CANDU FUEL CYCLE ECONOMIC EFFICIENCY ASSESSMENTS USING THE IAEA-MESSAGE-V CODE

Iosif PRODEA[1], Cristina Alice MĂRGEANU[1], Ilie PRISECARU[2], Nicolae DĂNILĂ[2], Corina AIOANEI[1]

The main goal of the paper is to evaluate different electricity generation costs in a CANDU Nuclear Power Plant (NPP) using different nuclear fuel cycles. The IAEA-MESSAGE code (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) will be used to accomplish these assessments. This complex tool was supplied by International Atomic Energy Agency (IAEA) in 2002 at "IAEA-Regional Training Course on Development and Evaluation of Alternative Energy Strategies in Support of Sustainable Development" held in Institute for Nuclear Research Pitesti. It is worthy to remind that the sustainable development require satisfying the needs of present generations without compromising the possibility of future generations to meet their own needs. Based on the latest public domain information in the next 10-15 years four CANDU-6 based NPP could be in operation in Romania. Two of them will have some enhancements not clearly specified, yet. Therefore we consider being necessary to investigate possibility to enhance the economic efficiency of existing in-service CANDU-6 power reactors. The MESSAGE program can satisfy these requirements if appropriate input models will be built. As it is mentioned in the dedicated issues, a major inherent feature of CANDU is its fuel cycle flexibility. Keeping this in mind, some proposed CANDU fuel cycles will be analyzed in the paper: Natural Uranium (NU), Slightly Enriched Uranium (SEU), Recovered Uranium (RU) with and without reprocessing. Finally, based on optimization of the MESSAGE objective function an economic hierarchy of CANDU fuel cycles will be proposed. The authors used mainly public domain information on the different costs required by analysis.

Keywords: CANDU fuel cycle, sustainable development, IAEA-MESSAGE.

1. Introduction

The recent rising in oil and natural gas prices started in the beginning of 2006, have actualized the necessity of alternative energy resources like the nuclear energy is. After more then a quarter of century when the building of five nuclear units was started at Cernavoda, only one nuclear unit is in operation and the second one is quite ready to be commissioned, this autumn. The units 3 and 4 are scheduled to be commissioned most probably after 2015 year. It is accepted that a

[1] Senior Researcher, Institute for Nuclear Research, Pitesti, Romania
[2] Prof., Department of Energy Production and Use, University "Politehnica" of Bucharest, Romania

more developed nuclear sector would have been more helpful for Romanian economy during the last two years when the oil and natural gas have become more and more expensive. Knowing that all the four units at Cernavoda site will be CANDU-type, we consider being necessary to perform a technical-economical study regarding the use of different nuclear fuel cycles for such a reactor's type.

2. The IAEA-MESSAGE Code

One of the most important IAEA[3] activity area is sustainable development. It is worthy to remember that the sustainable development means the promotion of those technologies which can satisfy the actual generation's needs without compromising the future generations' capacity to meet their own needs. The IAEA-PESS[4] fulfills consistent tasks regarding the sustainable energy development. This IAEA section has several dedicated tools to accomplish a large variety of sustainable energy development analyses among we mention, [1]: **MAED** (Model for Analysis of Energy Demand), **FINPLAN** (Model for Financial Analysis of Electric Sector Expansion Plans), **SIMPACT** (Simplified Approach for Estimating Environmental Impacts and External Costs of Electricity Generation), **WASP** (Wien Automatic System Planning Package) and, the last but not the least **MESSAGE** (**M**odel for **E**nergy **S**upply **S**trategy **A**lternatives and their **G**eneral **E**nvironmental Impacts). The MESSAGE code has firstly supplied to several European Eastern country in 2002 during an IAEA course entitled: "Regional Training Course on Development and Evaluation of Alternative Energy Strategies in Support of Sustainable Development using IAEA new tool MESSAGE". That course was held in Institute for Nuclear Research (INR) Pitesti. Some user's interface enhancements were summarized during another IAEA course held in 2005 at Flensburg University (Germany). A brief description of the IAEA-MESSAGE code will be presented below, after the Reference [2]. MESSAGE is a model designed for the optimization of energy system (i.e. energy supplies and utilization). The model was originally developed at International Institute for Applied Systems Analysis (IIASA), Laxemburg, Austria. The IAEA acquired the latest version of the model and several enhancements have been made in it, most importantly addition of a user-interface to facilitate its application. The underlying principle of the MESSAGE model is optimization of an objective function under a set of constraints that define the feasible region containing all possible solutions of the problem. The value of the objective function helps to choose the solution considered best according to the criteria specified. In general categorization, MESSAGE belongs to the class of mixed integer programming models as it has the option to define some variables as

[3] International Atomic Energy Agency
[4] Planning and Economic Studies Section

integer. A set of standards solvers (e.g., GLPK, OSLV2, OSLV3, CPLEX, MOSEK) can be used to solve the MESSAGE model, [2]. MESSAGE is designed to formulate and evaluate alternative energy supply strategies consonant with the user-defined constraints such as limits on new investment, fuel availability and trade, environmental regulations and market penetration rates for new technologies. Environmental aspects can be analyzed by accounting, and if necessary limiting, the amounts of pollutants emitted by various technologies at various steps in energy supplies. This helps to evaluate the impact of environmental regulations on energy system development.

3. Modelling of some CANDU fuel cycles using the MESSAGE code

According to studied literature [3], [4] and [5], four possible CANDU fuel cycles were chosen to be modelled. They are presented below along with their abbreviation which will be used in tables and figures.

1. NU = Natural Uranium,
2. SEU1.2% = Slightly Enriched Uranium with 1.2% U235,
3. RU_WR = Recovered Uranium Without Reprocessing,
4. RU_Reproc = Recovered Uranium with Reprocessing.

Corresponding to each of the four up-mentioned fuel cycle a nuclear energy technology was built in the MESSAGE input data model. The MESSAGE power flow diagram is illustrated in Figure 1.

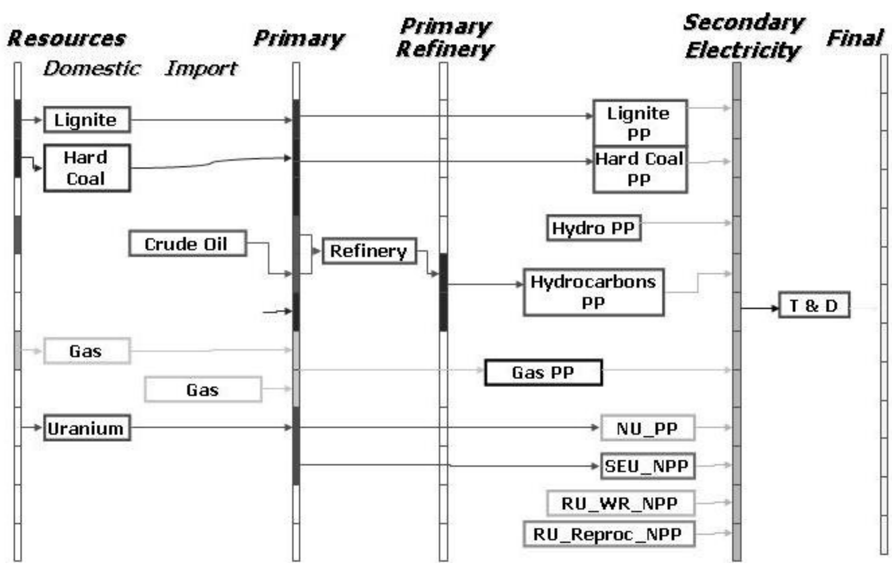

Fig. 1. Power System flow diagram.

The "NPP" suffix means that a Nuclear Power Plant (NPP) will be fuelled through the corresponding cycle. A technology can or cannot have an input, but it should always have an output. Some assumptions were made and presented below:

- the modelled period starts in 2005 year and ends in 2020;
- the reference year is 2000;
- discount rate is 5%;
- number of modelled periods is 5 and each period has 2, 3, 5, 5, 5 years, respectively.
- a constant annual electricity growth rate of 1% was assumed.

Table 1 shows a synthetic description of the four fuel cycles involved in our analysis. The data source was the References [3], [4], [5] and our calculations.

Table 1

The fuel cycle costs

Cycle	NU	SEU 1.2%	RU_WR	RU_Reproc
Import price ($/kgU)	0	0	1,300	1,300
Uranium Conversion ($/kgU)	8	8	0	0
Enrichment ($/kgU 1.2% SEU*)	0	811	0	0
Fabrication ($/kgU)	70	70	100	100
Reprocessing ($/kgU)	0	0	0	700
Spent fuel storage ($/kgU)	50	30	50	100
Final disposal ($/kgU)	80	80	200	200
Efficiency	0.3	0.9	0.4	0.5
Total O&M ** cycle costs ($/kg)	188	1019	1650	2400
Total O&M cycle costs ($/kWyr)	9	50	80	117

*[6], [7] Separative Work Unit (SWU) no ≈1.2/0.71=1.69, then multiplied by 80$/SWU, cf.[4] and finally by the amount of NU(kg) which leads to 1 kg of SEU 1.2%, i.e. ≈6. Thus, the enrichment cost becomes 1.69x80x6=811 $/kgU 1.2% SEU
**O&M=Operation and Maintenance

Other helpful hypotheses which allowed us to realize a simply (almost didactic) MESSAGE model were:

- all four nuclear units corresponding to nuclear technologies implemented in MESSAGE input are identical and have a brut power of 700 MWe;
- the Commissioning year is the same (1996) and lifetime is 30 years;
- the delay-time intervals (so called "lag time") were not taken into account;
- all non-nuclear (classical) energy technologies efficiency was reduced one hundred times in order to force MESSAGE to only take into account the "nuclear competition" between the four studied CANDU fuel cycles;

- the enrichment of Recycled Uranium is 0.83% U235, [4] and its Plutonium enrichment after reprocessing wasn't considered;
- due to a large range of RU prices found out in the literature, only an "average" import price of 1300 $/kg was assumed;
- as result, the third and the fourth technologies have no input;
- the efficiency of RU-based cycles was chosen accordingly to that of NU NPP which is about 0.3;
- in order to obtain MESSAGE energy cost units, some conversions were made, i.e.: from $/kgU to $/kWyr.

4. Results and discussions

One of the MESSAGE concepts is "the scenario" which is one alternative image of how the future might unfold, [8]. In our case a scenario is a possible development way of an energetic system. Three scenarios were chosen to be modelled: the basic scenario where all input data were introduced "as-is" (as they resulted from calculations), the Uranium price increase scenario and the RU price increase scenario.

4.1. The Basic scenario

Figure 2 shows the total electricity amount share when the input data are introduced as they were calculated. As it can be seen the MESSAGE code "chose" (based on the minimization of total costs-the default optimization criterion) to use preponderantly the "SEU1.2%" and "RU_WR" nuclear technologies to cover the established electricity demand through the studied period. It can also be seen a constant growth of "RU_Reproc" share in the total amount of electricity. A simple conclusion would be that the "SEU1.2%" and "RU_WR" are the most attractive technologies to be used in case of the Basic scenario.

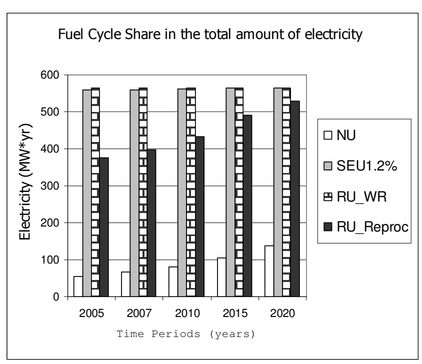

Fig. 2. Fuel cycles share in the total electricity amount-Basic scenario.

What it can happen if the Uranium and RU prices are changed? We'll see that in the next scenarios.

4.2. The Mined Uranium Price Increasing scenario

As the chapter title says this scenario will analyze what it can happen if the mined Uranium price grows. We carried out a lot of calculations using a large range of mined uranium prices in order to be able to see some differences in the MESSAGE outputs. The Figures 3, 4, 5 and 6 show the influence of mined uranium price growth.

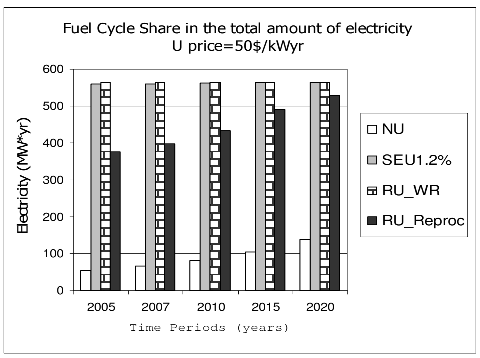

Fig. 3. Uranium price=50 $/kWyr.

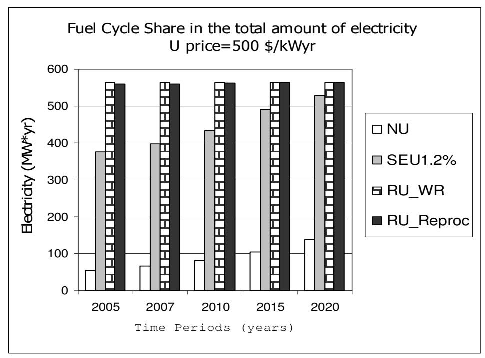

Fig. 4. Uranium price=50 $/kWyr.

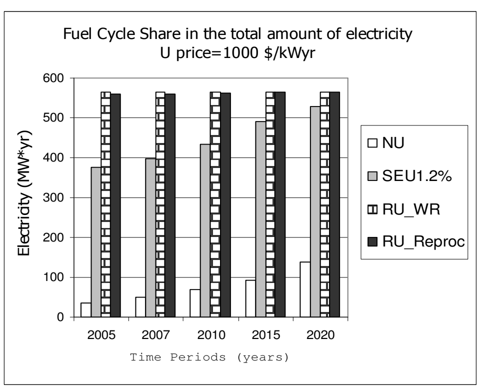

Fig. 5. Uranium price=1000 $/kWyr.

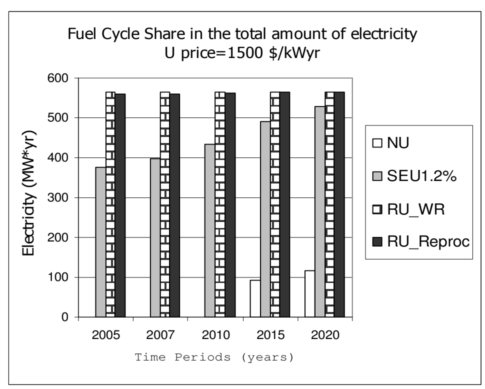

Fig. 6. Uranium price=1500 $/kWyr.

The first observation is that the most "affected" technology by the mined Uranium price increasing is the NU (Natural Uranium) technology. Knowing that the NU technology has the most U consumption to produce electricity unit, this behaviour shouldn't surprise us. On the other side, the NU technology has the lowest efficiency (see Table 1) and thus, the U price growth scenario leads to fewer and fewer share of its electricity generation in the total electricity amount. It is also worthy to notice the small "sensitivity" of the NU and SEU1.2% cycles on U price increasing, in fact this price had to be varied in a large interval (50 to 1500 $/kWyr), i.e. its marginal values ratio was about 30.

4.3. The Recycled Uranium Price Increasing scenario

In this case we assumed the RU price growths showed in Table 2. The results are illustrated in Figures 7 to 10.

Table 2

The imported Recycled Uranium price growth scenarios

Fuel Cycle	RU_WR price ($/kWyr)	RU_Reproc price ($/kWyr)
Basic scenario	80	117
Growth 1	100	150
Growth 2	100	200
Growth 3	200	300

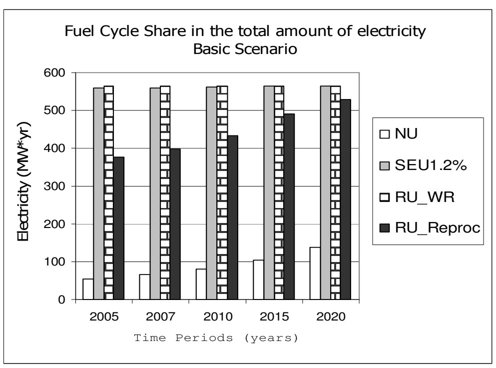

Fig. 7. Basic Scenario, RU pairs=(80,117).

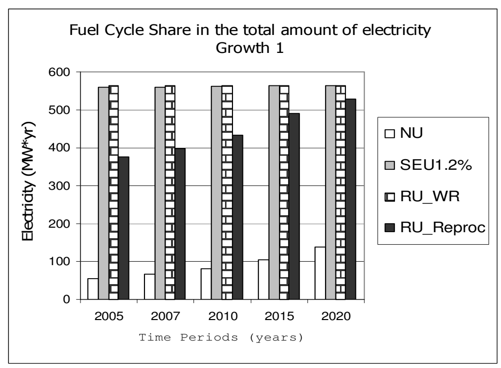

Fig. 8. Growth 1, RU pairs=(100,150).

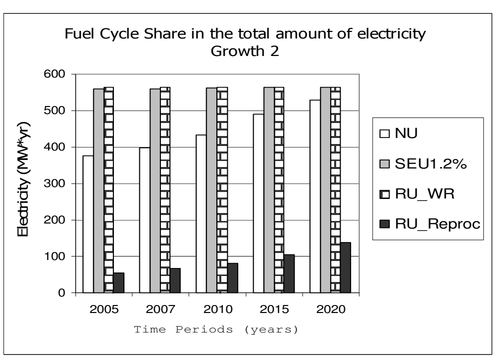

Fig. 9. Growth 2, RU pairs=(100,200).

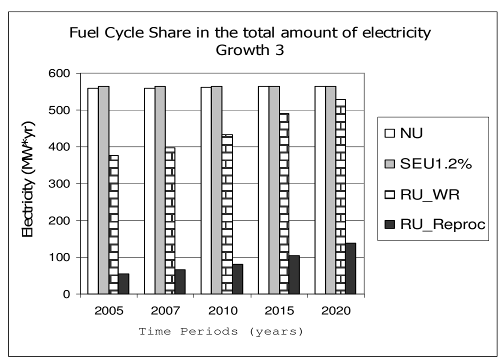

Fig. 10. Growth 3, RU pairs=(200,300).

We can observe how the RU fuel price increasing leads to its step by step electricity share decreasing. At this time, the RU price intervals are smaller in size than those from previous chapter scenario. Their values cover a range from 80 to 300 $/kWyr and that was sufficient to induce "visible" changes in MESSAGE outputs. In this case, the ratio between the interval margins is only about 3.75, oppositely to Mined Uranium price growth scenario when the ratio was 30.

5. Conclusions

A simplified CANDU fuel cycles analysis was carried out using the IAEA-MESSAGE code.

Natural Uranium (NU) and Slightly Enriched Uranium (SEU, having 1.2% U235 enrichment) fuel cycles showed a low sensitivity on mined Uranium price increasing. As opposed, the Recycled Uranium cycles with and without reprocessing showed a larger sensitivity on their fuel prices' growth (assumed to be imported). SEU1.2% fuel cycle supplied the largest shares in the total electricity amount during all studied scenarios, thus it can be considered the most sustainable CANDU fuel cycle in our analysis.

The RU without reprocessing and NU fuel cycles have settled together on the second position due to smaller differences between their cumulative shares in total electricity generation through all analyzed scenarios. The basic scenario shows a net advantage of RU_WR against NU while the RU price increasing inverses the situation. The RU with reprocessing fuel cycle seems to be less attractive for Romania especially, our country has neither industrial enrichment capacities nor Light Water Reactor spent fuel reprocessing facilities.

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