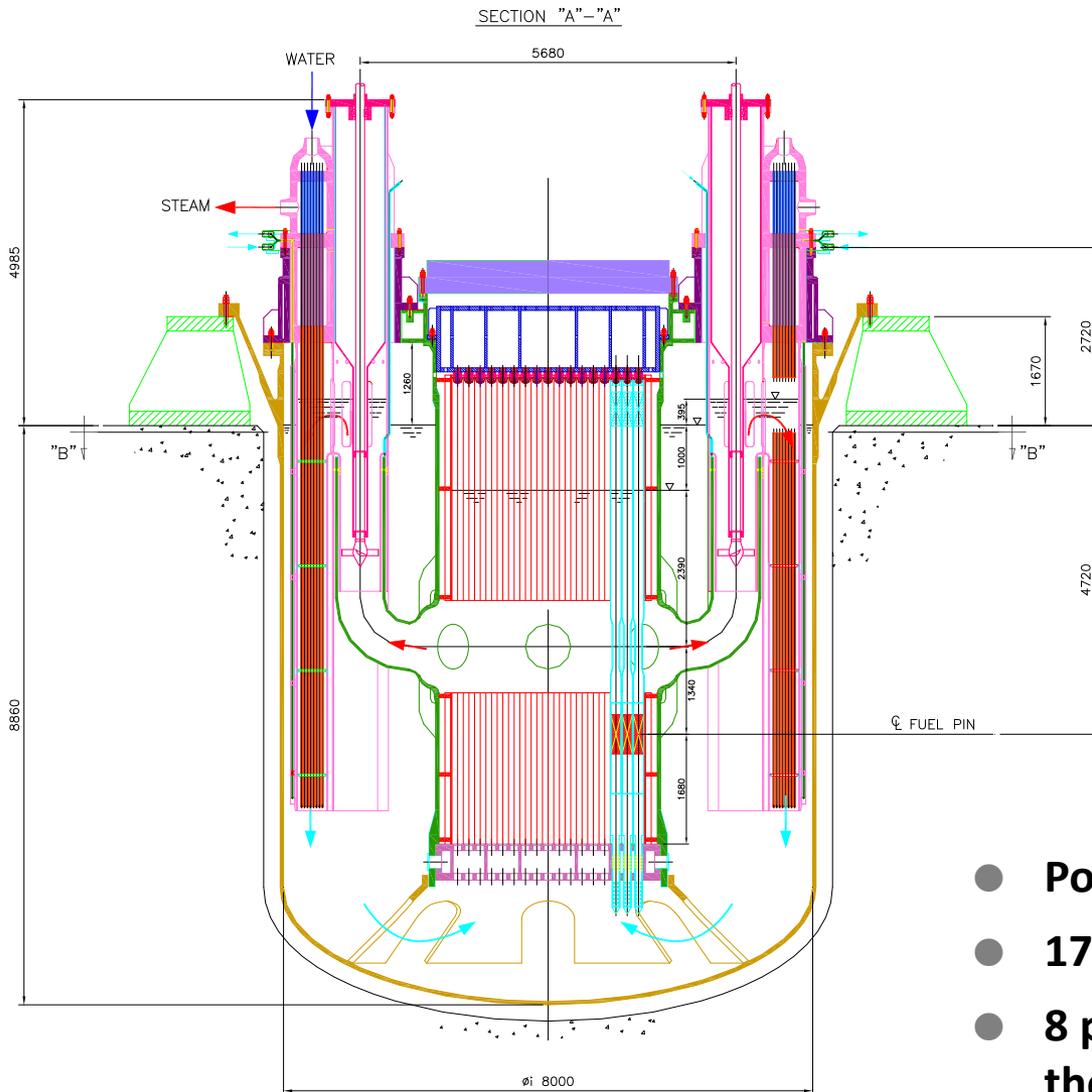
Plant type	Levelised Cost for plants entering in service in 2040 €/MWh
Advanced Coal with CCS	114
Advanced gas CC with CCS	80
Advanced Nuclear	64
Geothermal	37
Biomass	79
Hydro	65

LCOE For Different Energy Sources,
Data Elaborated From The Annual Energy Outlook 2014



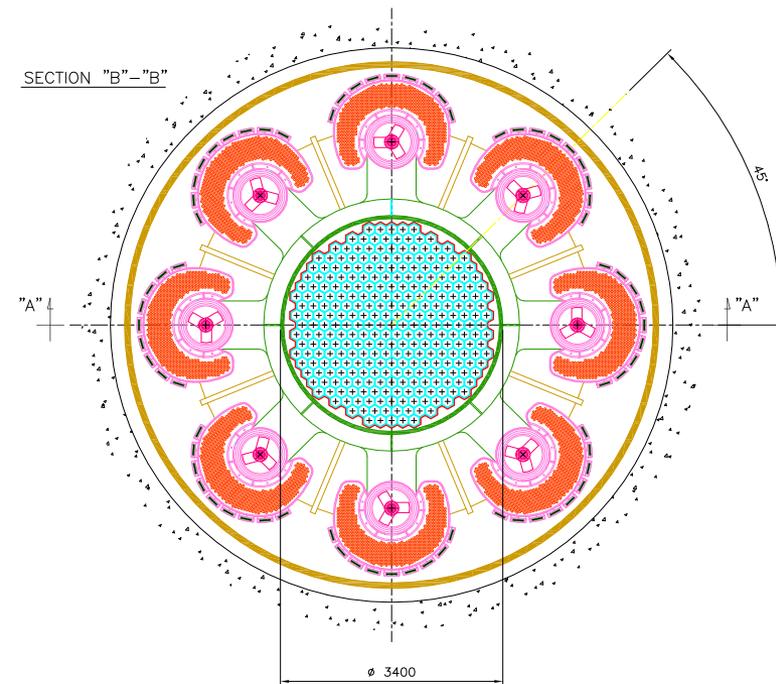
- ALFRED (Advanced Lead Fast Reactor Experimental Demonstrator) is a lead cooled reactor, of 120 MWe power, that will be connected to the grid to make a first step in the deployment of Lead cooled Fast Reactor (LFR) technology. The size of the reactor also fits the needs of a *Small Modular Reactor* (SMR), so that ALFRED on one side represents the LFR technology demonstrator, and, on the other one, the FOAK for a lead cooled SMR.
- Before building the demonstrator, substantial design and experimental activities (as well as supporting activities for licensing) are deemed necessary. The plan shall include at least two different phases:
- **First step (2013-2020):** ALFRED exp. infrastructures, experiments and design
- **Second step (2020-25):** ALFRED construction

ALFRED: Reactor block



Vertical section

Horizontal section



- Pool-type reactor of 300 MWth power
- 171 fuel assemblies in the core
- 8 pump-bayonet tube SG connected to the 8 secondary circuits



In March 2011 the Romanian Minister of Energy wrote a letter to LEADER Project coordinator proposing to host ALFRED in Romania.

Ansaldo response to the Romanian Minister welcome the Romanian proposal and inform of the transmission of the letter of interest to ESNII members.

In June 2013 the sub-secretary of the Italian Minister for Economic Development wrote to commissioner Oettinger to highlight the importance of Alfred in the European context and the intention to use synergies between RTD and infrastructural funds for ALFRED Project.

Response from Commissioner Oettinger received in August 2013 welcome the Italian/Romanian proposal and highlights the importance and the usefulness of the synergies to pool resources and reach the critical mass for project deployment.

The FALCON consortium has been set-up on December 18th 2013 by: Ansaldo Nucleare, ENEA and ICN Construction Site is Mioveni and

EU organizations are invited to join FALCON or a technical agreement (MoA).





Due to the strong interest manifested by several European Organizations a **Memorandum of Agreement (MoA)** has been defined to anticipate technical work already scheduled for the second phase of FALCON:

The interested organization can:

- Contact one of the FALCON members
- Agree on a technical activities program
- Sign the MoA with the FALCON member

All contributions in this phase are expected to be of an in-kind nature.

The aim is to constitute a network of organizations interested in the LFR technology development and ALFRED construction.





Proposed Technical activities

CRS4 (Sardinia - Italy), is proposing to support ALFRED design through an extensive use of CFD tools to refine and validate design solutions.

(MOA SIGNED - ACTIVITY STARTED)

NRG (Petten, The Netherlands) is proposing two activities:

- Feasibility study for material irradiation
- detailed CFD analysis of FAs

SRS (Rome, Italy) is proposing two studies:

- DHR (2) design and simulation
- Fuel Handling system studies

IIT (Milan, Italy) is proposing further studies on

- their PLD process used to deposit alumina layer on steel.

Layer already tested successfully in Lead at 700 C and heavy ions irradiation up to 150 dpa



Proposed Technical activities/2

KIT (Karlsruhe, Germany) is proposing many activities:

- Validation of the available computational models of ALFRED reactor using SIM-LFR system code
- SGTR events simulation in a lead pool reactor facility
- Design support and evaluation of grid spacers
- Al surface alloying process using GESA
- Computational fluid dynamic (CFD) analyses of ALFRED design related to FA flow blockage and lead freezing phenomena
- Verification and validation of SIM-LFR code for ALFRED design for the detailed simulation of fuel clad swelling and oxide layer formation taking into account irradiation history
- Re-evaluation of the most important set of transients for ALFRED design, taking into account the current design modifications

FALCON and the MoA



Genova University (Chemical department) is proposing to support the set-up of the Lead Chemistry Lab @ Brasimone and to contribute with researchers and students to the experimental tests.

ICN Pitesti and University of Pitesti: Coordination of ARCADIA (**Assessment of Regional Capabilities for new reactors Development** trough an **Integrated Approach**) :Development of human resources programmes-FP7 project; the main task-to develop a specific curricula

ICN Pitesti- development a pressure loop- LECOTELO – Lead technologies familiarization and material investigations-(under construction).

Additional contacts for MoAs:

CIRTEN (Consortium of Universities, Italy)

Discussions on going for E&T in the Lead Technology and additional research contribution

GRS (TSO, Germany)

contacts ongoing for validation of ATHLET and ATHLET-CFD for simulation of ALFRED reactor

KTH (Sweden)

Discussions on going
MOA sent also to IRSN

FALCON: one letter of intent to join FALCON received

FALCON the main challenges



To be able to reach the phase of ALFRED construction we will have to face several challenges:

- Based on *Partnership Agreement-România-2014RO16M8PA001.1.2 art.174*: “As regard the development of low-carbon energy technologies the objectives of SET Plan will be taken in due account” is necessary to start the diligences at EU level to develop the financial schemes for ALFRED see (http://www.fonduri-ue.ro/res/filepicker_users/cd25a597fd-62/2014-2020/acord-parteneriat/Partnership_Agreement_2014RO16M8PA001_1_2_ro.pdf)
- Declare South-Muntenia nuclear smart specialization
Such step are pre-requisite to be able to get cohesion funds !!
- Be able to erect facilities to support lead technology
- Show the safety features and obtain licensing

It is fundamental to have a transparent and efficient management of all activities. Activities in Romania and outside should be concentrated on one goal:

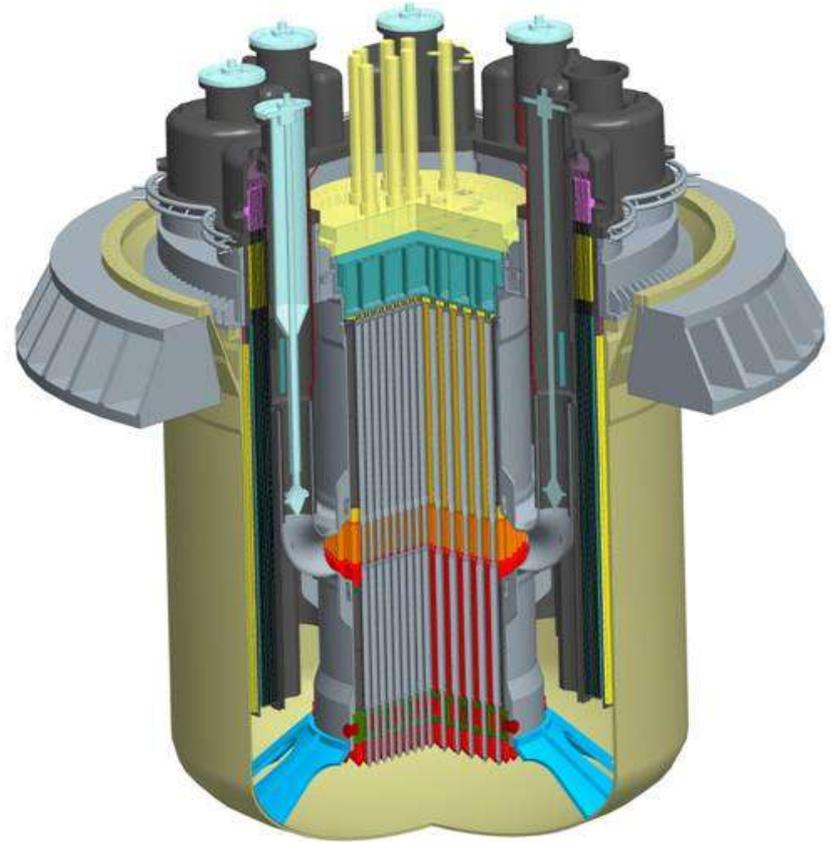
the ALFRED development and construction

CONCLUSION



- the lead fast reactor sustainability discussion has been started.
- The system inherent safety features strongly reduce the plant risk
- A strong reduction of nuclear wastes and of their radio toxicity confers to nuclear energy a new high sustainability level.
- As a matter of fact, the fuel cycle specific improvements based on the adiabatic reactor concept optimized through a “by design” approach have a strong effect on the environmental impact posing the bases for a reconsideration of the public resiliencies.
- The EROI foreseen for IV generation systems is at the top value with respect to the other CO₂ free, or strongly reduced, energy sources.
- Nuclear power plants are economically competitive with other sources, while cost extrapolation far away in time is quite difficult. The ELFR cost premium, with respect to generation III+, passive safety reactor, has been studied in details in the framework of the LEADER project and assessed to be of the order of 10%.
- *The Falcon consortium is rapidly progressing toward the final Alfred project definition (collaborations welcome)*

Thank you for your
attention



ALFRED

