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Long Term Assessment of Nuclear Technology Penetration using MESSAGE – The Case of Romania

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Abstract

The paper is doing a long-term simulation of the nuclear technology penetration for the Romanian power system using the IAEA MESSAGE optimisation model. The horizon taken into consideration is 2050 and 2070. The production and the demand are considered with various scenarios and the emissions of CO_2 are also evaluated. Given that the program is using a simplex optimisation algorithm only the optimal scenarios are retained in the given restrictions and specific objective function. This provides a useful support for the decision maker in selecting only optimal scenarios.

The results are destined to assess the impact of the nuclear technology on the implementation of the EU energy and climate change policy on a long term basis such that to eliminate short term effects in the power system. Given the specifics of the Romanian power system both electrical energy and thermal energy (CHPs) are considered in the main scenarios.

Keywords:	Nuclear energy system; Modelling energy system, CO_2 emissions mitigation; Electricity and heat cogeneration; Energy system security

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1. Introduction

The energy EU policy recently launched by the Commission is bringing along with the existing renewables penetration, emissions reduction and efficiency increase two more pillars i.e. interconnection of 15% of the energy consumption and the research in energy systems.

This approach gives a new area of research perspective, especially on the long-term energy systems development that needs to assess the impact of low or no emission energy technologies penetration beyond the short term spikes such that the one of renewables based on subsidies. These subsidized technologies are saturating after a period of fast penetration and need to be correlated with the rest of the system is clearly showing up.

Moreover, an integrated view is necessary on a long-term horizon for the system in order to assess the need to prepare investment and to secure the emissions reduction. Also, out of the various technological combination scenarios one should have the capability to select the optimal ones, given specific restrictions in the general frame of the economical optimization function.

The restrictions are reflected in the requirements of the EU policy summarized below based on the Road Map 2050 and other documents e.g. [6], [7], [8], [9].

2. Transforming the energy system

2.1. Energy saving and managing demand: A responsibility for all

Improving energy efficiency is a priority in all of the new scenarios related on the energy system decarburization. Current initiatives need to be implemented swiftly to achieve change. Higher energy efficiency in new and existing buildings is the key. Buildings – including homes - could produce more energy than they use. Investments by households and companies will have to play a major role in the energy system transformation. Energy efficiency has to follow its economic potential. This includes using the waste heat of electricity generation in combined heat and power (CHP) plants.

2.2. Switching to renewable energy sources

The second major pre-requisite for a more sustainable and secure energy system is a higher share of renewable energy beyond 2020.

Renewables will move to the centre of the energy mix in Europe, from technology development to mass production and deployment, from small-scale to larger-scale, integrating local and more remote sources, from subsidized to competitive. Many renewable technologies need further development to bring down costs.

Storage is currently often more expensive than additional transmission capacity, gas backup generation capacity, while conventional storage based on hydro is limited. With sufficient interconnection capacity and a smarter grid, managing the variations of wind and solar power in some local areas can be provided also from renewables elsewhere in Europe. This could diminish the need for storage, backup capacity and base load supply.

Renewable heating and cooling are vital to decarburization. A shift in energy consumption towards low carbon and locally produced energy sources (including heat pumps and storage heaters) and renewable energy (e.g. solar heating, geothermal, biogas, biomass), including through district heating systems, is needed.

2.3. Gas plays a key role in the transition

Gas will be critical for the transformation of the energy system. Substitution of coal (and oil) with gas in the short to medium term could help to reduce emissions with existing technologies until at least 2030 or 2035. On the other hand, gas heating may be more energy efficient than electric heating or other forms of fossil fuel heating, implying that gas may have growth potential in the heating sector in some.

2.4. Transforming other fossil fuels

Coal in the EU adds to a diversified energy portfolio and contributes to security of supply.

Oil is likely to remain in the energy mix even in 2050 and will mainly fuel parts of long distance passenger and freight transport. The challenge for the oil sector is to adapt to changes in oil demand resulting from the switch to renewable and alternative fuels and uncertainties surrounding future supplies and prices.

2.5. Nuclear energy as an important contributor

Nuclear energy is a decarburization option providing today most of the low-carbon electricity consumed in the EU. Some Member States consider the risks related to nuclear energy as unacceptable. Since the accident in Fukushima, public policy on nuclear energy has changed in some Member States while others continue to see nuclear energy as a secure, reliable and affordable source of low-carbon electricity generation.

New nuclear technologies could help to address waste and safety concerns.

As a large scale low-carbon option, nuclear energy will remain in the EU power generation mix.

2.6. Smart technology, storage and alternative fuels

Whichever pathway is considered, the scenarios show that fuel mixes could change significantly over time. Much depends on the acceleration of technological development. It is uncertain which technological options might develop, at what pace, with what consequences and trade-offs.

3. Brief description of the MESSAGE model

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) was first developed as model in IIASA (International Institute for Applied system Analysis) and later on taken over and extended by the IAEA (International Atomic Energy Agency) [4].

The model is based on a simplex (linear programing) algorithm [1] that finds the optimal scenario of energy technology penetration based on an optimality function and on several restrictions specified for the system under consideration.

The fact that the model allows discerning if a given scenario is optimal or not is an advantage at least for the capability to eliminate those scenarios that do not meet the optimality criterion, thus concentrate on the optimal ones. [3], [4], [15].

More evolved models may be used e.g. as developed in [2], but for the purpose of an initial assessment we decided to use the simplex that is at the basis of the MESSAGE initial program.

4. Scenarios, parameters and variables

In the determination of scenarios several parameters and variables were considered as presented in the Appendix 2. Our paper is only considering selected scenarios that reflect some of the requirements of the EU policy such as considering the distributed generation of heat from electrical energy sources or analysing the penetration of pumped storage hydro power plant, in the general framework of nuclear technology penetration in the power system of Romania. These considerations have reduced the number of selected scenarios that were run out of all possible ones. Several scenarios were run and only one has been chosen to be presented in here as a random example of the model possibilities. It should be underlined that the run scenarios are optimal scenarios that the model produces using a simplex algorithm given the specific scenario restrictions. The linear programming optimisation algorithm, in some cases, resulted in no optimal scenario with the given parameters and imposed restrictions. Having these optimal scenarios in place allows the decision maker to choose, based on economic criteria, a scenario; but whatever scenario is chosen it is an optimal one in its specific restrictions and objective function.

Present status of the energy system – in order to better understand the presented scenarios the present status of the energy system is given briefly (a list of recent data may be found in [5], [11], [12], [13], [14]). The generation of electrical energy in Romania is done from a balanced portfolio of technologies that includes 30% hydro, 20% coal, 18% nuclear, 15% hydrocarbures and the rest of 17% renewables (combining PV and wind and 0.7% biofuels).

There is a sizeable CHP generation (actually the CHP size has reduced continuously in the last 25 years still remaining important). Heat is also produced from heat only boilers either distributed residential or integrated into the heat networks serving to take over the heat demand peaks. Related to heating with renewable generation a massive introduction of heat pumps was considered as a potential extension of the heating options once the classic units were retired also by the penetration of nuclear units. This situation is reflected in the technology penetration figures in Appendix 1.

5. General MESSAGE case study development

The general MESSAGE case study for *the long term assessment of nuclear technology penetration in Romanian energy system* was developed by the ANDR and ICN-Pitesti team leaders using a preliminary model agreed by AIEA-PESS experts. The model improvement was implemented step by step based on the IAEA experts' recommendations.

The main improvements refers to use an updated study [5] on the classical and renewable long term contribution in national energy mix (as competitors up to 2070 to old and new nuclear technologies) and to use an Intermediary Level of energy between the Secondary Level and Final Level (in order to allow the independent control of the distribution and storage the electricity produced by the nuclear and renewable technologies, and the electricity and heat produced by the classical technologies). In the intermediary level works the hydro-pumping storage technology and the district heat storage and distribution technology were considered. These technologies are critical to ensure the security of total energy supply in the National Energy Mix (NEMix).

All classical, renewable and nuclear technologies are selected as possible competitors in the national long term energy mix, only if the associated technical and economic data are validated and defined in the general frame of the accessible references until February 2015. In respect with this principle, in this stage of the study, some innovative nuclear technologies (as eg. ALFRED – LFR) and the new proposal for carbon capture technologies (not expected to be validate until 2070), are not considered. The national energy mix considered in the model for the preliminary study, includes over 50 technologies. The Energy Chain is developed on 6 Energy Levels: Resources, Primary, Secondary, Intermediary, Final and Demand. There are 31 technologies "competitors" in energy production. There are 5 technologies in NEMix that transport, store and distribute to the demand level the energy in order to ensure the stability of the system on the all 24 load regions considered in NEMix.

The preliminary version of the reference case study was tested and agreed by ANDR and ISPE team in February 2015. This version was improved by ANDR team by taking into account the available internet information about the contribution of Hot Water Boilers and District Heat Mix and Distribution System used by the main national companies implied in provided the electricity an heat in the NEMix.

The code of the case studies, given in Appendix 2 (**NES**α**d**β**eh** ϑ**s**$\gamma\delta\varepsilon$**v**ζ**y**ϑ), includes the possibility to identify over the 2000 versions of the model in order to provide results for a specific selected of input data setting:

- 3 versions of the Nuclear Energy System – option/ scenario (α=Reference; Low; High)

- 3 versions of the Discount rate of investments (β=8%- reference; 5%- low; 10%- high)
- 3 version of the Scenario for the evolution of the demand of electricity and heat (ϑ=1 – reference; 2 – low; 3 – high)
- 3 versions of the "Specific options" to use support technologies & systems for energy transport storage & distribution (γ) like: „district station for Hot Water Mix and Distribution", "Hot Water Boilers, support for peak of gas CHP over-load heat requirements in the system" or „Electric Heat for cooking and for domestic boilers")
- 3 versions of the "Specific options" to use tax of CO2 emissions (δ = 0 for 10 [USD/tone CO2]; 1 for 5 [USD/tone CO2]; 3 for 30 [USD/tone CO2])
- 2 versions of the "Specific options" to bound renewable contribution in energy mix
- 3x2 version (ζ=23 –reference; 25 – low; 29 - high) of new nuclear investment cost vs the basic national concept (N) or new innovative concept (Q)
- the option to record the last year of the period of modelling (y) and to record if the program run in integer mode all the modelling period (eh – option) or was set to run in integer mode only until 2050 (ieh – option).

In a more comprehensive report conducted by Romania in an IAEA-INPRO project the modelling team have selected only 50 versions from over 150 optimal versions performed. The primary information about the case studies selected to be analysed in the INPRO national report are objective function, and elapsed time used by MESSAGE to run the specific case study. Elapsed time is important, when selecting the representative versions used to perform sensitivity NEMix assessment (some versions run over 180 hours – other only 20 minutes).

In what follows the results of a selected scenario (code [NES3d5eh2s200v23Ny70]) are presented in detail. It must be underlined that each of the considered scenarios has a similar set of results and the purpose of this presentation is to show one in detail. This scenario was chosen for demonstration purposes just to give the reader a flavour of the capability of the model.

As coded this is a rather complex scenario including: 4 CANDU units (operational 2 ones and those in construction – being approx. 40% ready/after 2019 + life extension)+ NEW NPP (Gen III+: LWR/ PWR/after 2035 – the LWR 1000MW units were chosen as a balance between the economy of scale and the size of the power system to ensure operational security)) + Gen IV(ALFRED)/after 2080 (not yet in the model until 2070); 5% discount rate; low demand; NO bounds of Hot Water Mix and Distribution (HWMixD) and Hot Water Boilers (HWB); 10 [USD/tone CO2] penalties of CO2 emissions; Reference investment cost for Nuclear; 2070 is the last year of modelling the CASE STUDY in MESSAGE.

It may be seen that the case is considering the penetration of nuclear technologies both the existing CANDU and advanced LWR technologies. The demand was chosen low given the trend of the energy efficiency policies and the price of the t of CO2 emissions taken at a low value to be conservative. This is the reason for choosing the power of the LWR units at 1000 MW due to operational reasons of the power system. Also, the investment cost for nuclear is at the reference value and the time horizon is 2070.

Some things to notice are the sharp increase of nuclear after the lifetime of some wind power parks reaches its limit and the associated reduction in CO2 emissions. Also, a sharp increase of the Uranium for nuclear fuel is seen accompanied by the need for more spent fuel deposit space. This aspect can affect in the future the public acceptance for nuclear.

The figures in Appendix 1 are giving the basic results in terms of the dynamics of the system.

6. Conclusions

In the framework of the EU energy policy the MESSAGE model was used to assess various scenarios of energy system development with time horizons in 2070. The main objective of the analysis was to assess first the optimality of the scenarios considered based on a simplex algorithm, second the impact of nuclear technology penetration such as emissions of CO2, need of Uranium for nuclear fuel, production of spent fuel for final repositories.

The capability of the model to run several versions of a scenario and to find by a simplex algorithm the optimal ones is a definite advantage that allows not only scanning various potential dynamics but also to cluster the optimal ones and provide the decision maker with a cluster of optimal versions to select from based on economic, financial, etc. considerations.

Thus the importance of the nuclear energy technologies penetration can be understood in the context of the whole energy system – the combined heat & power technologies and their district-heat facilities, support the increasing of nuclear energy technologies penetration in NEMix.

References

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[2] Purica, I., Nonlinear Models for Economic Decision Processes, Imperial College Press, London, 2010.

[3] An Introduction to MESSAGE, IAEA, Vienna.

[4] MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impacts, User Manual, IAEA, June 2007.

[5] ISPE Study code 8118/2014-1-S0071921-B2, Bucharest, December 2014.

[6] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

[7] Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community.

[8] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources.

[9] Decision no.406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020.

[10] IAEA Tools and Methodologies for Energy System Planning and Nuclear Energy System Assessments, IAEA, August 2009, https://www.iaea.org/OurWork/ST/NE/Pess/assets

[11] http://www.transelectrica.ro/sistemul-energetic-national

[12] http://www.anre.ro/ro/energie-electrica/rapoarte]

[13] http://media.cns-snc.ca/nuclear_info/candu_performance.html

[14] http://www.elcen.ro/

[15] https://www.iaea.org/OurWork/ST/NE/Pess/

Appendix 1

Basic MESSAGE result for case code [NES3d5eh2s200v23Ny70]

(Objective function = 689955 [US$'00] (MINimum)/ Elapsed time: 187h27m)

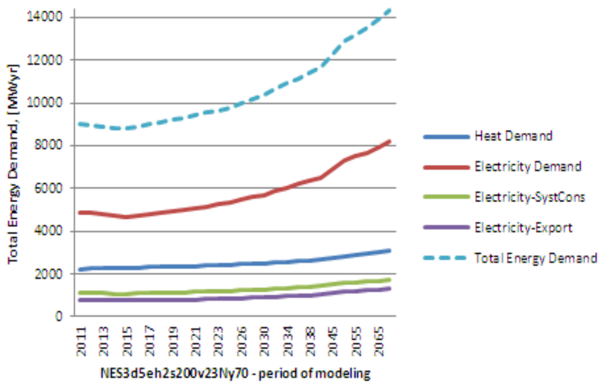

Figure 1: Total energy demand

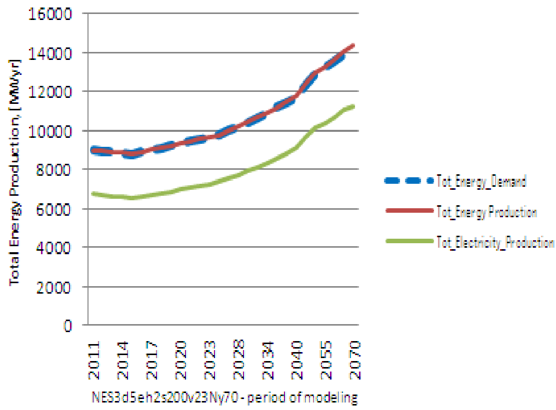

Figure 2: Energy production

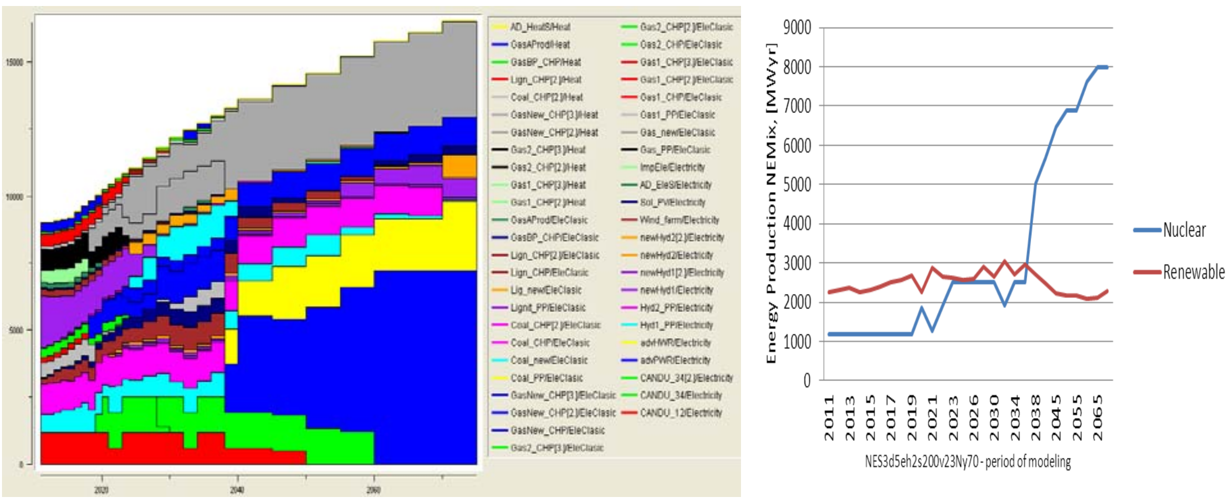

Fig. 3: Total energy production by competitors in NEMix and nuclear & renewable contribution

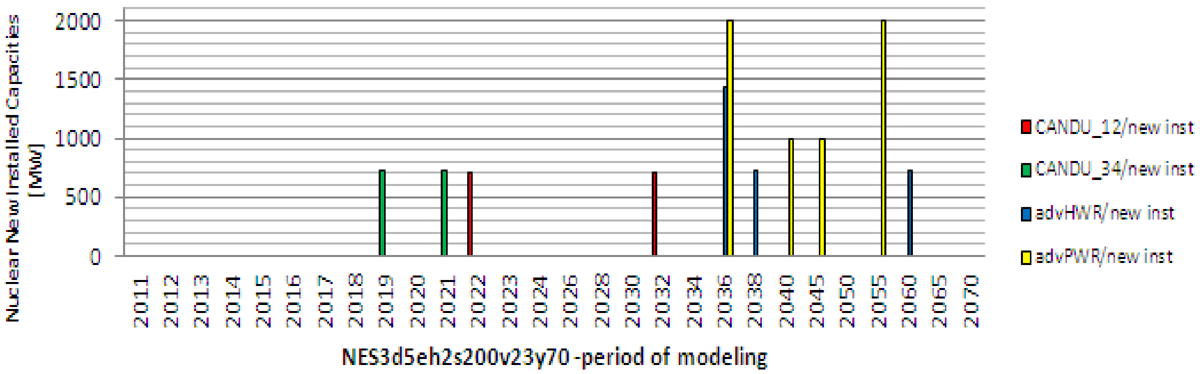

Fig. 4: Nuclear new installed capacities [MW]

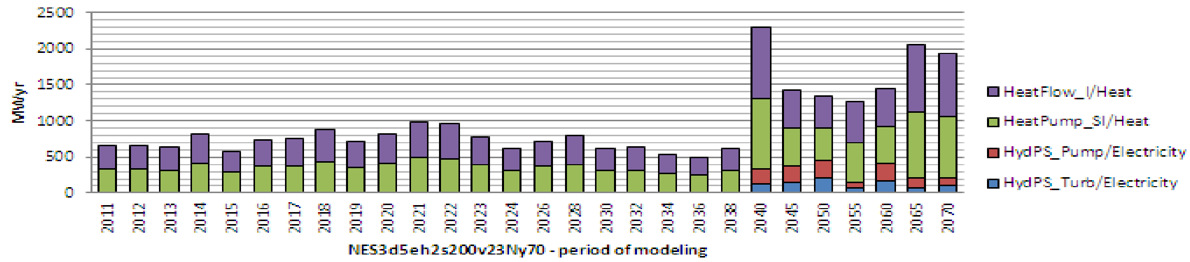

Fig. 5: Storage and re-distribution system (HydroPS & district heat distribution), [MWyr]

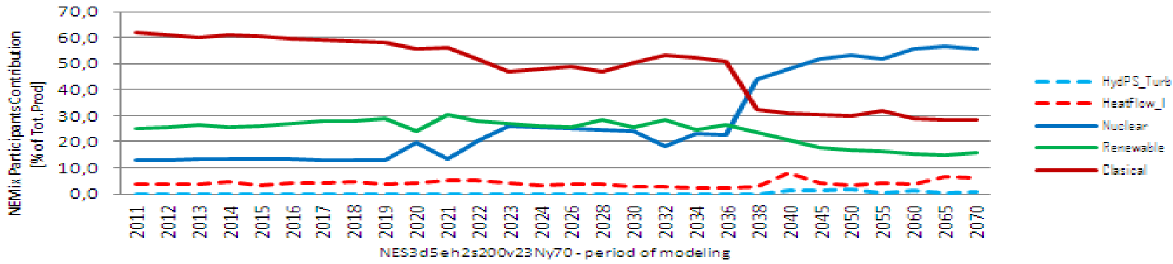

Fig.6: Re-Distribution system share in NEMix vs. competitor energy share production, [share]

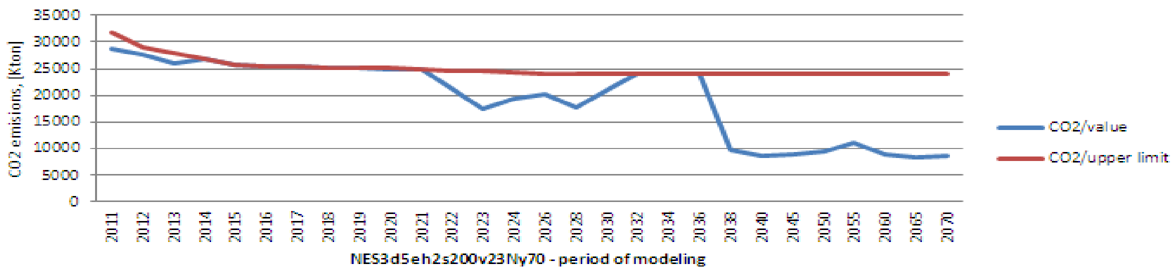

Fig.7: Evolution of CO_2 emissions, [kton]

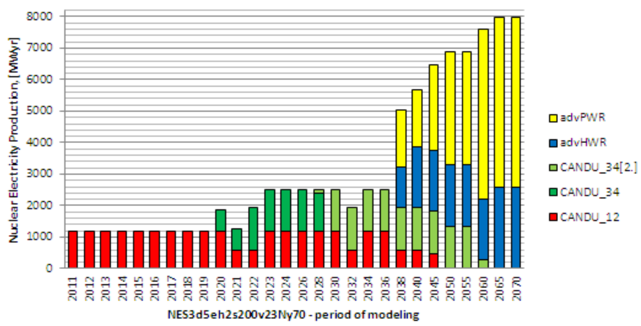

Fig.8: Nuclear Electricity production, [MWyr]

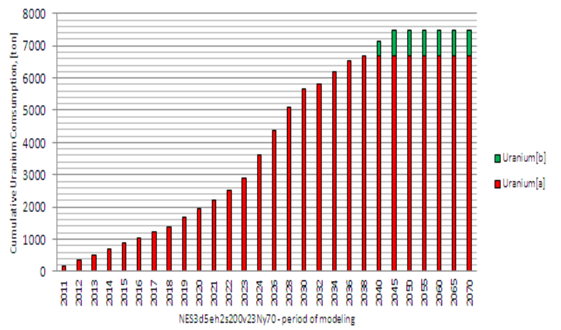

Fig.9: Cumulative Uranium consumption, [ton]

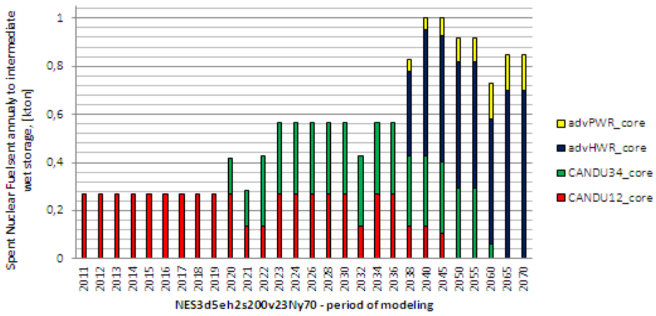

Fig.10: Spent nuclear fuel sent annually to intermediate wet storage, [kton]

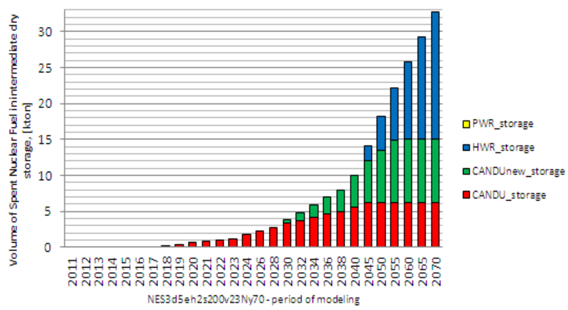

Fig.11: Volume of spent nuclear fuel in intermediate dry storage, [kton]

Appendix 2

CASE STUDY CODES

code		Meaning/ comments
[NES$\alpha d\beta eh\vartheta s\gamma\delta\varepsilon v\zeta y\theta$]		General code
NES		Nuclear Energy System – option/ scenario
α	1	Only 2 CANDU units (existing ones + life extension)
	2	4 CANDU units – national energy strategy in force 2013-2020 (existing ones and those in construction/after 2019 + life extension)
	3	4 CANDU units (existing ones and those in construction/after 2019 + life extension)+ NEW NPP (Gen III+: LWR/ PWR/after 2035) + Gen IV(ALFRED)/after 2080 (not yet in the model until 2070)
d		Discount rate of investments
β	5	5%
	8	8%
	10	10%
eh****		Scenario for the evolution of the demand of electricity and heat
ϑ	1	Reference Demand
	2	Low Demand
	3	High Demand
s		Specific options
γ		Option to use support technologies & systems for energy transport storage & distribution
γ	1	NO bounds of: HWMixD*, HWB**, El.HeatNucl***
	2	NO bounds of HWMixD and HWB,
	3	All additional innovative technologies are bounded
δ		Option to use tax of CO2emmisions
δ	0	10 [USD/tone CO2]
	1	5 [USD/tone CO2]
	2	30 [USD/tone CO2]
ε		Option to use a minimum contribution of renewable energy in mix
ε	0	NO bounds
	5	% of Renewable in the Total Electricity Production Mix, considered "fix/year" : 31,33,34,34,35,35,35,35,35,38...; last year:2035
v		Version of new nuclear investment cost vs. reference scenario and innovative scenario
ζ	23N	Reference investment cost for Nuclear
	25N	+18% Reference investment cost for Nuclear
	29N	-10% Reference investment cost CANDU34
	23Q;25Q;29Q	New Innovative System proposal to use Nuclear and Renewable electricity pick production in power the HWB for District Station (not in included in the model for the preliminary report)
y		Last year of modelling the CASE STUDY in MESSAGE
y	70	2070 is the last year of modelling the CASE STUDY in MESSAGE
	50	2050 is the last year of modelling the CASE STUDY in MESSAGE

* HWMixD – district station for Hot Water Mix and Distribution (HeatInFlow)

** HWB – Hot Water Boilers, support for peak of gas CHP over-load heat requirements in the system

*** El.HeatNucl – Electric Heat for cooking and for domestic boilers (solution not yet developed in Romania)

**** ieh – refers to the option to limit the optimisation process as integer only until 2050 – in order to extract faster partial results if the optimization process take over 100 hours