PRELIMINARY STUDY ON THE COST COMPETITIVENESS OF AN SMR USING LFR TECHNOLOGY IN ROMANIAN ENERGY SYSTEM

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Abstract

Energy has become a strategic factor in the global policy, a vital component and a cost factor for economic development and society's general progress. In the conditions of energy primary sources reduction, the energy sustainability can be reached by increasing the efficiency of its production, provision and consumption. Romania's energy system consists of a balanced and diverse portfolio of energy generating capacities, which includes: classic fossil fuel-fired power plants, one nuclear power plant (with two CANDU6 reactors in operation) and renewable capacities (hydro, wind and solar photovoltaic). Nuclear energy is a strategic option for Romania, due to its ability to assure the national energy independence and to have a significant contribution in meeting the EU decarbonation targets. The paper represents a preliminary study on the cost competitiveness of an SMR using LFR nuclear technology comparatively with competing classic technologies using fossil fuels (coal and gas) for electricity generation in Romania. The economic analysis was based on Levelized Unit Electricity Cost (LUEC), calculated using the IAEA NEST (NESA economic support tool) program. Preliminary results confirmed that in Romania's energy system, under the specific conditions defined, electricity produced by an SMR using LFR technology is cost competitive against the one generated by coal and gas fired power plants.

Keywords: *Sustainable development, Nuclear energy, SMR, LFR technology, LUEC*

Introduction

The daily life cannot be conceived without considering the energy input. Energy is a vital factor for the society development, representing also a strategic component of the policy at national, regional and global level.

To sustain the role of energy as a strategic factor in the society's overall progress, it should be assured the safety and security of energy supply, at affordable prices, and reducing the negative impact on the environment.

Sustainable development of the society is a relatively new concept, which entered in the international community attention on the background of the environment protection debates and is actually implemented based on a dynamic international framework (treaties, conventions, guiding lines, political measures, and financing mechanism).

Increasing of the security of energy supply, at affordable prices, and dealing with the climate change are two of the major concerns and challenges of the today's society. These major challenges have been considered in the European Union (EU) energy policy, envisaging a way to assure the energy security based on competitive and ″clean″ energy, taking into account the mitigation of climate change effects, escalation of global energy demand, and the uncertain future of the access to energy sources. Nuclear energy can be a solution to redevelop the energetic sector towards a sustainable path due the fact that is available, competitive and has a low impact on the environmental.

Romania's energy system consists of a balanced and diverse portfolio of energy generating capacities, which includes: classic fossil fuel-fired power plants, one nuclear power plant (with two CANDU6 reactors in operation) and renewable capacities (hydro, wind and solar photovoltaic). Nuclear energy share represents about 20% from the national energy production, becoming a strategic option for Romania based on its ability to assure the national energy independence and to significantly contribute in meeting the EU decarbonation targets.

Global interest in Small Modular Reactors (SMR) continuously increased due to their capability to meet the need for flexible power generation for a wide range of applications. Advanced SMRs offer many advantages such as small size, reduced capital investment, ability to be sited in locations not possible for larger nuclear plants, and provisions for incremental power additions. SMRs also offer distinct safeguards, security and non-proliferation advantages.

RATEN ICN Pitesti enrolled since early stages in European Consortium working to develop European Lead Fast Reactor, GenIV project. RATEN ICN platform is considered as the reference site for construction of ALFRED, the 300 MWth scaled demonstrator of LFR technology, developed to show the viability of this technology to be used in commercial nuclear power plants.

Taking into account above mentioned national interest in nuclear energy development, present study proposed to perform a preliminary economic analysis on the costs associated to an SMR using LFR nuclear technology comparatively with those of the classic technologies for electricity generation using fossil fuels (coal and gas).

Sustainable development and policies in the energy field

The *sustainable development* term was mentioned for the first time at the United Nations (UN) Conference on Human Rights held in Stockholm, Sweden, in 1972. Without an explicit definition for this term, the participants (representing 113 nations) agreed that the society's development and the environment protection should be treated in a common, unique, and mutually beneficial approach [1]. In the following years, a series of activities were developed based on the conference recommendations and the United Nations Environment Programme (UNEP), and in 1983 the UN World Commission on Environment and Development (WCED) was established.

The *sustainable development* concept was explicitly defined in the report "Our Common Future", prepared by WCED in 1987 [2]: *"Sustainable development means to meet the needs of the current generation without compromising the ability of future generations to meet their own needs"*.

To achieve a sustainable development, it is essential to harmonize three fundamental elements, namely: economic growth, social development of the humanity and environmental protection.

At the end of 2015, Romania has joined other 193 UN member states at the Summit for Sustainable Development, held in New York, USA. The participants adopted the *Agenda 2030 for Sustainable Development*, a global action to achieve the sustainable development, which includes 17 Global Goals (see Figure 1 below) to end poverty, protect the planet and ensure prosperity for all [3].



Fig. 1. The sustainable development global goals, [3]

At the EU level, sustainable development has become an objective since 1997 when it was included in the Treaty from Maastricht.

In 2001, the European Council held in Goteborg adopted the Sustainable Development Strategy and proposed the set of indicators for sustainable development. This strategy has been revised in 2006 when 7 priority axes were introduced, as follows [4]:

- climate change and clean energy;
- sustainable transport;
- conservation and management of natural resources;
- sustainable consumption and production;
- public health;
- social inclusion, demography and migration;
- global poverty and sustainable development challenges.

Sustainable development goals cannot be accomplished without a radical change in people's mentality leading to human communities able to assure a rational and efficient using of the natural resources, in conditions of economic prosperity, environment protection and social cohesion. The EU policies and activities are governed by the sustainable development, envisaging the quality of life continuous improvement for present and future generations based on an integrate approach of the economic development, environment protection and social justice.

In 2008, European Commission adopted the package "Energy-Climate Change" establishing the objectives and guiding lines for EU development until 2020 [5], with 3 fundamental objectives, namely:
- durability (expressing EU concerns for climate change by reduction of the greenhouse gases emissions at a level assuring the global warming effect limitation to only 2°C comparatively with temperatures in preindustrial period);
- competitiveness (assuring the effective implementation of the national energy market);
- security of energy supply (reduction of EU vulnerability to energy imports, interruptions in energy supply, energy crises and uncertainty in energy supply).

To accomplish these objectives, European Commission launched the Strategic Energy Technology (SET) Plan which identified a set of low carbon energy technologies to be developed in Europe. The plan sustains the Sustainable Nuclear Energy Technology Platform (SNETP) which promotes the research, development and demonstration of the technologies based on nuclear fission, and is structured around three main pillars, namely the projects NUGENIA, ESNII and NC2I (see Figure 2), [6].

NUGENIA aims to develop the R&D efforts to sustain the safety, reliability and competitiveness of the Gen II and III nuclear energy systems. ESNII (European Sustainable Nuclear Industrial Initiative) promotes the advanced fast reactors targeting the reduction of natural resources consumption and the minimization of radioactive waste generated by the NPPs operation. The main objective of NC2I (Nuclear Cogeneration Industrial Initiative) is to demonstrate innovative and competitive nuclear solutions for the cogeneration with low CO_2 emissions, process heat, electricity and production of H_2, [6].

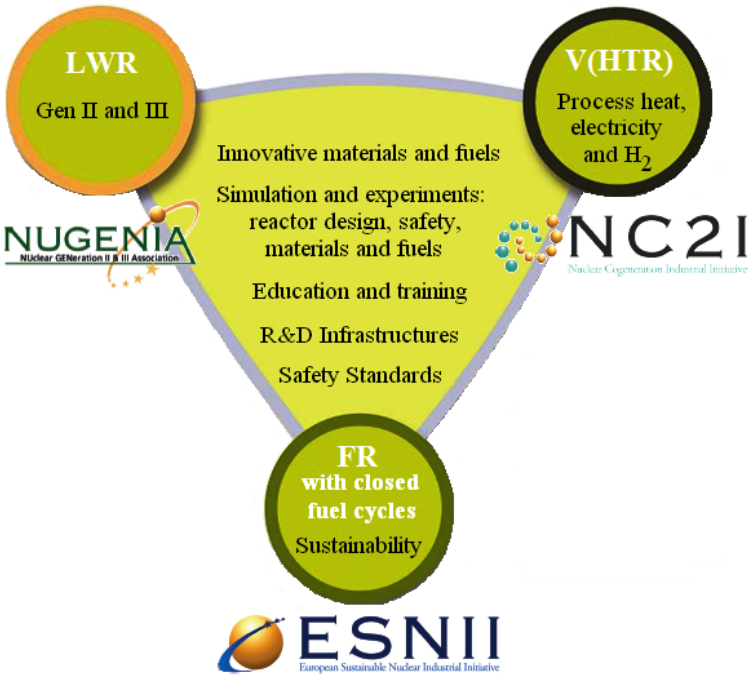


Fig. 2. SNETP activities and projects' themes, [6]

In 2015, the EU Energy Strategy was established, based on five priorities, as follows: ensuring of the energy supply, deployment of the internal energy market, increasing of the energy efficiency, reduction of the GHG emissions, research and innovation [7].

EU has taken a leading role in minimization of climate changes, both by sustaining global agreements and adopting policies concerning the climate changes. Is worthy to be mentioned here the Paris Agreement, ratified by more than 190 countries, after the global conference held in Paris, in December 2015. The global objective of this landmark agreement on long-term is ″to keep a global temperature rise well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius″, [8].

Nuclear energy can be a solution to the EU energy policy based on its availability, competitiveness and the low impact on the environment

Nuclear energy in the Romanian energy system

Based on economic, social and national security reasons, the Romanian state owns the majority package in the companies with natural monopoly on the transport of natural gas and electric energy, and also in the companies involved in the nuclear fuel cycle.

Eurostat data for 2016 show that in Romania the final price of electricity was well below the European average price. Thus, in 2015 Romania had the 6th lowest average price for home consumers (132 €/MWh), and the 3rd lowest average price for industrial consumers (80 €/MWh) comparatively with the other EU countries, [9].

Romania's energy system consists of a balanced and diverse portfolio of energy generating capacities, which includes: classic fossil fuel-fired power plants, one nuclear power plant (with two CANDU6 reactors in operation) and renewable capacities (hydro, wind and solar photovoltaic).

The short-term Energy Strategy of Romania for the period 2007-2020, promoted as main objective ″…to satisfy the energy needs on short, intermediate and long term, with costs as low as possible, adequate to a modern market economy and a civilized life standard, in conditions of quality, security of supply and with respect of the sustainable development principles″. Security of energy supply, Sustainable development and Competitiveness were defined as strategic objectives.

After several attempts to update this strategy [10, 11], the Department of Energy from Ministry of Economy elaborated in 2014-2016 the new national strategy in the energy field, which illustrates the present status of the national energy system, the objectives for 2016-2030 with prospects for 2050, and the national legislation harmonized with the EU energy policy [12]. Five fundamental strategic objectives were defined, as follows: increasing of the security supply, competitive energy markets, clean energy with reduced GHG emissions, upgrading of the energy governance system, reducing the poverty and protection of the vulnerable consumers.

To achieve these objectives, Romania needs to preserve its diverse and balanced energy mix, using efficiently the domestic energy resources and integrating modern technologies that allow using of fossil fuels on long term with reduced GHG emissions, renewable energy sources and nuclear energy.

Romanian Nuclear programme was launched in 1950, and shortly after, in 1957, a VVR-S research reactor was commissioned on Magurele platform, nearby Bucharest. In 1979, the second research reactor, a TRIGA dual core reactor, was commissioned at Mioveni, nearby Pitesti. Romania operates one nuclear power plant with two CANDU 6 reactors, other two CANDU reactors being in construction, at Cernavoda.

Figure 3 illustrates the open nuclear fuel cycle adopted by Romania, including domestic infrastructure and capacities both in the front-end and back-end. Natural uranium enrichment and spent fuel reprocessing are not allowed, according to the national laws; spent fuel is considered waste, its storage and disposal being envisaged.

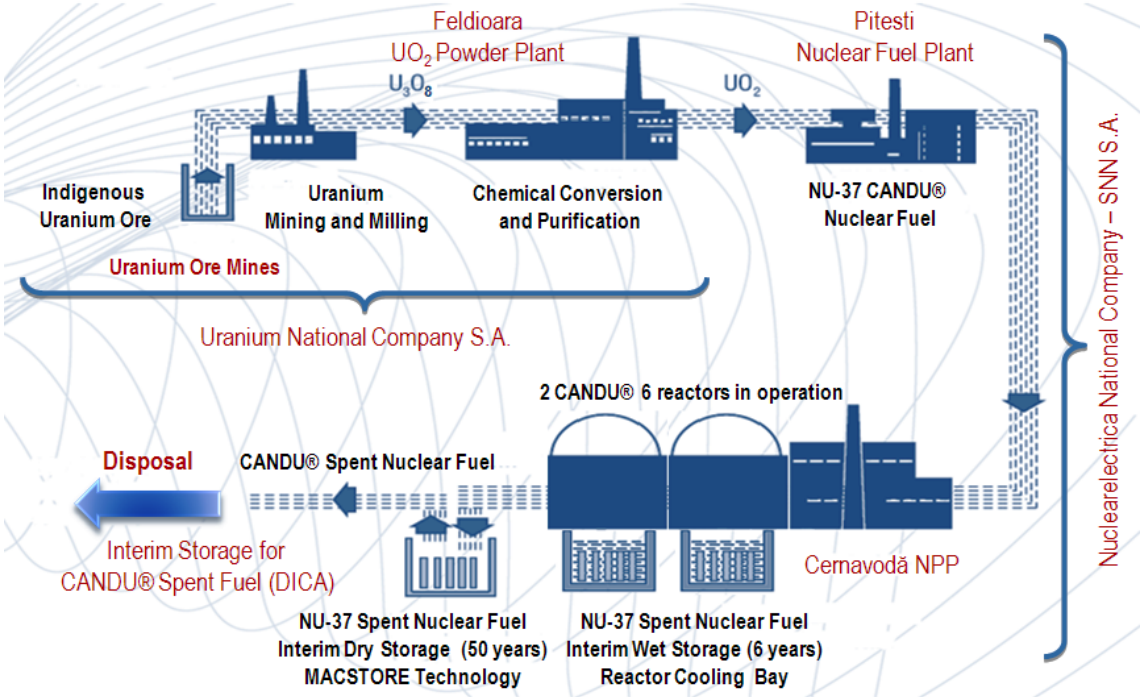


Fig. 3. Romania's Once-Through Nuclear Fuel Cycle

The motivation for nuclear power development in Romania is sustained by:
- enhancing security of supply to satisfy national energy demand
- assuring of a well-balanced and diverse national energy mix
- maintaining an energy affordable price for final consumers
- reducing GHG emissions
- successful operation of Cernavoda NPP (high capacity factors, reduced number of incidents, stability in energy production, etc.)
- existing capabilities (infrastructure, industry, human resources, experienced specialists)
- positive public acceptance towards nuclear
- increasing participation in international R&D projects, including innovative technologies development (European LFR).

Moreover, the electricity production and thermal heating sectors are facing major challenges caused by the technical aging of the existing capacities, which are operating already over their lifetime. In Romania about 55% (11 GWe) from the total installed capacity need to be replaced until 2035, from which about 28% (5.5 MWe) should be replaced till 2020.

Commissioning of Small Modular Reactors (SMR), with an installed capacity up to 30 MWe, could be a possible solution to cope with this major issue in sustainable development of the country, based on their ability to assure a flexible generation of energy for a large set of applications (electricity, process heat, cogeneration electricity /heat, production of hydrogen, desalinization, etc). Other benefits offered by SMRs can be also mentioned, as follows: small dimensions for modules, easy transportation, reduced capital investment costs, locations where large NPPs cannot be built, benefits regarding safety, security and proliferation resistance aspects.

RATEN ICN Pitesti enrolled since early stages in European Consortium working to develop European Lead Fast Reactor (LFR), GenIV project. The research and development of advanced reactors for a further future (operating after 2030) was launched in 2000, by the Department of Energy, USA, in the framework of Generation IV Forum (GIF), together with other countries conducting developed nuclear power programs. European efforts are represented in GIF by Euratom. Six Gen IV systems were identified, and three of them were taken into consideration at European level, in terms of vision and development strategies, namely: Sodium Fast Reactor as the reference technology, and LFR and Gas Fast Reactor as alternative solutions.

There are two main directions for LFR development in Europe: MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) and ALFRED (Advanced Lead Fast Reactor European Demonstrator); both installations represent keystones to demonstrate the economical and technical viability of lead cooled fast reactor technology.

Romanian Government approved in February 2011 a Memorandum which sustains the interest for hosting the ALFRED demonstrator. RATEN ICN Pitesti is responsible for the development of ALFRED project based on its efforts in development of European Lead Fast Reactor and collaboration in FALCON Consortium (Fostering ALfred CONstruction) [13]. ALFRED, a 300 MWth scaled demonstrator of LFR technology, is developed to show the viability of this technology to be used in commercial nuclear power plants; sitting process considers RATEN ICN platform as the reference site. The demonstrator was mentioned in National Strategy for Research-Development-Innovation and in Romanian Energy Strategy (2016), and also in the Government programmes for 2017-2020. In March 2018, a Memorandum CESINA – Nuclearelectrica (SNN) was signed, having the major objective to assure the technical support for ALFRED licensing, construction and operation. FALCON Consortium promotes a new perspective on ALFRED demonstrator (see Figure 4), with possible implementation in short term (2035-2040) as SMFR (Lead-cooled Small Modular Fast Reactor), [14, 15]

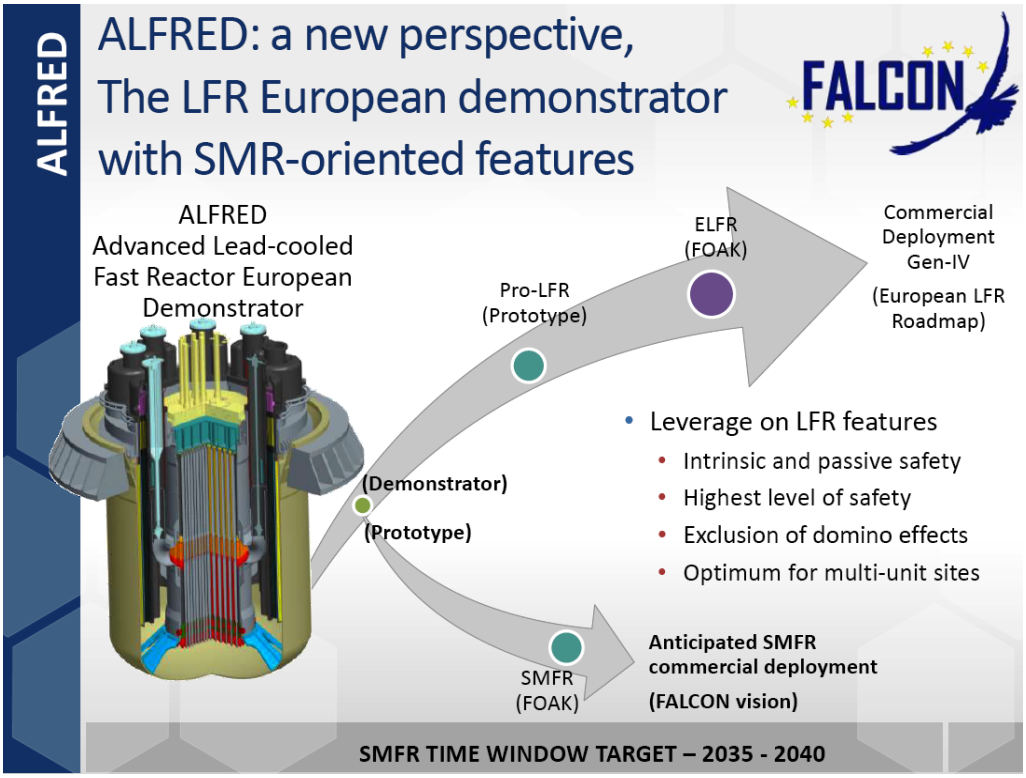


Fig. 4. SMFR, a new perspective of ALFRED LFR Demonstrator, [14, 15]

Assessment of the nuclear energy cost competitiveness

Main goal of the present study was to carry out a preliminary assessment on cost competitiveness of an SMR using LFR nuclear technology comparatively with competing classic technologies using fossil fuels (coal and gas) for electricity generation in Romania.

The economic analysis has been performed for four types of power plants competing in Romania's national energy system for electricity generation, representing: nuclear technology (*SMR_LFR, PWR_adv*) and classic technology on fossil fuels, but using advanced technologies for CO_2 capture (*Coal_PP* and *Gas_PP*).

The economic parameter of interest for the study was the Levelised Unit of Energy Cost – LUEC.

The electricity generation calculated costs are plant-level costs, at the station, and do not include transmission and distribution costs. Regarding the initial capital investment, the uniform investment schedule has been used for all considered technologies.

In order to perform the economic assessment on LUEC for considered technologies, a reference case was considered using an annual discount rate of 8%, this value being appropriate for the Romanian financial and economic environment.

Many economic studies carried out by the international organizations recommends using of the levelised discounted costs, also called Levelised Unit of Energy Costs (LUEC), as input for comparing electricity production costs of different plants. LUEC is equivalent to the average price that would have to be paid by consumers for electricity delivered at the plant ″gate″ to repay exactly all costs incurred by the owner/operator of a plant, at the selected discount rate, in a defined time frame (lifetime of the plant) and without profits.

LUEC (measured in mill$/kWh or 10^{-3} $/kWh) is composed by three levelized costs, [16]:

$$LUEC = LUAC + LUOM + LUFC$$

Levelized unit lifecycle amortization cost:

$$LUAC = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{CI_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}}$$

Levelised unit lifecycle operation & maintenance cost:

$$LUOM = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{O\&M_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}}$$

and Levelised unit lifecycle fuel cost:

$$LUFC = \frac{\sum_{t=t_{START}}^{t_{END}} \frac{F_t}{(1+r)^t}}{\sum_{t=t_{START}}^{t_{END}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} =$$

with: CI_t = Capital Investment expenses in year *t;* $O\&M_t$ = O&M expenses in year *t;* F_t = Fuel expenses in year *t;* P_t = Net electrical power of plant in year *t;* Lf_t = Load factor of plant in year *t;* 8760=24×(31×7+30×4+28) = number of hours in a year; t_{START} = beginning of project (start of construction period); t_{END} = end of the project (lifetime of plant); r = discount rate (takes the time value of money into account, i.e. money earned in the future has less value than received today. Discount rate value is linked to the interest that an investor has to pay for long term bonds).

The economic analysis has been performed by using the IAEA's NEST (NESA economic support tool) [16], tool recommended to be used by Member States to evaluate economic parameters as: levelised unit of electricity cost, internal rate of return, return on investment, net present value, total investment costs, limit of investment, etc. NEST estimates before mentioned parameters both for nuclear power plants and classic fossil-fuelled plants, and also for renewables.

Input data needed for NEST calculations include 4 sets of parameters [16], namely: i) specific economic parameters for any kind of power plants; ii) specific technical parameters for any kind of power plants; iii) additional NPP specific technical parameters; country specific economic parameters (according to a national economic and financial environment).

All the input data used to carry out the present study were public available data, from internet (organizations' web pages), public reports, international databases, as well as from international projects in which the RATEN ICN Pitesti specialists were involved. The following tables contain the sets of input data used for the present study.

Table 1 Power plants specific technical input parameters [17, 18]

Parameter	**Units**	**PWR_adv**	**SMR_LFR**	**Coal_PP**	**Gas_PP**
Net electric power	MWe	1000	250	600	400
Construction time	years	5	4	4	3
Life time	years	60	60	40	35
Load factor	%/100	0.9	0.85	0.85	0.85
Net thermal efficiency	%/100	0.33	0.42	0.40	0.52

Table 2 NPPs additional specific technical input parameters [17, 18]

Parameters	Units	PWR_adv	SMR_LFR
Nuclear fuel backend cost	$/kg	400	100
Spent nuclear fuel average burnup	MWd/kg	40	50
Reactor average power density	kW/kg	28.89	45.66
Natural U purchase cost	$/kgUnat	100	0
U conversion cost	$/kgHM	10	0
U enrichment cost	$/SWU	130	0
Nuclear fuel fabrication cost	$/kgHM	300	800

Table 3 Power plants specific economic input parameters [17, 18]

Parameters	Units	PWR_adv	SMR_LFR	Coal_PP	Gas_PP
Total Overnight costs	$/kWe	3400	3857	1200	700
O&M fixed costs	$/kWe	50	13	21	17
O&M variable costs	mills/kWh	0.92	0.7	1.3	1.44
Fuel price	$/GJ	-	-	5	9.76
Real fuel price annual escalation rate	%/100	-	-	0.02	0.02

Table 4 Country specific economic input parameters [17, 18]

Parameter	Units	NPPs	Classic PPs
Discount rate	1/year	0.08	0.08
Price of unit electricity sold	10^{-3} $/kWh	112	112
Tax rate	%/100	0.37	0.37
Market income	M$/year	3800	3800
Market share	%/100	0.185	0.235
Profit margin	%/100	0.2	0.2
Time of growth	years	6	3
Adjusting coefficient	%/100	1	1

The study used an annual discount rate of 8%, value considered appropriate for the Romania's economic and financial environment. Table 5 presents estimated LUEC values for considered energy technologies. It also contains the *Overnight Costs* (include pre-construction/owner's, construction and contingency costs), *Investment Costs* (include Overnight Costs and Interest During Construction) and *Total investment* (given as Investment costs x Net Capacity of the power plant).

Table 5 LUEC values for the studied nuclear and classic technologies

Tehnology	Net Capacity [MWe]	Overnight Costs [$/kWe]	Investment Costs [$/kWe]	Total Investment [10^9 $]	LUEC [10^{-3} $/kWh]
PWR_adv	1000	3400	4308	4308	60.10
SMR_LFR	250	3857	4693	1173	56.06
Coal_PP	600	1520	1849	1109	84.67
Gas_PP	400	1099	1285	514	102.46

The cheapest supplier of electricity is SMR_LFR, with the lowest LUEC – 56.06 $x10^{-3}$ $/kWh. The highest estimated LUEC value corresponds to Gas_PP – 102.46$x10^{-3}$ $/kWh, the most expensive supplier.

Comparatively with the lowest LUEC value characterising SMR_LFR technology, LUEC obtained for PWR_adv was 6.72% higher. For considered classic technologies, LUEC values were 34% (Coal_PP) and 45% (Gas_PP) higher than LUEC values corresponding to SMR_LFR.

As regarding the contribution of each levelised cost component (LUAC, LUOM, and LUFC) to LUEC, significant differences can be noticed between the analysed technologies, as it can be seen in Figures 5 and 6.

For the nuclear technologies (PWR_adv şi SMR_LFR), the main contribution to LUEC is given by the amortisation costs (90% for SMR_LFR - as a new technology, and 73% for advanced PWR). Meantime, LUOM and LUFC contributions to LUEC are reduced for PWR_adv (13%) and rather small for SMR_LFR (4-5%).

The situation looks completely different from the classic technologies side, where the fuel costs represent the main contributor to LUEC (70% for Coal_PP, and 82% for Gas_PP); the amortisation costs have a reduced share to LUEC (25% for Coal_PP and 15% for Gas_PP), LUOM contributing to LUEC with only 5% for Coal_PP and 3.6% for Gas_PP, respectively.

Some sensitivity calculations have been also performed considering the effect on LUEC due to the discount rate variation, drate being a very important data entry which reveals the “healthiness” level of the country’s economic, financial and commercial environment. New entry values were considered for the annual discount rate (5%, 10% and 12%) and LUEC variation is shown in Figure 7.

Annual discount rates of 3-5% characterize a regulated market and relatively low financial risks in recovering the investment. The higher the discount rates, the financial risks for investors, especially for long-term investment projects, are increasing. 10-15% discount rates correspond to deregulated market with high investment risks.

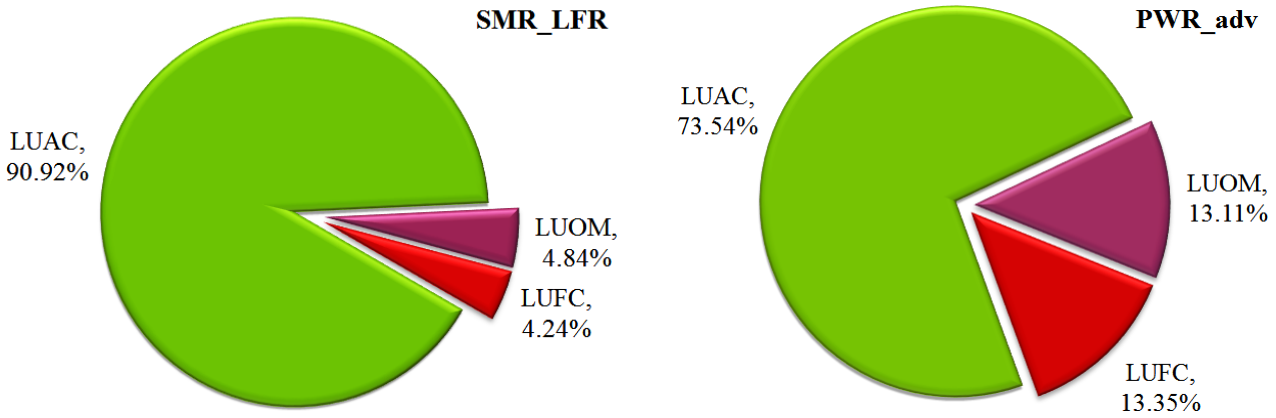


Figure 5 LUEC structure for the considered nuclear power plants

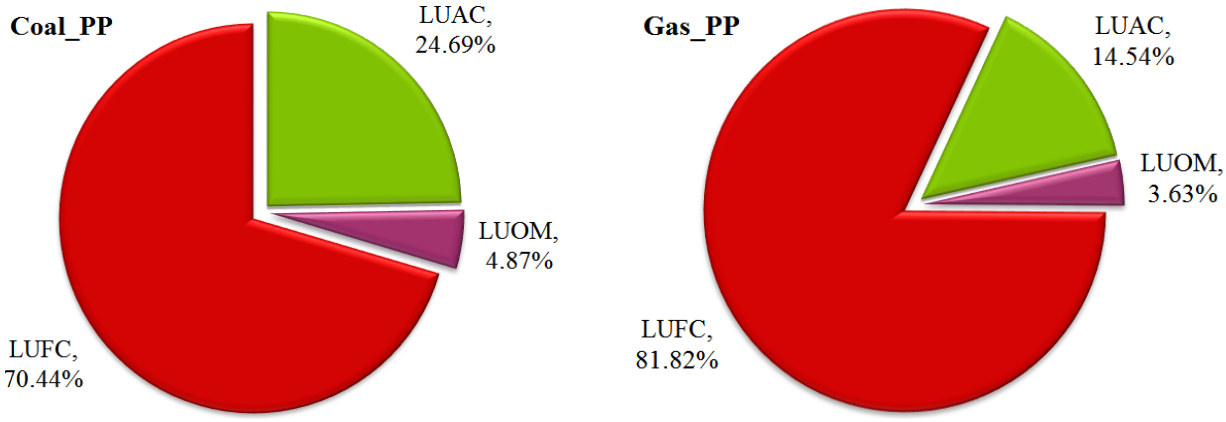


Figure 6 LUEC structure for the considered classic power plants

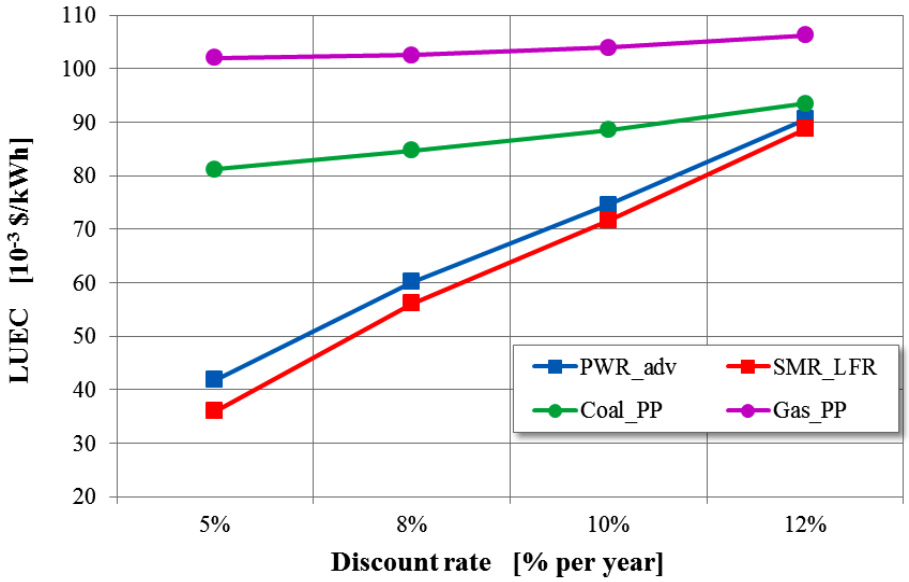


Figure 7 LUEC structure for the considered classic power plants

Figure 7 shows that increasing of the discount rate lead to greater LUEC values, the maximum variation of LUEC comparatively with the reference value being 37% (for SMR_LFR). It is also easily to notice a different behaviour for NPPs in comparison with the case of coal and gas-fired plants. Considering drate=8% as reference, LUEC for nuclear technologies decreased by about 30% for drate=5%, and increased by 20% and 35% for drate=10%, and drate=12%, respectively. The variation of LUEC for classic technologies was lower than 10% for Coal_PP and 4% for Gas_PP, respectively.

Another set of sensitivity calculations were performed to study the effect of some input data variation on LUEC values for SMR_LFR. Load factor and construction time, respectively, were in turn modified, the rest of input parameters being kept unchanged. Table 6 contains the comparison between LUEC values for the reference case and the two sensitivity cases considered.

Table 6 Effect of some input parameters variation on LUEC for SMR_LFR

SMR_LFR input parameters	**LUEC [10^{-3} $/kWh]**	**LUEC variation**
drate = 8% load factor = 85% construction time = 4 y	56.06	reference
drate = 8% *load factor = 92%* construction time = 4 y	51.73	7.07% (decreasing)
drate = 8% load factor = 85% *construction time = 5 y*	58.18	3.64% (increasing)

Considering a higher load factor (92% instead of 85%, that means an increasing of 8% relatively to the reference case), LUEC decreased by 7%. A longer construction period (5 years instead of 4 years, meaning about 20% longer time than in the reference case) led to LUEC increasing by 3.6%.

Conclusions

Nuclear energy is seen as a solution for global, regional and national sustainable development of energy power sector based on its' availability, competitiveness and low impact on the environment.

The paper proposed to study the nuclear technology economic competitiveness comparatively with classic technologies on fossil fuels (coal- and gas-fired power plants) included in the Romanian energy system.

Two types of technology have been considered: nuclear technology (PWR_adv and SMR_LFR) and classic technology on fossil fuels (Coal_PP and Gas_PP).

Levelised Unit Electricity Cost (LUEC) and its components (*Levelised unit lifecycle amortization cost* - LUAC, *Levelised unit lifecycle O&M cost* - LUOM and *Levelised unit lifecycle fuel cost* - LUFC) were calculated for considered technologies by using IAEA's NEST economic tool.

A reference case has been modeled taking into account the following assumptions: annual discount rate = 8% (corresponding to Romania's economic, financial and legal environment), electricity generation costs at plant-level (transmission and distribution costs not included), and uniform schedule for initial capital investment.

For the considered input data (public available data, from organizations' web pages, public reports, and international databases) nuclear technologies proven to be the best cost providers comparatively with the classic technologies on fossil fuels, the lowest LUEC being obtained for SMR_LFR. When SMR_LFR capacity is reduced under 250 MWe, PWR_adv becomes the best cost electricity provider.

For nuclear technologies, amortization costs represent the main contributor to LUEC (90% for SMR_LFR, as new technology, and 74% for PWR_adv). On the contrary, in the case of classic technologies, the main contribution to LUEC comes from the fuel costs (70-80%).

The paper also included sensitivity calculations in which some input parameters (annual discount rate, load factor, or construction time) were changed in turn, keeping the rest of input data without any modification, and LUEC new values were estimated.

Annual discount rate variation has the highest impact on LUEC, with about 37% variation from reference value for capital intensive technologies (nuclear technologies) comparatively with the classic ones (not more than 10%). In the case of SMR_LFR, considering an 8% higher load factor than for the reference case, LUEC decreased by 7%; one year delay in NPP's construction schedule (about 20% longer construction time than for the reference case) led to 3.6% higher LUEC value.

The economic analysis highlighted the nuclear energy cost competitiveness comparatively with other competing technologies for electric energy generation in Romania's national energy mix. Nuclear energy is a strategic option for electricity generation in Romania, being a stable component of the national energy mix.

References

[1] United Nations (1972) ″United Nations Conference on the Human Environment″, Stockholm, Sweden, avail. at https://sustainabledevelopment.un.org/milestones/humanenvironment .
[2] World Commission for Environment and Development (1987) ″Our Common Future″, report, available at http://www.un-documents.net/our-common-future.pdf
[3] United Nations (2015) ″Sustainable Development Goals – 17 Goals to Transform Our World″, available at https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[4] Council of the European Union (2006) ″Renewed EU Sustainable Development Strategy″, 10917/06, Brussels, Belgium, available at https://register.consilium.europa.eu/pdf/en/06/st10/st10917.en06.pdf
[5] European Commission (2008) ″2020 Climate & Energy″ Package, available at .https://ec.europa.eu/clima/policies/strategies/2020_en
[6] Sustainable Nuclear Energy Technology Platform (2013) ″Strategic Research and Innovation Agenda, SRIA 2013″, Brussels, Belgium, www.SNETP.eu
[7] European Commission (2015) ″A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy″, COM(2015) 80, available at https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy
[8] United Nations (2015) ″The Paris Agreement″, United Nations Climate Change Conference, Paris, France, available at https://unfccc.int/process-and_meetings/the-paris-agreement/the-paris-agreement
[9] European Commission (2017) ″EU energy in figures″, Statistical pocketbook, available at https://publications.europa.eu/en/publication-detail/-/publication/2e046bd0-b542-11e7-837e-01aa75ed71a1/language-en/format-PDF/source-search
[10] Romanian Government (2010) ″Elemente de strategie energetică pentru perioada 2011-2035 - Direcţii şi obiective strategice în sectorul energiei electrice″, Ministry of Industries, available at http://www.minind.ro/strategia_energetica_20112035_20042011.pdf (in Romanian)
[11] Romanian Government (2011) ″Strategia energetică a României pentru perioada 2007-2020 actualizată pentru perioada 2011-2020″, Ministry of Industries, available at http://www.minind.ro/energie/STRATEGIA_energetica_actualizata.pdf (in Romanian)
[12] Romanina Government (2016) ″Strategia energetică a României pentru perioada 2016-2030, cu perspectiva anului 2050″, Ministry of Economy, available at http://energie.gov.ro/wpcontent/uploads/2016/12/Strategia-Energetica-a-Romaniei-2016-2030_Final_19-decembrie-2.pdf, (in Romanian)
[13] Alemberti, A., Villabruna, G., Agostini, P., Turcu, I., Constantin, M. (2014) ″The FALCON Consortium: Continuing the Successful Italian Romanian International Collaboration″, Int. Conf. on Sustain. Devel. through Nucl. Research and Educ. NUCLEAR 2014, Pitesti, Romania
[14] Grasso, G. (2017) ″A safe and competitive Lead-cooled Small Modular Fast Reactor concept for a short-term deployment″, Int. Conf. of Fast Reactors and Assoc. Fuel Cycles (FR17), Yekaterinburg, Russian Federation
[15] Alemberti, A. (2018) ″The ALFRED Project: status, achievements and perspectives″, Int. Conf. on Sustain. Development through Nuclear Research and Education NUCLEAR 2018, Pitesti, Romania
[16] International Atomic Energy Agency (2014) ″INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics″, IAEA Nuclear Energy Series NG-T-4.4, Viena, Austria
[17] Margeanu, C.A. (2018) ″Romanian Experience in Nuclear Energy System Modelling with MESSAGE″, in *Experience in Modelling Nuclear Energy Systems with MESSAGE: Country Case Studies*, International Atomic Energy Agency, IAEA TECDOC series, no. 1837, Viena
[18] Alemberti, A. (2018) ″Ansaldo Nucleare Contribution to the I_NERI Project″, Progress Meeting of the Euratom-US International Nuclear Energy Research Initiative (I-NERI) Collab. Project ″Small Modular Lead Fast Reactors in Regional Energy Markets: Safety, Security, and Economic Assessments″, Amsterdam, The Netherlands