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**Titolo**

# Investigations on the Italian Nuclear Scenario

**Descrittori**

**Tipologia del documento:** Rapporto tecnico

**Collocazione contrattuale:** Accordo di programma ENEA-MSE: tema di ricerca "Nuovo nucleare da fissione"

**Argomenti trattati:** Energia nucleare, politica energetica

**Sommario**

La recente modifica della politica energetica Italiana è caratterizzata, nel lungo termine, dall'obiettivo di ricavare una quota pari al 25% del fabbisogno di energia elettrica da fonte nucleare, avendo come termine temporale il 2030. In questo rapporto, si riportano i risultati ottenuti in due scenari, uno di riferimento, l'altro di sviluppo, caratterizzati da una capacità nucleare installata di 19.5 e 35 $GW_{(e)}$ rispettivamente. Utilizzando il codice DESAE (Dynamic Energy System - Atomic Energy), di origine IAEA, sono state investigate le opzioni ciclo del combustibile aperto e riciclo del plutonio con l'intento di studiare la performance di sistemi nucleari ad acqua leggera rispetto a parametri quali consumo di uranio, quantità di combustibile spento, accumulo di plutonio fissile ed attinidi minori. A questo riguardo, i risultati confermano che sistemi nucleari caratterizzati da elevati valori di burnup sono più performanti. Per contro, sistemi a basso burnup sono più attrattivi, sulla base di un maggiore accumulo di plutonio fissile, qualora si pianificasse l'introduzione di reattori veloci e la chiusura del ciclo del combustibile. Il confronto tra ciclo aperto e riciclo del plutonio richiede approfondimenti di carattere sia tecnico che economico.

**Note**

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| REV. | DESCRIZIONE | DATA | | REDAZIONE | CONVALIDA | APPROVAZIONE |

## CONTENTS

# 1 INTRODUCTION

In 2008, Italy's gross total primary energy supply (TPES) amounted to 182.5 million tonnes of oil equivalent with a decrease of 0.6% with respect to 2007. Practically all the imported share of TPES (84%) was constituted of fossil fuels. The total share of fossil fuels, taking into account the domestic production, reaches nearly 91% of TPES [1].[1] These numbers clearly depict a country with an energy mix conflicting both with security of energy supply as well as climate change issues [2, 3].
The need of long term energy policy was mandatory in the perspective of more strict limits in greenhouse gases (GHG) emissions are recommended by EU and to maintain the competitiveness of Italian industry in the global market. Besides various actions undertaken to reform the Italian electricity sector, in 2009, a new law re-designed the long term energy policy, clearly stating the key role played by nuclear in tackling climate change and supporting country development [4]. A 25% nuclear share in the electricity generation mix by 2030, is one of the most ambitious announced objectives [4, 5]. This could allow, together with renewable sources expansion a sharp reduction of fossil source from current 76% to 50% [4]. Considering the effects on infrastructures, regulatory body, education derived from the decision to phase-out from nuclear business taken in 1987, an underlying hypothesis assumed in this paper is that only a proven and reliable technology, as for LWRs, could succeed in achieving mentioned target.
Two scenarios of nuclear electricity generating capacity, on the basis of electricity demand projections, were studied by means of the DESAE 2.2 code, a tool developed within the activity of International Atomic Energy Agency INPRO project [6-8].

# 2 PERSPECTIVES OF ELECTRICITY SECTOR

In 2009, the Italian electricity demand amounted to 320.3 TWh, secured for about 86% by domestic production while missing 14% by the balance of electricity import/export with neighbouring countries [9]. The composition of gross domestic production from conventional energy sources amounted to about 76%, hydro and renewable sources constituted the remaining 24%. The main conventional energy sources contributing to the net domestic electricity production were natural gas (66.4%), coal (16.7%) and oil (6.6%) [9]. At the end of 2009, the net electricity generating capacity was 95.3 $GW_{(e)}$ with a mean power available at peak of 67 $GW_{(e)}$, see Fig. 1.
While, on one hand, the new generating capacity installed after 2003 improved the capability to manage seasonal peaks of demand, see Fig. 1, on the other hand, the electricity sector is still strongly dependent on import of primary sources, furthermore Italy has one of the highest share of imported electricity among developed countries [4]. Besides security of electricity sources, environmental issues raising from the high share of fossil fuel and competitiveness, due to the high price of electricity paid by industrial consumers, are of concern. Moreover the high share of natural gas exposes Italy's economy to possible market crisis as recently experienced. In 2009, the Italian Government launched a new long term energy policy aiming at promoting

[1] imported electricity not taken into account.

the capability of Italy to meet future commitments on GHG emissions reduction meanwhile improving national competitiveness and security of energy sources. Nuclear technology is fundamental in the declared strategy and a 25% nuclear electricity generating capacity by 2030 was announced [4].
The developing scenario of nuclear energy deployment was defined extending the electricity projections available in [9]. In this analysis the requirement was to assure the availability of power to cope with seasonal peaks of load. A margin of 23% between demand and available power should be sufficient to achieve mentioned objective with a 99% confidence interval without taking into account electricity import or grid failure. In the period 2009-2019 it was assumed, for the developing scenario, an annual mean increase of electricity demand of +1.6% (+2.8% in 2015-2019), an annual mean development of GDP of +0.6% (+1.3% in 2015-2019) and finally +1.1% (+1.5% in 2015-2019) of electric intensity. An annual mean increase of seasonal peaks of electricity demand of +2.4% was considered. On this basis, a planned mean available power of 89 $GW_{(e)}$ was estimated at the end of the period, see Fig. 2.
The investigated developing scenario was defined extending the hypotheses assumed in 2015-2019 projections up to 2030 where the estimated power is nearly 128 $GW_{(e)}$. For the reference scenario it was assumed that the power projection at 2011, that is 70 $GW_{(e)}$, is sufficient to meet the electricity needs at 2030, see Fig. 2.

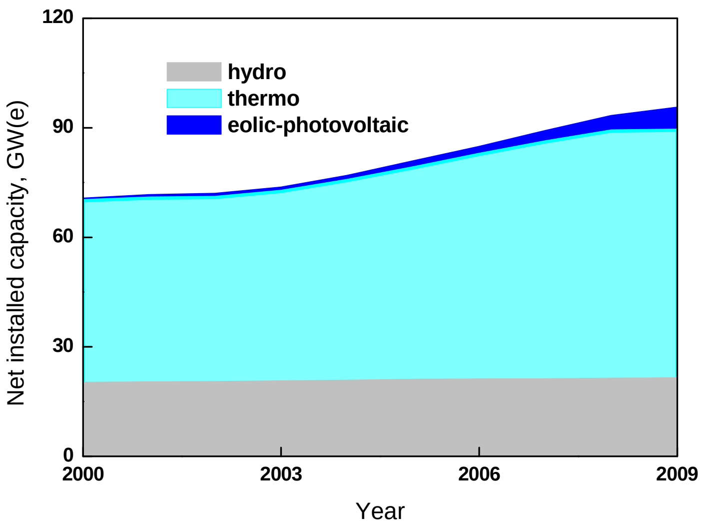


Figure 1: Net electricity generating capacity (Italy 2000-2009) [9]

The objective of 25% electricity generating capacity at 2030 gives, provided that plant loading factor is 0.9, an installed capacity of 35 $GW_{(e)}$ and 19.5 $GW_{(e)}$ for developing and reference scenario respectively. No new nuclear energy capacity is installed beyond 2030. The investigated scenarios are described in Table 1.

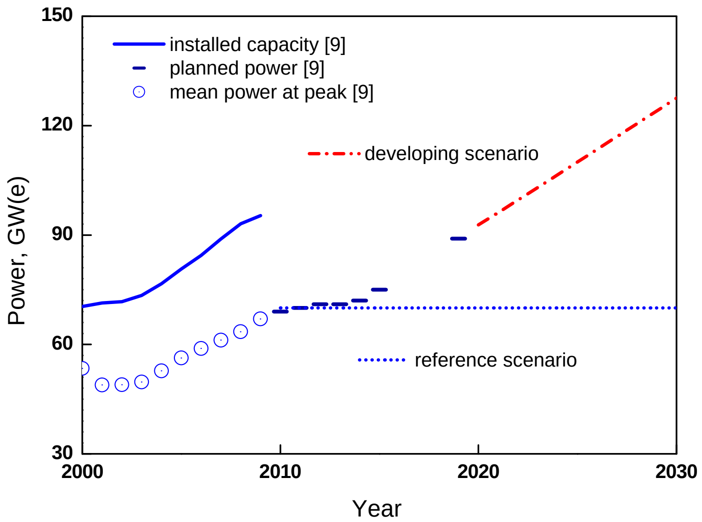


Figure 2: Reference and developing scenario for electricity generating power

Resuming hypotheses in calculations:

- scenarios cover the period 2000 – 2150;
- SNF are at first delivered to the interim storage nearby power plants, thereafter either to the final repository or reprocessed in case of plutonium recycling;
- in case of reprocessing, minor actinides produced under irradiation are directly disposed, together with fission products, to the final repository;
- according to [10], the total conventional uranium resources, identified and undiscovered, amounts to 15.969 million tonnes;[2]
- 2600 t/yr is the European reprocessing capacity [11];
- tails assays in natural uranium enrichment process are 0.18%;
- load factor 0.9.

Table 1: Investigated Italian scenarios, $GW_{(e)}$

| **Scenario** | **2015** | **2030*** | **2065** | **2080** |
|---|---|---|---|---|
| **Reference** | 0 | 19.5 | 19.5 | 0 |
| **Developing** | 0 | 35 | 35 | 0 |

* linear increase from 2015

[2] the total identified uranium resources (reasonable assured and inferred) amount to about 4.456 million tonnes in the < USD 80/kgU category and 5.469 million tonnes in the < USD 130/kgU category. The total undiscovered uranium resources amounts to 10.5 million tonnes.

## 3 SOFTWARE TOOL: DESAE

Calculations were performed by means of DESAE a software tool developed at the Kurchatov Institute to support the activities of INPRO, a project leaded by IAEA [6-8]. The code allows to predict financial and materials resources needed for a sustainable nuclear energy policy at country, regional and global level.

The analysis is performed on user-defined deployment scenarios where reactors, fuel cycle facilities and energy demand projections are properly defined. It allows to study both open and closed fuel cycles (U-Pu, U-Th, Pu-Th and other combinations) including recycling of U and Th. The code, not performing burnup or core management calculations, is fed with the inventories of fresh, equilibrium and spent core compositions, provided for a set of reactors available in the code library. The composition of fuel accounts for 18 isotopes, i.e. $^{230}Th$, $^{232}Th$, $^{232}U$, $^{233}U$, $^{234}U$, $^{235}U$, $^{236}U$, $^{238}U$, $^{238}Pu$, $^{239}Pu$, $^{240}Pu$, $^{241}Pu$, $^{242}Pu$, $^{237}Np$, $^{2421}Am$, $^{244}Cm$, $^{129}I$, $^{99}Tc$, with one additional variable accounting for the remaining fission products. The settling of fuel cooling time at interim storage is available separately for core and blankets.

The code performs calculations of materials consumption, for example iron, copper, zirconium, allowing the possibility to extend this analysis to user-defined materials not comprised in the standard database. Each scenario takes into account up to seven different nuclear energy systems (NESs) and four recycling plants for closed cycle option. With this regards reprocessing losses are not taken into account.

## 4 NUCLEAR ENERGY SYSTEMS

Thanks to their proven reliability and safety, light water reactors play a major role in the so-called nuclear renaissance; considering the 20-year stop due to the decision of phasing-out, this choice should be even more consistent with Italy's case. Open fuel cycle calculations were performed considering NESs based on thermal technology fuelled with $UO_2$ enriched in fissile isotope (4 wt% and 4.9 wt%). Besides reference light water (RLWR) and advanced light water reactor (ALWR), calculations were performed with a modified version of RLWR, named low burnup LWR (LBLWR). For plutonium recycling analysis, a LWR loaded with MOX fuel was selected (8.5 wt% fissile plutonium) named MLWR.

NESs models used in scenarios calculations and available in standard 2.2 DESAE, are characterized by fuel burnup and parameters dealing with natural uranium consumption and excess of fissile plutonium as reported Table 2.

## 5 RESULTS

In this section the results of DESAE are discussed pointing out in § 5.1, a once-through fuel cycle and the deployment of an homogeneous LWRs fleet, and in § 5.2, the introduction of plutonium recycling via MLWRs.

### 5.1 Open fuel cycle

Dealing with selected NESs, natural uranium consumption and SNF amount are presented in Table 3 for reference and developing scenario. These results confirmed that increasing burnup has a beneficial effect on uranium consumption and SNF, on this basis, ALWR turned out to be the most effective. Increasing burnup by about 22

GWd/t, moving from LBLWR to ALWR, leaded to a reduction of natural uranium resource consumption that was estimated to be around 22% for both scenarios. Nevertheless, even for a LBLWR fleet, the consumption expressed as percentage of uranium total identified resources, see Table 3, was fairly in good agreement with the share of Italy's capacity at global level that would be, with a projection of 600 $GW_{(e)}$ at 2030, 5.83% in the developing scenario [12]. While fission products inventory was mainly dependent on the energy demand scenario with minor impact of NES selection, excess of fissile plutonium and MAs were clearly affected by the discharge burnup of deployed reactors, see Table 4. Again ALWRs proved to be well performing with values in the developing scenario similar to those obtained by LBLWR in the reference scenario. This statement is consistent with a once-trough fuel cycle strategy, on the contrary, if fuel cycle closure and fast reactors deployment are foreseen, LBLWRs would be more attractive thanks to their higher excess of fissile plutonium.

Table 2: Basic reactors parameters

| NES | LBLWR | RLWR | ALWR | MLWR |
|---|---|---|---|---|
| Reactor Capacity, $GW_{(e)}$ | 1 | 1 | 1.52 | 1 |
| Heavy nuclei loading, t | 78.7 | 78.7 | 133 | 70 |
| $^{235}U$ enrichment, wt% | 4 | 4 | 4.9 | 0.15 |
| Fissile plutonium, wt% | - | - | - | 8.5 |
| Burn-up, GWd/t | 38.5 | 45.0 | 60.0 | 41.1 |
| Natural uranium consumption, t/ $GW_{(e)}$·yr | 197.3 | 170.6 | 153.8 | - |
| Excess fissile plutonium, kg/ $GW_{(e)}$·yr [3] | 184.9 | 159.0 | 112.6 | -1964.1 |
| SNF cooling time, yr | 5 | 5 | 5 | 4 |
| Plant lifetime, yr | 50 | 50 | 50 | 50 |

Table 3: Once-through – cumulative results at 2150

| NES | $U_{nat}$ consumption, t | | $U_{nat}$ consumption, %* | | SNF, t | |
|---|---|---|---|---|---|---|
| | reference | developing | reference | developing | reference | developing |
| LBLWR | $1.92 \cdot 10+^{05}$ | $3.45 \cdot 10^{+05}$ | 3.51 | 6.31 | $2.57 \cdot 10^{+04}$ | $4.62 \cdot 10^{+04}$ |
| RLWR | $1.66 \cdot 10^{+05}$ | $2.98 \cdot 10^{+05}$ | 3.04 | 5.45 | $2.21e^{+04}$ | $3.96 \cdot 10^{+04}$ |
| ALWR | $1.50 \cdot 10^{+05}$ | $2.69 \cdot 10^{+05}$ | 2.74 | 4.92 | $1.59 \cdot 10^{+04}$ | $2.85 \cdot 10^{+04}$ |

*with respect to uranium total identified resources USD< 130/kgU category

[3] difference between production and consumption of fissile plutonium per year of operation and power expressed in $GW_{(e)}$.

Table 4: Once-through – cumulative results at 2150

| NES | Fission products, t | | Fissile Pu excess, t | | Americium & curium, t | |
|---|---|---|---|---|---|---|
| | reference | developing | reference | developing | reference | developing |
| LBLWR | $1.03\cdot10^{+03}$ | $1.85\cdot10^{+03}$ | $1.63\cdot10^{+02}$ | $2.92\cdot10^{+02}$ | $4.12\cdot10^{+01}$ | $7.40\cdot10^{+01}$ |
| RLWR | $1.04\cdot10^{+03}$ | $1.87\cdot10^{+03}$ | $1.40\cdot10^{+02}$ | $2.51\cdot10^{+02}$ | $3.54\cdot10^{+01}$ | $6.36\cdot10^{+01}$ |
| ALWR | $1.01\cdot10^{+03}$ | $1.82\cdot10^{+03}$ | $0.97\cdot10^{+02}$ | $1.75\cdot10^{+02}$ | $2.74\cdot10^{+01}$ | $4.91\cdot10^{+01}$ |

The decay heat of spent nuclear fuel is nearly unaffected by selected LWR technology mostly depending on fission products inventories, see Figure 3.

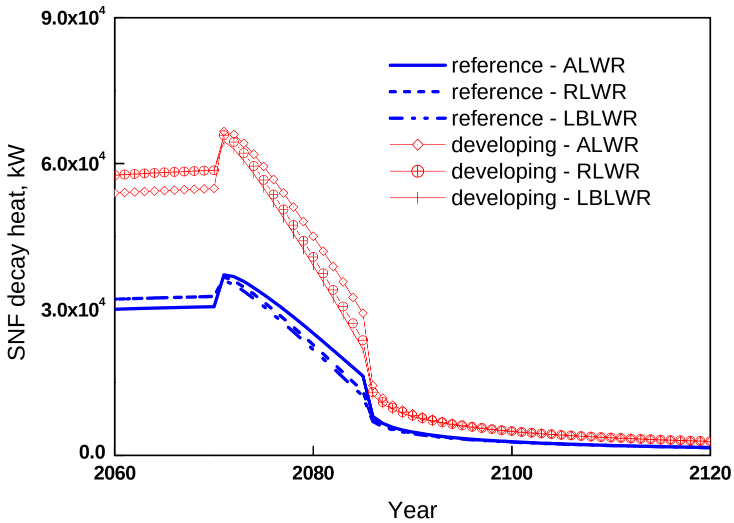


Figure 3: SNF decay heat in the reference and developing scenario (once-through)

The SNF decay heat diminishes in two decades by about one order of magnitude at an average value, at 2100, of about 2750 and 4950 kW for reference and developing scenario, thereafter the decrease is smooth, see Fig. 3.

## 5.2 Plutonium recycling

A modified developing scenario was analysed, with a thermal fleet composed of ALWR and MLWR, assuming, for the former, 33.2 $GW_{(e)}$ installed capacity at 2030 (linear increase from 2015), for the latter, 2 $GW_{(e)}$ installed capacity deployed in 2045-2095. Together with a reduction in natural uranium consumption, consistent with the share of MLWR, a significant decrease of americium and curium inventory, by about 61%, and fissile plutonium stockpiles, by about 97%, were achieved, see Table 5 and

Fig. 4. These results emphasize the beneficial effect of plutonium recycling in the long term perspective. In the middle term the limited uranium consumption reduction coupled with a decay heat comparable with once-through calculations (not shown) confirm the need of a detailed comparison between discussed fuel cycle strategies from a technical and, especially, from an economical point of view.

Table 5: Plutonium recycling – cumulative results at 2150

| $U_{nat}$ consumption, t | | Fissile Pu excess, t | | Americium & curium, t | |
|---|---|---|---|---|---|
| once-through | recycling* | once-through | recycling* | once-through | recycling* |
| $2.71 \cdot 10^{+05}$ | $2.55 \cdot 10+^{05}$ | $1.76 \cdot 10^{+02}$ | $4.72 \cdot 10^{+00}$ | $4.94 \cdot 10^{+01}$ | $1.91 \cdot 10^{+01}$ |

*multi-recycling

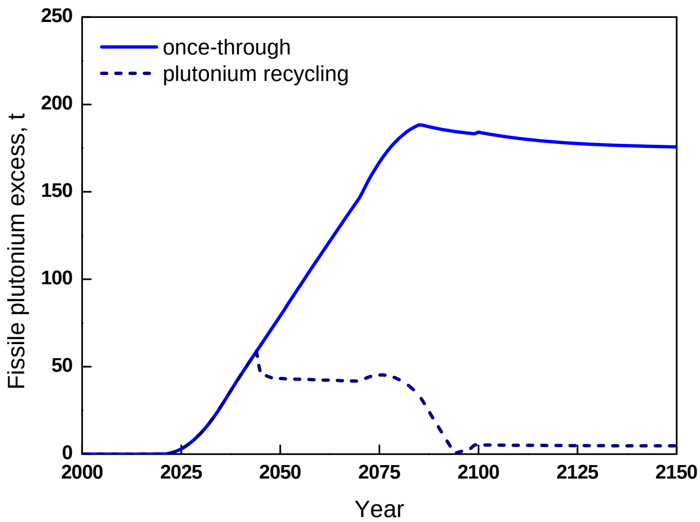


Figure 4: Fissile plutonium inventories in a modified developing scenario

## 6 CONCLUSIONS

In this document, some technical topics related to the objective of achieving 25% nuclear share in electricity generating capacity by 2030, as announced by the Italian Government, were discussed.
Relying on the official projections of electricity demand, it was depicted an ambitious scenario, named developing scenario, and a more realistic scenario, so-called reference scenario, considering, at 2030, an installed capacity of 35 $GW_{(e)}$ and 19.5 $GW_{(e)}$ respectively.
Thanks to their reliability and safety, it was assumed that LWRs are the most promising NESs to lead the foreseen Italian nuclear renaissance. In presented calculations, ALWRs turned out be well-performing in an open fuel cycle for their effective usage of fissile resources and minimisation of SNF. Their low fissile

plutonium balance should be addressed in case the deployment of fast reactors and fuel cycle closure is planned in the long term. The results concerning the option of plutonium recycling showed advantages especially regarding long term issues as the management of plutonium and MAs, in the medium term a broader assessment of investigated back-end strategies is envisaged.
As final remark, various parameters (restrictions on GHG emissions, changes in energy policy. GDP) are unavoidable sources of uncertainties in presented results, for this reason conclusions were drawn limiting to general principles.

**ACRONYMS**

| | |
|---|---|
| ALWR | advanced light water reactor |
| DESAE | Dynamic Energy System – Atomic Energy |
| EU | European Union |
| GDP | gross domestic product |
| GHG | greenhouse gases |
| IAEA | International Atomic Energy Agency |
| INPRO | International Project on Innovative Nuclear Reactors and Fuel Cycles |
| LBLWR | low burnup light water reactor |
| LWR | light water reactor |
| MA | minor actinide |
| MLWR | MOX light water reactor |
| MOX | mixed oxide fuel |
| NEA | Nuclear Energy Agency of OECD |
| NES | nuclear energy system |
| RLWR | reference light water reactor |
| SNF | spent nuclear fuel |
| TPES | total primary energy supply |

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